

Estimation of the Global Solar Energy Potential and Photovoltaic Cost with the use of Open Data

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ABSTRACT

There is an increasing demand for renewable electricity sources, due to the global efforts to reduce CO₂ emissions. Despite the promising effects, only a limited amount of electricity is currently produced globally from solar power. In order to help countries realize the importance of tapping into solar energy, it is crucial to reveal the potential amount of electricity that could be thus produced.

For this reason, open data were used to produce an interactive web map of the global solar energy potential. For the calculation of the potential, the top-down approach, generally used in the literature, was modified by introducing a better way of calculating rooftop areas, and accounting for temperature, which highly reduces PV panels' efficiency. Mean annual temperature data were introduced to improve its accuracy, and an approach to estimate rooftop and façade areas as a function of GDP was developed. The current global solar potential technically available was estimated at about 613 PWh/y. Furthermore, the cost of photovoltaic generation was computed and extremely low values, 0.03 - 0.2 \$/kWh, were derived.

Keywords

Global solar potential;
Photovoltaic;
Technical potential;
Economic potential;
Photovoltaic cost;
Interactive web map;
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1. Introduction

The demand for renewable sources of electricity is fast growing [1] as a result of the global efforts to reduce CO₂ emissions. In particular, solar energy plays a promising role for both developed and developing countries and it is foreseen as the most promising renewable energy source due to its benefits [2, 3, 4]. First and foremost, solar energy is clean, since it can produce electricity without emitting greenhouse and toxic gases such as CO₂ and NO_x. Furthermore, it can have positive effects from an economic standpoint, not only because after the initial investment it reduces electricity bills, but also because the renewable energy sector has the potential to create new jobs. In addition,

technologies exploiting solar energy are relatively easy to install on rooftops and therefore they can provide a way to produce clean electricity in rural locations [5].

In spite of the advantages of solar energy, the current global solar production is just a minor fraction of what is potentially available to develop, since solar energy covers only 0.05% of the total primary energy supply [5]. In order to change this, researchers need to provide policy makers with tools to easily assess the amount of electricity that can potentially be generated from solar energy by their countries, compared to what is currently generated and consumed. This requires a comprehensive estimation of the potential for each country to produce electricity from centralized and decentralized solar facilities.

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The first global approach to the PV (photovoltaic) potential estimation was performed by Sørensen [6]. His study did not address the economic potential issue as costs were not considered. Some years later, the research of Hofman et al. [7] included costs and focused on PV with concentrating cell technologies and electricity production from solar thermal systems. In addition, despite the large-scale character of the study, it did not cover the whole globe. Those two issues were later addressed by Hoogwijk [8] who assessed the theoretical, geographical, technical and economic potential of PV electricity globally. In this study the author used a set of linear equations to first calculate the amount of land suitable for PV installation and then the amount of electricity that can potentially be generated from it. In addition, the cost of photovoltaic electricity production per kWh was computed. In a more recent study, Sári et al. [9] estimated the solar electricity potential by considering the unit peak power, the system performance ratio, and the yearly sum of global irradiation. For their study they estimated the potential generated by a 1 kWp system per year with photovoltaic modules mounted at an optimum inclination and assuming a system performance ratio of 0.75. The results of their research are freely available as an interactive tool that allows the estimation of PV electricity generation at any location in the regions of Europe and Africa, Mediterranean Basin and South-West Asia.

In general, we identified three key issues with previous work that require a new study. First of all, PV technology changes substantially over time, meaning that there is a need to create an approach that provides scenarios valid also for the near future, for example by updating the panels' efficiency factors. The second important issue relates to the lack of ways in previous work to take the panels' temperature into account during the computations. This is crucial because it highly affects the electricity output of solar panels and if not properly taken into account may lead to overestimations, particularly in equatorial regions. Lastly, to assess the potential for urban PV installations, Hoogwijk proposed an estimation of rooftop and façade areas based on GDP (Gross Domestic Product) per capita. This was done simply because no measured data existed for the amount of rooftop and façades [11], but only rough estimates. The problem with this approach is that it highly underestimates the only available data we have of the

amount of rooftop and façade areas, i.e. the data provided by the IEA (International Energy Agency) for 14 OECD (the Organization for Economic Co-operation and Development) countries in 2002 [12].

This study tested ways to address these three issues and provide more accurate figures of the PV global potential. The standard top-down approach [10] that is widely used in the literature was modified and the solar energy potential for both centralized (i.e. solar power plants) and decentralized systems (i.e. PV panels installed on buildings' rooftops or façades) was calculated. We updated the panel's efficiency to better model the future of the solar industry. Moreover, we developed a way of calculating rooftop and façade areas for each country based on a polynomial regression using the data provided by IEA [12]. This way we estimated these data starting from the only reliable source available in the literature. Finally, we included temperature as a correction parameter. As mentioned, this is crucial to provide realistic PV potential figures in tropical and sub-tropical areas.

Interactive Web Map

For this project we used only open data, freely available online. This means that our results are in the public domain and can be presented online for free. We created an interactive web map, which harnesses the power of Web GIS (Geographic Information Systems) to optimize the fruition of the data to people who may not be familiar with its technology. Multiple projects of solar energy potential mapping have been conducted, mainly focusing on large cities and municipalities. San Francisco is the pioneer of solar mapping applications. In 2006 a solar map was developed by the local authorities to emphasize on existing photovoltaic and water heating installations in the city. The map is freely accessible online (<http://sfenergymap.org/>) and it provides users with information about the exact location of the building, the type of photovoltaic system, as well as the installers just by clicking on a certain building. The municipality of Berkeley also developed its own solar map depicting the PV installed in different land uses, the size of the modules and the installer. At a city level, Boston (<http://www.mapdwell.com/en/boston>), Los Angeles (<http://solarmap.lacounty.gov/>), and New York City (<http://nycsolarmap.com/>) have all developed their own

solar potential maps. All of them are interactive web maps, which enable users to estimate the electricity production from the PV systems on their properties, the energy savings, the carbon savings, the system payback period, the system costs, as well as the existing programs encouraging PV installations.

Those examples focus on mapping solar potential of cities or municipalities. Limited tools have been developed that examine larger areas. One example is the Photovoltaic Geographic Information System (PVGIS) generated for 25 European countries, as well as for Asia and Africa from the Joint Research Centre of the European Commission (<http://re.jrc.ec.europa.eu/pvgis/>). This application mainly estimates the potential solar electricity production derived from systems mounted at horizontal, vertical, and optimal inclination. Apart from the estimation of the yearly PV potential, it provides a database consisting of average values of global irradiation on horizontal and inclined surfaces on a monthly and annual basis, as well as other factors related to climate and photovoltaics. Another large-scale example is SolarGIS (<http://solargis.info/>). It is a geographical information system designed to integrate solar resource and meteorological data with several tools for planning and performance monitoring of solar energy systems. SolarGIS offers global coverage and detailed information but accessing the data requires payment.

The current project is to be seen as a logical continuation of previous solar energy mapping projects. Its main purpose is as a first step the identification of the suitable areas for PV installation, the estimation of the solar energy potential in these areas and the amount of electricity that can be produced, as well as the costs related to solar energy production. However, its final objective is the creation of an interactive web map depicting the results. Such a map will be of remarkable assistance for policy makers, since they will have access to a freely available tool that will help them identify the solar energy potential of countries in relation to their current solar PV energy generation and the total energy consumption status. This tool can also be used in order to spread the message that countries have the potential to produce a lot more clean energy and that even if oil prices are extremely low, this does not mean that investing in clean energy should not be attempted.

2. Materials and Methods

2.1. Study Area and Datasets

The study was conducted on a global scale using data that are freely available on the web to carry out estimations of photovoltaic solar energy potential.

The most important dataset for the global solar energy potential computations was the average amount of solar irradiation. The Surface meteorology and Solar Energy dataset (SSE - Release 6.0) [13], freely offered by NASA, was used. The spatial resolution of this dataset is 1-degree, which is approximately 100 km at the equator. A cubic spline smoother was used to downscale solar irradiation data to a resolution of 1 km, which was set as the target resolution for computing the solar potential. Average global temperature data offered from NASA were used to correct the efficiency of solar panels.

For the elevation the Global Multi-resolution Terrain Data 2010 (GMTED2010) digital elevation model (DEM) was used, since it is freely available from the U.S. Geological Survey (USGS) [16]. This dataset is a collection of elevation data from several different sources, such as the earlier version GTOPO30, the global Digital Terrain Elevation Data (DTED) from the Shuttle Radar Topography Mission (SRTM), Canadian elevation data, Spot 5 Reference3D data, and data from the Ice, Cloud, and land Elevation Satellite (ICESat) [15]. GMTED2010 is available at three spatial resolutions (30, 15-, and 7.5-arc-seconds). Forth project, a spatial resolution of 15-arc-seconds (app. 500 m on equator) was considered appropriate, since this work was performed at a global scale. The GMTED2010 products are a large improvement over previous sources of elevation data at comparable resolutions [18]. From the DEM, the slope derivative was computed and used for the geographical potential. The land cover data were provided by the GlobCover2009 [19, 20], which has a resolution of 300 m and 22 land cover classes.

In order to have a baseline for the computation, data regarding the amount of electricity produced by PV globally were collected in addition to data regarding the average electricity consumption. The cumulative installed PV power data were collected by SolarSuperState Association (SolarSuperState.org), which was a partner in this research, and from the study of Werner et al. [19]. The solar electricity production data were collected from the US Energy Information

Administration (EIA) for the year 2011, which is the most recent to provide full global coverage. This dataset refers to the total solar electricity production, i.e., the sum of PV generation plus production from concentrated solar power plants, which produce energy transforming solar energy into heat and not through the photovoltaic effect. We also collected average annual electricity consumption data, for 2011, from various sources: namely EIA and the CIA (Central Intelligence Agency) World Factbook.

For estimating rooftop and façade areas, GDP data for each country were collected from the International Monetary Fund (IMF) database for the year 2013.

2.2. Methodology

Based on the World Energy Council Report [20] there are four definitions for renewable energy potentials: Theoretical potential, Geographical potential, Technical potential, and Economic potential.

In order to compute the global solar potential the approach referred to as top-down approach [10] was followed. Starting from the global solar irradiance dataset, which represents the total amount of solar energy physically available on the earth’s surface, the amount of exploitable energy was finally reduced according to environmental factors and technical limitations. Additionally, the cost for PV electricity generation was calculated. The results were computed at 1 km resolution and the total technical potential per country was obtained by summing the cell values inside each country’s boundaries.

2.2.1 Geographical Potential

Geographical potential is the solar irradiation incident to the fraction of the earth’s surface suitable for the development of solar facilities. For the computation of geographical potential the equation of Hoogwijk [8] was used as a basis:

$$G_i = 10^3 \cdot I_i \cdot h \cdot A_{a,i} \tag{1}$$

where G_i (kWh/y) is the geographical potential of cell i , I_i (W/m²) is the time-averaged irradiance in cell i (extracted from the NASA irradiation data), h (h/y) is the number of hours in a year, and $A_{a,i}$ (km²) is the available area for PV installation in cell i .

Due to the solar irradiance dataset used for this research, Eq. (1) had to be adapted as follows:

$$G_i = 365 \cdot R_i \cdot A_{a,i} \tag{2}$$

where R_i (kWh/m² per day) is the daily irradiance in cell i , while 365 denotes the number days in a year.

The only unknown variable in Eq. (2) is the area, and for its calculation two slightly different approaches for centralized and decentralized systems were followed.

Geographical Potential - Centralized Systems:

For the computation of the suitable area for centralized systems we applied a multi-criteria approach. To assess the amount of area suitable for developing solar facilities forests, environmentally sensitive areas (ESA) and water bodies were first excluded from the computations. As a next step, an approach based on suitability factors [8] was used. Basically only a small fraction of each raster cell is considered suitable for development, based on its land cover. The list of suitability factors divided by land-cover is presented in Table 1. Moreover, since centralized plants require large flat areas, locations with a slope higher than 4% [8] were excluded. Areas with a solar irradiance below 950 kWh/m² per year were also excluded, since they are less appealing for investing in solar facilities.

Geographical Potential – Decentralized Systems:

For decentralized systems PV panels are intended to be installed on buildings’ rooftops and façades and for this reason the geographical potential is a function of the available rooftop area per cell. Direct measurements of these data are however not available [11], we only have estimates from IEA [12] and just for OECD countries. Thus, there was a need to find an approach capable of estimating rooftop areas for countries not covered by the IEA study. Hoogwijk [8] suggested that rooftop is related to the country GDP. In this study, we used the

Table 1: Suitability Factor used in this Research, divided by Land Cover Type

Land Cover Type	Suitability Factor (%)
Urban, Bioreserve, Forest	0
Arable, Shrub, Savannah, Tundra, Grassland	1
Extensive grassland, Desert	5

same assumption, but we updated by fitting a polynomial regression to model the IEA data as a function of GDP, so that rooftop and façade areas for each country where GDP data are available could be estimated.

2.2.2. Technical Potential

The technical potential is the geographical potential multiplied by efficiency factors and performance ratios of the solar panels. This study's estimation of technical potential was based on the approach of Hoogwijk. Basically the amount of solar irradiation incident to the fraction of the land suitable for energy production (i.e. geographic potential) was calculated and then the amount of energy that land could potentially generate if covered by PV panels was computed. However, this approach has been modified in two ways. Firstly, the efficiency factors were updated in order to reflect the latest technological advancements in the sector [21]; more specifically, an efficiency of 20% applied to both centralized and decentralized systems was used. Moreover, given that performance ratio is highly affected by temperature, an implementation based on the approach of Kawajiri et al. [22] allowed this study to take into consideration this effect.

The modified equation for the computation of technical potential is:

$$E_i = G_i \cdot \eta_m \cdot K' \cdot \{1 + a_{p_{\max}}(T_{Am} + \Delta T - 25)\} \quad (3)$$

where E_i is the technical potential in the cell i and η_m is the conversion efficiency, which corresponds to the amount of solar energy that can be transformed into electricity. The remainder of the equation was plugged in directly from Kawajiri et al. [22], where K' is a design factor, $a_{p_{\max}}$ is the maximum power temperature coefficient, T_{Am} is the 24h ambient temperature profile averaged over the month m , and ΔT is the average annual increase of modules' temperature. These parameters were calculated experimentally by Kawajiri et al. [22].

Another influencing factor for PV performance is dust. Research showed that the amount of dust accumulated on the surface of a PV module operates as an obstacle to the sunlight and decreases the overall efficiency [23, 24]. However, this factor is not considered in this research as certain measurements of

the amount of dust accumulated on the surface of the modules are required in order to assess how performance is influenced.

2.2.3. Economic Potential

In this work for economic potential the calculation of the installation costs for PV panels is considered. The cost of the PV electricity generation (\$/kWh) in grid cell i is computed with the following equation:

$$C_i = \frac{\alpha(M + B) + C_{O\&M}(M + B) + L}{e_i} \quad (4)$$

where C_i is the economic potential in the cell i , α (y^{-1}) is the annuity factor, M (\$/m²) is the investment cost of the PV modules, B (\$/m²) is the Balance Of the System (BOS) cost, $C_{O\&M}$ are the annual expenditures for the operations and maintenance of the photovoltaic systems as percentage of the total investment costs, while L is the annual land rental price (\$/m² per year). The e_i corresponds to the annual electricity output of a cell i . In other words, it is equal to the technical potential calculated in each grid cell i per unit suitable area (m²).

The annuity factor expresses the present value of PV and is calculated with the following equation:

$$\alpha = \frac{r}{1 - (1 + r)^{-LT}} \quad (5)$$

where r is the interest rate, taken in this case as equal to 10%, LT is the economic lifetime of the modules which is 20 years. In this research the annuity factor was 0.117. Regarding the land rental price, although it varies with the different land types and their quality, there is no proof of this correlation. For this reason, the average land rental cost used was 100 \$/ha per year, which is a globally accepted value. For the Operating and Maintenance cost, it is considered to cover a certain portion of the total investment costs, which corresponds to the sum of module and Balance of the System cost. Particularly, the value of 3% has been assigned to the $C_{O\&M}$. The Balance Of the System (BOS) cost that was considered is based on IRENA [25]. More specifically, 1.6 \$/W is recommended for ground-mounted modules while 1.85 \$/W for modules installed on the rooftops.

2.3. Interactive Web Map

One of the main objectives of this work is to provide a platform for practitioners and policy makers to easily consult the acquired results. For this reason an interactive web map was developed, since interactive cartographic information systems encompass numerous characteristics and functionalities that facilitate the presentation of complex information [26]. The results of this study are presented as a series of maps, where information about the solar potential of each country is made available. In addition to that, choropleth maps were created where each country is colored based on its ratio, to provide detailed information regarding the ratios between current energy production and the current total energy consumption or the solar potential.

3. Results and Discussion

3.1. Geographical Potential

As mentioned, two different approaches were used to compute the geographical potential for centralized and decentralized systems. For the centralized systems, areas unsuitable for PV installations were excluded based on values used in literature [27]. The remaining area that is available for development was further reduced using suitability factors that depend on land cover (Table 1). The maximum suitability factor may seem counterintuitive when applied to desert. However, we need to remember that the aim is to provide end users with realistic solar potential figures. For this reason it makes little sense to assume that entire deserted areas would be covered by solar facilities, when in reality only a small percentage would be built. Therefore the suitability factors used in this research are considered appropriate to provide realistic estimates.

For decentralized systems, which are installed on buildings' rooftops and facades, the available building area was calculated starting from the IEA estimates [12]. The IEA calculated, with an experimental approach, rooftop and façade areas for several countries: Australia, Austria, Canada, Denmark, Finland, Germany, Italy, Japan, Netherlands, Spain, Sweden, Switzerland, UK, and USA. Since these are the closest numerical estimates to actual observations available, they were used to estimate rooftop and façade figures for countries not covered by IEA. These data have a strong correlation with GDP, and for this reason a polynomial regression model was used to estimate total rooftop and façade

areas for each country not covered by IEA. This model fitted the IEA data very well obtaining an R^2 of 0.99 and a root mean square error of 218.33 km². However, the absence of real data for rooftop area does not allow accurate computations. Since the regression was used to predict missing data, it was expected that it would produce some artifacts. Those artifacts were detected in a limited number of countries and led to the underestimation or overestimation of the solar potentials. Only if precise data were available (e.g. Swiss solar cadaster) the potential estimations for decentralized systems would be more accurate.

3.2. Technical Potential

Regarding the technical potential, a considerable update to the previous approach was presented. First of all, the efficiency factor of PV panels was changed based on the latest technical advancements and a realistic value was selected according to the current state of the art in solar development. Even though researchers have achieved efficiencies higher than 40% using multijunction solar cells [28, 29], currently installed solar panels have an average efficiency between 14% and 18% [30] and the latest commercial models can reach 21% [21], which keeping into account losses from inverter, cabling and deviations of module temperatures, translates into a real efficiency of around 18% [29]. Since PV efficiency should increase to 23-30% in real terms in 2020 [2], the selected value is thought to be appropriate for providing an accurate estimate valid for the near future. In addition to the efficiency factor, temperature was also incorporated. This parameter highly affects the semiconductors and therefore decreases the power output of the PV cell. It is estimated that for an increment of one degree Celsius the power output decreases by 0.5% [29]. This means that if a panel reaches a temperature of 60°C its power output will be 17.5% lower than its nominal efficiency, calculated in laboratory conditions at 25°C. For this reason it is of extreme importance to consider temperature for the estimates.

The map of the technical potential is presented in Figure 1.

From the global map of the total (centralized and decentralized systems) technical solar potential (Figure 1) it is evident that the areas that have higher potential are the areas closer to the equator. This is a result of the effect of solar irradiation that is also reduced while moving from the equator to the poles. Higher solar

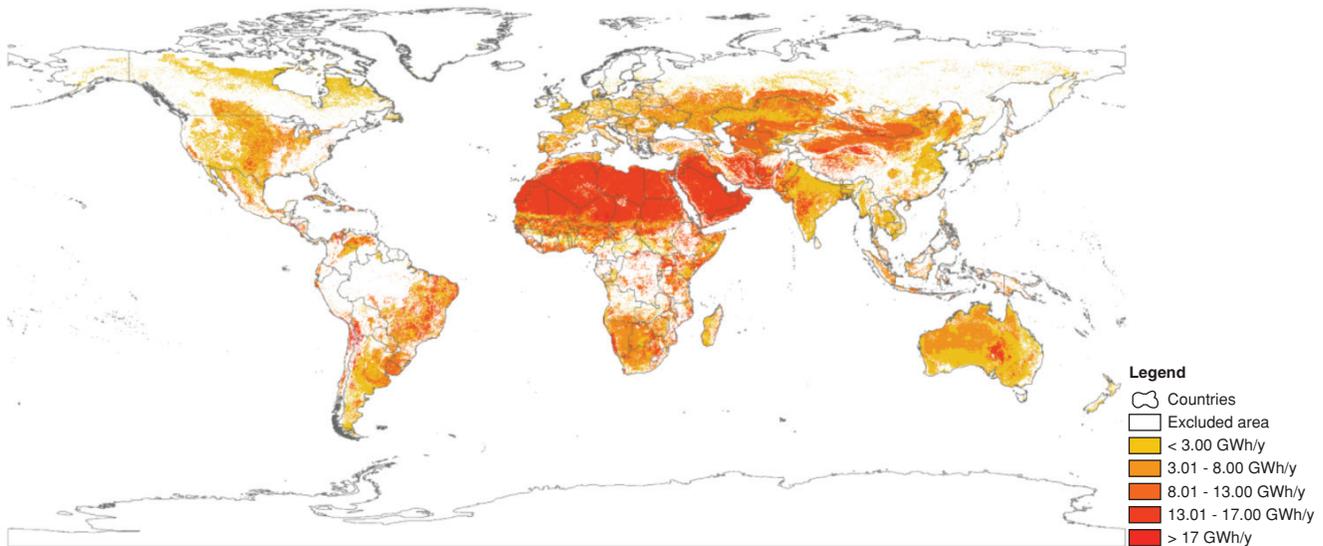


Figure 1: Technical Solar Potential on a 1 x 1 km Resolution

irradiation values and as a result higher technical potential is met in the northern part of Africa and Arabia peninsula. In addition, the largest part of Europe, North and South America and Oceania have technical potential values of around 3 GWh/y. The total global technical potential was estimated to approximately 613 PWh/y.

3.3. Economic Potential

In order to present an up-to-date estimation of the economic potential, the parameter values were updated to efficiently reflect the current technology. The prices of PV modules have been continuously decreasing during the last years. Although the estimation of global PV module prices is very difficult due to their wide variety, according to Solarbuzz [31] the global price of c-Si PV modules is 2.21 \$/W after having seen a dramatic reduction of 45% from 2008.

For the centralized systems, the electricity generation costs from PV were calculated to a range from 0.03 \$/kWh to 0.2 \$/kWh. In comparison to Hoogwijk's economic potential estimation, the estimated cost of this study for PV electricity generation is lower mainly due to the increased efficiency of the module conversion. For the decentralized systems, the maximum cost for electricity generation using PV was estimated to 0.18 \$/kWh.

Figure 2 shows that the economic potential values range with the geographical region. The lowest electricity generation costs (lower than 0.04 \$/kWh) were met in the northern part of Africa, in Saudi Arabia

and in some parts of Asia, whereas in the Southern part of the Sahara desert the economic potential is high despite the high irradiance of the area. This is the result of the introduction of the temperature factor, which decreases the performance of the modules.

3.4. Interactive Web Map

Several examples of web maps are available online to encourage the use of solar energy. The common thread of these web maps is that they all focus on providing citizens with ways to estimate the potential yield of PV panels on their properties. In this research we are more interested in providing practitioners and policy makers with a tool to facilitate the adoption of solar power at the political level. For this reason a series of maps was created to show realistic figures for solar potential for each country worldwide. Moreover, data regarding the potential impact that investing in solar energy may provide to individual countries are provided. For example, from the interactive web map it can be seen that Italy has one of the highest ratios between current solar energy production and current total energy consumption, with 34.5%, which is still very low considering that EU countries should produce 20% of their energy from renewable sources by 2020 [32]. Looking at the total solar potential for Italy (1180.88 TWh/y), it is evident that even if a small proportion of this is successfully developed, it can cover most of the total energy consumption for the whole country, which

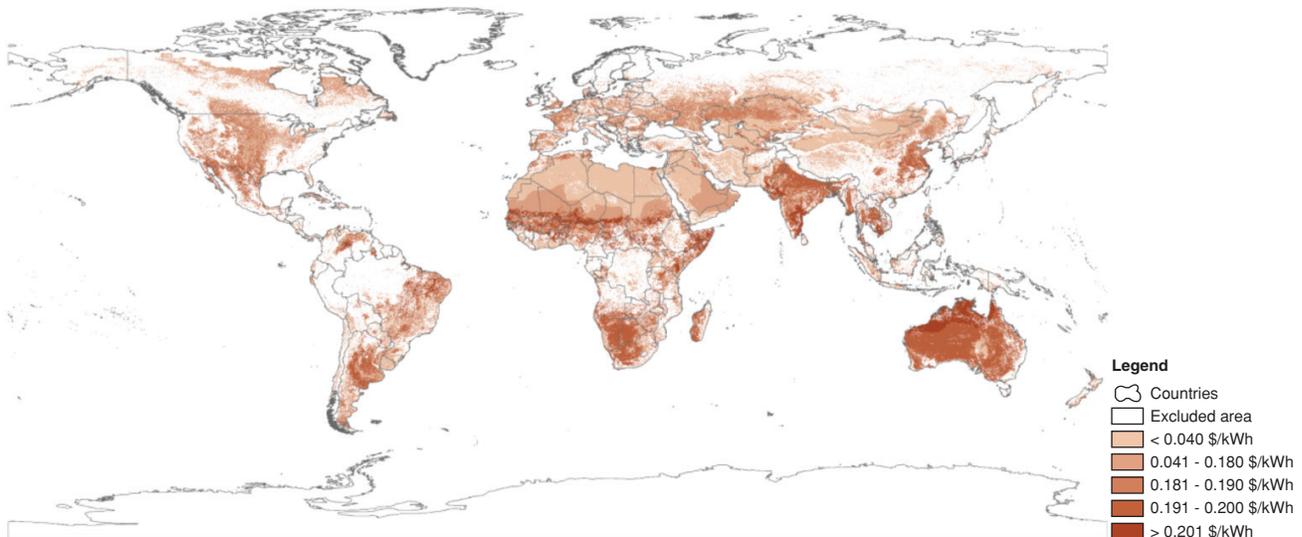


Figure 2: Economic Potential on a 1 x 1 km Resolution

is 311.23 TWh/y. Clearly it is not realistic to assume that Italy will develop the full solar potential due to the need to use land for other productive purposes and not only for energy production, but even just tapping 10% of it can cover around 38% of the total electricity consumed by the whole country each year. The web application can be assessed at <http://solarpotential.ethz.ch>.

3.5. Comparison with previous work

In this section the results obtained in this work are analyzed and compared with work previously published.

There are two aspects that were computed differently here and therefore require validation against measured data or accepted research: rooftop area, which was calculated with a regression approach starting from the IEA data [12], and technical PV potential, which was corrected by temperature. These results are presented also presented in Table 2.

3.5.1. Rooftop

Since Hoogwijk [8] is our reference work and provides global estimates, it was decided to provide readers with

Table 2: Comparison of the results of this study with values presented in the literature. For some countries not included in the IEA data and with GDP values very different from the countries considered by IEA [12], our estimates are also very different compared to the literature. However, for countries included in [12] or with economies in a similar range (e.g. China), our results are very close to the literature data and future scenarios. For some countries we only have either Rooftop estimates or PV potentials, and that is the reason for some missing data in the table.

Country	Reference	Rooftop (Km ²)	Rooftop (Km ²) Estimated	PV Production	PV Production - Estimated
Bangladesh	Mondal et al. [33]	4,670	255	439,524 GWh/y	60,417 GWh/y
Brazil	Miranda et al. [36]	1,679.81	848.53	54.24 TWh/y	214.27 TWh/y
Spain	Izquierdo et al. [38]	571 ± 183	568		
Germany	Grau et al. [39]	1064	1464	167,000 GWh/y	224,942 GWh/y
China	Grau et al. [39]	5000	5170	1,220,000 GWh/y	1,120,327 GWh/y
Canada	Rosenbloom and Meadowcroft [40]			246,000 GWh/y	136,152.85 GWh/y
Malaysia	Oh et al. [41]			56,940 GWh/y	72,395 GWh/y
United States	National Renewable Energy Laboratory [42]			800 TWh/y	55 TWh/y

results computed using their approach, for additional information. The results will be presented in alphabetical order.

The first country analyzed is Bangladesh, which was studied by Mondal et al. [33]. Here the rooftop area is estimated to be 4,670 km². The estimates in this work indicate a total rooftop/façade area of 255 km², much lower than Mondal et al. [33]. Bangladesh was not part of the training data used to fit the regression model, and its GDP is much lower compared to the OECD countries used for training. This means that Bangladesh is in the lower end of the polynomial line, which tends toward very low estimates. For obtaining additional information the approach suggested by Hoogwijk [8] can be tested. Here the available rooftop (in m² per capita) space is calculated using the following equation:

$$\text{Rooftop} = 0.06 \cdot \text{GDP}_{\text{capita}}^{0.6} \quad (6)$$

The GDP per capita in Bangladesh is 1,092 USD [34], which makes the Rooftop per capita equal to 3.99. Since this figure is related to individual urban cells, it can be multiplied by the urban population in Bangladesh, which is 53.316 million [35]. These data can be fed into Equation 6 to obtain 212.78 Km², which still highly underestimates the figure presented by Mondal et al. [33]. Unfortunately, [33] do not provide any information regarding the origin of this figure therefore it is very difficult to know its accuracy.

Similar results were obtained for Brazil, which has a total rooftop area of 1,679.81 Km², according to Miranda et al. [36]. The authors calculated their figures based on data regarding: the number of residences with a given range of built area, per consumption bracket, the number of residences in a given consumption bracket, and the number of residences per type house or apartment. Thus, these data may be considered with a high probability of being close to reality. Brazil's GDP is \$2,346B [37], which is between Italy and the United Kingdom, both of which were part of the training data. However, according to IEA [12] Italy has a total rooftop area of 763.53 km², while the United Kingdom has a total rooftop area of 914.67 km². Since these two figures were used in the training set a total rooftop space for Brazil of 848.53 km² was obtained, again underestimating the real figure. With Equation 6, since Brazil has a GDP per capita of 11,384.6 USD [34] and an urban population of 176.058 million [35], the rooftop space resulted in 2868.131 km², higher than the real figure and further from reality than the estimate produced in this paper.

The next country analyzed is Spain, for which a detailed study by Izquierdo et al. [38] provides an accurate estimate of the total rooftop space, which is equal to 571 ± 183 km². Spain was part of the training data, therefore in this case the estimates provided here are much closer to reality with a total rooftop space of 568 km². If Equation 6 is solved, with a GDP per capita of 30,262.2 USD [34] and an urban population of 36.824 million [35], Spain results to have a total rooftop space of 1078.52 km², thus overestimating reality.

Similar results were observed for Germany, which has a total rooftop space of 1064 km² [39]. Since it was also part of the training dataset a figure of 1464 km² was obtained, while with Hoogwijk's approach a figure of 2335.41 km² is obtained (GDP per capita equal to 47,627.4 USD, and urban population of 60.743 million).

In the same article Grau et al. [39] examined the PV potential of China, for which they provide a total rooftop figure around 5000 km². With the approach by Hoogwijk [8] China's rooftops would be estimated at 9484.39 km² (GDP per capita equal to 7,593.9 USD, and urban population of 742.299 million), thus almost doubling the figure presented in [39]. With the approach presented here, even though China was not part of the training data, its total rooftop area was estimated at 5170 km².

In conclusion, in some cases this approach seems to produce better results compared to previous work. In particular, for countries that present a relatively high GDP it seems to work well. The exception is Brazil, which has a GDP between Italy and the UK, but much more space to build solar panels. In this case an approach based on urban population seems to produce better results. In fact, if only the urban population figures are taken into account Brazil, Germany and Spain result to be linearly correlated. However, in this case the exception is Bangladesh, which has an urban population similar to Germany but a total rooftop space much larger.

3.5.2. Technical PV Potential

Once again, global estimates are not available in the literature. However, research that provides estimates of technical PV potential for various countries was found.

In Bangladesh, for example, the work by Modal et al. [33] presents a figure of PV rooftop potential of 50,174 MW, which can be transformed into 439,524 GWh/y, considering panels with an efficiency factor of 10%. In

this work a constant efficiency factor of 20% is considered globally. However, since the estimates for rooftop space were much lower than the figure produced by Modal et al. [33], the PV potential figure presented here is also much lower. In fact, a PV potential for rooftop equal to 60,417 GWh/y was estimated.

For Brazil things change, because Miranda et al. [36] reported a technical PV rooftop potential of 54.24 TWh/y, while in this work a figure of 214.27 TWh/y was obtained. This despite the fact that rooftop area estimated here was lower than in Miranda et al. [36]. A minor percentage of this difference can be explained by the higher efficiency factor of 20%, while they used 15.4%. However, the large majority of this difference can probably be explained by the much more complex method the authors used in their study. As mentioned, they had access to many more data regarding location and geometry of rooftops. From these they were able to calculate the PV potential only on rooftops where the installation of PV panels was actually feasible. In this work global and inherently imprecise data were used, and thus it is difficult to discriminate between suitable and unsuitable rooftops, only suitable and unsuitable raster cells can be identified.

Rosenbloom and Meadowcroft [40] reviewed all the research work that estimated potential PV generation in Canada. They report a figure of 246,000 GWh/y for rooftop PV, based on panels with a 15% efficiency. The estimates produced here indicate a potential production of 136,152.85 GWh/y, very close to their work.

Grau et al. [39] estimated that by 2020 29% of the electricity consumed in China would be produced by PV. If the EIA consumption figure for 2011 is considered, this potential production can be computed at around 1,220,000 GWh/y. According to the estimates in this work, China can produce 1,120,327 GWh/y from residential rooftops, which is very similar to the figure proposed by Grau et al. [39] considering a 17% efficiency.

For Germany Grau et al. [39] estimated that by 2020 31% of its electricity consumption can be covered by PV production. From the consumption data, this percentage means a PV production of around 167,000 GWh/y can be calculated. This considering panels with a maximum efficiency of 17%. In this work, we estimate German rooftop production at 224,942 GWh/y, which is relatively close to [39].

For Malaysia, Oh et al. [41] report a solar PV potential of 6500 MW, which transformed means 56,940 GWh/y.

[41] does not provide figures about the efficiency factor, so it is difficult to fully use their results for comparison. However, results in this paper report a total PV rooftop production of 72,395 GWh/y, which is close to [41].

Finally, the National Renewable Energy Laboratory [42] reported a rooftop PV potential in the United States of 800 TWh, with an efficiency of 13.5%. This is based on the rooftop space calculated from Denholm and Margolis [43], which is not reported. This paper indicates a potential production of only 55 TWh. This large discrepancy is difficult to explain because the US were among the countries for which a rooftop estimate was provided by IEA [12], so it was part of the training data. It may be that Denholm and Margolis [43] estimated a much higher figure of rooftop space.

Overall the estimates provided in this work are a good approximation of the figures presented by more detailed studies. There are clearly some limitations regarding the level of accuracy that can be provided with the data used. For example, the total rooftop space was computed with a polynomial regression starting from other estimates from IEA [12]. Despite this lack of data this approach is still able to achieve good results for several countries meaning that it can be used to obtain initial estimates for areas not covered by more detailed studies.

4. Conclusions and Further Research

In this study we modified methods available in the literature to calculate the global solar energy potential. The accuracy of previous estimates was increased by including temperature, which highly affects the PV performances, and by providing a better way to calculate rooftop and façade PV potentials, validated against the IEA data. In addition, the cost of PV electricity generation was calculated, based on values that reflect the current economic situation.

The acquired results are presented in an interactive web interface available online. From this website practitioners and policy makers can obtain more information regarding the potential for developing solar energy. These data provide a good way of disseminating the message that several countries could cover large parts of their electricity demands by just developing a fraction of their solar potential.

More work is certainly needed to further increase the accuracy of our figures. For example, the keystone of this research is the solar irradiation map provided by

NASA. There are a couple of problems with this map though: the first is that it provides data only until 2005, and therefore there is no way to account for the changes after that year, which in a context of climate changes may be important. The second issue is related to the coarse resolution of these data, which for small countries means that the computation of the potential relies on a very limited number of observations. Therefore one way to further increase the accuracy of the solar potential estimates is obtaining more accurate irradiation data. Moreover, ways for fast updating of the electricity figures for each country should be found. At the moment these are referred to 2011, simply because these data were simple to gather. However it would be interesting to have ways of updating the map with the current figures. The amount of rooftop and façade data is also another point which needs further investigation. Observed data are simply not available on the global scale. In this research the total rooftop area per country available for PV applications was expressed as a function of the nominal Gross Domestic Product. Although the estimations derived fit the estimations of the IEA for a limited number of countries, in reality there is no proven correlation between them. For this reason, an overestimation or underestimation of the available rooftop area was observed in some countries. More accurate estimations or measured data will certainly provide more realistic results. Several studies have started looking into automatic ways of extracting rooftop area from GIS data (examples of such systems are developed by Laycock et al. [44]; Hofierka et al. [45] and Silván-Cárdenas et al. [46]) but they are still in an early stage.

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