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SOLAR THERMAL ELECTRICITY GENERATION: THE SPANISH EXPERIENCE

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Abstract. *The solar thermal electricity installed capacity in Spain reached 2,054 MW. Today, this energy source consists on 2% of the domestic Spanish installed capacity and more 300 MW are currently under construction. Thus, the objective of this work consisted on identifying the main aspects related to the solar thermal electricity market development in Spain. The following steps were considered: (i) solar resources mapping: there are areas in the south of Spain with annual Direct Normal Irradiation (DNI) incidence levels over 2,000 kWh/m^{2}year. (ii) Subsidies: the Spanish government subsidies were identified, as this was the key in providing feasibility to this energy source. (iii) Technology: the main plant layouts and collector technologies were identified, as well as the efficiency levels obtained. Finally, based on the Spanish experience, the Brazilian potential for solar thermal generation was evaluated. It was shown that Brazil consists on a great opportunity for the implementation of concentrated solar plants. Nevertheless, in near-term more economical and proven alternatives are possible to be considered.*

Keywords: *solar thermal electricity, concentrated solar power, renewable energy.*

1. INTRODUCTION

Solar energy is a clean and abundant energy source. The main challenge facing renewables is to ensure a constant rate power supply and that the production and distribution of electricity is comparable in price to conventional sources. At present, there are two groups of solar electricity generation: photovoltaic (PV) and solar thermal power plants. While PV technology converts sunlight directly into electricity, solar thermal technology uses the Direct Normal Irradiation (DNI) to heat a fluid and then produce electricity based on a thermodynamic heat engine (Deloitte, 2011). Concentration technologies used for solar thermal power plants can also be applied to industrial heat demands to medium or high temperature.

The first commercial solar thermal plant started operation in California in the mid-eighties. This market was paralyzed, nevertheless, as a result of the reduced prices of fossil fuels and the corresponding cancellation of the existing pilot projects. While other technologies to generate electricity from renewable sources began to receive support in the late nineties, it was not until 2004 when it was settled in Spain – and also in the United States – a framework that allowed the construction of commercial size solar thermal plants. The first unity (PS10) began operation in Spain in early 2007. This was the answer to meet the participation targets for renewable energy and to reduce external electricity dependence.

The global leadership position attained by the Spanish industry has been a result of the combination of two main factors: continued support for research and technological development since the late seventies and the existing regulatory framework in Spain that allowed incentives for renewable generation.

Based on these aspects, the objective of this work is to study the main characteristics that allowed the solar thermal electricity development in Spain to the position of leadership in the world today. Considering the Spanish experience, it is also discussed about the necessary aspects for the implantation of the solar thermal energy in Brazil, being a country with continental size with areas of high DNI incidence.

2. SOLAR THERMAL PLANTS FOR ELECTRICITY GENERATION

The four technologies used for solar thermal electricity generation in the world are: Parabolic Trough, Linear Fresnel, Central Receiver Solar Tower and Parabolic Dish. These are also called Concentrated Solar Power (CSP) systems, in which sunrays are directed into a line or point focus and the concentrated thermal energy than converted in electricity in a heat engine. In Tab. 1 are shown the operational parameters of each technology. The presented parameters are the maximum fluid temperature attained, the thermodynamic cycle in which the heat engine is based, the annual solar to electricity efficiency attained and the plant capacity factor range.

Table 1. Parameters of the different solar thermal power technologies (Téllez, 2011)

Solar Thermal Power Technologies	Fluid Temperature	Thermodynamic cycle	Efficiency (annual average)	Capacity Factor
Parabolic Trough	400ºC	Rankine	13%-15%	20%-50%
Linear Fresnel	350ºC	Rankine	9%-12%	20%-30%
Central Receiver solar tower	250ºC-1100ºC	Rankine Bryton Combined	13%-16%	Up to ~ 85%
Parabolic Dish	600ºC-800ºC	Stirling	20%-22%	No information

3. SOLAR THERMAL ELECTRICITY IN SPAIN

3.1 History

The seventies oil crisis motivated many governments to find alternatives regarding power supply. At this time was created in Spain the *Plataforma Solar de Almeria* (PSA) where was implemented the *Central Electro Solar de Almeria* (CESA 1). This was the first experimental solar thermal plant in Spain. The CESA 1 was inaugurated in June 1983. During the beginning of the eighties, nevertheless, the oil price was gradually down. This made most countries to dismantle the renewable electricity generation projects (V. Ruiz, *et al*., 2010).

In 1997 was created in Spain the Electricity Industry Act, which grouped the renewable energy sources into the Special Regime and allowed financial support to develop this sector. The installed capacity of the wind plants was improved in the first moment, and in 2007 the PS10 (*Planta Solar 10*) solar plant was inaugurated. This was the first commercial CSP plant in Spain. This 11 MW capacity plant situated in Sanlucar (Seville) generates enough electricity to supply 5,500 homes (ABENGOA, 2011). This was the first of many solar thermal plants currently in operation, and which places Spain as a world reference in this technology.

3.2 Solar potential in Spain

3.2.1 The solar irradiation

Solar irradiation reaches the earth in the form of electromagnetic waves with different frequencies (AEMET, 2011). The solar irradiation can be classified in three types: diffuse, direct and global. The direct normal irradiation (DNI) represents 80% to 90% of solar energy that reaches the earth's surface in a clear day; in a cloudy day, the direct component of the irradiation is close to zero and a CSP plant does not generates electricity. This kind of technology needs the direct component of the solar irradiation routing sunrays into a point or line focus where it is positioned the heat collector element of the heat engine. Flat plate collectors, on the other hand, can capture the diffuse irradiation. Therefore, the ideal locations to install CSP plants require sites with many sunny days during the year. These are especially semi-arid places located at latitudes below 40° (Deloitte, 2011). In this sense, the regions with the greatest potential in the world are the deserts of North Africa, the Middle East, North-Western India, the Southern of the United States, Mexico, Peru, Chile, Northeast of Brazil, Australia and Southern Europe. The mean accumulated DNI in the South region of Spain is 2,000 kWh/m^2 per year. This is equal to 2,600 kWh/m^2 per year in North Chile. The world map indicating the most feasible places for CSP plants operation is shown in Fig. 1.

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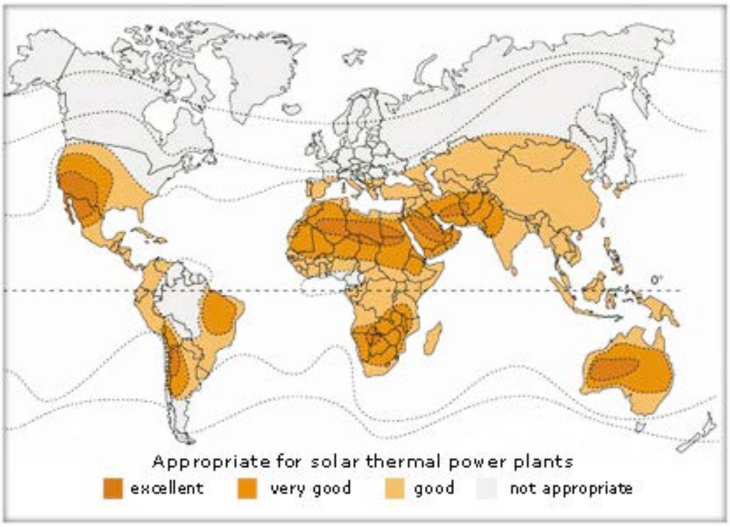

Figure 1. The most feasible sites for CSP operation (SOLARPACES, 2013)

3.2.2 The Spanish DNI map

In Fig. 2 it is shown the Spanish DNI map (IDEA, 2011). This map was constructed based on satellite and weather stations derived data.

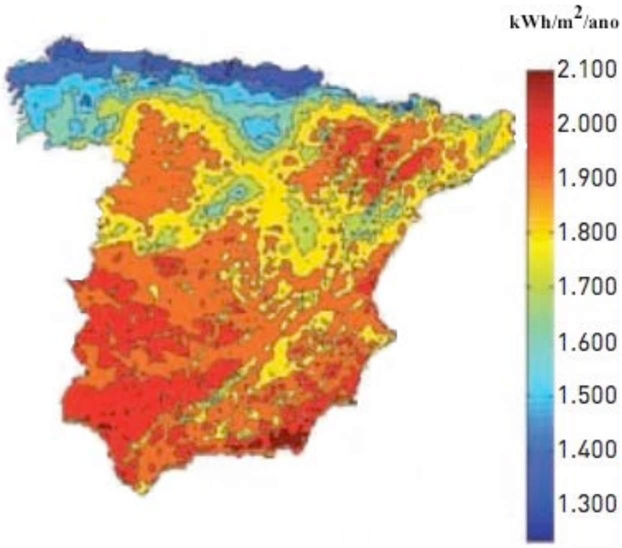

Figure 2. The Spanish Direct Normal Irradiation map (IDEA, 2011)

The lower DNI incidence level of around 1,160 kWh/m^2 per year is found in the north region, whereas in the south region this is increased to around 2,180 kWh/m^2 per year. Based on this information, Huelva, Seville, Cádiz, Córdoba, Granada, Almeria, Caceres, Badajoz, Ciudad Real, Murcia and Lerida are the most suitable areas to the operation of CSP plants. In addition to the DNI, the following aspects must be considered for site selection (Téllez, 2011):

- DNI value greater than 1,825 kWh/m^2 per year;
- There may not be a protected area, urban or swampy;
- There may not be an area of land with a slope greater than 3%;
- The area has to be smaller than 5 km^2;
- This area should have access to water, electricity grid and road.

3.3 The Spanish support system for the renewables sources and cogeneration plants

Before 1997, the Spanish electricity matrix was characterized by a dependence on external resources and fossil generation. With further pressure related to environmental greenhouse gas emissions, the electricity sector was reformulated with the objective to increase the share on renewable sources. The Spanish total electricity installed capacity reached 102,415 MW in December 2012 (REE, 2012). As can be seen in Fig. 3, the renewables represented almost 50% of the total capacity. Considering this amount, the wind energy consists on the greatest share, with 22 GW, followed by hydropower, with 18 GW. Solar energy had 6 GW capacity, divided in photovoltaic (4 GW) and solar thermal (2 GW). Fossil sources are represented by combined cycle (natural gas) plants, with 25 GW, and coal plants (11 GW). The nuclear energy consisted on 8 GW installed capacity.

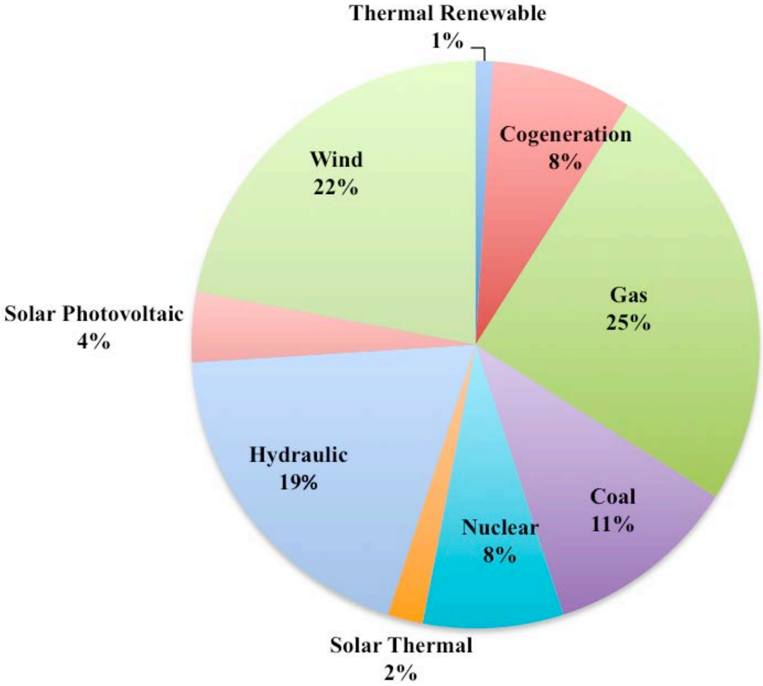

Figure 3. Spanish electricity matrix in 2013 (REE, 2012)

In Spain, the improvement of the renewable share installed capacity was obtained due to governmental incentives that provided stable prices for renewable electricity commercialization. The Electricity Industry Act in 1997 created the Special Regime, in which it was grouped renewable power generation and cogeneration plants, except the hydropower unities (Pérez, 2010). To explain the Spanish support system it is essential to understand basically how the electricity market works. In this chapter it will be explained the operation of the electricity market, the actors involved, the system of incentives and the problems that have been observed.

3.3.1 Spanish electricity market

There are three agents that operate of the Spanish electricity market. The private agent REE (*Red Electrica de España*) is the instrument responsible for technical management. It ensures continuity of electricity supply and coordinates production and transmission. The OMIE (*Operador del Mercado Iberico Electrico*) is a private agent that manages the electricity market. Since 2009 the CNE (*Comisión Nacional de la Energía*), under the Ministry of Energy of the Spanish Government centralizes all information and liquidates the renewable incentives.

The energy produced by the generators is commercialized in daily and intraday open markets. These two markets are managed by the OMIE. Both markets are operated every day with the difference that the daily market is closed once a day considering the next 24 hours. The intraday market, on the other hand, is closed every four hours of the day, totalizing six sections each day. It permits adjusting the daily market deviations. On each market, vendors (generators) make offers to sell and buyers (distributors) to purchase the energy at OMIE for each hour included into the corresponding section (OMIE, 2013).

All producers not belonging to the Special Regime should participate in the open market. Special Regime producers may choose to participate on open market or charge a fixed tariff. This choice must be communicated to the government at the beginning of the year and is valid for all year.

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3.3.2 Incentive system for the Special Regime

For all renewable electricity sources there are two ways to access the incentives. It is offered to the producers the option of charging a fixed tariff determined by the government. They have yet the option to participate in the open market mentioned above, charging the market price plus an additive also determined by the government. The latter option has the advantage of encouraging the participation of producers in the electricity open market, and promoting the production of renewable electricity in peak demand hours.

The Cap & Floor system was introduced to avoid too high or low prices – the compensation is framed between maximum and minimum limits. This system reduces the risks of market participation. The incentives are paid according to the different generation technologies over the life of the plant, decreasing after 25 years of operation. In the Special Regime, the thermal solar technology is within the solar energy group (group b.1) and it is classified at the subgroup b.1.2. The two commercialization modes mentioned above are possible for plants with up to 50 MW capacity. For higher capacity unities, only the open market option can be accessed. In Tab. 2 it is presented the incentive values for solar thermal plants for January 2012 (BOE, 2011).

Table 2. Incentives for a solar thermal plant in January 2012 (BOE, 2011)

Plant Age	Fixed Rate (c€/kWh)	Reference Supplement (c€/kWh)	Upper Limit (c€/kWh)	Lower Limit (c€/kWh)
First 25 years	29.8957	28.1894	38.1751	28.1936
After that	23.9164	22.5515		

3.3.3 Payment of the incentives system

The electricity tariff in Spain consists of two parts, the market price, and the access fees. The cost of incentives for renewable energy and cogeneration is included in the consumer tariff as part of the access fees. The access fees include additional costs such as: transport and distribution of electricity, the tariff deficit, the nuclear moratorium and incentives for renewables. The incentives for renewables in 2013 will reach 9 billion of Euros, while in 2009 it was 5 billion of Euros. The solar thermal energy incentives for this year will be 1.2 billion Euros, representing 13.3% of the total (CNE, 2013).

3.3.4 The tariff deficit

The tariff deficit consists on the difference between the value consumers pay in the electricity tariff and real generation costs recognized by government. This deficit was officially created in 2002, with the objective of keeping electricity prices stable in order to avoid the negative effects of inflation (BOE, 2002). Although after 2005 the electricity tariff started to be gradually increased the debt continued to grow. Currently it reached 24 billion of Euros.

3.3.5 Changes in legislation for 2013

Renewables installed capacity share had a significant increase in Spain in recent years due to the favourable legislation, what increased incentive costs. In this context, the tariff deficit associated with the current European crisis conducted to a number of changes in the electricity legislation. Two main changes for the solar thermal producers can be mentioned: selling the electricity by a fixed rate charge only and removing the incentives to the electricity generated by the natural gas backup systems, which was allowed up to a 15% share. It will be created also a new tax for renewable generation (BOE, 2013).

3.4 Solar thermal plants in Spain

Currently in Spain there are 45 CSP plants connected to the grid. The total installed capacity is 2,054 MW (PROTERMOSOLAR, 2013). Due to the Spanish legislation, which allowed choosing between the two types of incentives for CSP plants lower than the limit of 50 MW, all the existing plants do not exceed this limit. In Fig. 4 are represented the 45 operating plants (red colour), the six plants under construction (yellow colour) and the four plants in project phase (green colour).

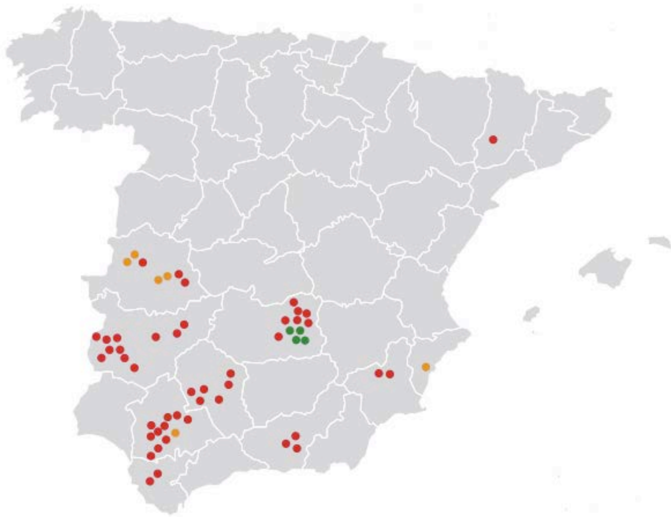

Figure 4. Spanish CSP plants location map (PROTERMOSOLAR, 2013)

The Parabolic Trough technology consists of 96% of the total installed capacity, what represents 1,972 MW. Among the Parabolic Trough plants in Spain, there are three different configurations: plants with thermal storage system; plants without thermal storage; and a biomass-solar hybrid plant. There are 21 plants without storage, all of them with 50 MW capacity. For a typical meteorological year, these plants are able to produce around 100 GWh annually with a Capacity Factor (CF) of 23%. Some of these plants have a natural gas backup system. There are 18 plants with thermal storage system that allows 7.5-9 hours of additional operation. All these plants have 50 MW capacity and for a typical meteorological year it is possible to generate up to 170 GWh, developing a 39% CF. Finally, the hybrid solar-biomass plant in the province of Lerida, northern of Spain has an installed capacity of 22.5 MW, generates around 98 GWh and develops a 49.72% CF.

Currently, the central receiver technology represents 2% of the solar thermal installed capacity in Spain (50 MW), with three operating plants. Within this technology, there are two configurations: saturated steam and molten salt working fluids. There are two plants working on saturated steam (PS10 and PS20), located in Solúcar (Seville). These two plants have a water-steam thermal storage system of an hour capacity each, obtaining a CF of 25% and 27% respectively. The capacity of the PS10 and the PS20 plants are 11 MW and 20 MW, respectively, producing around 24 GWh and 44 GWh per year. The molten salt Gemasolar plant has an installed capacity of 20 MW and has a molten salt thermal storage system that provides 15 hours of additional operation. The Gemasolar plant obtains a CF of 62.8% and produces around 110 GWh per year.

Finally, there are two Fresnel plants in operation in Spain with 30 MW and 1.4 MW capacity, achieving a CF of 19% and 16% respectively. These two plants produce around 50 GWh and 2 GWh per year.

In Tab. 3 are presented typical CF obtained in conventional electricity generating plants for comparison (NREL, 2013). As it can be seen, the solar thermal plants without thermal storage reaches CF indexes that are comparable to the photovoltaic and wind plants. Nevertheless, the hybridization or the implementation of thermal storage systems turns possible improving the CF to levels comparable to the hydropower plants. Further development of hybridization appears to be the way to obtain base load power supply.

Table 3. Capacity Factors of other electric generation plants (NREL, 2013).

Electric generation plants	CF (%)
Photovoltaic	15-25%
Wind	20-40%
Hydropower	35-90%
Nuclear	85-90%
Coal thermoelectric	85%

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4. SOLAR THERMAL ELECTRICITY POTENTIAL IN BRAZIL

4.1 Brazilian electricity matrix

In Fig. 5 it is presented the Brazilian electricity matrix in March 2013 (ANEEL, 2013). Brazil has one of the largest hydraulic potential in the world and, at present, it is the main energy source for electricity generation. The Brazilian total installed capacity is 122,916 MW, and the hydraulic consists of 84,690 MW.

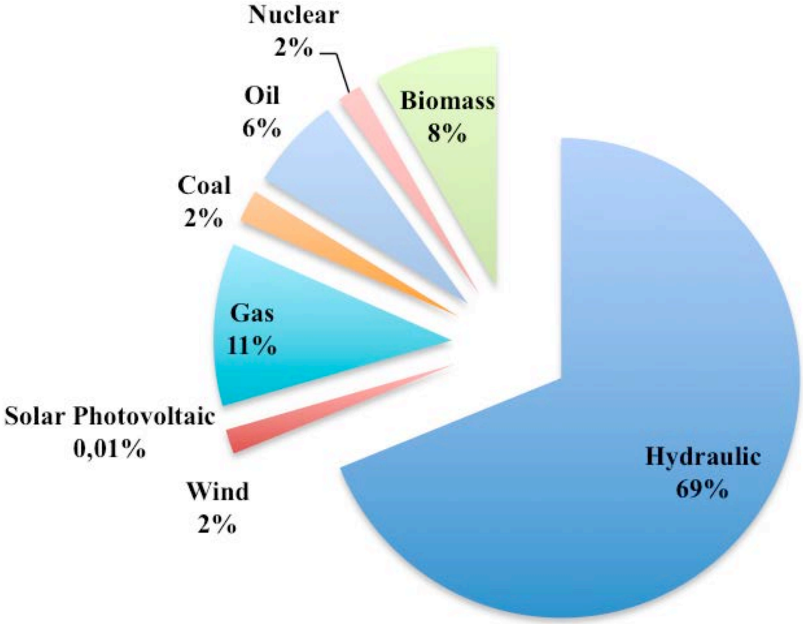

Figure 5. Brazilian electricity matrix in 2013 (ANEEL, 2013)

A few years ago the hydraulic power supply was about 80% of the total installed capacity. Since July 2012 this percentage is below 70%. This reduction in share is due to the growth of biomass and wind sources in the recent years. In future it is expected that the hydraulic share will keep lowering as the major basins for hydroelectric generation are getting exhausted near the most important consumption centres (Bueno *et al*., 2006).

The thermal plants appear in the second position in the Brazilian mix. Regarding to this, there are different facilities considering the fuel used: the main fossil fuel sources used are natural gas, coal and oil. This group amounts a 23,897 MW installed capacity and represents 19.5% of the total. Regarding the biomass electricity generation plants, its total installed capacity has increased considerably in the recent years, growing from 7.8 GW in 2012 to 10.2 GW in 2013 – representing today 8.4% of the total capacity. Projections indicate that by 2020, electricity generation from biomass reaches 20.1 GW, accounting for 11% of the Brazilian matrix. The electricity generation based on biomass plants in Brazil uses: sugarcane bagasse, black liquor, wood, biogas and rice husk. Among these, the sugarcane bagasse cogeneration plants represent 83% of the biomass total capacity. Currently, there are 369 cogeneration plants in the sugarcane sector amounting 8.89 GW – 6.73% of the total installed capacity in the Brazilian electricity matrix (ANEEL, 2013).

Wind power is receiving increased investment by PROINFA program (*Programa de Incentivo às Fontes Alternativas de Energia Elétrica*) coordinated by the Ministry of Mines and Energy. The wind power capacity in Brazil increased from 1,077 MW in 2012 to 2,045 MW in 2013, accounting for 1.7% of the total capacity today (ANEEL, 2013). The decreasing cost of electricity from wind and the huge Brazilian wind potential (143.5 GW) indicate that this source can occupy in the medium-term an important position in the country (Bueno *et al*., 2006).

Brazil has the sixth largest uranium reserve in the world. Currently the Angra III nuclear plant is under construction with 1,300 MW capacity, thus completing the cycle started with Angra I connected in 1985. The two operating nuclear power plants in Brazil amount 2,007 MW installed capacity. This represents 1.6% of the total (Bueno *et al*., 2006).

Finally, solar energy today represents a low share in the electric matrix with 8 MW installed capacity and accounting for less than 0.01% of the total. All the operational plants are based on photovoltaic technology and there is no CSP installation in Brazil. In the next point it will be analysed the Brazilian solar potential identifying the possibility of including this technology in the Brazilian electricity matrix.

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4.2 Solar potential in Brazil

The Brazilian solar potential is greater when compared to the typical DNI found in South Spain, as shown in Fig. 6 (Bueno *et al*., 2006). The higher incidence level is observed in the San Francisco river valley, in Bahia, reaching 2,300 kWh/m^2 per year. Also, as discussed in the next section, the North region of the São Paulo presents high incidence level, above 2,100 kWh/m^2 per year.

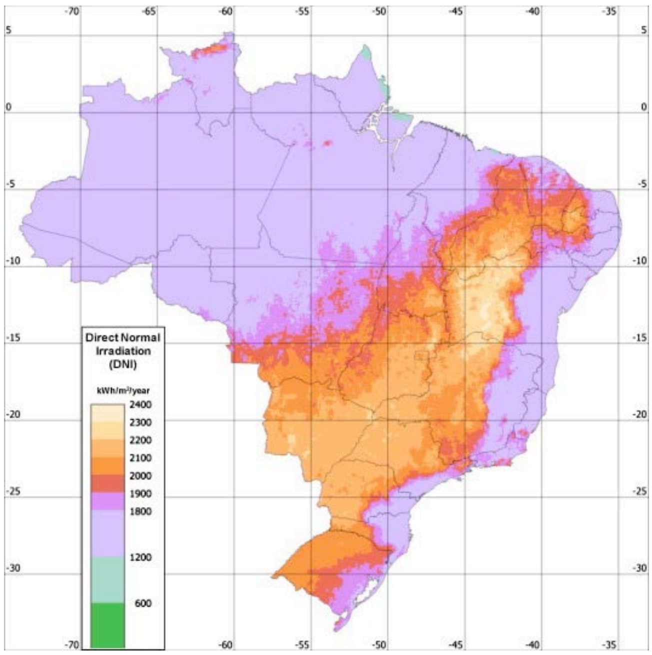

Figure 6. The Brazilian Direct Normal Irradiation map (Bueno *et al*., 2006)

4.3 The feasibility of solar thermal plants in Brazil

As presented in the previous section, the most feasible region for CSP operation in Brazil is located in the San Francisco river valley. This is a semi-arid area where there are sites that agree with selection criteria presented in Section 3.2.2. Nevertheless, the solar thermal electricity generation is associated with higher costs when compared to the conventional sources such as hydropower, thermal plants and wind generation. As shown in Tab. 4, the mean Levelized Cost of Electricity (LCOE) of CSP plants is estimated in 261 US$/MWh, whereas the conventional sources operate below 100 US$/MWh (EIA, 2013). In the case of Spain, the solar thermal electricity generation was turned feasible due to a set of governmental incentives created in order to minimize the external electricity dependence and minimize the fossil capacity share.

Brazil, on the other hand, has a clean electricity matrix when compared to many developed countries and there is a great potential for biomass thermal electricity. In the last decade it has started the modernization cycle of the cogeneration units with the objective of increasing energy exportation to grid. This consists now on an additional product beyond sugar and ethanol. Thus, in 2010 a total of 8,777 GWh of electricity was exported to independent consumers. This amount was produced by 129 sugarcane companies connected to the grid and represented 2% of internal demand (Souza, 2012). Further improvements are possible considering the use of higher steam parameters, the reduction of process steam consumption and the modernization of thermal cycles using regeneration.

In this sense, the implementation of solar thermal electricity in a near-term in Brazil could be associated with the sugarcane cogeneration plants, which are located mainly in the State of São Paulo, where the DNI incidence levels are above 2,100 kWh/m^2 per year – above the typical DNI found in South Spain. The solar energy integration into conventional steam power plants has been investigated as it consists on an opportunity for increasing the capacity factor of original units. This concept cannot only be applied to new plants, but also for retrofitting existing ones. The utilization of existing infrastructure turns possible the reduction of solar energy implementation costs. Furthermore, as the solar energy can be used to displace base case fuel consumption, there is the possibility of constant rate power supply without the not mature and high price thermal storage systems.

However, as mentioned before, the major basins for hydroelectric generation are getting exhausted near the most important consumption centres. Regarding the biomass based electricity generation plants, there is a limit considering the availability of land since there will be competition with food crops. Based on these aspects, the CSP operation is to emerge as a great alternative in Brazil for the electricity matrix diversification and installed capacity expansion. The technological improvements indicate cost reductions for next years (NREL, 2013), what can be associated with the great Brazilian solar DNI potential.

Table 4. LCOE of electric generation plants (EIA, 2013)

Electric generation plants	LCOE (US$/MWh)
Hydropower	90
Nuclear	108
Solar Thermal Energy	261
Conventional Coal	100
Photovoltaic	144
Wind	86
Biomass	111

5. CONCLUSIONS

The start of solar thermal electricity generation in Spain happened after the connection of the first plant in 2007. In the last six years it was observed a rapid installed capacity growth, reaching the leadership in 2012. This was possible due to Spanish government incentives for renewable energies, which allowed a large development of these technologies. Nevertheless, associated with capacity improvement, it was also increased the incentives to pay, what occasioned the tariff deficit economic problem. Thus, it is demanded today to reformulate the existing incentives system, but ensuring economic viability of new plants. Considering the existing solar potential in Spain, the experience gained along these years, and forecasting a significant cost reduction over next years, the solar thermal technology presents a high potential for improving the Spanish installed capacity. In this sense, investigations which are being carried out in the existing research centres are the basis to provide solar thermal generation in competitive costs.

Observing the Brazilian electricity matrix, it can be concluded that there is a relatively small presence of electricity generation by fossil fuels. That is due to the strong presence of hydropower generation in Brazil. However, the existing basins are getting exhausted and it will not be possible a considerable increase in hydraulic capacity in coming years. Another source with a major presence is biomass. Despite the significant increase expected in installed capacity in the coming years, biomass availability is limited. Considering these aspects and the future increase in electricity demand, it makes important to develop alternative sources in Brazil. The increasing wind installed capacity in the last two years represents this scenario. Solar energy has an insignificant presence in the Brazilian electricity matrix and considering the existing potential, it corresponds in a good opportunity to cover the increased electric demand in future. Considering the current cost of solar thermal technology implementation, an existing option in Brazil is associated to the integration of solar energy in biomass plants. The possibility of using existing infrastructure could significantly reduce the implementation costs. In near-term, this alternative seems viable to develop solar thermal technology in Brazil.

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