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Review and validation of Solar Thermal Electricity potential methodologies

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ABSTRACT

With the strong dependence of national economies on energy, interest in solar energy potential assessments is increasing in countries with high solar radiation levels. This article reviews four methodologies proposed in the literature by four different organizations (IDAE, Greenpeace, NREL, and DLR) and proposes a new one (LRS) for assessing the potential of Solar Thermal Electricity (STE) generation in a given country. Derived from these five methodologies, nine cases are studied (IDAE, GP2, NREL1, NREL3, DLR2, DLR2′, LRS1, LRS2, and LRS3). In this study, we followed a two-step STE potential assessment procedure. In the first step, suitable areas for locating STE plants in the country are identified. In the second step, STE plants are assumed to be built and operated in the suitable areas selected in the first step, and the annual electricity generated by these hypothetical plants is estimated.

To compare the assessed methodologies, all cases have been applied to the same test country: Spain. Because a relatively large number of commercial STE plants are in operation in Spain, the location of these commercial plants was used to define a simple but effective validation test. A validation process is proposed for the IN-OUT decision based on the buffers containing each existing STE plant. Inside each buffer, a mix of suitable and unsuitable pixels is often included. Thus, the process starts with the decision whether a plant could be considered "IN" the suitable area or not. After the evaluation of the percentage of pixels considered as suitable inside the buffer, and comparing with only the power block pixel location, the second option was selected since it provides good results and simplifies any further treatment. The validation process also considers a minimum of near 90% of the STE plants "IN" suitable areas in order to consider a specific case valid. This means that if a case leaves out more than 10% of the real STE plants, it was considered far from reality and rejected. Cases IDAE, NREL3, DLR2, and the new LRS3 have been validated using the described validation procedure and the last three have very close results with similar levels; this is an important outcome that aims to compare potential assessments performed in different countries by different institutions.

1. Introduction

Three main factors influence the degree of interest of a country in renewable energies [1]. The first factor is the relevance the country assigns to decreasing its energy dependence on other countries, i.e., the importance the country attributes to energy as a national security matter. The second factor is the degree to which the use of renewable energies for power generation minimizes the country's greenhouse emissions and, therefore, contributes to economic savings in terms of emissions rights. The third factor is the relevance that the country assigns to the contribution to employment usually associated with the deployment of renewable energy projects [2].

Thus, under the current circumstances of increasing awareness with regard to the dangers of energy dependence, and increasing economic pressure to reduce greenhouse emissions and to decrease unemployment figures, it is no wonder that interest in renewable energy potential assessments is rising. In most cases, these assessments are used to gain a general high-level understanding of the maximum amount of energy of a given renewable source. This energy can be generated in a given period of time either in a specific area or at regional or national level, even though, the amount and the level of detail of the data needed to carry out such an assessment is usually not high-resolution at all, but quite specific.

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With regard to Solar Thermal Electricity (STE), Spain is currently the country with the highest installed power capacity at 2.3 GWe. However, Spain is expected to soon be overtaken by the USA [3]. There are a total of 50 STE plants in operation in Spain, with a cumulative production of 4442 GW h in 2013, 4958 GW h in 2014 [4] and 5158 GW h in 2015 [5]. Most of these power plants (45) employ parabolic trough technology, which is also the technology of choice in many other countries [3]. Further consideration of STE plants hybridized with combined cycle gas turbines could present additional benefits, such as improved yield and efficiency in peak periods or reduced CO_2 emissions [6].

There have been several analyses that have estimated the potential of STE production in different countries and regions. These analyses assist in decision-making by policymakers and industry, providing fundamental data using which the techno-economic scenarios can be improved. This is the case for the International Energy Agency's Technology Roadmap for Solar Thermal Electricity [3], which estimates that STE plants will provide up to 11% of global electricity generation by 2050 (4400 TW h), with 1000 GW of installed capacity worldwide.

The main studies on STE potential in Spain have been done by the Institute for Energy Diversification and Saving (IDAE) [7] and by Greenpeace (GP) [8]. In the rest of the world, the most relevant studies thus far have been conducted by the National Renewable Energy Laboratory (NREL) [9,10], with a focus on the USA, and the German Aerospace Centre (DLR) [11], with a focus on the Mediterranean region. The four different methodologies used in these four reference STE potential assessment studies are analysed in this paper, paying special attention to the detailed inputs required by each methodology in order to generate their results.

The IDAE methodology takes land uses into account, however, there is no limitation related to slope and solar radiation level. The GP study includes a detailed terrain slope assessment, while the NREL and DLR methodologies include limited terrain slopes values. In addition, NREL and DLR take into account a minimum direct normal irradiation[1] (DNI). Finally, NREL also adds a requirement for a minimum area of 2 km^2 as an inclusion criterion.

Most of these methodologies take into account different levels of potential: total potential, technical potential, and economic potential. However, these potential levels are not presented in a harmonized manner, and each methodology deals with these three concepts (total, technical, and economic potential) by taking different considerations into account. In the current study, we intend to apply the methodologies up to their technical potential.

All Solar Thermal Electricity potential methodologies require detailed spatial data analysis. Because of this, they are heavily based upon the use of Geographical Information Systems (GIS) [12]. This is not unique to STE potential assessment. There are many examples of the use of GIS applied to different renewable energy technologies, including: wind energy [13], hydroelectric [14], biomass [15,16], geothermal [17], and the integration of different renewable technologies [18–22].

To compare the four STE potential assessment methodologies from the literature, we applied each methodology to Spain and analysed the results. One outcome of this preliminary analysis was that the different methodologies provide a large range of STE potential for Spain, mainly due to their different ways of analysing the territory [7,8]. This prompted us to propose a new methodology based upon the best practices and the most rational criteria from the previous methodologies.

[1] In this document, we use DNI as direct normal *irradiation*, because we use it as an annual energy value, although DNI usually refers to direct normal *irradiance*.

2. Methodology

In the current study, four methodologies proposed in the literature were analysed for STE potential assessment, corresponding to four organizations (IDAE, GP, NREL, DLR) as well as one additional Land-Radiation-Slope methodology (LRS), based on the previous ones. Nine cases (IDAE, GP2, NREL1, NREL3, DLR2, DLR2′, LRS1, LRS2, and LRS3) derived from the five methodologies are considered. In all of these cases, we analyse two well-differentiated steps: the first related to suitable land identification, and the second related to the energy estimation. In order to compare these results, the cases have been applied to Spain.

The STE potential assessment procedure is applied to the parabolic through collector technology (PTC). The first step deals with the selection of suitable areas for STE plants construction all over the country. In order to validate the first step, we used 47 locations, 45 PTC and 2 linear Fresnel plants locations as if they were PTC. We considered that, since linear Fresnel is very close to PTC in terms of geometry and land use, this approach is reasonable. The second step is related to electricity generation. We applied an equation for estimating the electricity at a selected pixel if a STE plant were constructed in that pixel. This step, no matter what actually exists in that pixel, provides information about hypothetical electricity generation. In order to test the procedures, we applied an equation for electricity production validity for PTC. The electricity results are only related to this technology.

2.1. Methodology for identifying suitable areas

This first step is assessed in depth in the current study. We have revised and implemented all considerations for each methodology in order to derive whether each 100 m by 100 m pixel is considered suitable or unsuitable as a site for STE plant construction. This compelled us to look for all input information required by each methodology and to harmonize the layers with the same geometry and projection. A review of the needed layers and considerations for each methodology is described below.

The IDAE methodology takes into account land uses, applying information from the *Corine Land Cover* (CLC2006) [23]. However, there is no limitation related to the slope of the terrain. As a result, a large number of zones are considered suitable, distorting the outcome for suitable areas and overestimating electricity potential. The GP, NREL, and DLR methodologies analyse the slope of the terrain in more detail and consider it separately from land use. NREL and DLR also use a minimum DNI. Finally, NREL also adds the requirement of a minimum area of 2 km^2.

A classification of the issues considered by each methodology was conducted for the three main types of considerations: land constrains, radiation, and slope. This classification is the basis of the new methodology, LRS, which is based on the revised methodologies and develops minimum criteria for potential assessments. Thus, LRS is a combination of land constraints from the IDAE methodology and a minimum DNI of 5 kW h/m^2/day. From these base criteria, we tested three different cases of varying slope percentage values, i.e., LRS1, LRS2, and LRS3 (1%, 2%, and 3% slopes, respectively). Fig. 1 shows detailed information related to the LRS methodology. This new proposal does not take into account geomorphology, as it requires more knowledge of the geotechnical conditions necessary for construction of a STE plant. This could be the subject of future studies.

The results from each methodology will depend on the criteria and different constraints taken into account. For a better understanding of the comparative results, Table 1 presents the criteria considered by each methodology for the selection of suitable areas. These are summarised using the proposed classification.