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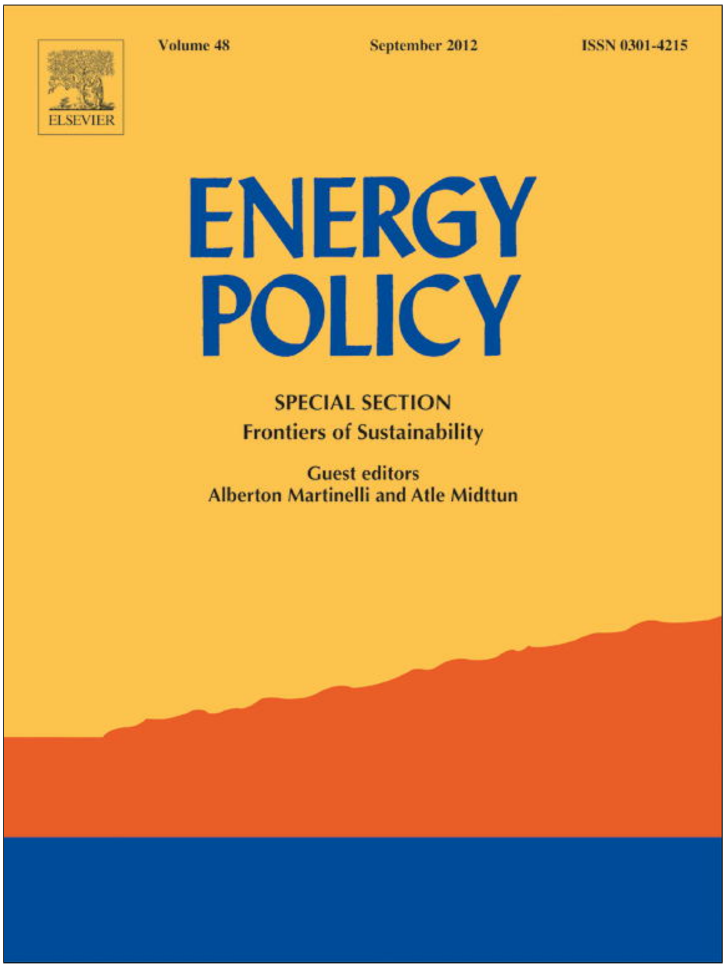

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Scenarios for solar thermal energy applications in Brazil

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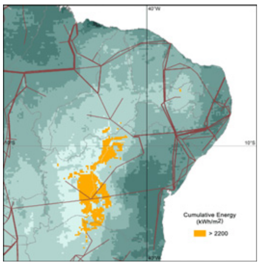
HIGHLIGHTS

- ► Scenarios for solar thermal applications are presented.
- ► Payback is typically below 4 years for small scale water heating systems.
- ► Large-scale water heating systems also present high feasibility.
- ► The Brazilian semi-arid region is the best sites for CSP and chimney tower plants.

GRAPHICAL ABSTRACT



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ABSTRACT

The *Solar and Wind Energy Resource Assessment* (SWERA) database is used to prepare and discuss scenarios for solar thermal applications in Brazil. The paper discusses low temperature applications (small and large scale water heating) and solar power plants for electricity production (concentrated solar power plants and solar chimney plants) in Brazil. The results demonstrate the feasibility of large-scale application of solar energy for water heating and electricity generation in Brazil. Payback periods for water heating systems are typically below 4 years if they were used to replace residential electric showerheads in low-income families. Large-scale water heating systems also present high feasibility and many commercial companies are adopting this technology to reduce operational costs. The best sites to set up CSP plants are in the Brazilian semi-arid region where the annual energy achieves 2.2 MW h/m^2 and averages of daily solar irradiation are larger than 5.0 kW h/m^2/day. The western area of Brazilian Northeastern region meets all technical requirements to exploit solar thermal energy for electricity generation based on solar chimney technology.

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1. Introduction

The energy demand, resulting from technological advances, social and economic development, is being blamed as the most important impact factor in climate change and environmental issues as revealed by the scientific community (IPCC, 2007; Sims, 2004). The energy consumption increased more than three fold after the Industrial Revolution and recent studies showed a growth trend in energy demand because of the enhancement in quality of life in developing countries. The current growth rate points out that the energy consumption in developed countries will be surpassed by the consumption in the developing countries during the next 10 years (Goldemberg and Villanueva, 2003).

In addition to the environmental concern, energy security is another important issue driving both government and non-government organizations to explore energy alternatives to meet the energy requirements in order to sustain the economic development. In summary, the energy security and the environmental concerns are boosting up research and development in renewable energy technology in order to promote sustainable growth.

The mid and long term energy planning and policy requires reliable information on renewable resources. The SWERA (Solar

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and Wind Energy Resource Assessment) project was coordinated by United Nations Environment Program (UNEP) under financial support of the Global Environmental Facility (GEF). The SWERA has generated a high quality database on renewable energy resource for several developing countries around the word, and make it available online at no cost in http://swera.unep.net/. Renewable energy information provided through SWERA includes atlases of solar and wind energy resources, regional assessments, interactive online maps, geospatial database and energy analysis models. For Brazil, the available information on solar energy resource includes the seasonal and annual averages for global, diffuse, direct normal and latitude tilted surface solar irradiation provided by model BRASIL-SR in 10 km × 10 km (Martins et al., 2008a and b; Pereira et al., 2006). All the products were prepared under the coordination of Brazilian Institute for Space Research (INPE). The Solar Energy Laboratory of University of Santa Catarina (LABSOLAR/UFSC), the Brazilian Centre for Research in Electricity (CEPEL) and the US Renewable Energy Laboratory (NREL) were partners in this enterprise.

This paper aims to present scenarios derived from the SWERA database for feasibility analysis of solar thermal energy applications in Brazil. The case studies presented here can help and encourage decision makers and entrepreneurs to establish energy policies and initiatives in Brazil. The paper includes scenarios for water heating applications, concentrated solar power plants, and solar chimney plants. For each application, it will be presented a general overview on current status of the technology in Brazil. Sections 4 and 5 present geospatial analysis concerning the suitable location for CSP and solar chimney plants in Brazilian territory.

2. Solar energy resources in Brazil

The scenarios for solar energy were created using the solar energy resource database provided by the radiative transfer model BRASIL-SR by using satellite data from 1995 to 2005 as input data. The model BRASIL-SR is a physical method developed by INPE and based on radiative transfer model described in Stuhlmann et al. (1990). It uses cloud cover data acquired from geostationary satellite images together with climate data to parameterize the radiative processes in atmosphere (Martins, 2001).

Maps for annual, seasonal and monthly averages for solar irradiation were prepared at 10 km × 10 km horizontal resolution. Although, this spatial resolution is not enough for project implementation, it makes possible to perform simulations with adequate accuracy for energy planning and pre-design facilities. Fig. 1 presents the annual average of daily total of global solar irradiation at the surface. The seasonal maps as well as the complete solar database are available for free download at http://swera.unep.net or at http://sonda.ccst.inpe.br/. If more detailed simulations are necessary, the SWERA project has also made available the typical meteorological years (TMY) for the 20 Brazilian cities distributed throughout all Brazilian regions as showed in Fig. 2.

In spite of the different climate characteristics along the Brazilian territory, the solar irradiation is fairly uniform. The uppermost daily solar irradiation – 6.5 kW h/m^2/day – occurs in semi-arid climate area of the Brazilian Northeastern region. This area presents low rainfall throughout the year (roughly 300 mm/year) and the lowest annual average cloud amount in

Fig. 1. Annual average of daily sum of global solar irradiation for Brazilian territory.

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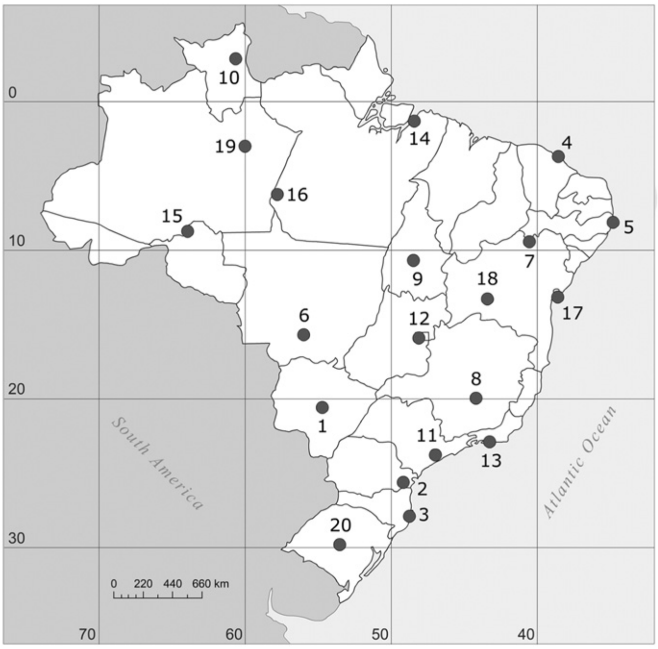

Fig. 2. Location of the cities for which the typical meteorological year (TMY) was generated during the SWERA project. The TMY Database is available to download at http://swera.unpe.net/.

Brazil. The influence of the Tropical High Pressure associated with the South Atlantic Tropical Anticyclone provides a stable condition of low nebulosity and high incidence of solar irradiation for the region throughout the year.

The lowest daily global solar irradiation – 4.25 kW h/m^2/day – occurs on the shore of the Brazilian Southern region where precipitation is well distributed all over the year. The annual average of daily horizontal global solar irradiation in any region of the Brazil is much larger than in most of the EU countries where projects to harness solar resources are greatly disseminated.

The Amazon region receives lower daily solar irradiation than the Brazilian Southern region during the Austral Summer (December to February) in spite of being closer to the Equator. This is due to climate characteristics in Amazon: larger cloud coverage and rainfall during the summer as a consequence of strong influence of the Inter-Tropical Convergence Zone (ITCZ).

In addition, the seasonal variability of solar irradiation is smaller in the Northern region than in the Southern and Southeastern regions. The climate in these last two regions is characterized by two seasons: a wet season from November to April, and a dry season from May to October. The temperate climate and the influence of the meteorological systems contribute to enhance the nebulosity in Southern and Southeastern regions during the wet season. During the dry season, the climate in these both regions are characterized by very low precipitation, mild temperatures and more days with clear sky conditions (Pereira et al., 2006).

The reliability and confidence levels, as well as the resource variability, were discussed in details in earlier publications (Martins et al., 2008a; Pereira et al., 2006; Beyer et al., 2004). In summary, the model slightly overestimated the global solar irradiation in all Brazilian regions. The BIAS deviation around 6% and RMSE (root mean square error) nearly 13% were obtained throughout Brazilian territory. The largest data deviations were observed in the Amazon region and it was explained by the prevailing climate in this region with large precipitation in summer. Reduced maintenance in the ground measurements sites located in remote areas could also contribute to increase observed deviations between model estimates and ground data (Pereira et al., 2006, Martins et al., 2005). By the way, the model BRASIL-SR has presented similar performance as other radiative transfer models used in SWERA for mapping solar resource in other world regions (Beyer et al., 2004).

3. Thermal solar energy applications for water heating

Thermal solar energy (i.e., solar radiation directly used to generate heat) is one of the oldest applications of the solar energy resource. The solar thermal power can be employed in two different ways: low or high temperature applications. The low temperature systems include water and space heating (or cooling) for commercial and residential buildings (Kalogirou, 2004).

The concentrated solar power (CSP) technology is a high temperature application of solar thermal that is turning into an attractive alternative to produce electricity (IEA, 2010). In addition to CSP, solar chimney technology can be considered a thermal application since the solar energy is used to warm up the air inside greenhouse-like circular structure in order to produce air movement capable to rotate a turbine (Dos Santos Bernardes et al., 2003, Schlaich and Schiel, 2001).

The reasons that hinder the large-scale use of thermal solar energy are related to lack of reliable information on resource variability and uncertainties, discontinuity during the night time period and low energy density when compared to the use of electricity, firewood and fossil fuels. In Brazil, the thermal use of solar energy is still small when compared to the energy generated by biomass and fossil fuels burning since they have larger energy density and can be easily stored (Martins and Pereira, 2011).

This paper aims to spread the knowledge about the advantages of solar heating taking into consideration the environmental issues as well as the financial viewpoint. Despite the high initial investment, the payback period is short, as it shall be discussed later on in further details.

3.1. *Water heating market in Brazil*

The widespread application of thermal solar energy in Brazil is water heating in dwellings. Thermal solar energy applications in other areas, such as the agro-industry, request for greater investments compared to the low value added to production. For this reason, the technologies in use are generally not very sophisticated.

The solar water heating would be the most promising application of solar thermal energy if not for a particular characteristic that sets Brazil apart from other countries regarding water heating. During the 1960s and 1970s, huge investments were made in the hydroelectric energy generation by the Brazilian government. Unfortunately, the economic expansion did not follow the growth rate achieved in electricity production. At that circumstance, electric showerheads became widely used in the country owing to incentives for the consumption of the exceeding electricity. Electric showerheads are high power equipment – usually above 4 kW – but with a low load factor since they are switched on typically for only few minutes a day. Fig. 3 shows the total and per sector demand of electricity in Brazil during the day. By observing the total energy demand curve, a high peak can be perceived in early night time hours. The same pattern is reproduced in the residential consumption curve. Most of the Brazilian people get back home after a work day in the early night time and make use of water heaters for personal care or home activities. This behavior profile allows us to conclude that the use of showerhead for water heating is the major responsible for the "peak demand time" in electricity consumption. The showerhead

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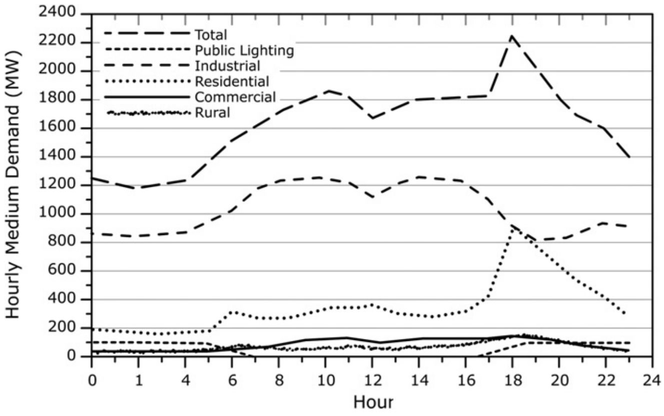

Fig. 3. Hourly demand of electric energy per sector in Brazil. (Pereira et al., 2008).

replacement should be considered as an effective measure to improve the rational use of electricity in Brazil and to reduce the energy demand at the peak demand time.

Currently, there is no government programs specifically formulated to promote the adoption of solar water heating technology in dwellings, public buildings or for industrial applications. Only ''PROCEL'' and ''My Home My Life'' can be mentioned as a government initiative that indirectly supports the solar water heating systems. The PROCEL program regulates standards, requirements and actions aiming at to improve energy efficiency of equipments and buildings. The PROCEL was created to promote a more efficient electricity generation and consumption so as to reduce costs and support investments in the electricity generation (ELETROBRAS, 2011; Pereira et al., 2008).

The Brazilian government program ''My Home My Life'' was implemented at end of 2009 to reduce the deficit in housing for families with low income. This program requires the use of solar heaters in the financed dwellings. Despite of triggering an increasing demand for heaters, this initiative is a direct incentive for market expansion of solar heaters.

In addition to national government actions, there are many regional initiatives from medium to large size cities to promote the solar water heating by regulating discounts in municipal taxes and making this technology as mandatory requirement for new public and private buildings. Currently, more than 5 million m^2 of solar heating collectors are installed (DASOL, 2011). However, this area is small when compared to that of countries where the solar energy resources are lower, such as Germany. Fig. 4 shows the installed capacity in thermal megawatts per group of 100,000 inhabitants in several countries. It can be observed that Brazil has a very low rate, which indicates the large market still available in the country (Weiss et al., 2006).

There are several industries for solar heating systems in Brazil, all focusing their production on flat panel solar collectors with glazing. Over the last years, some industries started manufacturing plastic collectors without glazing used mostly for heating pools. Collectors with evacuated heat pipes are not manufactured in Brazil.

3.2. Residential solar heating scenario

Currently, the Brazilian market for solar heating systems is concentrated in high-income strata. The reason for that is associated to the high initial investment required for a solar heating system when compared to the electric showerhead alternative. The adoption of solar water heating systems in high-standard dwellings is already included in the project design and, therefore, the initial investment is attenuated in the total cost of the building.

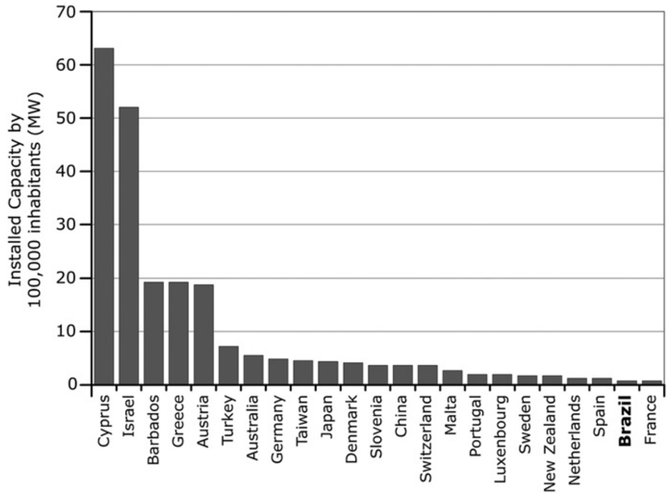

Fig. 4. Installed capacity of solar collectors for water heating per group of 100,000 inhabitants in 2004 (Pereira et al., 2008).

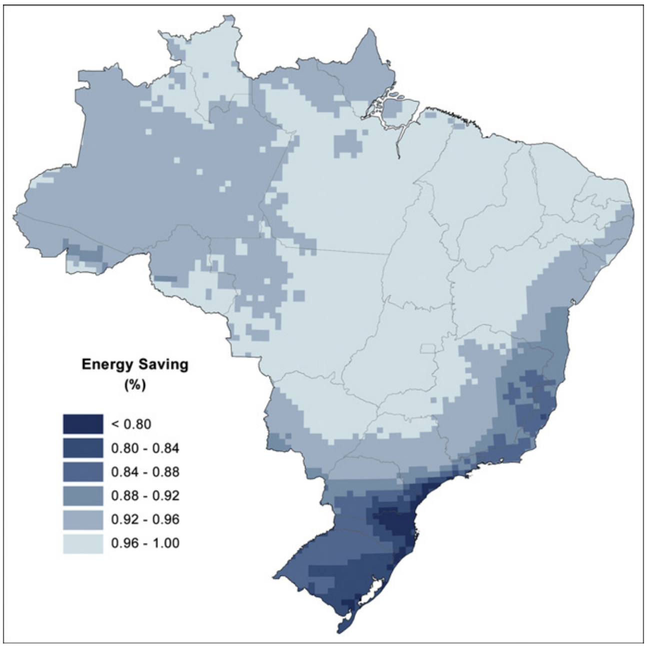

Fig. 5. Percentage of saved energy if a standard solar water heating system designed for low-income families in Brazil is used to replace showerhead. The solar heating system has 4 m^2 flat-plate solar collector with glazing and a storage tank of 300 l for hot water at 60 °C in the storage tank.

On the other hand, the electric showerhead is the most common alternative used in dwellings for the low-income families since it does not require any investment for hot water distribution. Recently, some manufacturers launched solar heating compact systems suitable for reduced demands of hot water which has a hot water distribution grid installed outerwalls in order to reduce installation costs.

The most widely used scheme to simulate the performance of solar heating systems based on monthly average of solar radiation data is the F-chart method (Klein and Beckman, 2000). By using the F-chart method together with SWERA database, it is possible to map the fraction of saved electricity by adoption of solar water heating systems in Brazil. Based on this map, the detailed economic analysis and specific cases of practical interest were carried out.

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The first scenario considered was a compact system designed to replace the electric shower in households of low-income families consuming around 300 l per day of hot water at 40 °C (temperature after mixing with cold water at the delivering point). The simulation assumed water temperature equals to 60 °C at storage tank. A standard flat-plate solar collector with a single glass cover was considered. The collector area was 4 m^2 and its efficiency parameters were 0.67 kJ and 20.66 kJ/(m^2 h K) that meet the requirements for Efficiency Class A System established by INMETRO (Brazilian Institute of Metrology, Quality and Technology). More detailed information can be found at http://www.inmetro.gov.br/consumidor/pbe/ColetoresSolares-banho.pdf.

One important issue related to solar water heating systems is Legionnaires disease. As well as temperature, the time taken for completely replace the volume of water held in the storage vessel is an important aspect. Research has shown that legionella bacteria is killed in few minutes at 60 °C (IEA, 2001). The simulated scenario assumes that the total volume (300 l) of the storage tank is consumed in one day.

The required energy to achieve the final water temperature was obtained taking into account the monthly average of local temperature data. The percentage of saved energy per dwelling is presented in Fig. 5.

The map presented in Fig. 6(a) shows the energy savings per year considering the described system. Although the fraction of energy savings per dwelling is higher at locations with warmer weather like Northern, Northeastern and Central regions, the total energy savings per year are quite similar for all Brazilian regions. Bearing the market breakthrough in mind, the payback period for this solar heating system is presented in Fig. 6(b). The payback time map was prepared considering an estimated total cost of US$ 500 for the compact low cost system described above. It was also considered the electricity price at 0.12 US$ per kW h and the interest rate of 10% per year. The payback time is smaller mainly for regions with larger energy demand and located in the subtropical climate in Southern and Southeastern regions.

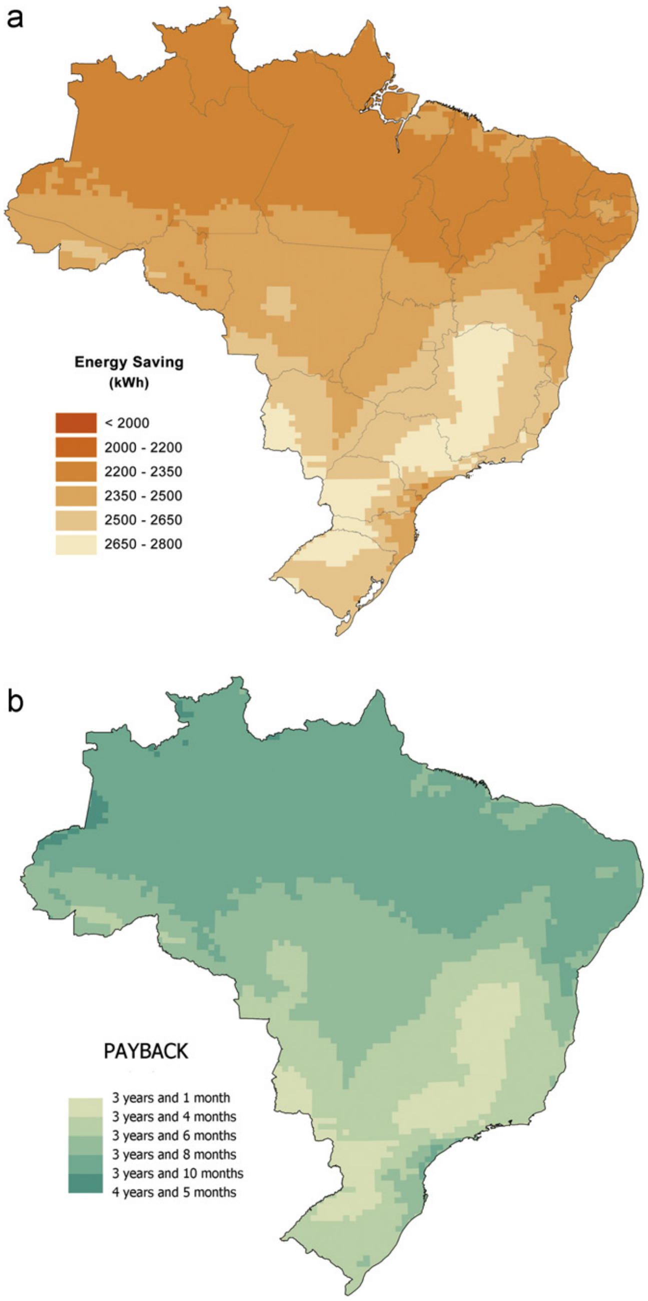

Fig. 6. Annual energy savings (a) and Payback period (in years) (b) for a typical residential heating system for low-income families in Brazil.

3.3. Large-scale solar heating scenario

The large-scale solar heating systems may deliver hot water for domestic applications and for any application in which the required water temperature is compatible with that supplied by the available solar heating systems in market. The multi-family residential sector like multiple housing units or vertical buildings, where solar heating can work together with a large central heating system, is a major example of application for such systems. In general, the payback periods in such cases are shorter than those for single home systems once the cost of supplied energy decreases as the system size increases.

The large scale systems for solar water heating present a better payback on investment, but two major features hold back their

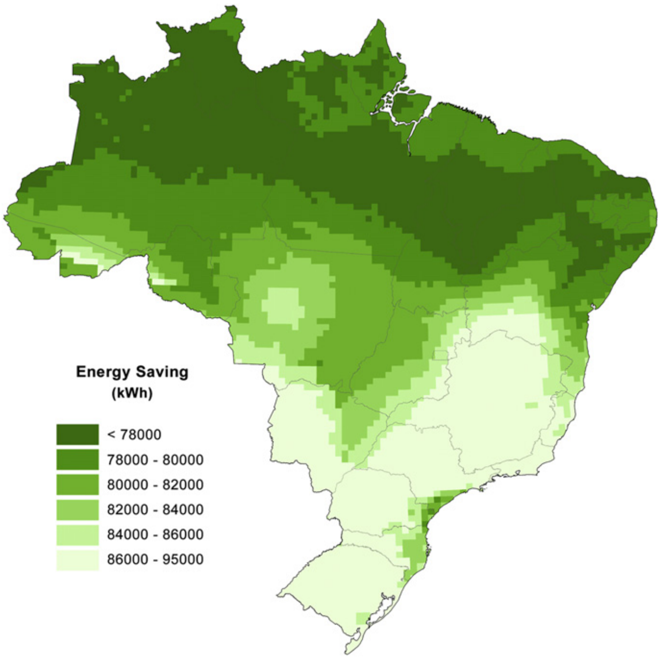

Fig. 7. Annual energy savings for large scale heating system in Brazil for the following heating system configuration: 140 m^2 flat-plate solar collector with a single glass cover to provide 10,000 l of hot water per-day at 60 °C in the storage tank.

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deployment: the installation costs and the large area required to install them on top of the buildings.

Another issue that contributes for hindering the employment of solar water heating systems is related to the lack of knowledge regarding its benefits, which leads building dealers to opt out since it implies higher construction costs. This mindset is gradually changing and, currently, there are some building companies that use solar heating as an additional selling advantage. The choice in favor of solar heating is most widespread in hotels and motels once the savings in operational and maintenance costs are easily cast as an additional profit. There is an additional advantage for hotel complexes and tourist locations in the Brazilian Southern and Southeastern regions, the increase in energy demand along the high tourism season occurs when the availability of the solar resource is larger (from December to March).

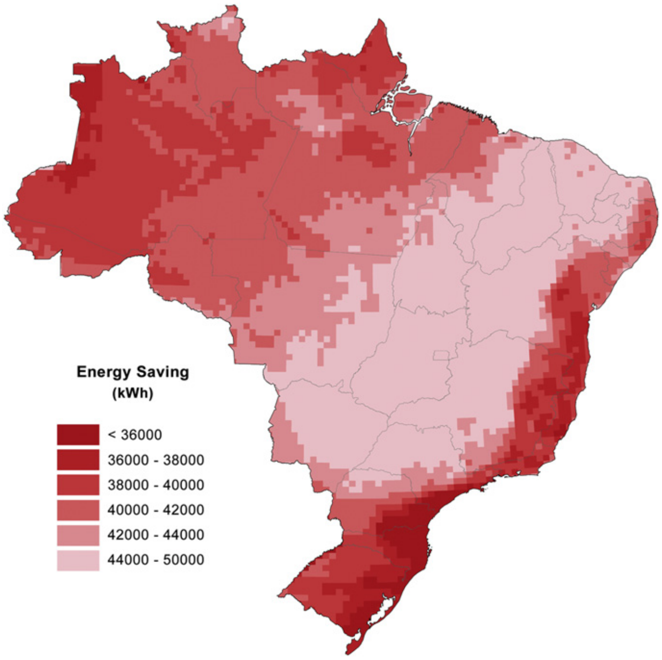

Fig. 8. Energy savings to maintain the water temperature at 28 °C in a 50 m^2 pool by using a solar heating system with 50 m^2 of flat-plate solar collector with a single glass cover.

It is difficult to precise the energy savings, as well as the payback time during the system life cycle because the economic analysis always depends on a series of factors that vary for each case. The cost of auxiliary energy, discount and inflation rates, cost of the equipment, depreciation, and taxes are some of the economic parameters that should be taken into consideration in the economic analysis, and therefore, it is recommended that it should be performed for each particular case. Duffie and Beckman (1991) present a complete description of methodologies for evaluating the economic viability of large-scale solar heating systems. In order to illustrate an example of economic feasibility analysis, a solar system with 140 m^2 to provide a 10,000-l per-day of hot water at 60 °C in the storage tank was considered. A standard flat-plate solar collector with a single glass cover was considered. The performance characteristics were similar to those used in the analysis presented in earlier topic in order to meet the requirements for Efficiency Class A System established by INMETRO. Fig. 7 shows the results obtained for the energy saving of this system.

Again, the Legionella contamination is also very important (IEA, 2001). Explicit regulations and guidelines have to be met

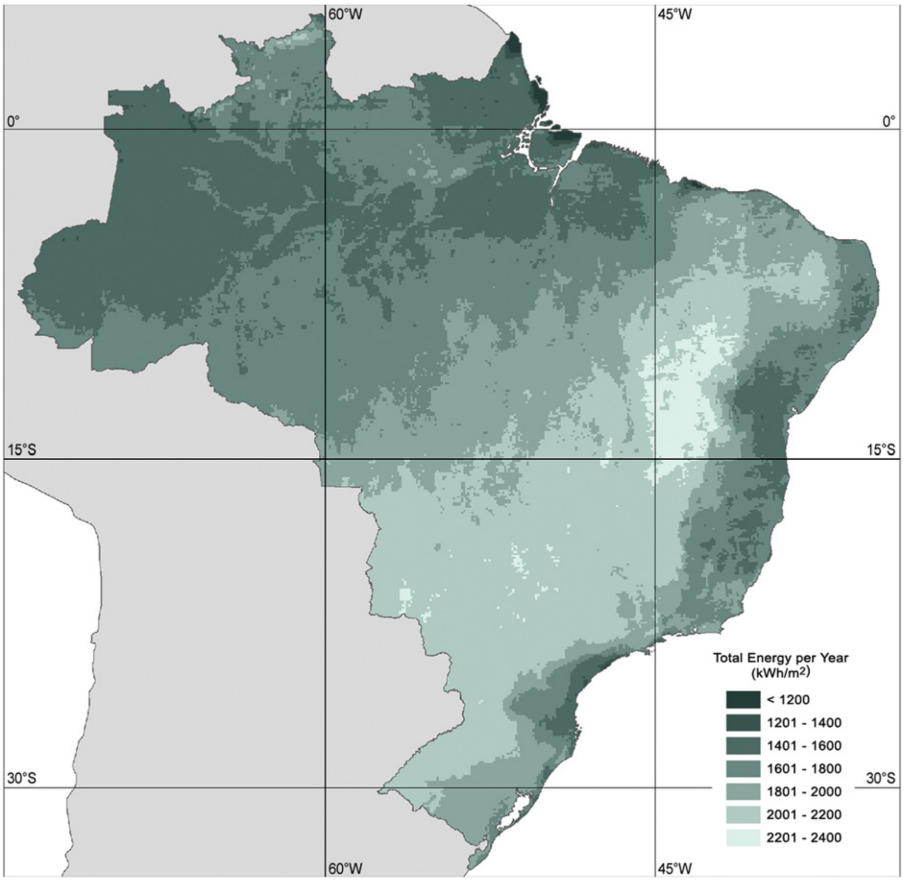

Fig. 9. Annual total energy (MW h/m^2) from direct beam solar irradiation in Brazil.

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according to the Health Surveillance organizations in order to prevent Legionella contamination and to increase health safety (ANVISA, www.anvisa.gov.br).

3.4. Solar heating of pools scenario

In Brazil, solar systems to deliver hot water for pools compete mainly with electric heat pumps. A biomass fuel, like wood, is also deployed because of its low cost. In the latter case, the replacement for solar heating has the advantage of reducing air pollution due to gases and particulate emissions.

The larger coefficient of performance (COP) of heat pumps decreases the electricity savings provided by the solar water heating system. The COP is defined as the ratio of the change in heat at the "output" (the heat reservoir) to the supplied work. However, it must be taken into consideration that COP drops considerably as the ambient temperature decreases so the electricity savings increase for the same thermal energy produced by the solar heating system. The use of a solar heating system combined with the heat exchangers of a heat pump is an alternative to improve the performance of the entire system, but this solution needs to be better developed to achieve a commercial configuration.

Fig. 8 shows the annual energy savings for a heated pool, with an area of 50 m^2, maintained at a temperature of 28 °C, using a solar heating system with the same area. The performance characteristics used in the simulation were those for a plastic solar flat-plate collector without cover and thermal insulation considered to be one of the most efficient in this category for the Brazilian market.

4. Concentrated solar power plants

Many studies point out the solar thermal power as one of the major alternatives to meet the future electricity demand (Schwer and Riddel, 2004; Sargent and Lundy, 2003; Tyner et al., 2001). Briefly, the conversion path of solar energy relies on four basic elements: concentrator, receiver, transport-storage and power conversion. Temperatures up to 500 °C are achieved in the receiver which absorbs the concentrated solar radiation. The heat stored by the working fluid in the receiver is used to generate steam employed to move a conventional turbine.

The two most developed technologies to concentrate solar radiation are the "parabolic troughs" and the "solar towers" (not to be mistaken with Solar Chimneys). The main concept behind the parabolic trough technology is the heating of a working fluid streaming through a pipe disposed in the focus of a parabolic mirror system tracking the Sun path. In turn, solar towers technology is based on a spatial distribution of mirrors arranged to reflect the solar radiation on a fixed receiver placed at the highest point of a tower.

The main requirements for both technologies are the very high direct solar irradiation, accessibility to hydro resources, and proximity to electricity distribution grid (Guimarães et al., 2005). The two major power plants in operation are in the Mojave region (USA) and Sanlucar La Mayor (Spain) where cumulative direct solar energy achieves 2.8 MW h/m^2 and 2.1 MW h/m^2 throughout the year (SANDIA, 2001), respectively. Mehos and Owens (2004) have considered that CSP plants are economically feasible in USA regions where the minimum value of annual solar energy achieves 2.4 MW h/m^2.

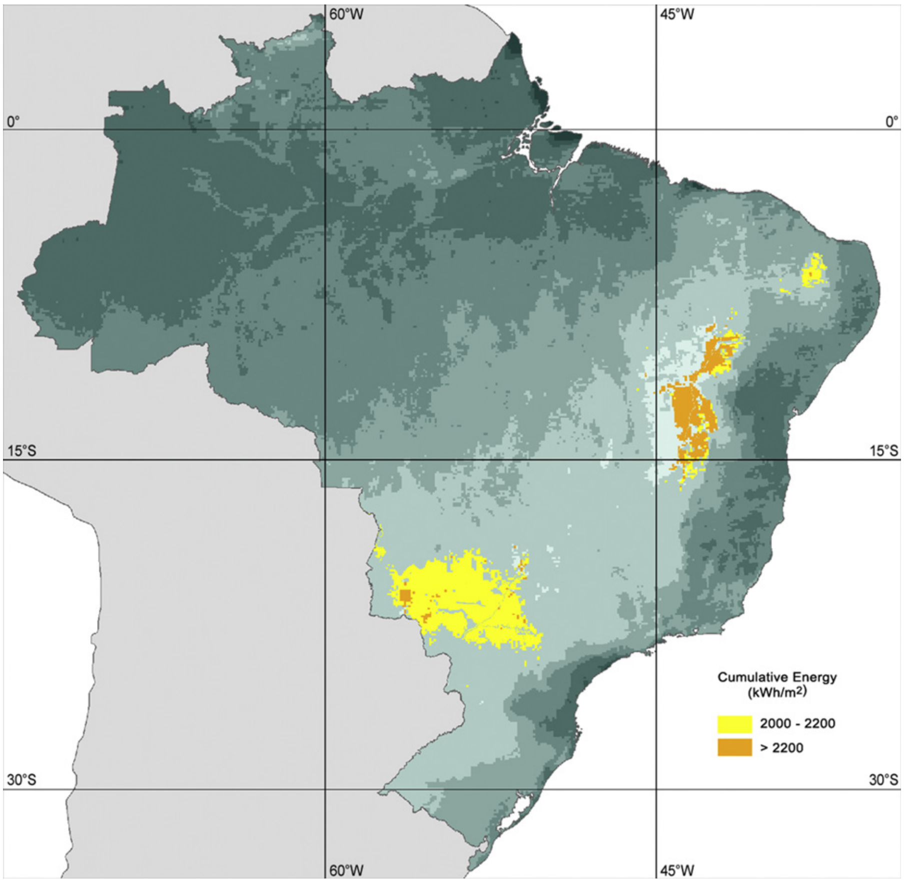

Fig. 10. Areas with monthly mean direct solar irradiation larger than 5.0 kW h/m^2/day. The yellow area represents the regions where the annual solar energy is larger than 2000 kW h/m^2 while the orange area indicates the regions where annual solar energy is larger than 2200 kW h/m^2. (For interpretation of the references to color in this figure legend, the reader is reffered to the web version of this article.)

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In Brazil, Guimarães et al. (2005) pointed out areas with solar resource at 2.1 MW/m^2 in semi-arid region of the Brazilian Northeast as the best locations for operation of CSP plants. For that study, the authors have employed solar radiation maps obtained by interpolation techniques of ground data. However, most of the ground data were based on insolation hours which present large uncertainties, particularly during the months of high nebulosity.

In this work, direct solar irradiation maps produced in SWERA using the radiative transfer model BRASIL-SR were employed to develop a similar work and to identify prospective sites to install CSP plants. Fig. 9 presents the annual total energy in the direct beam solar irradiation in the Brazilian territory. The solar energy per year reaches values larger than 2.0 MW h/m^2 in the most of the Brazilian territory, including the part of Southeastern region close to the major electricity consumers due to large industrial and urban areas in São Paulo and Minas Gerais states. Values larger than 2.2 MW h/m^2 were found mainly at the semi-arid region of the Brazilian Northeast where low precipitation and large number of clear sky days are the key climate characteristics.

The yellow and orange areas in Fig. 10 stand for the regions where the monthly average of direct solar irradiation is larger than 5.0 kW h/m^2/day in any month along the year. The map

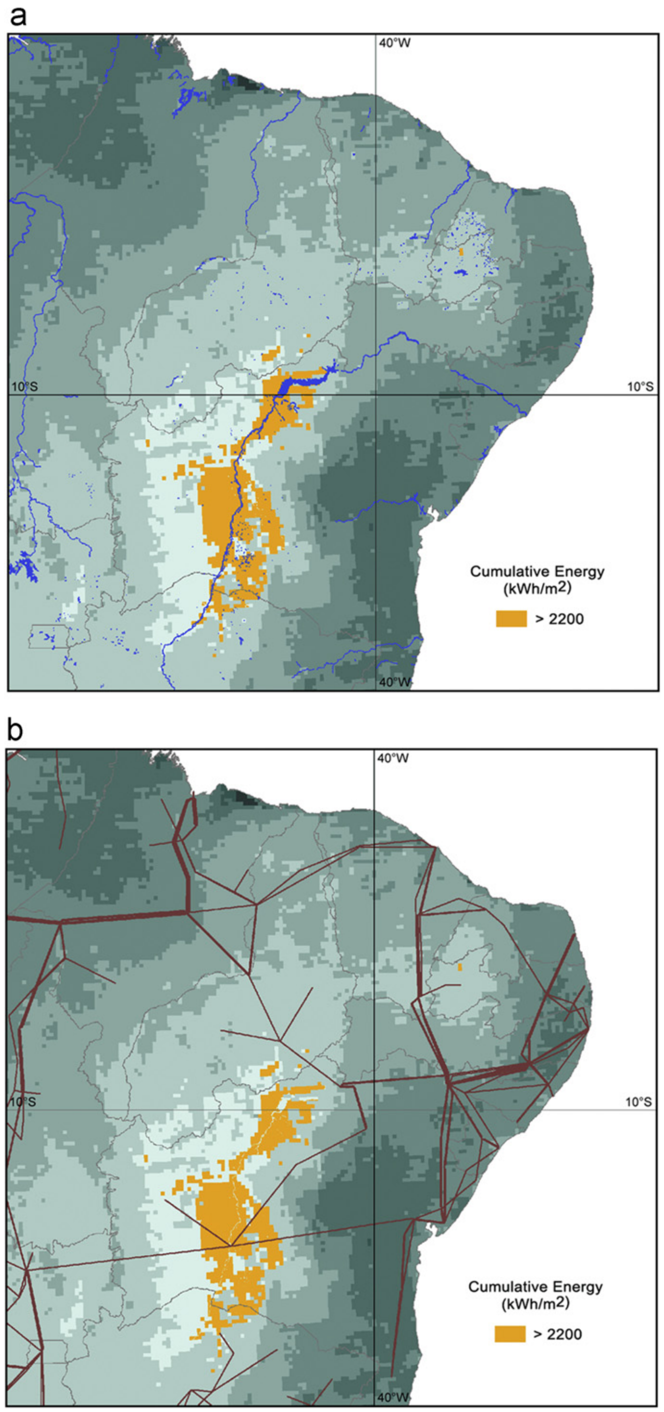

Fig. 11. Composite map presenting solar resource data for Brazilian Northeastern region together with (a) flooded areas and main rivers and (b) electricity grid (kV) of the Brazilian inter-connected distribution system.

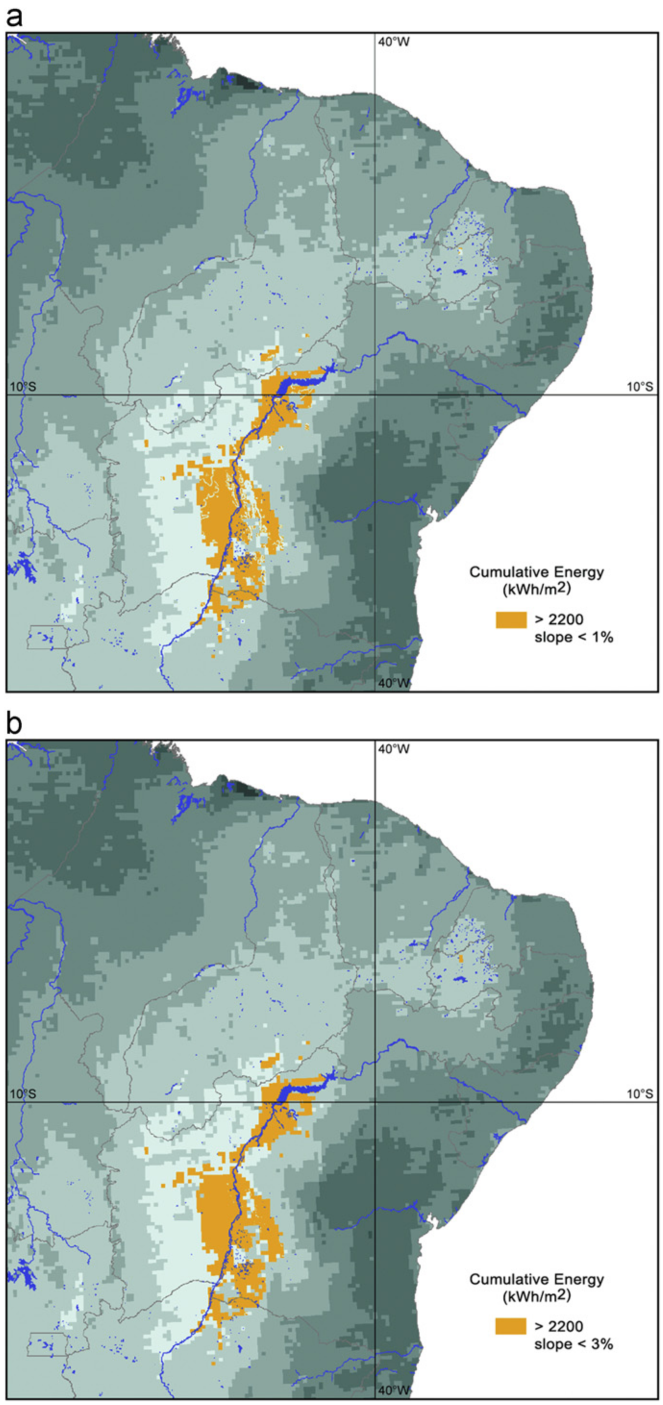

Fig. 12. Solar resource map presenting solar resource data: the orange area stands for region with terrain slope lower than 1% (a) and 3% (b).

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shows that Northeastern region is the most favorable area for investment in CSP plants because it receives large annual cumulative solar energy and presents lower variability along the year.

Taking into consideration only the Northeastern region, Fig. 11 includes the geographical information for major rivers and the electricity grid together with solar energy resource data. As mentioned before, the orange area stands for the best region for CSP plant operation. The São Francisco basin traverses the orange area improving the economic feasibility for CSP plant at this region. Besides that, this area is linked to the Brazilian Electricity Inter-connected Grid System by 230 kV, 440 kV and 550 kV power lines.

Mehos and Owens (2004) suggest some other restrictions to select the areas to install CSP plants like land use, ownership with commercial restrictions and soft terrain slope in contiguous areas greater than 10 km^2. The map presented in Fig. 12 shows the same area presented in Fig. 11 excluding the sites where terrain slope are greater than 1% and 3%. Unfortunately, the land use information is not available for this work, but most of the area is occupied by basic agricultural activities.

5. Solar chimney plants

Alternative technologies for electricity generation from solar energy could also be considered, in addition to CSP, in high-insolated flatlands areas of relatively low commercial value such as the semi-arid region of Brazil. The solar chimney principle is based on the rise of heated air near the surface inside a large greenhouse-like circular structure. The air rises through a tall tower located at the center of the structure. The rising air drives turbines even along the night as consequence of the heat irradiation by the heated surface inside the circular structure.

One solar chimney project is in the final stage of feasibility evaluation in Australia (http://www.enviromission.com.au) and will generate 200 MW with a life cycle expectance of 25 years. According to EnviroMission Limited, responsible for the Australian project, the selling price for the generated energy will be based on the average peak pool electricity price paid to generators plus an additional renewable energy credit incentive paid by retailers. Further value is expected to be added to the internal rate of return through the emerging carbon trading.

In Brazil, the C&T News Agency of the Ministry of Science and Technology (2004) has announced that the "EdRB of Brazil" is in view of building a similar structure in the state of Maranhão (Brazilian Northeastern region), but other areas are also under consideration. The SWERA database were used to indicate the best site opportunities in Brazilian territory taking into consideration the key issues for this application such as high solar irradiation along the whole year, low wind velocities, distance to electricity grid, low terrain slopes and land use restrictions.

Fig. 13(a) indicates regions in Brazil with monthly mean global incoming solar radiation above 5 kW/m^2/day all year round and total annual incoming solar energy larger than 1800 kW h/m^2. Furthermore, the selected regions have also averaged annual wind speed below 3.5 m/s. Fig. 13(b) is a subset of the previous result in which areas of natural forests, environment protected areas, indian land reserves, rivers and lakes were removed. In addition, the terrain slopes up to 1° requirement was adopted to identify the blue area in Fig. 13(b) presenting the suitable areas for this electricity generation technology. The blue area located mostly in Maranhão fulfills the best conditions for solar chimney plants and it is also close to the Brazilian interconnected electricity distribution grid.

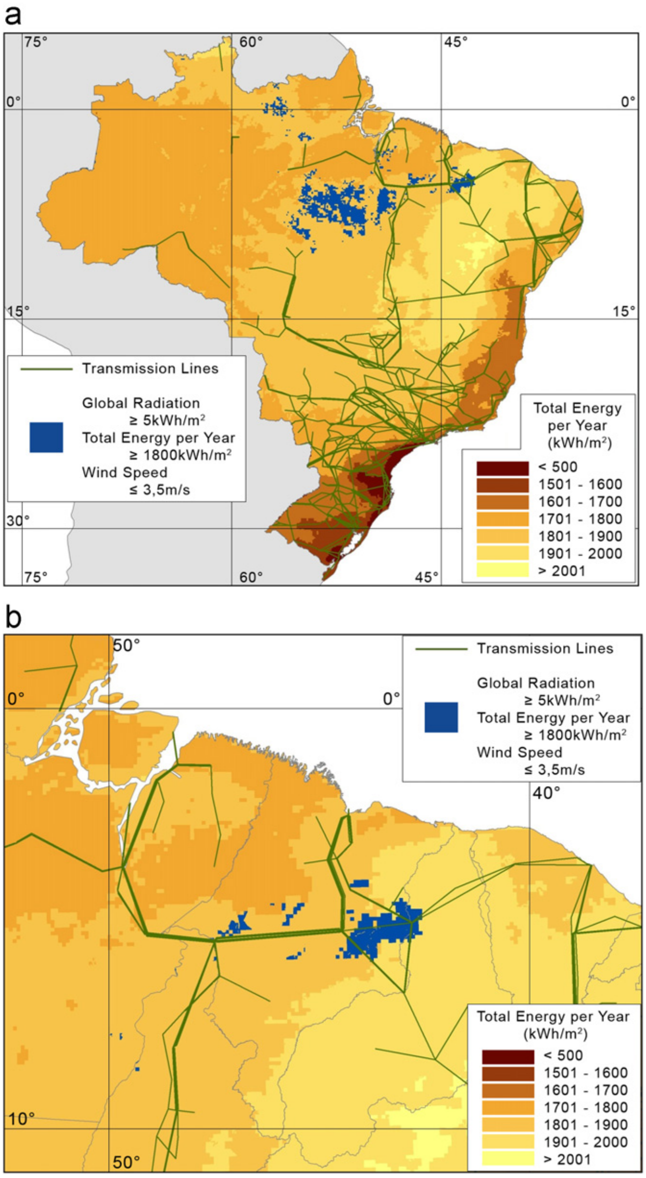

Fig. 13. Composite map presenting solar resource data for Brazilian Northeastern region together with electricity grid (kV) of the Brazilian inter-connected distribution system. (a) The blue areas presents annual energy larger than 1800 kW h/m^2·, monthly mean solar irradiation larger than 5 kW h/m^2/day all year round, wind velocities lower than 3 m/s, 5 m/s. (b) The blue areas are the regions in Maranhão meeting all the criteria decribed in (a) excluding terrain slopes larger than 1° and forests, land reserves and military areas.

6. Conclusions

This paper describes the major scenarios for solar thermal applications in Brazil by using the Solar and Wind Energy Resource Assessment Project (SWERA) database. The results presented here demonstrate the feasibility of thermal applications of solar energy for water heating and electricity generation in Brazil.

The water heating in residences presented a short payback period even for residences of low-income families when used to replace the electric showerhead. If government incentives were implemented, Brazil would cut back significant amount of electricity generated by conventional sources like hydro, nuclear, and chiefly fossil fuel, including natural gas.

Large-scale water heating systems also presented good feasibility in the whole Brazilian territory. Actually, hotels and other

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touristic and private public enterprises are adopting this option to reduce operational costs. Solar heating systems for pools present benefits if compared with other energy sources like biomass or electric heat pumps. However, the performance of solar systems grows considerably as the ambient temperature decreases.

The best sites to set up CSP plants are in the Brazilian Northeastern semi-arid region where the annual cumulative solar energy achieves 2.2 MW h/m^2 and the daily average of solar irradiation is larger than 5.0 kW h/m^2/day. Besides that, this region presents low terrain slope and it is bounded by the São Francisco river basin and served by the Brazilian interconnected electricity distribution grid. All these features contribute to the economic feasibility of CSP projects in this Brazilian region.

The western area of Brazilian Northeastern region, more precisely the states of Maranhão and Piauí, shows great technical potential for implementation of solar chimney plants. The selected region presents large solar irradiation (more than 1.8 MW h/m^2 a year), low terrain slopes, low wind velocity and it is served by the Brazilian interconnect electricity distribution system.

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