Projecting the design and distribution of European CSP plants for the year 2050

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Abstract
Europe is transitioning towards a clean and sustainable future where traditional fossil fuel sources will soon be replaced by renewable sources like solar energy. While solar PV is the most popular technology available these days, more advanced solar technologies like concentrated solar power (CSP) may receive more attention in future. Since CSP plants operate by concentrating direct normal component of solar irradiance through their optical mirrors, the power output from CSP plants are extremely sensitive to meteorological conditions including cloud cover. In this study, we have developed a simulation model to identify best locations of CSP plants in Europe, to design a resource-dependent capacity distribution, and a simple parametric power model to derive CSP plant output for a ten year period of time [2003-2012], along with an algorithm to retrieve solar irradiance data from satellite images. The model is thoroughly validated against available data and existing literature. The goal is to formulate technically and economically feasible CSP plant design using resource assessment and performance monitoring to facilitate its grid integration by the year 2050.

Keywords
CSP — DNI — performance

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Introduction

Over the last couple of years, solar power has gained widespread popularity, which came with an expansion of the technologies associated with it. Apart from the most popular solar photovoltaics (PV) technology, concentrated solar power (CSP) is emerging to be another prospective clean and sustainable option for the future power system. CSP technology uses mirrors to reflect and concentrate solar irradiance onto a receiver to heat up a fluid which facilitates the spinning of traditional steam turbines to generate electricity. Unlike solar PV, which can effectively utilize the diffuse component of sunlight, CSP output is exclusively dependent on the direct normal component of solar irradiance. Hence, its performance is extremely sensitive to cloud and other atmospheric conditions. As CSP industry requires high solar irradiance throughout the year, proper site selection is crucial to ensure its cost-effective and technologically feasible operation. CSP is usually used on utility-scale generations as a centralized technology, which means fewer number of units are adequate to produce high quality power as long as the selected locations remain mostly cloud-free and over the latitudes close to the equator.

In this work, power generation from CSP plants have been modeled for selected European countries for a future power system with high shares of renewables. This task is part of the project - RESTORE-2050, which investigates the storage and balancing needs for a pan-European power system by the year 2050.

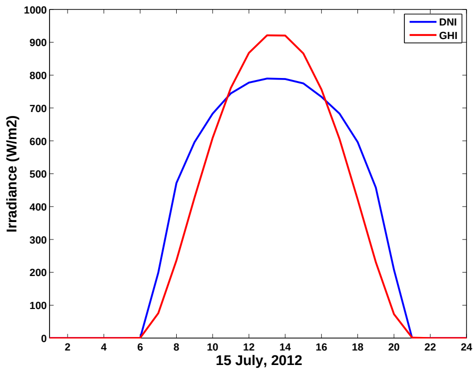
1. Model

The model developed here comprises of three main components to finally derive country-level power time series from CSP plants:

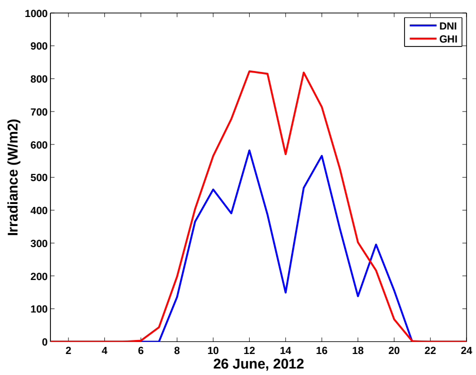
- the irradiance model
- the capacity distribution model
- the power model

1.1 The irradiance model

For this study, solar irradiance is retrieved from the Meteosat first and second generation (geostationary) satellites for the



(a) clear-sky condition



(b) cloudy condition

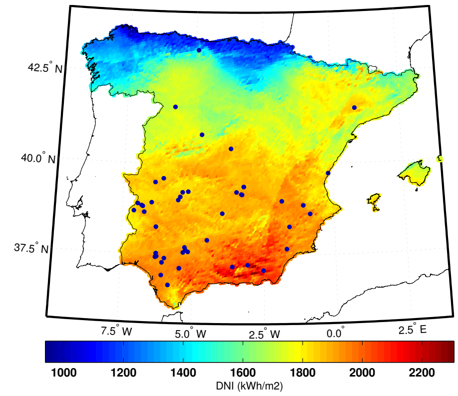
Figure 1. Solar irradiance on a single location (36.69°N, 5.85°W) in Spain shown for different meteorological conditions.

period 2003-2012 using the Heliosat method [1, 2]. The global horizontal irradiance (GHI) retrieved in this way is then converted to the direct normal irradiance (DNI) as the mirrors and other concentrating optics require abundant direct solar irradiance to effectively focus solar irradiance to the temperatures needed for electricity generation. DNI is given by the direct solar irradiance received by a surface oriented perpendicular to the direction of the sun and is given by:

$$\mathrm{DNI} = \frac{\mathrm{GHI} - \mathrm{DHI}}{\cos\theta} \tag{1}$$

where, DHI is the diffuse component of irradiance on horizontal plane and θ is the solar zenith angle.

Fig. 1 shows the enhanced sensitivity of DNI over GHI to atmospheric conditions like cloud cover. While DNI exhibits a relatively flat diurnal profile compared to GHI on typical clear-sky days, it is significantly reduced under clouds, which in turn, strongly diminishes the power output from CSP plants.



(a) clear-sky condition

Figure 2. The concept of simulation for 2050 stands as 100 MW_p plants distributed over regions receiving year-round DNI about the threshold.

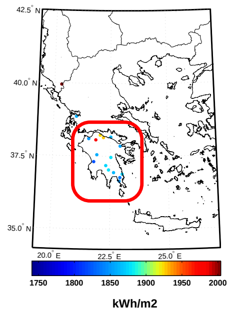
	Original	Scaled
Spain	108.9	9.9
Italy	70.2	6.4
Greece	19.0	1.7

Table 1. Installed capacities (GW) for 2050: Original values are from EWI Energynautics report [3] while the scaled values are to match the overall capacity provided by Pfluger et al. [4].

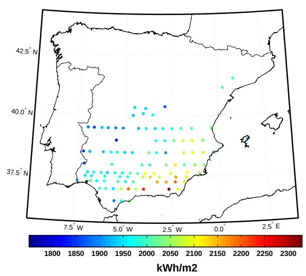
1.2 The capacity distribution model

As CSP industry needs guaranteed high solar irradiance throughout the year, only a hand full of European countries are projected to invest in such plants in future. According to the EWI Energynautics report [3], only Spain, Greece and Italy, which receive sufficient direct sunlight throughout the year, are suitable for building and operating CSP plants. Hence, only these three countries are investigated here for the CSP feed-in. For the projected installed capacities, a few different meta-studies were used to allow investigation based on different scenarios. With the assumption of renewable penetration close to 100% by the year 2050, [4] and [5] have provided installed capacities for different renewable generations. For Europe, they projected 18 GW and 81 GW of CSP capacity, respectively. To further obtain the country-level CSP capacities, the projections from the EWI Energynautics report [3] were considered. These values were then scaled-up to match the value given for Europe in the previous two studies [4, 5]. The results are summarized in Table 1.

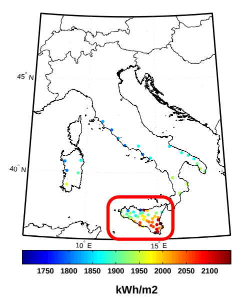
In order to apply a resource-dependent distribution of CSP plants, a minimum threshold of average available DNI is required to be set for proper technical and economical performance. According to a DLR report [6], this threshold is set to 1800kWh/m^2 per year for technical potential and 2000kWh/m2 per year for economic potential. Hence, a threshold of 1800kWh/m^2 of average DNI is set to select the best locations for CSP installation in Spain. For Italy and



(a) Greece 17 plants



(b) Spain 99 plants



(c) Italy 64 plants

Figure 3

Greece, however, this threshold is quite inadequate to implement a large number of CSP plants. So, a threshold is reduced to 1750kWh/m2 per year for these two countries.

In Spain, most of the CSP plants that are operational today have 50MW capacity [7]. There are also a few larger (100 MW) operational CSP plants in Spain. Assuming reasonable development in CSP technology and the expanded market by 2050, each CSP plant is modeled with 100 MW capacity in the simulations. The distribution of CSP plants as of today and as implemented in the model for 2050 within Spain with average DNI from 2003-2012 is shown in Fig. 3.

1.3 The power model

The power generated from CSP plants is very sensitive to its system configuration. Among all available technological designs, parabolic trough comprises 96.3% operational CSP

	detail	value	source
L_{pst}	electric parasitic loss	11.1%	[10]
L_{hce}	HCE thermal loss [W/m^2]	42.629	SAM
L_{sfp}	solar field piping heat loss [W/m^2]	10.05	SAM
η_{trb}	turbine gross efficiency [%]	36.4%	[10]
η_{opt}	optical efficiency [%]	60.2%	[10]
A_{asf}	active surface area [m^2]	685,666	[11]

Table 2

plants in Spain with solar tower, parabolic dish and linear fresnel systems cumulatively holding the rest of the share (3.0, 0.1, 0.7% respectively) [8]. Hence, our model is adopted to the design of parabolic trough configuration. There are multiple factors hat can significantly influence the power generation from CSP plants, such as duration and intensity of solar irradiance, solar field size, system efficiency etc. These factors can be parametrically modeled using the first principles of heat transfer and thermodynamics as:

$$P_c sp = (1 - L_{pst})\eta_{trb}.A_{asf}(\mathrm{DNI}.\eta_{opt}.L_{hce}.L_{sfp}) \quad (2)$$

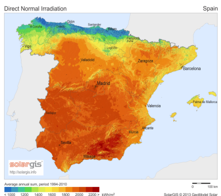
This parametric expression has been adopted from the Solar Advisor Model (SAM) developed by NREL, in conjunction with Sandia National Laboratory and in partnership with the U.S. Department of Energy [9]. The parametric values used in this work are tabulated in Table. 2.

2. Evaluation

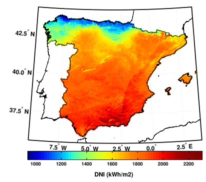
Thorough evaluation of a newly developed model against available measurements and existing studies is absolutely essential prior to its application. However, this is particularly difficult in the context of this work, for two main reasons:

1. CSP is a relatively new technology
2. Very limited number of CSP plants are fully operational today in Europe

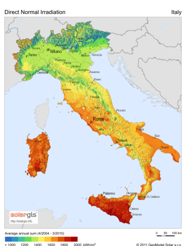
which makes long-term CSP data availability an important obstacle for our model evaluation. As a workaround, we have evaluated our derivation of solar irradiance (both GHI and DNI), as the latter very closely follows the power profile of CSP plants. We have used the SolarGIS database for the comparison of solar irradiance data. SolarGIS is designed specifically for solar energy research, which integrates solar resources and meteorological data for performance monitoring. The country-level solar irradiance maps provided by SolarGIS have been compared with our own model simulations and the results show fairly nice agreement [Fig. 4]. It is to be noted here that the remaining differences may be attributed to the different time periods over which the data have been averaged out. For example, the irradiance map of Italy shown in Fig. 4 from SolarGIS is derived for average DNI calculated from April 2004 - March, 2010. To present a close comparison, the DNI map of Italy from our own simulation was recreated for the period 2004-2010, instead of the full simulation period. However, for Spain, SolarGIS provided the DNI map with average annual sum computed from 1994-2010. To represent the longest time period coverage possible in our simulation, the DNI map of Spain was recreated for the period 2003-2012.



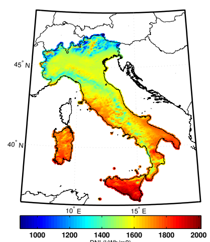
(a) Spain - SolarGIS



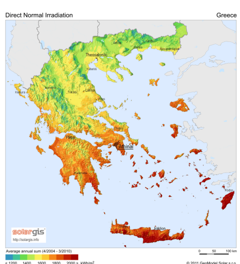
(b) Spain - Own simulation



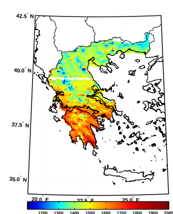
(c) Italy - SolarGIS



(d) Italy - Own simulation



(e) Greece - SolarGIS

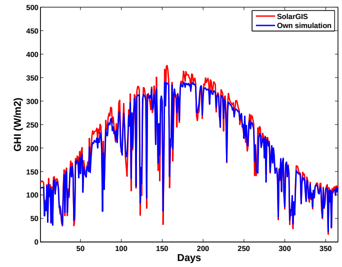


(f) Greece - Own simulation

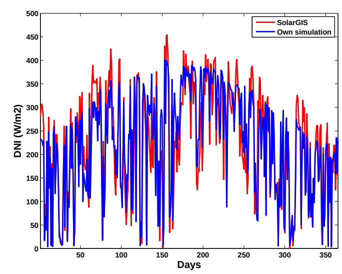
Figure 4. Comparison of DNI between SolarGIS and own simulation over Spain (top), Italy (middle) and Greece (bottom).

Irradiance time-series from SolarGIS is only available for a single site in Spain: Almeria (37.09°N and 2.36°W) at hourly resolution. Data is available from January, 1994 to June, 2012. So, our results are compared with this time-series for the overlapping periods of 2003-2011 at the nearest available model grid point (37.09°N, 2.45°W). The results of are shown in Fig. 5 for daily values of GHI and DNI for the year 2006.

Additionally, a few more numbers from our simulations were cross-checked with sparsely available information retrieved from literature survey. Although these values do not directly correspond to the simulation model derived for this project, they still provide some insights on the goodness of



(a) GHI



(b) DNI

Figure 5. Daily average solar irradiance time-series for Almeria, Spain, for the year 2006.

our model's performance. We have looked into the capacity factor values from two CSP plants in Spain: Andasol and Valle. The Andasol plant became operational in 2009 and currently comprises 3 plants each with 50 MW capacity. The Valle power plant became operational in 2012 and currently has 2 plants each with 50 MW capacity. Both plants are well equipped with thermal storage systems. A few literatures have reported capacity factors of these plants between 37.7-41.0% for Andasol and around 37.0% for Valle. Our simulations at the nearest model grid points under no storage scenario indicate that Andasol plant capacity factor of 24.6% in 2010, 26.4% in 2011 and 27.3% in 2012. For Valle power plant, similar model set up revels a capacity factor of 25.1% for 2012. While access to thermal storage systems is definitely on of the main causes of this discrepancy, other factors like different considerations for solar field area also contribute to the differences in gross annual generation from the model and the literature. Both plants had an active surface area of 102ha, whereas our system was configured for a much smaller solar field area, around 68.6 ha. Also, the capacity factors reported in the literature do not specify the exact year that it corresponds to.

Several studies have reported rough estimates of CSP capacity factors, for example, 23-50% [8], 25-28% [12], 24% for demonstrated CSP plants [6]. Our results of Spain varies between 23-27% for scenarios without any consideration for thermal storage coupling.

Acronyms

CSP Concentrated Solar Power.

DHI Diffuse Horizontal Irradiance.

DNI Direct Normal Irradiance.

GHI Global Horizontal Irradiance.

PV Photovoltaics.

SAM Solar Advisor Model.

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