An assessment of the regional potential for solar power generation in EU-28

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HIGHLIGHTS

- A European suitability map for the solar energy (PV) systems deployment is created.
- PV systems can contribute in a sustainable energy production in many regions in EU.
- There is no correlation among the EU investment and the suitability in solar energy.
- Using marginal lands to place PV systems might avoid the uptake of agricultural land.
- Validation of the EU suitability map demonstrated a satisfactory degree of accuracy.

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ABSTRACT

In this study we aim at assessing the potential of European regions to solar power generation and its comparison with recent European Union (EU) incentives for the development of this renewable energy source. In this study we use a multi-criteria assessment (MCA) supported by Geographical Information System (GIS) to combine already existing information on solar radiation with other geographical factors such as slope, land use, urban extent and population distribution, as well as proximity to the power grid to generate a suitability map for photovoltaic (PV) power plants across the EU at high spatial resolution. A validation exercise showed that the resulting suitability map is a good predictor of appropriate locations for the deployment of PV power plants. The suitability map was in addition compared to the regional distribution of European funds for development of solar energy from the EU Cohesion policy (2007–2013 programme). Regions were classified according their overall suitability for solar energy power systems and the allocated solar investments by the EU Cohesion policy. This analysis allowed to identify potential mismatches between fund allocations and actual regional suitability for solar energy. It is recommended that future fund allocations take into account suitability criteria for solar energy for optimised results of public policies. © 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

The climate and energy legislative package launched in December 2008 established different measures to mitigate climate change, promote renewable energy and energy efficiency. This EU framework includes the Renewable Energy Directive (2009/28/EC) which aims at promoting the use of renewable energy sources (RES) within the energy system and transport sectors (CEU, 2008; EC, 2009). A legally binding EU target, among others, was set, according to which 20% of the total energy consumed in the EU must be produced from RES (Tampakis et al., 2013). Solar energy is one of the renewable energies capable of contributing to the reduction of foreign energy dependence as well as energy-related environmental impacts (IPCC, 2011; Panwar et al. 2011).

According to Eurostat data (Eurostat, 2012), Germany was the largest producer of solar energy in Europe in 2012, with 2.26 Million toe (tonnes of oil equivalent) produced, followed by Italy (1.62 Million toe), and Spain (0.7 Million toe). Other countries with high suitability for solar energy generation, such as France, Greece and the United Kingdom produced much more modest amounts in 2012, with respectively 0.345, 0.145 and 0.102 Million toe.

Supporting the deployment of solar energy systems, NREP (National Renewable Energy Plans) detail the Member state strategies and measures to meet the binding 2020 target for the total...
Solar energy consumption (CD, 2009). Additionally, the EU Cohesion policy (EC, 2014) is a complementary instrument, among many initiatives to promote social and territorial cohesion, which is also used to promote solar energy and thus supporting the Renewable Energy Directive targets (EC, 2013a).

Solar radiation can be converted into sustainable-produced electricity by using photovoltaic (PV) technology. Large-scale photovoltaic (PV) systems provide significant environmental benefits and advantages when compared to conventional, non-renewable energy sources, the reduction of greenhouse gas emissions, and the reuse of marginal lands being two key examples (IPCC, 2011). However, the large area required may cause undesirable impacts on land use, landscape, and biodiversity (Graebig et al., 2010). Ideally, these installations should be located on unused, low productivity agricultural and/or pasture land and, in general, areas covered by grasslands or scrublands to minimise such impacts (Turney and Fthenakis, 2011; Tsoutsos et al., 2005). Non-ideal locations are those characterized by forest land cover, extreme remoteness, instability and high degree of existing development.

Solar energy potential can be defined as the physically available solar radiation on the earth’s surface (Angelis-Damakis et al., 2011). Various global and European studies have been carried out in order to estimate solar energy potential. This estimation relies on different factors among which solar radiation is considered essential (Tsoutsos et al., 2005). The use of (meteorological) satellite data and/or interpolation methods are the most typical approaches for the determination of solar radiation and were used, for instance, in the Heliosat method1 and Meteonorm database2 (Angelis-Damakis et al., 2011), respectively. At a European scale, Šůri et al. (2007) presented an analysis of solar electricity generation from their previous development of the Photovoltaic Geographical Information System, PVGIS (EC, 2013b; Šůri et al., 2005), concluding that the contribution of solar energy to the energy systems was still considerably low at the time despite its enormous potential as energy source. A more ambitious project is presented by Grossmann et al. (2013) in which an optimisation method for site selection, generation and storage of solar electricity generation across large geographical areas is developed in order to solve the problem of the intermittent nature of solar electricity. Additional questions were also addressed regarding site location given geopolitical and environmental concerns and transmission line costs, among others.

However, the solar estimated potential (theoretical potential) is significantly reduced when technical, economic, social and environmental factors and constraints for the deployment of solar energy systems are considered. The determination of such limiting factors enable us to identify more accurately the suitable areas for installation of photovoltaic (PV) systems (Hoogwijk and Graus, 2008), and in turn determining the feasibility and sustainability of energy system developments.

Solar energy is considered environmentally and socio-economically beneficial if a proper design, planning, siting and management. It also enjoys favourable public acceptance, as studies from Tampakis et al. (2013) and Tsantopoulos et al. (2014) have shown. However, wider and faster adoption of solar energy systems requires appropriate incentive schemes, or innovative business models to limit high initial costs and long-term uncertainties regarding expected rents (Bauner and Crago, 2015; Overholm, 2015; Malagueta et al., 2013; Phillips, 2013; Santoyo-Castelazo and Azapagic, 2014).

### Table 1

| Criteria | Description | Data source |
|----------|-------------|-------------|
| **Constraints** | Protected and sensitive natural areas | CORINE LC-refined (Batista e Silva et al., 2013a) |
| | Built-up areas, wetlands, water bodies and forest | PVGIS project (EC, 2013a, 2013b) |
| | Solar radiation | SRTM, 2013; PVGIS project (EC, 2013a, 2013b) |
| | Topographic parameters (slope, aspect, elevation) | JRC population grid map (Batista e Silva et al., 2013b) |
| | Population potentially affected | Teleatlas |
| | Proximity to roads | EC-DE REGIO |
| | Proximity to the electricity grid | |

The contribution of this paper mainly falls on the representation of a European suitability map for the installation of PV systems based on a Geographical Information System Multi-criteria Assessment (GIS-MCA) method using a set of relevant geographical variables. Afterwards, the EU regional investment assigned to the development of solar energy systems is analysed against the EU suitability map. This assessment could help allocating more efficiently the EU regional funds for solar energy generation. The main purpose of this paper is twofold: 1) to estimate the degree of suitability for the installation of PV systems across Europe, both at detailed level (1-km grid resolution) and aggregate level (NUTS3 regions); and 2) to analyse the allocation of EU Cohesion funds in relation to the European suitability map for solar energy production systems. Finally, the study presents a validation process of the European suitability map, and summarises the main conclusions.

### 2. Material and methods

A GIS-MCA approach was proposed to produce a European suitability map for the development of large-scale solar power plants2. In this context, the ‘suitability’ was defined as the quantification of the appropriateness of each location to hold PV systems, and it was determined by a set of biophysical and socioeconomic factors, which were mapped at pan-European level using the available data sources (see Table 1 and Annex I). Fig. 1 illustrates the workflow designed to achieve the two objectives of this study. In the next sections, the methodology is described in more detail, focusing separately on the components that integrate the European suitability map for the installation of solar power plants.

#### 2.1. Identifying the land availability: natural and artificial constraints

The deployment of PV systems in certain areas can be constrained by technical or environmental reasons. To capture most of these aspects, we considered constraints like areas in which the development of PV systems is either technically unfeasible or not recommended due to environmental sensitivity. Two types of information were used: the location of sensitive natural areas and specific land use/cover types (Table 1 and Annex I).

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1 Webpage: www.helioclim.net.
2 Meteonorm. Meteonorm version 6.1 – handbook; 2008. Webpage: www.meteonorm.com.
Sustainable natural areas. The main impact on natural areas and biodiversity is due to land take by the power plant itself. The impact on natural ecosystems is dependent upon specific factors such as the topography of the land, the area of land covered by the solar panels and associated components, the type of the land, the distance from areas of natural beauty or sensitive ecosystems, and the biodiversity in the area. Nationally designated areas were assumed to represent the most sensitive environmental and ecological sites and areas in Europe, as recognised by each European country, and were therefore considered inappropriate for the development of solar power plants.

Current land uses/cover. Built-up areas, forest, wetlands and water bodies are land use/cover features in which the installation of PV systems is mostly unviable due to low accessibility, instability, or degree of existing development (Turney and Fthenakis, 2011; Tsoutsos et al., 2005; Janke, 2010). Ideal locations are normally those that are, on one hand, undeveloped, and on the other hand have short vegetation types that do not prevent insolation. Although small scale solar systems can be installed as well within city environments (roof tops, parking lots, and even windows of residential, commercial or industrial buildings), built-up areas were left out because the herein study focuses on large-scale photovoltaic systems only.

By combining the above-mentioned constraints, we created a binary layer representing the available land surface for the development of PV energy systems at a European scale.

2.2. Identifying the land suitability: biophysical and socio-economic factors

The geographical potential can be defined as the theoretical potential restricted to the solar radiation at areas suitable for the installation of PV production systems. Many different suitability factors can be taken into account to estimate the geographical potential to determine the degree of suitability to set up a solar energy system, such as population density, urban areas, land use/cover, terrain (Hoogwijk and Graus, 2008). The selected suitability factors chosen in our study took into account review of relevant and specialized literature. Solar radiation, orientation and slope, population, transport network and electricity grid have been identified as being the most relevant for the exploitation of this renewable energy source. A brief explanation of each suitability factor and the main data sources are described below.

Solar radiation. Probably, the first and foremost of factors determining the theoretical potential is solar radiation. It can be defined as the solar energy (light) arriving at the surface of the Earth on a yearly basis (kW h/y). According to Suri et al. (2007) the poorest regions in the EU in terms of solar radiation are those that fall below 900 kW h/m².

Topographic parameters. At a landscape scale, topography is the major factor modifying the distribution of insolation. Variability in elevation, surface orientation (slope and aspect), and shadows cast by topographic features create strong local gradients of insolation (Suri et al., 2007, Azoumah et al., 2010). A percentage of slope ranging from 16 and 30 was considered poorly suitable while greater than 30 was considered technically unviable.

Population. Large-scale solar PV installations have relevant implications on near residential areas, such as emission of pollutants and visual intrusion in rural settings. In terms of populated areas, the appropriated site for the solar farm should consider a buffer distance in order to avoid most direct impacts and resistance of the local communities (Turney and Fthenakis, 2011; Tsoutsos et al., 2005, Janke, 2010). In this sense, locations at distances greater than 500 m from cities/residential areas (more than 1 inhab/ha) were considered more suitable for PV system installations.

Transportation network. Easy access to PV systems is a relevant factor for both construction and operation phases, particularly for maintenance purposes (reparation, clearing of vegetation, panel washing) (Janke, 2010). Therefore, this study considered locations closer to existing roads more suitable than those far from existing road network, with a cut-off value of 5000 m for unfeasible locations.

Electricity grid. Other essential criterion for the selection of the most suitable site is the distance to the transmission lines network (Janke, 2010; Azoumah et al., 2010). The higher the proximity to the existing electricity grid, the lower transmission costs and power losses.

Table 1 and Annex 1 summarise the main criteria (constraints and suitability factors) that were combined through a GIS multi-criteria analysis in order to generate the European suitability map for the installation of PV energy systems.

2.3. Combination of layers in a GIS multi-criteria analysis (GIS-MCA)

In the first step, the land availability was identified by subtracting the areas with strong restrictions to the development of large-scale solar farms such as protected areas and certain land use/cover classes (see Section 2.1). Second, the land suitability for solar farms was obtained by the identification of the suitability factors specifically, solar radiation, orientation, slope, nearby population, proximity to the electricity grid and accessibility to roads. For each of these suitability factors, a quantitative scoring was

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4 The highest adaptability is assigned a value of 100, the lowest is assigned 1 and not suitable areas are assigned 0.
applied to each class representing the suitability to hold PV energy systems based mainly on value judgement and literature review (Janke, 2010; Azoumah et al., 2010). Each factor map was then normalised from 0 (poorly suitable) to 100 (very suitable) thus ensuring inter-comparability.

The GIS-MCA analysis used in this study is based on the weighted linear addition (WLA) technique\(^5\), thereby integrating all individual suitability factors maps in one layer in order to estimate the overall suitability at each location (pixel), as shown in Eq. (1) (Perpiña Castillo et al., 2013):

\[
r_i = \sum_{j=1}^{n} w_j v_j
\]

where \(r_i\) is the overall suitability level of each location (pixel) \(i\); \(w_j\) is the weight of each factor \(j\); \(v_j\) is the assigned suitability value in each factor \(j\). After review of the literature and expert opinion, all factors were assigned equal weights (1), except for solar radiation which was assigned the double weight (2) (Janke, 2010; Azoumah et al., 2010).

After the whole GIS-MCA, the resulting raster layer represents the suitability of the land to hold PV systems, ranging from 0 (non-suitable) to 100 (very suitable) at a European level at 1-km grid resolution.

2.4. Policy-related suitabilities for PV systems deployment

Concerning the improvement of the environment and the preservation of agricultural and forest areas (Hoogwijk and Graus, 2008), degraded/contaminated lands could be an interesting option for the installation of new PV systems providing additional positive implications. While productive, high quality soils should be preserved, soils with poorer conditions, such as those affected by medium to high saline concentration, severe erosion, or contamination by heavy metals could be devoted to alternative uses such as solar energy production\(^6\). Below we list and justify the factors which we selected to identify areas which could be used for solar energy production without jeopardising high quality soils and current and future food production.

Saline concentration. Salinity affects crops through inhibiting the uptake of water. Moderate salinity affects growth and reduces

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\(^5\) A specific spatial tool was used to overlap all the spatial suitability factors (rasters), multiplying the assigned suitability value by their given weight and summing them together.

\(^6\) Degraded and contaminated lands can be recover for many different purposes. In Perpiña Castillo et al. (2015) is presented an alternative use of these categories for energy crop production.
yields; high salinity levels may kill the crop (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012). High and medium salinity concentration areas (greater than 4 dS/m) were proposed as potential locations for solar farms installations, and were taken from the SINFO project (ESDAC, 2013a).

Soil erosion. By removing the most fertile topsoil, erosion processes reduce soil productivity. For agriculture purposes, erosion is undesirable due to the loss of soil nutrients and drainage problems. Areas classified with very strong, strong and moderately strong erodibility levels (greater than 10 t/ha/yr) were proposed as preferred locations for solar farms installations, as those areas are less suitable for crops (ESDAC, 2013b).

Contaminated lands. High concentrations of Cadmium (Cd), Copper (Cu), Mercury (Hg), Lead (Pb) and Zinc (Zn) can be linked to human activities such as heavy industry/manufacturing and intensive agriculture. Such areas should not be used for food production, and can therefore be considered preferable locations for solar energy facilities, among other alternative uses. We identified such areas by applying threshold values derived from the work Micó et al. (2007) on heavy metal concentration maps from Rodríguez et al. (2008).

2.5. EU cohesion policy

The Cohesion policy is one of the most important policy instruments of the EU, involving a substantial share of the EU budget and involving every region from each Member State. The Cohesion policy for the programming period 2007–2013 represented approximately 1/3 of the EU budget, totalling circa 347 billion euros of Cohesion and Structural funds (Europa, 2013). Cohesion policy investments are channelled to EU’s regions in order to promote competitiveness, economic growth and job creation, while reducing economic, social and territorial disparities between regions, thus contributing to the ‘Europe 2020’ growth strategy (Batista e Silva et al., 2013a). The main investment compartments are research and development (12%), aid to the private sector (12%), environment (17%), infrastructure (32%), human resources (22%) and technical assistance (5%). In the multi-annual financial period 2007–2013, a total of 1071 Million Euros, or roughly 0.31% of the whole programme, were allocated to solar energy investments across the European regions. As Fig. 2 shows, regions in Italy, Spain, France, Check Republic and Croatia have been allocated the highest volumes of the EU funds to promote solar energy. In Section 3.2 of this paper, the spatial allocation of the funding was compared against the European suitability map for solar energy system deployment.

2.6. Validation

A validation process of the European suitability map for the installation of solar power plants was applied with the purpose of evaluating the quality of the resulting map and, in turn, to assess if the methodology met its purpose of identifying the most suitable regions to develop solar energy technologies. It can be reasonably assumed that the locations of existing solar power plants were determined by geographical suitability and technical criteria. Therefore, the location of existing solar power plants are used as an independent source to assess the validity of the suitability map described in this paper.
The validation strategy consists therefore on comparing whether the suitability levels of the location of existing solar power plants are significantly higher than a random set of locations. If this hypothesis is true, then it can be concluded that our suitability map is useful in predicting the location of current solar power plants and thus a useful instrument to identify locations suitable for additional installations across Europe. This strategy is determined by running five times a total number of 50 random points per country in order to have a large sample. To each random point, the suitability value of the cell in which it falls was assigned and, for each run, the basic statistics and box-plots were computed. The data collection of the existing largest solar power plants for different countries was done via internet sources. First, we obtained from Wikipedia (2013) a list of solar power plants currently operating in five European countries: Germany, Spain, Portugal, Italy and France. When available, we used geographical coordinates to geo-reference the power plants. Each single power plant was checked using the Google Earth software, to ensure that each was geo-referenced with highest accuracy. A total of 120 points was obtained for the above-mentioned countries. Fig. 3 shows the spread of the existing solar farms and the basic statistics per each country under study were computed considering the whole sample (see Section 3.3, Table 3).

3. Results and discussion

3.1. The European suitability map for the installation of PV energy systems

The spatial constraints and suitability factors were combined within a GIS environment to generate a European suitability map.
to the development of large-scale PV systems with a resolution of 1-km grid (Fig. 4). Large differences on the degree of suitability can be observed not only at European level but also within countries. The results demonstrate that the largest variability of suitability for PV systems deployment at the national level can be seen in France, Spain and Italy, owing to the geographical extent of those countries, their variations on climate conditions and the suitability factors selected. However, a dominant trend was evident, with overall suitability increasing from North to South, due to solar radiation, which is negatively correlated with latitude.

In fact, the results showed that the most suitable areas were located in the Southern parts of Europe (Mediterranean regions) where the highest levels of solar radiation occur (Italy, Portugal, France, Spain, Greece, Malta and Cyprus). Some countries of Central Europe and eastern parts of Europe (Germany, Slovenia, Hungary, Bulgaria, and Romania) were characterized by low to moderate suitability for PV systems applications. The less favourable group of countries were those of Northwest Europe (Ireland, United Kingdom, North France and Germany and Benelux), Northeast part of Central Europe (Poland, Check republic, Slovakia) and the Baltic States (Estonia, Latvia and Lithuania) including Sweden and Finland.

A regionalized European result is displayed in Fig. 5 where the average estimated suitability values were computed taking into account the available land surface per each NUTS3 region. The regional map indicates sometimes large differences within countries. It must be highlighted the case of Italy, Spain, Romania ad Greece where the degree of suitability varies from the lowest to the highest within the country. In a normalised scale of suitability levels (from 0 to 100), Italy varies from 46 (very low suitability, in the central part) to 99 (the highest value, in the southeast part), Spain varies from 52 (low suitability, in the northern part) to 95

Fig. 5. Regional distribution of the average suitability levels for the installation of large-scale PV systems in Europe (NUTS3 level).
Fig. 6. Suitability and regional investment for solar energy in EU’s regions (2007–2013).

Fig. 7. Scatter plot of the average suitability levels computed per NUTS2 region against the allocation of investment (measured in Million euros) in solar energy.
Table 2
Main statistics of the existing PV systems suitability values distribution per each country.

|            | All countries | Germany | Spain | France | Italy | Portugal |
|------------|---------------|---------|-------|--------|-------|----------|
| Number     | 120           | 20      | 45    | 13     | 37    | 5        |
| Minimum    | 66            | 68.5    | 77.3  | 71     | 72.7  | 74.9     |
| Q1         | 79.8          | 72.4    | 84.4  | 73.4   | 83.1  | 75.9     |
| Median     | 85.3          | 74.0    | 87.1  | 82.6   | 85.4  | 91.8     |
| Q3         | 89.5          | 77.6    | 90.9  | 86.1   | 87.4  | 92.1     |
| Maximum    | 95.3          | 82      | 95.3  | 89.1   | 91    | 92.5     |
| Mean       | 83.6          | 74.7    | 87.1  | 80.5   | 85    | 85.4     |
| S. Deviation | 6.5     | 4.04    | 4.56  | 6.3    | 3.98  | 8.2      |

* Q1 = first quartile.
* Q3 = third quartile.

Table 3
Statistics of the overall suitability per each country under study.

|            | Germany | Spain | France | Italy | Portugal |
|------------|---------|-------|--------|-------|----------|
| Minimum    | 39      | 43    | 41     | 31    | 47       |
| Maximum    | 86      | 98.9  | 95.9   | 99.5  | 100      |
| Mean       | 62.1    | 75.6  | 71.8   | 72.41 | 73.1     |
| S. Deviation | 5.4     | 7.3   | 5.7    | 8.15  | 7.2      |

(high suitability, in the southern part), France varies from 45 (very low suitability, in the eastern part) to 95 (high suitability, in the southern part), Romania varies from 42 (very low suitability, in the Northern part) to 93 (high suitability, in the southern part) and Hungary varies from 60 (low suitability, in the North-eastern part) to 93 (high suitability, in the south-eastern part).

3.2. Assessment of the EU investment in solar energy

Fig. 6 compares the average suitability for photovoltaic systems to the allocated EU funds for solar energy at regional scale (NUTS2 level). The threshold between high and low suitability was defined according to the frequency distribution of the regional suitability levels. With regard to the distinction between high and low investment levels, 10 million Euro was used as threshold. Although straightforward, this analysis, enables a quick identification of four types of situations:

1. Regions with high suitability levels and high investment levels;
2. Regions with high suitability levels and low investment levels;
3. Regions with low suitability levels and high investment levels, and;
4. Regions with low suitability levels and low investment levels.

Results show that among the large number of regions classified as highly suitable for solar energy, only 11 (out of 276 regions) were actually allocated a high investment level, representing 45% of the total solar investment. On the other hand, large investments were allocated to the whole of Czech Republic and Slovenia, whose regional solar suitability levels were comparatively low. The majority of the regions, however, scored low investment levels regardless of their suitability levels.

As mentioned in Section 2.5, the reciprocities between solar energy and land use can be increased if aspects like degraded/contaminated and low productivity lands are used as location factors for photovoltaic systems. In the map of Fig. 6, a set of symbols were added to the regions with high levels of solar suitability, representing a significant percentage of land affected by severe erosion, and high concentration of salt or contaminants (heavy metals) on soils. The figure also represents regions which contain significant share of degraded and low productivity lands (sever erosion, high salinity and contaminated lands).

Overall, Fig. 6 seems to indicate that there is little correspondence between suitability for photovoltaic energy and allocated investments at regional level.

In Fig. 7, the scatter plot indicates the absence of correlation between the two variables at NUTS2 level, which was further confirmed by Spearman’s rho test, which was applied to determine the strength of the correlation and independency of the variables. The test yielded a $\rho=0.149$ with a $p$-value=$0.0071$ which indeed confirms an essentially random relationship between the two variables.

It must be noted that the actual nature of the projects financed by the EU funds under the “solar energy” expenditure category can include other types of investments than only on photovoltaic systems, which is probably emphasising the differences between the total investments and the suitability map herein used. Unfortunately, micro-data on actual project types is extremely scattered and has not been yet systematised and published by the European Commission, which prevented a more refined analysis.

3.3. Validation of the European suitability map for the installation of PV energy systems

Before the validation process, an exploratory analysis (Table 2) of the distribution of the suitability values assigned to the existing PV system was operated at a country level. Using the quartiles, the first and third, it was possible to identify how many solar farms are above a certain threshold and providing an initial measure of the model’s performance. Specifically, 91 solar farms out of 120 are above of the threshold established by the Q1 (25th percentile), which means that 75% of the solar farms in operation were assigned suitability values greater than 79.8. Similarly, 64 solar farms are above of the threshold of the median (50th percentile) which means that 50% of the solar farms in operation score a suitability higher than 85.3. Finally, 27 solar farms are above of the threshold stabilised by the Q3 (75th percentile) meaning that 25% of the solar farms in operation were assigned suitability values higher than 89.5.

As indicated in Section 2.7, in order to test to what extent the European suitability map (Fig. 4) approximates to the potential suitability values of existing PV systems, a validation process was performed. Specifically, two validation approaches were applied: 1) A first straightforward validation approach by comparing the median suitability in each country (Table 3) against the median of the distribution of the suitability values assigned to the existing PV systems; 2) A random location of points’ strategy. The main conclusions of the validation can be drawn from Fig. 8 and Tables 2, 3 and 4.

As it can be observed the median suitability of the existing PV systems (Table 2) were considerably higher with respect to the overall country values (Table 3), meaning that PV systems were installed in places which were represented by higher suitability.
Fig. 8. Box plot represents the distribution of the solar farm suitability values compared with the suitability values assigned to the random location of points per each run at country level. In each box-plot, the bottom of the lower tail represents the minimum value and the top of the upper tail represents the maximum. The lower line of the box represents the 25th percentile, the upper box of the 75th percentile and the middle line in the box represents the median. DE (Germany) is assigned colour orange, ES (Spain) is assigned colour yellow, FR (France) is assigned colour green, IT (Italy) is assigned colour red and PT (Portugal) is assigned colour blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

values\textsuperscript{12}. However, the random location of points’ strategy is in our opinion more appropriate to measure the validity of the European suitability map. Table 4 and box-plot graphs for each random run in Fig. 8 report the dispersion and the main statistics of the distribution for both (average) existing solar farm suitability values (solid colours) compared with the (average) suitability values assigned to the random points per each run at country level. The last box plot (grey colour) includes all the existing solar farms in all countries showing a median (85.3) and a mean (83.6) of the suitability levels considerably high. Moreover, the dispersion of the distribution is relatively small being represented by the standard deviation (6.5). Noted that the maximum value reaches 95.3 and the minimum 66 out of 100, which revealed a satisfactory result.

When average values per individual country were considered, the findings of the analysis were also good. Looking at Fig. 8 it can be stated that the means of the suitability values from the existing solar farms were statistically significant higher\textsuperscript{13} than those from the random location points. To reach this point, first, it was needed to apply a normality test (Shapiro–Wilk) in order to identify whether the sample, both existing solar farms and random points, came from a normally distributed population. The test yielded p-value less than the significant level (0.05) rejecting the null hypothesis, mainly for the random location points distribution. Thus, a non-parametric test (Kolmogorov–Smirnov) was then applied to analyse whether the two underlying distributions differed. In summary, both distribution were highly significant different in a favour of the distribution corresponding to the solar PV systems currently in operation, proving that the European suitability map can be a valuable tool for the future location of solar farms by demonstrating better results. It must be stressed the case of Spain and Portugal (greater than the overall median), however the former country account for a higher mean (87.1), higher maximum value (95.3) and less dispersion (4.56) in its distribution.

3.4. Discussion

Recently the European Commission has published the actions set out to reach the ambitious vision of becoming a resilient

\textsuperscript{12} An overall average of more than 14% for Spain 13.2%, for Germany 13.7%, for France 10.8%, for Italy 14.8% and for Portugal 14.4.

\textsuperscript{13} p-values for all the countries and for both distribution were less than 0.05 (significant level), rejecting then the null hypothesis that the distributions were originally similar. Just for the case of Portugal, the p-value is close to 0.05 but it can be owing to the small number of existing FA.

\textsuperscript{14} Before legally binding target was set to 20% in 2020.

\textsuperscript{15} National Renewable Energy Action Plans.
An example of tax reduction can be seen in the UK where not full and subsidies aiming to encourage the use of renewable sources. Changes to legislative framework in form of tax incentives, rebates to reduce solar PV adoption times and other economic barriers significantly (Bauner and Crago, 2015; Overholm, 2015). Second, a change to legislative framework in form of tax incentives, rebates and subsidies aiming to encourage the use of renewable sources. An example of tax reduction can be seen in the UK where not full VAT rate is charged (West et al., 2010). The successful cases on solar technologies deployment of Spain and United States are normally dependent on subsidies (MCA methods becoming a powerful tool to evaluate the potential adoption of solar technologies). In Brazil (Malagueta et al., 2013) unlike in Spain and USA, adopted a multi-criteria incentive policy and together with the high potential in some northeastern regions might reach 2.8% of Brazil’s electricity generation on 2040. Finally, in order to minimise social disapproval and impacts on the environment potential undesirable effects (such as landscape deterioration, noise, toxics, land use change, ecosystems depletion and so on) must be taken into account and carefully evaluated previous the solar power adoption (Santoyo-Castelazo and Azapagic, 2014).

As it can be drawn from the above explanation, many aspects are integrated in solar energy deployment. In this line, different approaches have been developed when focused on the different dimension of the potential impacts. Life cycle analysis (LCA) mostly assess environmental impacts associated with all the stages of a product life (the full environmental footprint) though some effort is being made to also integrate social and economic aspects (Lehmann, 2011). Other widely applied method is a multi-criteria analysis (MCA) which is able to address multi-dimensional and complex sustainability assessment problems (Toldborg et al., 2014). Geographical Information Systems (GIS) are often joint with MCA methods becoming a powerful tool to evaluate the potential for sources of renewable energies including the location problem (best selection placement) (Phillips, 2013). Last but not least, the use of environmental impact assessment (EIA) procedures is useful as a mechanism to evaluate sustainability of a project, procedure, policy or proposal highlighting the potential impacts and the prevention measures needed (Turney and Ethenakis, 2011).

Concerning the GIS-MCA method applied in this study, the selection of the criteria was a crucial step. The six criteria selected comprising biophysical, socio-economic and environmental dimensions were carefully chosen based on relevant literature review, on the availability of spatial information and on the capacity to hold large-scale solar power plants. This is a limitation of the whole procedure as certain criteria, due to the absence of a geographical component, are difficult to be integrated. In addition, it is broadly considered that one of the main drawbacks of this method is the associated uncertainty on both the input data and the weighting of the criteria, which has a strong influence on the MCA’s outcomes (Toldborg et al., 2014; Daim and Abu Tah, 2013). In our GIS-MCA model solar radiation was the variable with the highest assigned weight and, therefore, site location were influenced by this condition primarily. Nevertheless, not only the weighting is an essential step but also the classification within each variable. Especially, for solar radiation different cut-off values can be found in the literature such as those proposed by Malagueta et al. (2013) and the one followed through our approach (Suri et al., 2007).

A comparison of suitable and existing solar power plants was performed as a validation exercise. The main hypothesis in this regard was that the PV systems currently in operation where located assuming technical, environmental and socio-economic factors. Accordingly, the most suitable areas from the European suitability map matched with the highest suitability assigned to the existing solar power plants. Although this validation analysis was based on only a limited set of countries (Spain, Italy, Portugal, Germany and France), the results were statistically significant, thus confirming the validity of the map. Nonetheless, samples from other countries with on-going solar energy investments (e.g. Eastern European countries) would have been desirable.

4. Conclusion and policy implications

The development of a sustainable and efficient energy system is one of the biggest challenges of the EU and worldwide. As population and energy demand are increasing renewable energies can play an important role contributing to reduce GHG emission, fossil fuel dependencies, social and economic development, a more security supply, and, in the end, a more sustainable energy production development (IPCC, 2011). Since decades, many studies have been devoted to solar energy technologies, from different perspectives (costs, technology improvement, suitable location, environmental impacts, and so on) as a viable energy alternative (Daim and Abu Tah, 2013).

This paper proposes a method to create a European suitability map for solar power systems (PV systems) deployment by combining biophysical and socio-economic factors based on a multi-criteria analysis in a GIS environment. Solar radiation, distance to urban areas, topography, grid electricity network and proximity to roads were selected as suitability criteria, while taking into account natural and artificial areas as constraints (Figs. 9 and 10 in Annex I). Our method can be understood as an initial filter to identify areas with a greater degree of suitability compared to others. One of the main conclusion from the European suitability map is that there is still a large unexploited solar energy potential.

A validation exercise of the European suitability map for solar energy development was carried out based on exiting solar power systems located in France, Italy, Spain, Germany and Portugal. The validation showed a good fit between European suitability map with current solar farms, as opposed to random locations. Results showed that 75% of the solar plants in operation were assigned suitability values greater than 79.8 out of 100. However, the lack of similar studies made it difficult to compare our suitability map with others produced by other authors and/or using different methodologies.

An interesting aspect that retains from this paper is the proposal to include degraded and contaminated lands as criteria for the location of large-scale photovoltaic power plants. This option attempts to avoid the uptake of valuable agricultural land while providing positive reciprocities between solar energy and land use.
As such, highly saline soils, areas affected by severe erosion and contaminated lands by heavy metals were identified as preferred locations for the installation of solar farms. Regions with both high photovoltaic suitability levels and large shares of poor soil conditions were used to illustrate optimal locations for solar energy investment.

The EU, through its structural and cohesion funds, has been helping regions to exploit this energy source. However, this study also found no evidence of correlation between the regional allocation of EU investment in solar energy during the programming period 2007–2013 and the regional suitability for photovoltaic systems. The allocation of EU resources by Member States to projects developing solar energy seems to have been governed by different criteria than regional suitability as captured through this index. It is argued that an improved allocation of investments can be achieved if regional suitability for solar energy is taken into consideration (certainly among other factors) to increase the potential returns of public financial efforts.

Annex I

Fig. 9. Natural and artificial constraints for the development of PV energy systems at European scale. (a) Represents the land use/cover included in the analysis. (b) Shows the natural and protected areas.
Fig. 10. Suitability factors for the development of PV energy systems at European scale. (a) Illustrates the solar radiation in (kW h/m²). (b) Represents the classification according to the slope in percentages. (c) Shows the population potentially affected. (d) Shows the proximity to roads and (e) depicts the proximity to the electricity grid.

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