Assessing vulnerabilities and limits in the transition to renewable energies: Land requirements under 100% solar energy scenarios

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Abstract

The transition to renewable energies will intensify the global competition for land. Nevertheless, most analyses to date have concluded that land will not pose significant constraints on this transition. Here, we estimate the land-use requirements to supply all currently consumed electricity and final energy with domestic solar energy for 40 countries considering two key issues that are usually not taken into account: (1) the need to cope with the variability of the solar resource, and (2) the real land occupation of solar technologies. We focus on solar since it has the highest power density and biophysical potential among renewables. The exercise performed shows that for many advanced capitalist economies the land requirements to cover their current electricity consumption would be substantial, the situation being especially challenging for those located in northern latitudes with high population densities and high electricity consumption per capita. Assessing the implications in terms of land availability (i.e., land not already used for human activities), the list of vulnerable countries enlarges substantially (the EU-27 requiring around 50% of its available land), few advanced capitalist economies requiring low shares of the estimated available land. Replication of the exercise to explore the land-use requirements associated with a transition to a 100% solar powered economy indicates this transition may be physically unfeasible for countries such as Japan and most of the EU-27 member states. Their vulnerability is aggravated when accounting for the electricity and final energy footprint, i.e., the net embodied energy in international trade. If current dynamics continue, emerging countries such as India might reach a similar situation in the future. Overall, our results indicate that the transition to renewable energies maintaining the current levels of energy consumption has the potential to create new vulnerabilities and/or reinforce existing ones in terms of energy and food security and biodiversity conservation.

Key-words: Solar potential, Energy footprint, Land-use, Transition to renewable energies, Energy security.

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1. Introduction

Most governments are developing policy frameworks to promote the penetration of renewable energy sources (RES) to improve energy security (increasingly threatened by the depletion of conventional fossil fuels) while mitigating emissions to limit anthropogenic climate change and other negative externalities of conventional energy sources (IPCC, 2014; Johansson, 2013; REN21, 2015; WEO, 2014). Among renewables, wind and solar are estimated to have the greatest potential (de Castro et al., 2013; IPCC, 2011; Smil, 2010), with projections often assuming that the resource base provides no practical limitation if adequate investments are forthcoming (e.g., IPCC (2011)).

While fossil fuels represent concentrated deposits of energy and thus can be exploited at high power rates (200-11,000 W_e/m^2), the technologies harnessing renewable sources are characterized by power densities several orders of magnitude lower. Hence, for delivering the same power, RES are substantially more land intensive (Smil, 2015). For example, typical ranges of net power density found in the literature are: 2-10 W_e/m^2 for solar power plants, 0.5-7 W_e/m^2 for large hydroelectric, 0.5-2 W_e/m^2 for wind; and ~0.1 W_e/m^2 for biomass (de Castro et al., 2014; MacKay, 2013; Smil, 2015). While wind farms are partially compatible with other uses (e.g., agriculture) or can be located offshore, biomass plantations, hydroelectric reservoirs and solar farms tend not to allow double use, that is, in practice they monopolize the occupied land. In the case of solar power, the potential in urbanized areas is limited due to the fact that cities are currently not designed to maximize solar reception (Izquierdo et al., 2011; La Gennusa et al., 2011; Ordóñez et al., 2010; Sorensen, 1999).

Hence, the transition to RES will add to the pressure in the global competition for land, which is already driven by many factors (Smith et al., 2010). In particular, the dedication of land to produce energy has been identified as a potential concern not only for preserving natural ecosystems, their services and biodiversity, but also because of its competition with land use to cover human needs (i.e., food, fiber, shelter and infrastructure). These concerns arise in parallel with the current rapid expansion of modern RES technologies and the steady decrease in their costs over recent years (Deutsche Bank, 2015; REN21, 2015). Thus, this transition could aggravate existing vulnerabilities and create new ones in terms of energy security, biodiversity loss, and food sovereignty, among others (Johansson, 2013; MacKay, 2013; Nonhebel, 2003; Rao and Sastri, 1987; Scheidel and Sorman, 2012; Smil, 1984). As a recent example, the occupation of just ~0.1% of Italian agricultural surface area by PV systems provoked an intense debate in the country that ultimately lead to the ban of incentives for this technology on agricultural soil (Squatrito et al., 2014).

The relevance of the land requirements of renewables is the subject of ongoing debate, with most studies focusing on 100% RES scenarios having estimated that the additional land requirements will not be a compelling constraint for the transition (e.g., Jacobson and Delucchi (2011), WWF (2011), Jacobson et al., (2015), Teske et al., (Greenpeace et al., 2015) and García-Olivares (2016)), while a few have found land availability to be a relevant biophysical constraint that may limit the feasibility of the transition within the current socio-economic system (e.g., Mackay (2013)). With our work, we contribute to the debate by estimating a conservative, lower bound for the land-use requirements to supply all current consumed electricity and final energy domestically with solar energy for 40 countries, devoting special attention to uncertainties such as future efficiency improvements. We focus on solar energy since, among renewables, it has the highest power density and biophysical potential (de Castro et al., 2013; IPCC, 2011).

First, we concentrate on the land-use requirements and biophysical feasibility of supplying all current consumed electricity with solar technologies in a given region as proposed by Denholm and Margolis (2008) for the states of the USA and Šúri et al. (2007) for 30 European countries. A few estimates of solar land-use requirements have been published to date by various authors for advanced capitalist economies such as the USA and European states (Denholm and Margolis, 2008; MacKay, 2013; MIT, 2015; Šúri et al., 2007; Turner, 1999), and by Jacobson and Delucchi (2011) at a global level, while other studies have focused on comparisons with other energy technologies (Fthenakis and Kim, 2009). In general, these analyses have come up with relatively low values of solar land-use requirements, thereby minimizing the importance of land to sustain high penetration levels of solar energy. For example, Šuri et al. (2007) found that just 0.6% of the land surface area of the EU25 and 5 EU-candidate countries, all corresponding to rooftop photovoltaic (PV), would suffice to cover the total electricity demand, with a range of 0.1-3.6% depending on the country. Denholm and Margolis (2008) found that the land required to supply the electricity consumed in the USA by solar plants (assuming 25% on rooftops) was between 0.3 and 0.7% of the total surface area (with a range of 0.1-8% depending on the state). However, these analyses have not considered two key issues included in our analysis, and these have the potential to substantially increase the land-requirements of solar power plants:

- In a 100% solar-based energy system, a substantial redundant capacity should be deployed in combination with storage capacity to cope with the intermittence and seasonal variability of the solar resource (MacKay, 2013; Trainer, 2010, 2012, 2013a),
- The real land occupation of solar technologies is five to ten times higher than the estimates usually considered, which are based on ideal conditions (de Castro et al., 2013; MacKay, 2013; Ong et al., 2013; Smil, 2015).

Although a diversified supply combining different renewable resources as a function of their local availability would make it possible to reduce the overcapacity and storage requirements to cope with solar intermittency to some extent, this effect would be partially offset by the fact that for most countries solar has a power density three to five times higher than wind, and one to two orders of magnitude higher than bioenergy and is slightly better than large hydropower (de Castro et al., 2014; MacKay, 2013; Smil, 2015). The approach applied does not fully correspond to an "extreme scenario" for two additional reasons: (1) there is a positive relation between the electricity consumption per capita and income (i.e., most countries have been experiencing electrification of the energy system for decades), and (2) the future deployment of renewables will require that this trend be intensified since they mainly produce electricity (Armaroli and Balzani, 2011; Smil, 2008). In the period 1990 to 2007, the annual growth in the global net electricity production (+1.9%) outpaced the annual growth in total energy consumption (+1.3%), a trend which is expected to strengthen in the next few decades. For example, the International Energy Agency (IEA) in its New Policies Scenario expects the world electricity demand to grow by 2.1% per year on average between 2012 and 2040 (i.e., +80% cumulative growth in the period), its share of total energy use rising in all sectors and regions (WEO, 2014). Thus, the land occupation by solar/RES in the future is likely to be higher than estimated in our study for current electricity consumption.

Additionally, a third factor, critical for assessing potential vulnerabilities, is considered: over recent years, advanced capitalist countries have specialized in economic activities with high added value (reducing their share of energy intensive sectors and manufacturing industries) while some emerging economies, like China and India, have undergone a process of rapid industrialization, increasing their share in the global economy, and are exporting enormous volumes of manufactured products to developed countries (Baiocchi and Minx, 2010; Weber, 2009). This shift of economic activities between countries has also had consequences in terms of energy use. Arto et al. (2016) showed that an increasingly large proportion of the energy used by emerging countries is being devoted to sustain the welfare of advanced capitalist economies by means of international trade. Hence, together with data on the electricity use per country, we will consider the net electricity consumption after accounting for international trade for each country, i.e., its electricity footprint, estimated from the multi-regional input-output model (MRIO) WIOD (Dietzenbacher et al., 2013).

In a second stage, we replicate the analysis to explore the land implications and biophysical feasibility, for each country, of supplying all current final energy consumption by solar systems. Again, this approach must not be seen as an extreme, e.g., the world primary energy demand is expected to increase by almost 40% by 2040 (WEO, 2014). Thus, the exercise performed will allow us to test MacKay's affirmation that: "…in a world that is renewable-powered, the land area required to maintain today's British energy consumption would have to be similar to the area of Britain. The same goes for Germany, Japan, the Republic of Korea, Belgium and the Netherlands" (MacKay, 2013). If these numbers were to be confirmed, far from enhancing their energy security as usually claimed, the transition to renewable energies in some countries in the current socio-economic context would instead increase their external dependence and vulnerability (Johansson, 2013; Lilliestam and Ellenbeck, 2011; Moriarty and Honnery, 2016; Trainer, 2013b).

The paper is organized as follows: Section 2 includes the literature review related to the estimation of land requirements for solar technologies and describes the materials and methods used, Section 3 presents the results obtained and discusses them, Section 4 assesses the main assumptions and uncertainties considered in the analysis and Section 5 outlines our conclusions.

2. Materials and methods

In order to assess the total land requirements of solar generation at the country level, we performed a literature review related to estimating land requirements for solar technologies which informed the choice of methods used in the analysis. These methods were implemented in the following steps:

- Calculation of the electricity and final energy consumption by country for the year 2009 from a terrestrial-perspective (electricity/final energy use) and a consumption-based perspective (electricity/final energy footprint) (Section 2.1),
- Estimation of a likely range for the solar power density by country considering future technological advances (Section 2.2),
- Conservative estimation of the overcapacity needed by country to deal with the intermittence and seasonal variations in the solar resource (Section 2.3),
- Estimation of the potential share of the electricity to be covered by rooftop PV on buildings by country (Section 2.4).

Having estimated these factors, the land-use requirements per country to supply an amount of energy by solar power can be obtained by applying the following formula:

$$Land - use = \frac{energy \cdot (1 - rooftop\ PV)}{solar\ power\ density} \cdot overcapacity$$

Equation (1)

2.1. Multi-regional input-output model

Input-output tables display the interconnection between different sectors of production, making it possible to track the production and consumption in an economy. Traditionally, energy consumption has been described by the “energy use” indicator that refers to the amount of energy used within the borders of a country. However, in the last decade, the acceleration of economic processes linked to globalization (e.g., specialization and offshoring) has resulted in a shift of economic activities between countries and in a dramatic growth in international trade. Advanced capitalistic economies have specialized in economic activities with high added value, while reducing their share of energy intensive sectors and manufacturing industries (Baiocchi and Minx, 2010; Weber, 2009). In relation to this, MRIO tables allow us to track the global supply chains of products consumed by including the trade between different countries. In this paper, we combine the common “electricity use” (or territorial-based) indicator with the concept of an “electricity footprint” (or consumption-based) indicator which relates to the electricity consumed worldwide to produce the goods and services demanded by the people living in a given country.

We apply the WIOD (Dietzenbacher et al., 2013), a set of MRIO tables that comprises information for 35 industries, 59 products for the 27 member states of the European Union (EU-27), and 13 non-EU countries (Australia, Brazil, Canada, China, India, Indonesia, Japan, South Korea, Mexico, Russia, Turkey, and the United States of America (USA)), as well as the Rest of the World (RoW) as an aggregated region. These 40 countries represent 65% of world's population and 90% of the GDP. Although the WIOD presents data from 1995 to 2009, here we concentrate on the last year of the series to perform a static analysis.

The energy (electricity and final energy) use and footprint per country are obtained following the methodology described in Arto et al. (2016). Since the proposed analysis assumes that all the electricity production is substituted by solar power plants, we took the total final electricity consumption as well as the electric power transmission and distribution losses from the IEA Energy Balances for the year 2009 (IEA, 2016a). Consistency is ensured by considering own consumption by the solar power plants in the f_2 factor (see Section 2.2).

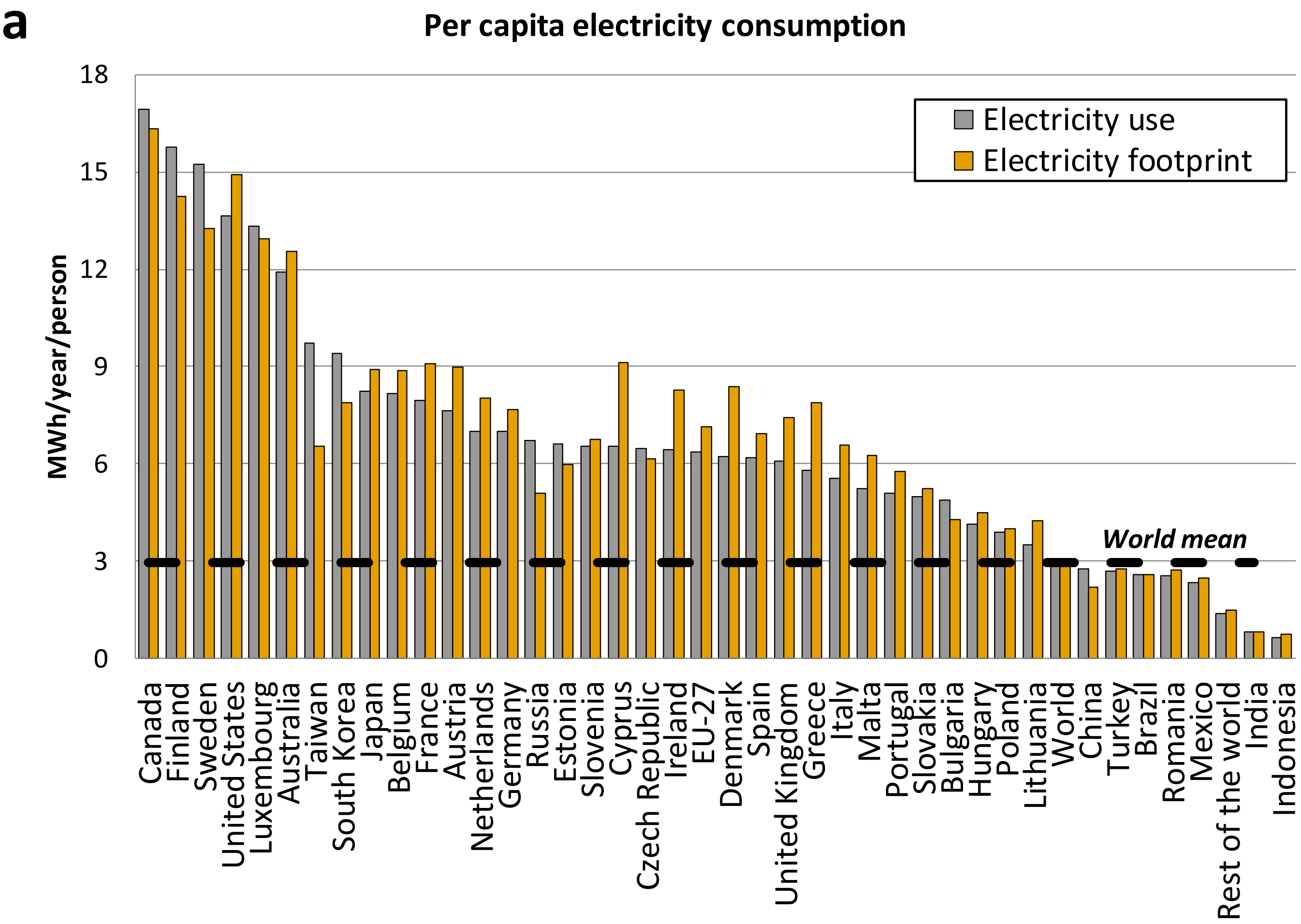
2.1.1. Electricity and final energy consumption

The electricity and final energy consumption (use and footprint) calculated for the target countries in 2009 is shown in Figure 1a and b (see Table A1). The countries are sorted in descending order according to the national means in terms of energy use.

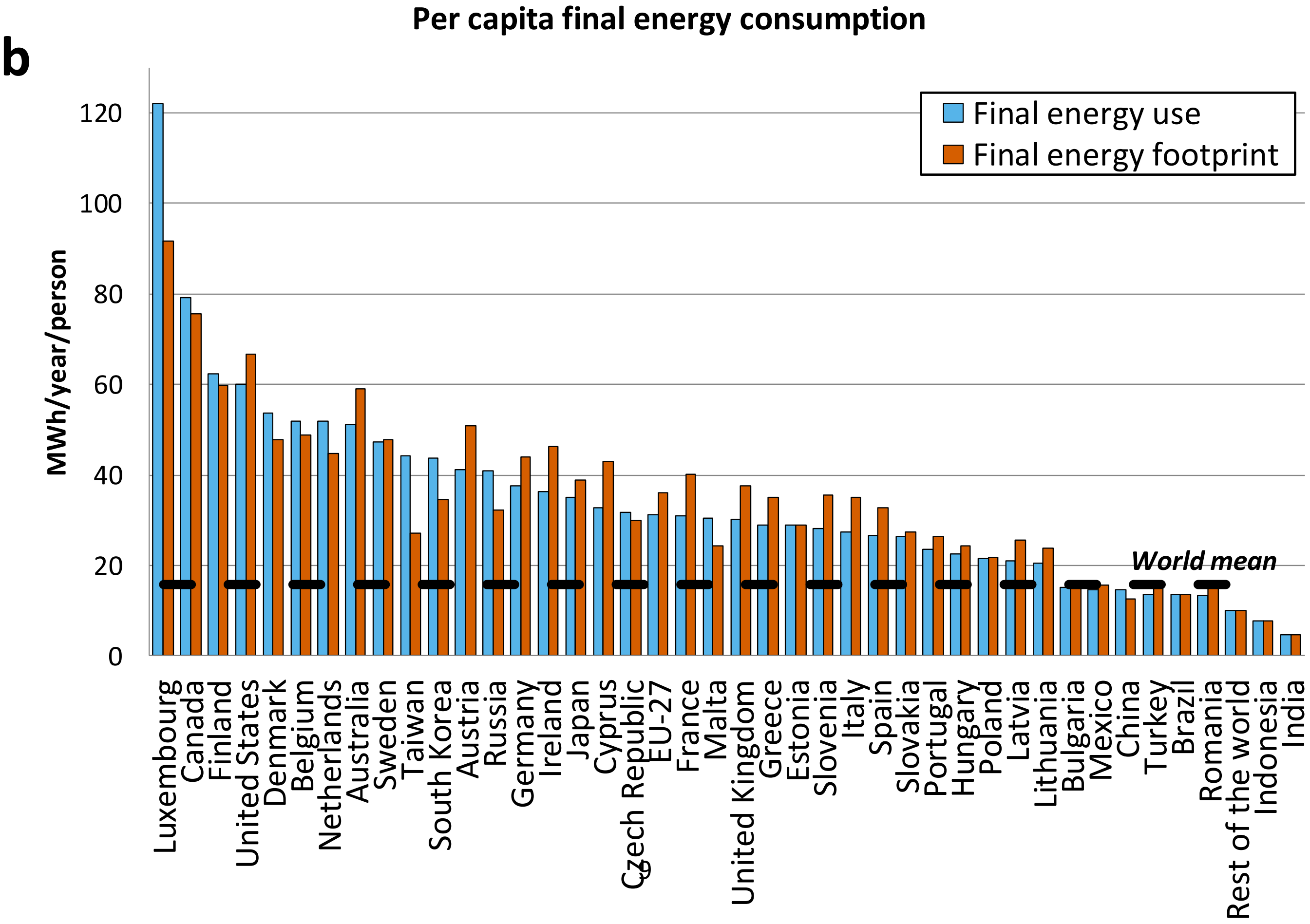
For countries with the highest electricity use per capita (Canada, Finland, Sweden and USA), the electricity use ranges from 13.5 to 16.5 MWh/person/year with differences between the electricity footprint and electricity use per capita of -13% (Sweden) to +9% (USA). At the other extreme, in the countries with the lowest electricity consumption (India, Indonesia, Mexico and China), the electricity use ranges from 0.5 to 2.5 MWh/person/year, with differences between the electricity footprint and use use of -21% (China) to +15% (Indonesia). Most European countries are characterized by electricity footprints per capita higher than their electricity use, notably Greece (+36%), Denmark (+35%), Ireland (+29%) and the UK (+22%), whereas countries such as Russia (-24%), China (-21%) and South Korea (-16%) are net exporters of electricity embodied in trade (Figure 1a).

In relation to per capita final energy consumption, similar trends can be observed (Figure 1b). The advanced capitalist economies consume over 20 MWh/person/year, while emerging and developing economies consume below the world average of 16 MWh/person/year. The per capita footprint of the advanced capitalist economies is almost +10% greater than their final energy use on average, with some countries showing notably greater differences such as France (+30%), the UK (+28%) and Italy (+25%). On the other hand, negative differences of -22%, -21%, and -14%, were found for Russia, Korea and China, respectively.

These results are in accordance with the general assessment of energy footprint resulting from globalization and the increase in specialization and phenomena such as delocalizations, the advanced capitalist countries tending to be net importers of energy from the rest of the world (Arto et al., 2016).



Per capita electricity consumption



Per capita final energy consumption

Figure 1: (a) Per capita electricity use (in white) and footprint (in red), and (b) per capita final energy use (in white) and footprint (in blue); both in MWh/person/year by country (decreasing order) for 2009. The world mean is depicted by a dotted black line. For the numbers, see Table A1.

2.2. Solar power density at country level ($\rho_e{}^i$)

The net solar power density per country i ($\rho_e{}^i$) is estimated following the top-down approach from de Castro et al. (2013) and Smil (2015). I^i represents the annual average solar irradiance for the country i (W_e/m^2) and the factors f_1, $f_2{}^i$ and $f_3{}^i$ account for the losses related to the cell efficiency conversion, the average performance ratio over the plant's life cycle and the land-occupation ratio, respectively. In this way, we estimate the average power delivered to the country grid in electric watts per square meter (W_e/m^2) that a PV plant would give to society in each country over the expected park lifetime:

$$\rho_e{}^i = I^i \cdot f_1 \cdot f_2{}^i \cdot f_3{}^i$$

Equation (2)

Thus, this indicator relates the energy demand to the required PV infrastructure in terms of installed capacity and its total land-use requirements. In the following sections, each parameter is discussed in order to obtain a robust and likely range at the country level.

The assumed distribution of solar technologies and configurations (e.g., concentrated solar power (CSP) with or without storage, fixed PV, tracking PV, etc.) has been found to be a key factor in the assessment of solar land occupation (de Castro et al., 2013; Denholm and Margolis, 2008). However, power densities for PV fixed tilt parks are roughly the same as or even better than other solar technologies. For example, PV tracking systems require additional space to avoid self-shading (higher f_3, see Section 2.2.4), and this is not fully compensated for by the increased irradiance on the surface of the panel (de Castro et al., 2013; Luque and Hegedus, 2011; MacKay, 2013). CSP facilities also are reported to occupy similar or even larger surface areas, and require even more space in the case of including storage due to the extra space need for storage facilities (de Castro et al., 2013; Ong et al., 2013; Smil, 2015). Moreover, CSP plants are a less universal solution than PV, since (1) they only use the direct irradiance (PV also uses diffuse), (2) they require higher levels of irradiance to be economically optimal (+50%), and (3) they adapt less well to terrain unevenness (Deng et al., 2015; Hernandez et al., 2015).[1] Given these factors, in this work, we concentrate on PV fixed tilt parks in order to provide a conservative, lower bound for the land requirements of solar technologies.

2.2.1. Solar irradiance (I^i)

We estimate the average solar irradiance per country applying a Geographical Information System (GIS) tool: specifically, we overlapped the annual average solar irradiance data from NASA SSE (2008) (latitude tilt radiation,

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[1] Additionally, restrictions on water use in the arid regions that often have the most appropriate solar resources for CSP would reduce plant efficiencies due to the implementation of dry-cooling technologies.

i.e., the radiation incident on a surface positioned such that the tilt coincides with the latitude, which is the optimal angle for PV panels to take advantage of the solar resource at each location) with the surface area of each country. The results obtained can be seen in Table 1. This table also reports the coefficient of variation[2] (CV) in order to assess the robustness of the estimation. In fact, the CV is less than 10% for most of the countries; however, as expected, there are larger variations in solar irradiance across the territory of larger countries, e.g., the USA (23%), Russia (16%) and China (14%).

Country	**Average solar irradiance (W_e/m^2/year)**	**CV (%)**
Cyprus	248	-
Malta	238	-
Australia	235	8%
Mexico	226	7%
India	210	5%
Brazil	209	7%
Indonesia	203	6%
Taiwan	190	-
Portugal	185	6%
Turkey	181	7%
China	179	14%
Spain	178	9%
Greece	173	5%
South Korea	166	2%
Italy	161	8%
USA	160	23%
Bulgaria	155	2%
Japan	150	6%
Slovenia	141	2%
Romania	140	5%
France	140	9%
Hungary	138	4%
Austria	132	3%
EU-27	125	-
Slovakia	124	4%
Denmark	122	2%
Czech Republic	120	3%
Latvia	120	4%
Lithuania	120	2%
Netherlands	119	5%
Belgium	119	4%
Poland	118	3%
Estonia	118	2%

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[2] CV is a standardized measure of dispersion of a frequency distribution. It is the ratio between the standard deviation and the average.

Germany	118	6%
Luxembourg	117	1%
Canada	117	15%
Russia	113	16%
United Kingdom	108	7%
Ireland	104	6%
Sweden	104	10%
Finland	102	8%

Table 1: Estimates of the annual average solar irradiance and coefficient of variation (CV) for the countries in the WIOD database from (NREL, 2014). The data are surface area-weighted averaged to the different solar irradiance levels in each country. For Taiwan, Malta and Cyprus, we approximated the country irradiance using the irradiance level of its CRC due to the small size of each country (see Section 2.3). The value for the UE-27 is calculated from the area-weighted values of each country member (not from GIS calculation).

2.2.2. Cell efficiency conversion (f_1)

Current average efficiencies from single and polycrystalline silicon cells are between 10 and 12% (de Castro et al., 2013; Smil, 2015). The best current research cell efficiencies under standard test conditions (STC)[3] are as follows: 8.6-17.9% for emerging techniques, 13.4-23.3% for thin films, 20.4-27.6% for crystalline silicon cells and 26.4-44.7% for multi-junction cells (Smil, 2015). Although future technologies will improve on current efficiencies, it is unclear whether future parks will increase average efficiencies beyond 20%. For example, thin film technologies (currently representing roughly 10% of the share (ISE, 2014)) might lead the way in the future due to their economic advantage (MacKay, 2013). In relation to multi-junction cells, their higher efficiency is gained at the cost of substantially greater manufacturing complexity and price. Moreover, they are mostly installed in double tracked systems where the greater demand for space is not compensated for by a better power density. To date, their use has been limited to special applications, notably in aerospace where their high power-to-weight ratio is worthwhile. On the other hand, single-junction cells have a maximum theoretical efficiency of 34%, a thermodynamic limit known as the Shockley–Queisser limit (Luque and Hegedus, 2011).

Further, material constraints might emerge at significant solar power deployment levels (e.g., copper, silver) (de Castro et al., 2013; García-Olivares et al., 2012). In general, the efficiency of the cells made with abundant materials (e.g., amorphous silicon) tends to be relatively lower than those made with materials that are less abundant (e.g., cadmium telluride or polycrystalline silicon).

Thus, to take into account the uncertainties in future technological developments and market share, we consider 15 to 25% to be a plausible range for the future average cell efficiency conversion of installed PV capacity (de Castro et al., 2013). At the lower limit, simpler and cheaper technologies such as thin-film or amorphous silicon would

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[3] PV modules are rated in laboratories at STC in watts of peak power (Wp). This is the power the module would deliver to a perfectly matched load when the module is illuminated with 1 kW/m^2 of insolation power of a certain standard spectrum (corresponding to bright sunlight) while the cell temperature is fixed at 25ºC and air mass at 1.5 spectrum). An array of modules is rated by summing up the watts peak of all the modules (Luque and Hegedus, 2011).

dominate the market, while the upper limit would reflect a situation in which the more complex and expensive technologies were substantially deployed. This parameter is set equally for all countries since the current PV market is global (REN21, 2015).

2.2.3. Average performance ratio over the park's life cycle (f_2)

Solar cell efficiencies are rated in laboratories under controlled conditions, which will be different from real outdoor installations (generally, the irradiance being lower and the temperature higher). There are also losses in the wiring and the inverter, and related to the time for maintenance, among other factors. The ratio between the actual and the nominal output is therefore expressed by a gross measure, the performance ratio (PR). There are many PRs defined in the scientific literature, these ranging from 0.4 to 0.8, considering different limits and conditions (de Castro et al., 2013; Luque and Hegedus, 2011). Solar manufacturers, however, usually perform PR calculations that do not take into account factors such as the average degradation of the photovoltaic cells over the expected plant lifetime, electrical losses from the current meter to the connection to the electricity grid, losses due to failures of modules or inverters, corrosion and cabling issues or energy self-consumption (other than electric) for the maintenance of the solar park installations. Including these additional losses makes it possible to estimate the average performance ratio over the park's lifetime. Following this approach, de Castro et al., (2013) estimated a PR value of 0.67. Prieto and Hall (2013) estimated this parameter performing an energy output analysis under actual operating conditions in Spain, taking into account the future degradation of the cells but ignoring availability and self-consumption, shading and other losses, and obtained a PR value of 0.655. Thus, in this work, we take the value 0.65 as a reference for the parameter f_2. However, in warmer climates, the PR is lower because the efficiency of the cell falls with increasing temperature. Luque and Hegedus (2011) report a 5–10% reduction when the ratings are made at 45°C instead of under STC (i.e., 25°C), and hence, we apply a 7.5% reduction for the countries analyzed that lie within the tropics.

2.2.4. Land-occupation ratio (f_3)

The land-occupation ratio is the actual land occupation of PV cells over the total land occupation of solar photovoltaic power plants. This includes the space required around the modules to avoid shading, for substations to allow for maintenance including access roads, service buildings, etc., i.e., all land enclosed by the site boundary.

Near-field shading considers local obstructions, such as trees, walls, rooftop equipment, and neighboring rows of panels, and can have a substantial impact on PV output.[4] This factor cannot be explicitly taken into account in this work due to the top-down approach applied; however, it is already implicitly included in our estimation of f_3 (see, for example, the Lieberose park surface area occupation in Figure 2 in de Castro et al., (2013)). For multi-row commercial systems, row-to-row shading is inevitable, but designers have the ability to choose array geometry to

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[4] Near-field shading is electrically equivalent to mismatch. If one module in a string is shaded it may have the same effect as if the entire string were shaded, as the entire string can only carry the same amount of current as its weakest link. Shade on as little as 5–10% of an array can be predicted to reduce its output by over 80% (Luque and Hegedus, 2011).

satisfactorily minimize this type of shading loss. For a given location, latitude and climate are the key factors. Usually, the target is to limit annual shading losses to 2–4%. In practice, this means spacing rows such that the setback ratio (SBR) is at least 2:1 in sunny, lower latitude regions and at least 3:1 for cloudier mid-latitude regions (see Figure 2) (Luque and Hegedus, 2011). Given this, we will consider that the countries that lie within the tropics (i.e., between 23.5°N and 23.5°S parallels: Australia, Brazil, India, Indonesia, Mexico and Taiwan) have a 50% higher f_3 than those in the regions in the mid-latitude regions (see Table 3). In other words, in those regions, the PV arrays can be placed with a smaller separation distance since the sun tends to be higher in the sky than at lower latitudes. As a reference for the mid-latitude regions, we will consider the data from the top-down analysis using satellite images which includes data from real parks from Germany, Canada and Spain between 40°N and 52°N, yielding land-occupation rates around 0.23 from de Castro et al. (2013) (see Table 2).

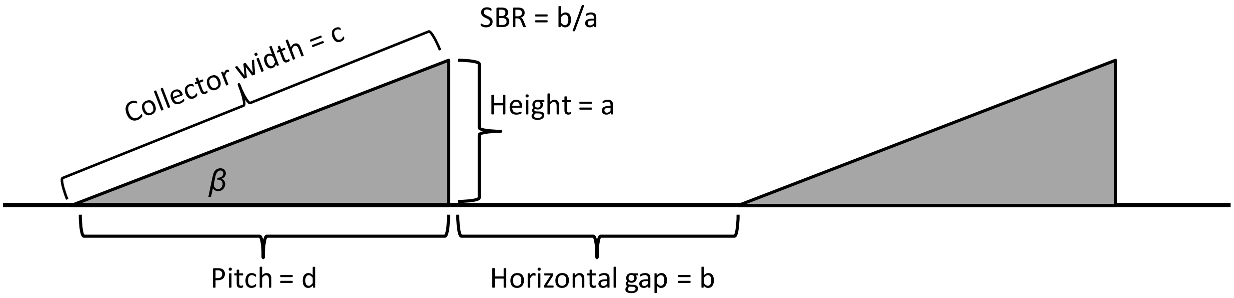

Figure 2: Row spacing geometry with module facing to the left at tilt angle *β*. Adapted from Luque and Hegedus (2011).

Solar park (latitude)	**f_3**
Finsterwalde (51.5°N)	0.27
Sarnia (43°N)	0.23
Olmedilla (40°N)	0.22
Strasskirchen (49°N)	0.24
Lieberose (52°N)	0.18
Mean	**0.23**

Table 2: Land-occupation factors from de Castro et al., (2013) from locations that lie between the parallels 23.5° and 51°.

The evolution of the SBR varies non-linearly with the latitude of the site. For the sake of simplicity, we classified our set of countries into four categories: “Tropics”, “Temperate 1” (for locations between the 23.5° and 51° parallel), “Temperate 2” (between 51° and 56°) and “Temperate 3” (higher than 56°) (see Table 3). Figures from an installer guide (NABCEP, 2012, Fig. 20) were applied to estimate the land-occupation ratio, f_3, for each category to ensure between 2 and 4 hours of sun at the winter solstice for each country latitude value (see Section 2.3).[5]

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[5] The results from de Castro et al. (2013) suggest that the latitude is not the only factor driving the factor f_3, since different plants at different latitudes can have similar f_3 values. Technical factors ones such as the correct design of the configuration of

Geographical region		**SBR**	**f_3**
Tropics	< 23.5°	2:1	0.34
Temperate1	23.5° < x < 51°	3:1	0.23
Temperate2	51° < x < 56°	4:1	0.17
Temperate3	> 56°	6:1	0.11

Table 3: Four categories of geographical regions that represent the f_3 associated with the setback ratio (SBR) that avoids shading at the winter solstice between 2 and 4 hours. Source: (NABCEP, 2012). f_3 from the geographical region Temperate 1 as the reference.

Table 4 summarizes the estimates of the likely ranges of the parameters f_1, f_2 and f_3, and Figure 3 shows the estimated range of solar power density by WIOD country applying Equation (2). The whole range is 1.1-12.1 W_e/m^2/year (Figure 3). The spread is significant for all regions, due to the uncertainty in the efficiency conversion from solar irradiance arriving at the panel to the cell (f_1 between 0.15 and 0.25, 66% difference). Among the countries with the highest power density values, those in the tropics such as Australia, Mexico, India, Brazil and Indonesia have notably high values of between 8.4 ± 2.1 and 9.7 ± 2.4 W_e/m^2/year. However, most countries are characterized by more modest values of 3 to 8 W_e/m^2/year. Finally, the lowest values are found for regions that are located in parallels even further from the equator, such as Russia, Poland, Denmark, Netherlands, the UK and Ireland (2-4 W_e/m^2/year) and the Baltic states and Nordic countries (< 3 W_e/m^2/year).

Loss factor	**Units**	**Description**	**Future range estimate**	
f_1	Ad	Efficiency conversion from solar irradiance arriving at the panel to the cell	0.15-0.25 (current estimate: 0.12)	
f_2	Ad	Average performance ratio over the park's life cycle including degradation, losses, failures, etc.	Tropics	0.60
			Rest	0.65
f_3	Ad	Land-occupation ratio	Tropics	0.34
			Temperate 1	0.23
			Temperate 2	0.17
			Temperate 3	0.11

Table 4: Estimates of the current and likely future values of the loss factors f_i. See discussion of the estimates in Section 2.2. The countries within the tropics are: Australia, Brazil, India, Indonesia, Mexico and Taiwan.

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the infrastructure in the field (and sometimes the shape of the field itself (see, for example, the Olmedilla plant in de Castro et al. (2013, Fig. 6)) are found to be critical to maximize the solar power density of each plant.

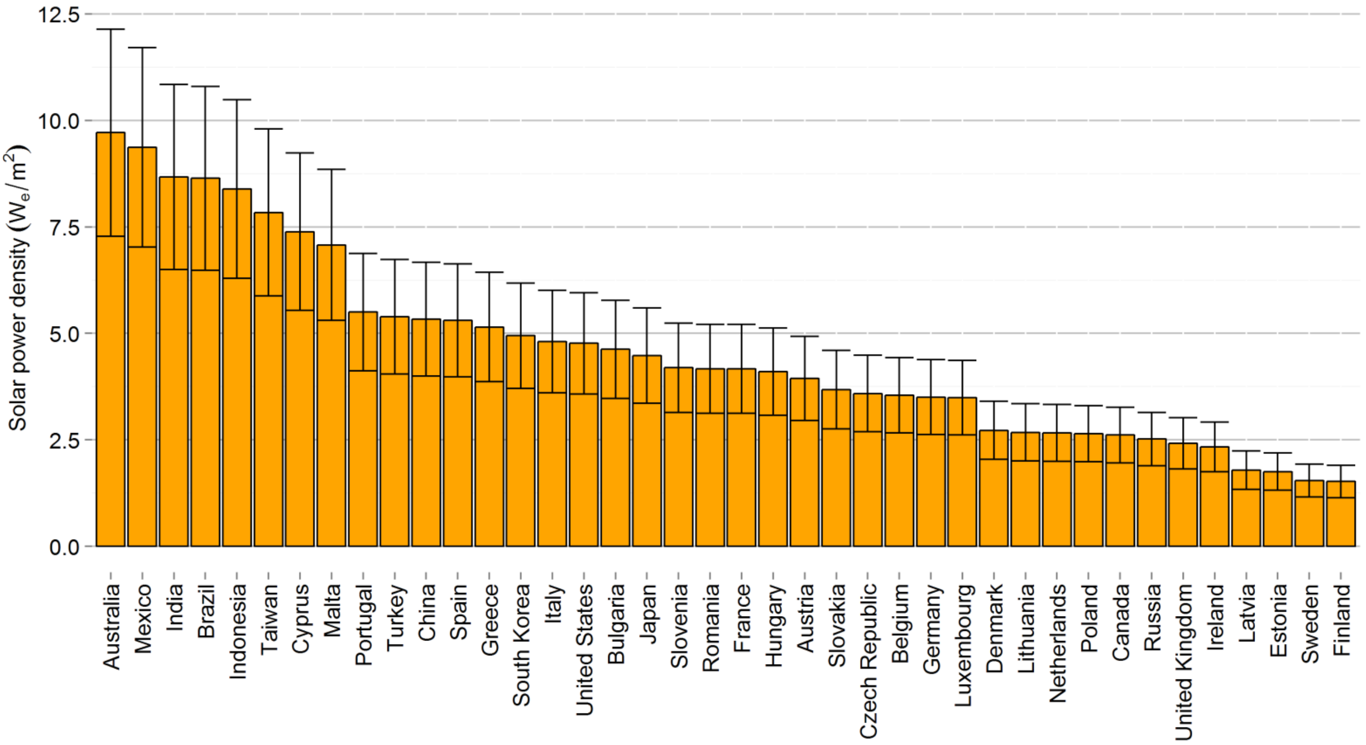

Figure 3: Estimated average solar power density per country (W_e/m^2/year) considering uncertainty in the efficiency of future PV modules and specific geographical characteristics.

2.2.5. Comparison with other values estimated in the literature

Few studies have provided power density estimates of solar technologies that analyze real power plants. Smil (2015) reviewed the largest PV projects in operation, finding a range of 3-9 W_e/m^2/year depending on the technology and geographical location of the site. De Castro et al. (2013) and Ong et al. (2013) highlighted the importance of assessing the entire land occupation of solar parks through the analysis of satellite images to identify plant configuration, direct land use and project area boundaries, since official project data are often unavailable or do not reflect the actual occupation of the infrastructure. Ong et al. (2013) analyzed 72% of installed and under-construction utility-scale PV and CSP capacity in the USA, finding a generation-weighted average of the total land-use requirements[6] of 6.9 W_e/m^2/year for small PV, 8.3 W_e/m^2/year for large PV and 8.1 W_e/m^2/year for CSP. These values are lower than those applied by Denholm and Margolis (2008), who took a PV ground-based array power density value for fixed panels which translated to a ~30% overestimation of the power density. Our estimated average power density for the USA is in the range of 3.6-6 W_e/m^2/year, which is even lower than that found by Ong et al. (2013). This difference can be explained by several factors, in particular, the fact that they used a higher PR derived from solar manufacturers, and the fact that most of the current parks are installed in areas with very high irradiance levels (i.e., exceeding 250 W_e/m^2/year, in California and Arizona; see also the CV obtained for the USA in Table 1). On

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[6] The total estimated area corresponds to all land enclosed by the site boundary, and the direct area comprises land directly occupied by solar arrays, access roads, substations, service buildings, and other infrastructure.

the other hand, only 15% of the projects analyzed by Ong et al. (2013) refer to completed projects; and hence, they relied to a large extent on manufacturers' data, which have been shown to systematically overestimate the power density of the real parks (de Castro et al., 2013).[7]

In terms of land use energy intensity (the inverse of ρ_e), our equivalent range is 9.4-99.8 m^2yr/MWh. Specifically, the values for all countries, except for the Scandinavian and Baltic countries (Finland, Sweden, Estonia, and Latvia), lie within the range found in a literature review (Horner and Clark, 2013). However, this review only included one study at typical Scandinavian solar irradiance (see ref [5] in Horner and Clark (2013)) without taking into account the additional shadowing in these latitudes (f_3=0.33).

2.3. Overcapacity and storage requirements due to short-term and seasonal variations

For each location, the solar resource is variable over time, with both short-term variability (e.g., cloudiness, day-night) and seasonal variability (e.g., winter-summer), the latter completely uncorrelated with the demand. Usually, a grid can accommodate up to only 20% electricity from renewable sources without a need for dedicated storage facilities (Armaroli and Balzani, 2011; Lenzen, 2010). Thus, with the hypothesis that all the national electricity would be produced by solar power, a certain level of (1) storage, (2) overcapacity and (3) flexible demand should then be considered. In this work, we focus on the two first elements, distinguishing between short-term and seasonal variability.

For the short-term variability, we focus on hydro pumping storage as proposed by other authors (Denholm and Margolis, 2008). Although electric batteries might also address the short-term variability,[8] hydroelectric pumping storage is currently the best solution due to its demonstrated functioning, competitive cost, high efficiency, long storage times (up to years) and fast response (Armaroli and Balzani, 2011). This solution would require the construction of a certain amount of additional capacity to compensate for the related losses, which for pumped storage are typically of the order of 25% (χ factor in Equation (8), i.e., a round-trip storage efficiency of 75%) (Denholm and Kulcinski, 2004; Denholm and Margolis, 2008; MacKay, 2013). These losses apply only to the fraction of demand passing through storage (f_{stor}). The estimation of this fraction should ideally be done at the country level comparing hourly load to hourly PV supply (e.g., (Wagner, 2014)), which is far beyond the scope of this paper. Instead, as a reference value, we used the middle of the range (60-70%) found by Denholm and Margolis (2008) for a variety of regions in the USA. This approach based on hydro pumping is simplistic and conservative since it may be impossible to achieve the required storage volumes depending on the population density and the climate and geography of the country (Trainer, 2012). For example, MacKay (2013) estimated that summer/winter balancing for the UK would require lakes for pumped storage occupying 5% of the area of the country, which is physically unfeasible. Trainer (2013a) estimated for Europe that generation from pumped storage would have to be scaled up

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[7] The report also lacks of information to assess differences in the estimation of the f_3 parameter. For example, the only table that would allow for a comparison (Table 5), reports only seven parks with a power density of 4-6.7 We/m2/year, which are all values lower than the reported average (8.3 W_e/m^2/year).

[8] In particular, electric cars may act as storage devices. The IEA (2016b) estimates that "125,000 cars could be equivalent to 300 MW of flexibility – a medium size pump storage plant or a successful stationary demand side response program".

by a factor approaching 20.[9] CSP with storage could also help to mitigate the short-term variability, though unlike hydro it would not be a universal solution, since it requires high irradiance locations with low cloudiness to operate at profitable rates (typically desert areas). Additionally, CSP has a higher seasonal variability than PV. For instance, in Spain, the ratio of the highest/lowest monthly production is 9 for all CSP installations but 2.6 for the PV facilities (REE, 2016).

In relation to seasonal variability, depending on latitude (e.g., winter-summer) and the regional climate characteristics (cloud cover, monsoon, etc.), there may be substantial differences in average monthly irradiance levels (Smil, 2015; Trainer, 2012). For example, although the minimum average monthly irradiance level represents over 90% of the annual average for cities such as Jakarta (Indonesia) or Rio de Janeiro (Brazil), in other cities such as London (UK), Paris (France) and Berlin (Germany), this ratio falls below 40% (NASA SSE, 2008). These differences are reflected in actual PV electricity generation: for example, in 2014, the electricity from solar in Germany was over 5 TWh in June and just 0.4 TWh in December, an order of magnitude difference.[10] This difference cannot be exclusively attributed to the difference in monthly irradiance since the minimum is only around 30% lower than the maximum (see Table B1), and is likely related to the increased shadowing in winter (especially critical on rooftops, see Section 2.4). Thus, previous studies considering only average annual irradiance levels without including the seasonal variability when estimating the solar potential of different countries and states (e.g., (Denholm and Margolis, 2008; Šúri et al., 2007)), underestimate the actual capacity (and land-use requirements) required to produce the electricity in months in which the irradiance is substantially lower than the annual average (Trainer, 2012, 2010).

Apart from hydro pumping storage systems to compensate for the seasonal variations are not yet available and alternative technologies of large-scale storage are still in the R&D phase (Wagner, 2014). Thus, here we propose a novel approach to produce a conservative estimate of the additional capacity required to take into account seasonal variations at different geographical locations. We posit that, for each country, the total installed capacity should be able to cover the electricity consumption in the month with the lowest solar irradiance level.[11] This process consists of the following steps:

a) Since within a given country (and especially those with large surface areas), there may be locations with very different solar irradiance potentials, we start by estimating a reference geographical coordinate center (the country-specific "central reference coordinate", CRC^i) with longitude CRC_{lg}^i and latitude CRC_{lat}^i.
b) CRC_{lat}^i was taken at approximately[12] +1/3 of the distance between the minimum and the maximum longitude relative to the country i, from its closest area to the equator. For example, the latitude in the case of Spain

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[9] However, the identified total technical potential for hydropower in Europe only doubles current installed capacity (IPCC, 2011).
[10] http://www.solarwirtschaft.de/en/photovoltaic-market.html
[11] In most countries, the winter consumption of electricity is higher than in summer (excepting those in tropical regions with a substantial use of air conditioning). Thus, the approach is internally consistent since by assigning a monthly annual average to winter, we are in fact underestimating the actual demand of electricity.
[12] For some countries with very low irradiance and an elongated geographical shape such as Finland and Sweden the +1/3 criteria was softened to move the CRC to the south.

ranges between 36°N and 44°N and thus its CRC_{lat} would then be 36+(44-36)*1/3 ~ 39°N. The reason to take 1/3 instead of, for example, ½, was to consider that locations with better solar resources are more economically attractive and will tend to be occupied first (as is occurring for CSP plants in the USA (Ong et al., 2013), for example, although there are exceptions such as Australia where the majority of plants are close to the largest cities in the south of the country).

c) CRC_{lg}^{i}: starting from CRC_{lat}^{i}, we take the longitude values encompassed by the country. From this set of values, we select the longitude with the smallest difference between the value in the month with the lowest irradiance and the annual value, i.e., the most favorable longitude given the latitude. For example, Spain is characterized by the latitude 39°N and spans the longitude values 0, 1, 2, 3, 4, 5, 6 and 7°W (large variations can exist: for example, for Luxembourg there was only one longitude value while for Russia there were 90). The longitude level with the smallest difference between the value in the month with the lowest irradiance and the annual average was 0°W (thus, the CRC for Spain is 39°N 0°W). We call this ratio the seasonal variability (SV) and in the case of Spain it is estimated to be 0.7 (see Table B1).[13] Minor adjustments were made to ensure that the CRC annual average irradiance is greater than the country average (compare with Table 1).

Hence, the overcapacity factor per country i to deal with short-term and seasonal variations can be expressed as (see the country values in Table B1):

$$f_{overcapacity}^{i} = \frac{1 + \chi \cdot f_{stor}}{SV^{i}} \qquad \text{Equation (3)}$$

These overcapacity requirements can be as low as +30% (Australia) or 3 to 5-fold for those countries with a lower SV (typically northern European countries). In fact, as shown by Weitemeyer et al. (2015) with an hourly resolution study for Germany, while a 50-80% share of intermittent renewable sources may require relatively low levels of storage and overcapacity, a system 100% based on intermittent sources substantially increases these requirements, i.e., there is an asymptote when approaching the full intermittent energy mix. Our result for Germany (2.8-fold overcapacity) is in good agreement with their range.[14]

Figure 4 illustrates the seasonal and geographical variations in the solar irradiance at the CRC for five representative countries. The CRC for the UK represents a typical northern European country characterized by a low irradiance and

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[13] The following case illustrates the conservative nature of the estimated SV in this analysis. In Spain, the PV electricity production in 2014 in two months (January and November) was less than 60% of the annual average of PV electricity production. In 2015, December was the worst case for PV generation. Considering other renewables in December 2015, wind electricity production was 88% of the annual average, hydroelectricity was 61% of its annual average and CSP only 20% of its annual average. Therefore, even an ideal renewable mix will likely require overcapacity/storage for some months, and our SV is likely optimistic (own calculations based on (REE, 2016)).

[14] In fact, their study: (1) assumes no grid limitations, and (2) considers seasonal storage capacities and technologies (such as hydrogen) that are currently not commercially available on a gigantic scale. In their own words: "… the results derived from our approach for large-scale systems […] exhibit lower bounds for the actual storage demand" (Weitemeyer et al., 2015).

large seasonal variations (with winter values below 50% of the annual average, while reaching almost 150% in summer). The CRC for Greece is typical of that for Mediterranean countries, where significantly high irradiance values are reached during most of the year although still with a substantial seasonal variability. The Indonesian CRC represents a country with a high and stable solar irradiance over the year, while that for Australia shows an area with very high and stable solar irradiance. The influence of the monsoon is visible in the Indian CRC, provoking a decrease in the summer months from over 250 W_e/m^2 to below 200 W_e/m^2.

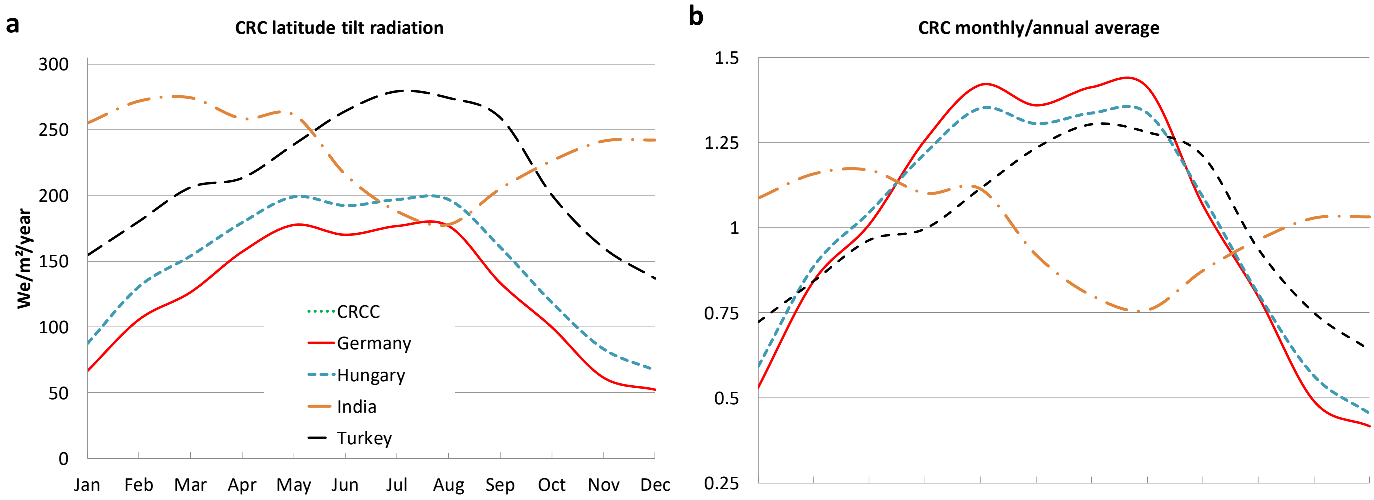

Figure 4: Seasonal variations in solar irradiance (latitude tilt) at the estimated CRC for 5 countries: Australia, Greece, India, Indonesia and the UK. a) Monthly evolution (W_e/m^2/year) and b) the ratio between each month and the annual average value (%).

The SV is the key parameter to model the required overcapacity in order to deal with the seasonal variations in different geographical locations. It represents a rough estimate of the magnitude of the total solar PV capacity required to supply the electricity demand of the month with the lowest irradiance level in relation to the average annual level (see Equation (8)). Since neither daily peak demands nor variations within each month are taken into account ("good" sunny days vs. "bad" cloudy/rainy days), and the SV is the result of taking optimistic assumptions in relation to the CRC, the estimated overcapacity represents a lower bound (Trainer, 2013a).

To finish this section, we remark that the estimated losses and overcapacity parameters are not independent of each other. For example, current parks are designed to optimize the *yearly* (average) output instead of maximizing the output for the period of the year with the least favorable climatic conditions (e.g., winter). In the second case, the distance between panels would then need to be increased, thereby reducing the actual f_3 (that is, there is a trade-off between SV and f_3).

2.4. PV potential on buildings and in urban areas

Actual land requirements for solar plants are reduced by considering the potential of solar electricity to be produced on buildings and in urban areas.[15] Studies that evaluate this potential at a regional or country level are very common in the literature (e.g., (Bergamasco and Asinari, 2011; Byrne et al., 2015; Izquierdo et al., 2011; Jo and Otanicar, 2011; La Gennusa et al., 2011; Ordóñez et al., 2010; Paidipati et al., 2008; Wiginton et al., 2010)). Despite the potential being substantially reduced when considering shading, orientation, and other availability factors, it is generally found that rooftop PV could cover from a very low to moderate share of the electricity consumption. However, there is a substantial lack of standardization and no consensus method in the literature, with different methodologies achieving a different geographical coverage and different levels of spatial resolution (Melius et al., 2013). Hence, global estimates based on a consistent methodology across regions are scarce. For this reason, we have developed our own approach with the objective of making a rough assessment of the rooftop PV potential in each WIOD country. For this, we rely on GIS-based methods that represent a more objective and accurate approach for identifying rooftop availability than others based on constant values (Mainzer et al., 2014; Melius et al., 2013).

It has been estimated that it would only be possible to cover a small percentage of today's urban areas with solar panels (<2%), assuming acceptable efficiency (La Gennusa et al., 2011; Sorensen, 1999), since existing urban and architectural designs were not conceived to incorporate solar modules and are poorly compatible with them. Ordóñez et al. (2010) performed an extensive GIS-based analysis for all urbanized areas in Andalusia (Spain) taking into account the maximum occupation of roofs (9.4% of the urbanized area; Instituto de Estadísticas de Andalucía (2015)). Without taking into account non-usable buildings, e.g., those under heritage protection, or shadows between buildings (personal communication), they found a potential of 3% of surface area covered in relation to the urbanized land in that region. Thus, in current conditions, a plausible maximum range dedicated to PV systems would be in the order of 2-3% of urban areas.

However, in practice, there are other uses for rooftops: daylighting, solar thermal, roof-top gardens or terraces, etc. Although some uses might be compatible with rooftop PV (and sometimes even complementary, e.g., green roofs, hybrid solar collectors, etc.), others will compete for the available roof space, some of these uses already being promoted as sustainable/green practices. For example, solar thermal is a promoted and competitive technology already occupying many suitable locations (Cansino et al., 2011; REN21, 2015) (including in high latitude regions (Hagos et al., 2014)), and needs to be close to consumers due to the technical difficulty of transporting heat over large distances without incurring in high losses, unlike electricity (IEA, 2006). Globally, solar thermal already accounts for about 1.2% of water and space heating in buildings (REN21, 2015). For example, a GIS study for Spain found that after satisfying up to 70% of the service hot water demand in every municipality, around 80% of the suitable roof area of the country was identified as available for rooftop PV (Izquierdo et al., 2011).

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[15] Other studies such as that of Šúri et al. (2007) did not consider the land-use requirements for solar plants by assuming a priori that all the PV power would be roof-mounted panels.

Thus, studies that do not take into account these competitive uses are likely overestimating the actual surface area available for rooftop PV. Hence, we derive the net power density for rooftops in each country ($\rho_{e,rt}{}^{i}$) from Equation (2) but with the land-occupation ratio ($f_{3,rt}$) corresponding to the range 1-2%,[16] and with $f_{2,rt}$ less than the performance ratio in Equation (2) taking into consideration the lower relative efficiency of rooftop PV systems over ground-mounted systems (see Equation (4)). Although by deploying PV systems on buildings the system is situated at a potential point of use (eventually minimizing transmission and distribution requirements and losses), rooftops are less efficient than ground-mounted systems since (1) the orientation and tilt of the roof is given and will ordinarily be suboptimal, and (2) there is a correlation between the size of the plant and its capacity factor (Cp).

$$\rho_{e,rt}{}^{i} = I^{i} \cdot f_1 \cdot f_{2,rt}{}^{i} \cdot f_{3,rt}{}^{i} \qquad \text{Equation (4)}$$

How efficient is rooftop PV in relation to ground-mounted installations? To answer this question, we compare countries with a high proportion of rooftop systems like Italy and Germany (Smil, 2015) with countries with almost all ground-mounted systems like Spain. For the case of Italy, we could calculate the Cp as a function of the power of the installation (GSE, 2015) (see Table 5). The Cp for <20 KW plants (mainly rooftop) is around 80% of the Cp for >1,000 KW plants (mainly ground mounted). Therefore, for the Italian case, the $f_{2,rt}/f_2$ ratio would be around 0.80 under present conditions when the rooftop PV installations cover less than 1% of the built-up surface area of the country. Germany has an average irradiance of 66% of that of Spain, but only a Cp of 53% of that of Spain (Table 1, (Wirth, 2015)), and therefore the efficiency of the solar system of Germany is 0.53/0.66 ≈ 0.80 of that in Spain and this difference could be attributed to the poorer performance of rooftop systems. The case study for Andalusia, carried out by Ordóñez et al. (2010), a region with a very good average irradiance (~ 200 W_e/m^2) and considering the maximum occupation of roofs and module panels with f_1 = 20%, found a Cp of 0.096. If we compare this number with the present Cp for Spain as a whole of 0.197 (with less average irradiance than Andalusia and with more than 97% of PV ground–mounted systems (Prieto and Hall, 2013)), then the performance ratio of rooftop/ground mounted would be $f_{2,rt}/f_2 < 0.5$. The study of Ordóñez et al. (2010) maximizes the power produced and not the efficiency of the system, and therefore in current roof systems far from the maximum occupation potential, the ratio $f_{2,rt}/f_2$ is higher.

Capacity of installed plants	Cp (%)
< 20 KW	12.2
< 200 KW	12.7
< 1,000 KW	14.0
> 1,000 KW	15.1

Table 5: Solar PV capacity factor depending on the capacity of the installed plant for the year 2013 in Italy (GSE, 2015).

Hence, Equation (4) can be rewritten as:

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[16] Although in principle this ratio might improve in the future if urban norms were focused on maximizing PV rooftop output, its influence would be substantially reduced by the fact that buildings have a very long lifetime and in many countries the stock of buildings will not increase much in the future (especially in more industrialized countries) due to projected population stagnation.

$$\rho_{e,rt}{}^{i} = I^{i} \cdot f_1 \cdot (f_2{}^{i} \cdot 0.8) \cdot f_{3,rt}{}^{i}$$ Equation (5)

The urbanized area for each country (BU^i) was approximated by the category “Built-Up” from the Global Agro-ecological Zones Data Portal version 3.0 that identifies the estimated share of land cover/land use required for infrastructure and settlement (FAO/IIASA, 2011). We consider this database since it is the most up-to-date synthesis of global information sources. Since the urban area is included in the built-up area, by applying the factor of land occupation to the built-up area, we are in fact providing an upper boundary for the actual potential of rooftop PV.[17]

2.5. Land-use requirements for solar power: summary

Calling $E_{rt}{}^{i}$ the potential electricity output from rooftop PV and $E_{tot}{}^{i}$ the total consumption of electricity of that country for a given year (here 2009), rt^i represents the share of the electricity covered by rooftop for each country in relation to the total consumption (the values for each country are shown in Appendix C). We subtracted the current production from hydropower from the electricity consumption (see Section 2.1.1) for the same year for each country in order to represent the results in terms of land use excluding water bodies (see Figure D1) (US EIA db, 2015). In any case, since the power density of hydropower is similar to solar (0.5-7 We/m2 (Smil, 2015)), the conclusions in terms of land use would not vary significantly under the assumption that solar would also produce the electricity currently supplied by hydro. However, we judge the first option to be more realistic since the dams and related existing hydro infrastructure have lifetimes of over 100 years, are consistent with a 100% renewable scenario and we are assuming the operation of hydro pumping storage.[18]

$$E_{rt}{}^{i} = BU^{i} \cdot \rho_{e,rt}{}^{i} \cdot \frac{SV^{i}}{1 + \chi \cdot f_{stor}}$$ Equation (6)

$$rt^{i} = \frac{E_{rt}{}^{i}}{E_{tot}{}^{i}}$$ Equation (7)

Thus, with $\rho_e{}^{i}$ representing the energy density for country i, χ the storage losses in pumping hydro to compensate for the short-term variability and SV^i the overcapacity required to address the seasonal variation in each country, the land-use requirements for solar power in each country (LU^i) can be expressed as:

$$LU^{i} = \frac{E_{tot}{}^{i} \cdot (1 - rt^{i})}{\rho_e{}^{i}} \cdot \frac{(1 + \chi \cdot f_{stor})}{SV^{i}}$$ Equation (8)

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[17] With this hypothesis, we expect to compensate for developments not taken into account such as PV potential on facades.

[18] However, with this approach, we are not considering inter-annual rain variability and hence not addressing the question of, for example, the electricity supply in a dry year during a cloudy winter.

3. Results and discussion

3.1. 100% Solar electricity mix scenario

Table E1 shows the total land surface area occupied by solar facilities to cover the electricity use and footprint per country (except for current hydro generation). As expected, the countries with the largest populations and highest levels of electricity consumption per capita lead the ranking: EU-27 ($220 – 380 \cdot 10^3$ km^2), the USA ($95 – 170 \cdot 10^3$ km^2), Russia ($65 – 115 \cdot 10^3$ km^2) and China ($45 – 100 \cdot 10^3$ km^2), and those with the smallest size and populations are at the bottom: Malta (50 – 85 km^2), Cyprus (110 – 200 km^2) and Luxembourg (490 – 830 km^2).[19] Hence, to comprehend the implications in terms of land use for each country, a relative perspective must be taken. Figure 5a depicts the land associated with the solar electricity footprint and use for each WIOD country as a share of the total land. To facilitate the interpretation of these results, different land uses are depicted from GAEZ (FAO/IIASA, 2011). Specifically, the countries that would need to occupy, proportionally, a larger area to cover their current electricity consumption with solar would be (in decreasing order): the Netherlands, Malta, Belgium, the UK, Luxembourg, South Korea, Germany, Finland, Taiwan, Denmark and Japan. The absolute land cover share for these eleven countries ranges from 50-60% (the Netherlands) to 10-11% (Japan), these countries in most cases requiring a surface area *similar* to or *larger* than that of the land currently cultivated (range: electricity use – electricity footprint). Another useful indicator to comprehend the scale of these land requirements is to compare these land requirements with the land currently dedicated to infrastructure and settlement (built-up): for most of the advanced capitalist economies, the area required would be of the same or a higher order of magnitude (see Table E1).

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[19] Countries with a high share of hydroelectricity such as Slovenia and Brazil also have low land requirements due to the methodology applied (see section 2.5).

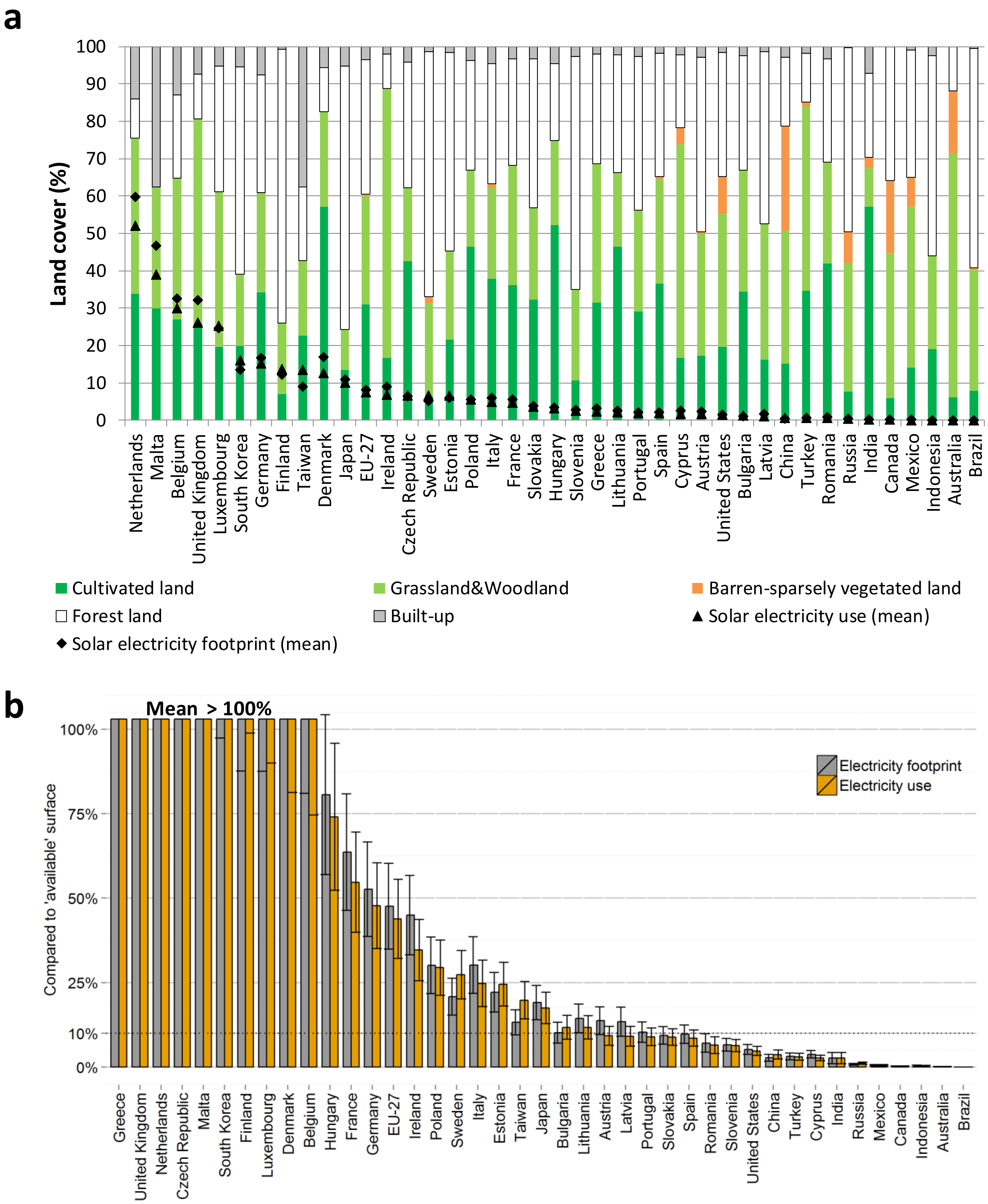

Figure 5: (a) Land associated with the solar electricity footprint and use (mean values) for each WIOD country as a share of the total land. Different land uses are depicted: cultivated, grassland and woodland and barren/sparsely vegetated, built-up and forest. The countries are ranked from the highest to the lowest share of total land required to cover the current electricity use. (b) Land occupation by solar power plants to cover the electricity use

and footprint for 2009 as a share (mean and range) of the total "available" surface area by WIOD country. The available surface area for each country is the terrestrial surface area after subtracting that occupied by agricultural uses, forest products and built-up areas. Source: (FAO/IIASA, 2011) and own calculations. Land-use data for Taiwan extracted from the CIA World Factbook: https://www.cia.gov/library/publications/the-world-factbook.

When comparing our results with other studies in the literature, our median value for USA is roughly three times higher than the land requirements estimated by MIT (2015) (0.4% of the land area of the country) due to the consideration of the need to cope with the variability of the solar resource, and the real land occupation of solar technologies. Our low range for the USA (1.1%) is close to the upper range found by Denholm and Margolis (2008) of 0.3-0.7%, while the differences with our higher bound (1.9%) can be explained by the additional factors considered in our study as well as the influence of having averaged the solar irradiance over the whole surface area of the country (see Section 2.2.1). However, we find substantial differences with results of the study by Šuri et al., (2007) for UE-28+5 EU countries. We recall that their study assumes all the solar power to be installed on rooftops, and hence the comparison with our results is not straightforward. For example, they found that countries such as Netherlands, Germany and Spain would need around 3.3%, 1.7% and 0.3% of their total surface areas, respectively, and a figure of 0.6% for the whole UE-25+5. However, after including the rooftop PV potential and subtracting the current hydro generation, we still found for these countries that the supply of the current electricity use would require 52.4% ± 13.7, 15.2% ± 4.0 and 1.9% ± 0.5 of the total land surface areas, respectively, and 7.5% ± 2 for the UE-27. Thus, the differences are greater than one order of magnitude, and they are attributable to the overly simplistic hypothesis of the aforementioned study. Our results are closer to studies that take into account the intermittency of solar in particular and RES in general. For example, Wagner (2014) found that around 540,000 km^2 (excluding water bodies) would be required to supply (domestically) the current electricity consumption of 29 European countries with hydro, wind and solar, which is higher than our estimated range for the members of the EU-27 (220,000-380,000 km^2). Further, a study focusing on supplying a level of electricity for the USA similar to current levels of consumptiondemand with 80% RES found that, "gross land-use impacts associated with renewable generation facilities, storage facilities, and transmission expansion totaled less than 3% of the land area of the contiguous United States" (NREL, 2012), which is again a higher figure than our range for 100% RES for that country of 1.1 to 1.9%. Hence, these figures confirm the conservative nature of our approach to estimate the land requirements of solar as a proxy of total RES land requirements.

On the other hand, the countries on the right side of Figure 5a represent countries where the additional pressure on land use is found to be less strong, e.g., Brazil, Australia, Indonesia, Mexico and Canada (<3%). These countries are characterized by low population density (see Table E1) and/or are located in areas with extraordinary irradiance levels (see Table 1). We also note that barren/sparsely-vegetated land, where the actual competition for land might be lower, is mostly located in regions where the additional pressure on land is found to be less challenging (the USA, Russia, China, Canada and Australia).

However, these results must also be put in context: the degree of land competition will critically depend on the use of land at the country level. Given this, we define for each country its “land availability”, consisting of the terrestrial land that is currently neither being used by the primary sector (arable land, permanent crops, permanent meadows and pastures and productive forest area (FAOSTAT, 2015)) nor built-up (FAO/IIASA, 2011). Furthermore, we consider an additional land use for a biodiversity buffer to safeguard the resilience and stability generated by biodiversity. We apply here the value of 12% of the territory as considered in the Brundtland Report and for the calculation of the standard ecological footprint (Wackernagel et al., 2002; WCED, 1987). This value is a conservative lower bound, which has been strongly criticized as being unable to a ensure an effective protection of biodiversity (Vačkář, 2012). For example, the UNEP and IUCN give 17% as a reference value (Juffe-Bignoli et al., 2014), while Soulé and Sanjayan (1998) argued for a minimum share of 25-50%.

This definition of land availability must be taken as a first conservative approximation, since its availability would in fact be reduced by many other factors including orography (e.g., mountains), protected areas (e.g., in the EU-27, an average of around 27% of the land is protected, which is more than twice our 12% assumption), and locations with suboptimal resources, that would more than offset other positive factors such as eventual productivity gains in the agriculture sector (see Deng et al., (2015) and Farthing et al., (2016)). The estimated land availability per country is depicted in Figure F1.

Taking into account this definition of land availability, the pressure on land would be very high in many countries, with some of them even requiring more surface than the estimated available land (see Figure 5b). The latter would be the case (in mean electricity use values) for: Greece (not even having enough available land for the assumed biodiversity buffer), the UK (almost 7x), the Netherlands (over 3x), and Czech Republic (over 2x), as well as Malta, South Korea, Finland, Luxembourg, Denmark and Belgium (between all and 2x their available surface). The EU-27 as a whole would require around 50% of its available land. In fact, few advanced capitalist economies would require less than a 10%[20] of the available surface such as Portugal, Slovakia, Spain and the USA (below 5 and 10%), as well as Cyprus, Canada and Australia (below 5%). For Austria, Latvia, Romania and Slovenia, the land requirements in this scenario are also below 10%: however, for these countries, hydroelectricity contributed over 35% of the electricity consumption in 2009 (see Figure D1). Our results help to explain why, when solar is scaled up, parks are often being located in agricultural areas and biodiversity hotspots (e.g., (Bocca et al., 2015; Hernandez et al., 2015; Squatrito et al., 2014)).

In relation to the differences in land-use requirements when accounting for the electricity demanded from the territorial and the consumption perspective, the estimation of the electricity footprint worsens the situation for countries with a higher electricity footprint than use (see Section 2.1). For example, in median values, the

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[20] This 10% “threshold” has been chosen arbitrarily, and it is far beyond the scope of this paper to state which levels of solar occupation would be excessive or unfeasible in practice. That would require analysis of the extent to which additional pressure on current land uses would affect agricultural production (i.e., crop prices) and eventually be an additional driver for deforestation, among other negative effects.

Netherlands would require almost an additional 8% of total land (from 52 to 60%), UK an additional 6% (from 26 to 32%) and Denmark an additional 4.5% (from 12.5 to 17%). For other countries like Spain, characterized by an electricity footprint notably higher than the electricity use, higher irradiance levels mitigate this difference, Spain requiring only an additional 0.3% (from 1.9% to 2.2%) in terms of total land and 1.2% (from 8.6 to 9.8%) in terms of available land. At the EU-27 aggregate level, the additional land-use requirements when computing the electricity footprint would be 0.6% for total land and almost 4% for available land. At the other extreme, we find countries whose land requirements are substantially reduced when taking into account the net embedded electricity footprint in trade. These include exporting countries such as Taiwan (from 13.6 to 9.1% in terms of electricity consumption).

3.2. 100% Solar final energy mix scenario

We replicate the analysis, this time computing the land requirements to cover the final energy use of each country. In terms of total land-use (Figure 6a), the first notable finding is that for six countries the supply of final energy use from solely solar energy would be physically unfeasible: the Netherlands, Luxembourg, Malta, Belgium, the UK and Denmark. Other countries would require vast amounts of land that would likely also make this scenario unfeasible in practice: most notably Germany, South Korea, Taiwan and Finland (over 50% of the total country land); but also Japan, Ireland, Czech Republic, Sweden, Poland, Estonia and Italy (over 30%). For the whole EU-27, we find that land requirements would reach 45.5% ± 11.5 of the total land. In this sense, MacKay's (2013) results are confirmed. The list of countries requiring a less than 10% share of total land is: Spain, the USA, Romania, China, and Turkey (above 5%); as well as Bulgaria, Russia, India, Canada, Indonesia, Mexico, Brazil and Australia (below 5%). Table E2 shows the total land surface area (km^2) occupied by solar facilities per country and the associated land per capita (m^2/person) in terms of final energy use and footprint.

Analyzing the results in terms of "available" land, over 20 WIOD countries would require more than the estimated available surface. These countries are most of the EU-27 member states (all except for Lithuania, Slovakia, Romania, Portugal, Spain, Bulgaria, Slovenia and Cyprus) and South Korea. Seven of them would require a surface area at least an order of magnitude higher than the current estimated available land (Greece, the UK, Netherlands, Luxembourg, Czech Republic, Malta and Denmark). The EU-27 would require more than twice its estimated available surface area. Japan would require around 80%. On the other hand, the only countries with requirements 10% of the available land would be Russia, Indonesia, Mexico, Canada, Brazil and Australia. The USA, Cyprus, Canada and Australia would be the only advanced capitalist countries requiring less than 25% of the available land.

In terms of final energy footprint (Figure 6b), we observe similar trends to those found for electricity footprint: advanced capitalist economies (e.g., Slovenia, Spain, Japan, Spain and Portugal) would require a larger area to cover their energy footprint than to cover their energy use (+11.2%, +9.5%, +9% and +6%, respectively), while exporting countries such as Taiwan (-37%), and BRIC countries such as China and Russia would reduce their land needs (-4% and -2%, in terms of available land).

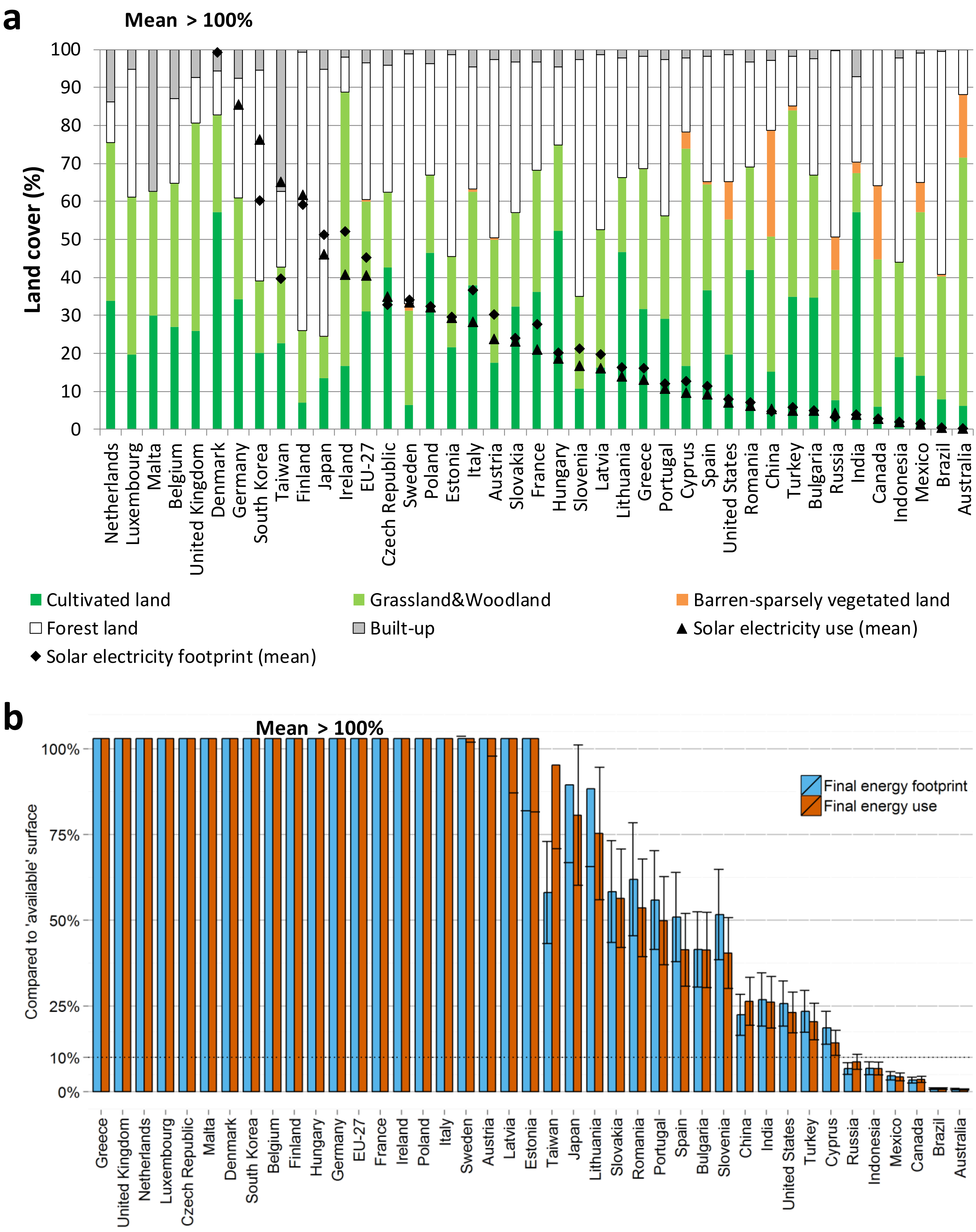

Figure 6: (a) Land associated with the solar final energy footprint and use (mean values) for each WIOD country as a share of the total land. Different land uses are depicted: cultivated, grassland and woodland and barren/sparsely vegetated, built-up and forest. The countries are ranked from the highest to the lowest share of

total land required to cover the current electricity use. (b) Land occupation by solar power plants to cover the electricity use and footprint for 2009 as a share (mean and range) of the total "available" surface area by WIOD country. The available surface area for each country is the terrestrial surface area after subtracting the areas for agricultural uses, forest products and built-up areas. Source: (FAO/IIASA, 2011) and own calculations. Land-use data for Taiwan extracted from the CIA World Factbook: https://www.cia.gov/library/publications/the-world-factbook.

Studies proposing a 100% total energy mix supplied by RES for individual countries are less common than those focusing on the transition solely in the electricity sector. This might be due to the great complexity of designing models that encompass all the final energy types in an economy, as well as the fact that the electricity sector is usually seen as the easiest sector to decarbonize (e.g. (IPCC, 2014)). Among the exceptions are several studies applying the EnergyPLAN model. However, comparisons are not straightforward, since this model does not include a land-use module. For example, Lund and Mathiesen (2009) find for Denmark that a 100% RES system would require a flow of biomass that would be twice the domestic potential of the estimated residual biomass resources including waste, acknowledging that this scenario would require a deep reorganization of land use at the country level (or rely on imports). A similar analysis for Ireland lead to analogous conclusions (Connolly et al., 2011). These findings are in accordance with our results, namely, that the land requirements for a 100% total energy mix supplied by RES would require around 30-50% and 30-110% of the total surface of the country, in the cases of Ireland and Denmark respectively, and over 100% for the available land for both countries. In fact, the land footprint in 2008 is estimated to be of the same order of magnitude as and twice the territorial area of Ireland and Denmark respectively (Arto et al., 2012). These figures indicate that even in the event of internal reorganization of land use, in the future, it would not be possible to cover both energy and food needs domestically in these countries in a 100% total energy mix scenario at current consumption levels. A study for UK analyzing the implications of meeting *just* 15% of final energy demand with RES by 2020 concluded that a large part of the RES needs should be covered by imports (Ward and Inderwildi, 2012). Hence, these analyses are consistent with the results we obtained indicating that, in the future, there might be a trade-off between land for food, land for energy and land for biodiversity conservation in certain countries, implying also trade-offs between food and energy security. Of course, these trade-offs will impact other regions of the globe through indirect land use changes, as it has already happened with the promotion of biofuels in the EU (Laborde, 2011; Valin et al., 2015). Nonetheless, quantitative analysis of these dynamics is not described in the literature, most energy models not including a comprehensive representation of the land-use system (Otto et al., 2015).

The literature focusing on the transition to a 100% RES system at a globally aggregated level usually finds that land requirements will not pose significant constraints on this transition (García-Olivares, 2016; Greenpeace et al., 2015; Jacobson and Delucchi, 2011; WWF, 2011). For example, Jacobson and Delucchi (2011) find that just an additional 0.41% of the global land area (1% including spacing area) would be required for a global 100% RES system. García-Olivares (2016) finds a similar footprint of ~1% of global continental surface area for PV and CSP plants in his global

100% RES mix proposal. Our results cannot be directly compared with these globally aggregated analyses, which assume that large quantities of electricity/energy could be *technically* transported at a continental scale between areas with high levels of renewable resources (e.g., solar from deserts and wind from marine platforms) to the regions of consumption, which are often distant. Nevertheless, we judge that geopolitical and economic barriers, as well as concerns over energy and food security, will effectively pose significant constraints on the setting up of such large-scale intercontinental infrastructure (see section 4.1 for a discussion of this assumption in comparison with the "country's self-sufficiency" approach followed in this study).

4. Assessment of assumptions and uncertainties in estimating the land-use requirements of the transition to RES

In this section, five central assumptions of the analysis are assessed: the countries' self-sufficiency in electricity/final energy consumption and 100% solar share (section 4.1), the combination of static and dynamic approaches (section 4.2), the estimation of solar power density at country level (section 4.3), the implications of not accounting for the energy return on energy inverted (EROI) (section 4.4) and the estimation of PV potential in buildings (section 4.5).

4.1. Country's self-sufficiency in electricity/final energy and 100% solar share

Most countries in the world are connected to the grid of neighboring countries, thereby allowing for some degree of electricity trade. While some countries are an "energetic island" (e.g., Australia, Japan, China, and Turkey), others export (e.g., Bulgaria, Canada, and France) or import (e.g., Italy, Hungary, and Portugal) considerable amounts of electricity. The external dependence of total energy is usually high for advanced capitalist economies due to the dependence on fossil fuel imports (UN Comtrade, 2015). However, improving energy security is a key policy objective for most governments, and self-sufficiency through the increase in RES production is one of the commonly cited instruments (Johansson, 2013; US ACT, 2007). The EU members are not an exception, although representing a special case due to the planned progressive integration of each members' systems into a pan-European scheme (the "Energy Union") (European Commission, 2014)), eventually allowing for greater electricity trade. For this reason, the results are reported here also at the EU-27 level. In any case, the process is slow: a minimum interconnection target (which should be achieved by 2030) has been set at 15% of installed electricity production capacity of the member states, well below the required levels of interconnection to balance supply and demand at the European level (Wagner, 2014).

There is another potential scale of integration discussed theoretically in the literature that goes beyond the regional scale: the intercontinental scale. Many studies focusing on the technical feasibility of a global 100% renewable mix propose these interconnections (in combination with other strategies such as smart grids, storage or demand management) as a solution to renewable intermittence and fluctuation, as well as to the unequal distribution of the resource (e.g., high solar irradiance near the tropics and wind at northern latitudes and on sea platforms). In this way, the increase in transportation losses would be largely offset by the use of locations where the available resource is more abundant (Armaroli and Balzani, 2011; García-Olivares et al., 2012; Jacobson and Delucchi, 2011;

Trainer, 2013a). Although several projects have been proposed, none is currently under way (Breyer et al., 2015; DESERTEC, 2003; Gulagi et al., 2017). For example, the DESERTEC project aiming to harness solar energy from deserts, producing large amounts of electric power by CSP plants based in Northern Africa and the Arabian Peninsula, and transmit it through high-voltage direct current (HVDC) transmission lines to Europe (DESERTEC, 2003). Its connection with the electricity generated by PV, wind, hydro, geothermal and biomass in European countries would lead to an integrated regional framework (Armaroli and Balzani, 2011). However, these kinds of projects are very sensitive to geopolitical circumstances and depend on gigantic investments. In fact, the DESERTEC consortium dissolved some years ago and there are no imminent prospects for its reactivation (Smil, 2015). On the other hand, although significant new construction of HVDC lines is currently under way (particularly in China and Brazil), very little of the new capacity actually crosses country borders except in the EU. The feasibility of large intercontinental grids operating within the next few decades critically depends on future global societal pathway uncertainty. Under pathways characterized by an intensification of globalization and market integration processes (including international trade growth), these forecasts may prove valid. However, under scenarios dominated by fragmentation and regionalization of the relationships between countries, the functioning of these systems would be unrealistic (MEA, 2005; Raskin et al., 2002). In fact, these regional and intercontinental interconnection processes require that the participants collaborate to share and commonly manage their resources. Alternatively, this could also be achieved through force, with the strongest countries seizing locations with abundant renewable resources from countries not willing to collaborate. On the other hand, large intercontinental grids of thousands of kilometers and large areas dedicated to RES generation systems in foreign territories might also be an “easy” target to paralyze the economic activity of the importing regions. Moreover, given the lower power densities of RES in relation to fossil fuels, the surface required for RES generation systems is much higher, and hence, the geographical area to be secured by importing regions substantially increases, thereby substantially increasing their vulnerability (Lilliestam and Ellenbeck, 2011)

A renewable mix portfolio would mitigate the variability of the solar resource, eventually reducing the need for storage and overcapacity considered in this analysis. For example, in Europe, the annual cycles of wind and PV are partially complementary since the lower solar irradiance in winter is generally balanced by increased wind (and vice versa in the summer). There is also generally a trade-off between the installation of additional generation capacities and storage capacities to balance the intermittence of resources that is not captured by our approach (Armaroli and Balzani, 2011; François et al., 2016; Wagner, 2014; Weitemeyer et al., 2015). However, this complementarity is far from perfect. In any region there is a (low) probability of extreme combinations in the availability of natural resources, such as no wind over large parts of Europe during the winter. Moreover, there can be extreme annual variations in the availability of natural resources; for instance, the output of wind turbines in any given area can vary by up to 30% from one year to the next (Brower et al., 2013; Li et al., 2010). With hydroelectricity covering currently a mere 15% of the current global electricity consumption and already being close to its technical potential in many countries (IPCC, 2011), only wind could cover a substantial share of the remainder in a sustainable way. Moreover, wind generation could moderate the impact in terms of land use since, despite its lower power density, both offshore deployment and double land use are possible. On the other hand, technical (Lenzen, 2010) and biophysical limitations (de Castro et al., 2011; Miller et al., 2011) hinder large-scale deployment of wind energy. We have chosen to give priority to overcapacity (following a conservative approach, see Section 2.3) rather than storage, since economic options for large-scale and seasonal storage are currently neither technically available nor foreseen at the required scale. Moreover, storage losses would be higher than considered here, as hydro pumping cannot be generalized (MacKay, 2013; Trainer, 2012). Other sources of variability such as low rain years have not been considered; and, by taking the monthly irradiance average, we are not accounting for short-term solar variability (i.e., over hours, days, weeks). Finally, we have not allowed for the fact that demand peaks at certain times of day at levels much higher than the average (Trainer, 2013a), conservative estimates of these peaks being +30%, while other studies have yielded estimates several times higher. Coping with these factors would require greater levels of storage and/or overcapacity (higher SV). Moreover, the system should be designed for the minimum of all the energies in the mix, that might well be close to the minimum in a full 100% solar system (Trainer, 2012).

4.2. Static vs. dynamic projections

The proposed analysis follows a hybrid approach by combining static data (i.e., electricity consumption values for 2009) with dynamic factors (e.g., the uncertainty range for the future evolution of cell efficiency). The objective of this approach is double: on the one hand, to replicate the methodology followed in previous studies to allow comparability (Denholm and Margolis, 2008; Šúri et al., 2007), and on the other, to perform a vulnerability study in order to identify countries for which the objective of high solar power deployment might be unfeasible due to land constraints. This approach does not fully correspond with an "extreme scenario" when considering the expected increases in electricity and energy production globally for the coming decades (Armaroli and Balzani, 2011; WEO, 2014). In particular, emerging economies are expected to substantially increase their income and population levels in the coming decades. Let us take the case of India. Our estimated land requirements in terms of total land use seem relatively low for both covering electricity (0.4% ± 0.2) and final energy (3.8% ± 1.1) consumption. However, its population density is very high (over 400 people per km^2 of terrestrial land), a large share of their land being required to produce feedstock (almost 60%, see Figure 5a) or built up (~7%). Hence, in terms of land availability the situation worsens substantially, especially in terms of final energy (26.1% ± 7.5). Population growth (projected to be +30% to 2050 (UN, 2015)) combined with the expected increase in energy consumption (currently around a third of the global average, see Figure 1) are likely to drive land requirements to unfeasible levels. Similar reasoning could be applied to other emerging countries such as China and Nigeria (Deng et al., 2015).

In relation to the estimated "land availability", it could be argued that improvements in agricultural yield might to some extent compensate for increases in food demand due to population growth and diet shift in the future.

However, after decades of improvement due to agricultural intensification (based on inputs such as fertilizers, energy, water and capital equipment), yields might be approaching biophysical limits in some developed countries, and could stagnate for socio-economic reasons in developing countries (Alston et al., 2009; Grassini et al., 2013; Sands et al., 2014).

4.3. Estimation of solar power density at the country level

Various factors affect the estimation of the solar density for each country (see Section 2.2.1). The consideration of country average irradiance levels might be seen as a conservative assumption since areas with more irradiance are likely to be occupied more intensively. On the other hand, there are other important variables that influence the location of new power plants such as proximity to the consumer demand and existing electricity transport infrastructure. This is the case of, for example, Australia and Germany, where the locations used are mainly sub-optimal in terms of irradiance. However, we tried to compensate for this effect by selecting favorable parameters for the overcapacity factors (e.g., SV, CRC, etc.). In some cases, these parameters are even unrealistic since they correspond to locations of high mountains (i.e., less cloud cover, e.g., China CRC) or protected areas.

As stated above, large solar parks usually have higher power density levels than smaller ones. Hence, factors such as existing promotion policies and development frameworks will determine the number of each to be installed (i.e., planned economy, investment of large companies or small cooperatives or producers, self-production, etc.). Moreover, if land competition is to play a relevant role in future solar deployment, the factor f_3 might even decrease due to the need to adapt to the accessible fields.

4.4. Not accounting for EROI

The EROI is defined as the ratio of the amount of usable energy acquired from a particular energy resource (E_{out}) to the amount of energy spent obtaining that energy resource (E_{in}). Thus, accounting for the EROI of the solar PV systems would increase the required installed capacity to deliver the same output of net energy to the society. Defining r as the relative losses (E_{in}/E_{out}, see eq. 10), the total capacity to install in order to compensate for the energy invested would be given by the series $1+r^2+r^3+\ldots$, which is the Taylor series of 1/(1-r) (see eq. 11).

$$EROI = \frac{E_{out}}{E_{in}}$$ Equation (9)

$$r = \frac{1}{EROI}$$ Equation (10)

$$Total\ capacity = 1 + r^2 + r^3 + \cdots = \frac{1}{1-r} = \frac{EROI}{EROI - 1}$$ Equation (101)

An examination of the EROI literature on solar PV energy generation shows differences in the assumptions, parameters and methodologies employed (Hall et al., 2014). Assuming a conventional value of 10:1 and applying the Eq. 10, an overcapacity of 10/(10-1)-1≈11% would be then required in an hypothetical 100% solar energy system. The extended EROI ($EROI_{ext}$) broadens the conventional analysis by considering all the energy used to create and run a PV facility, including the fabrication of the PV modules (more than 95% of the power used for the manufacture of solar PV cells being electricity (Briner, 2009)), but also for the energy required for transportation, installation, maintenance, and all the other required energy inputs. The estimation of the $EROI_{ext}$ of PV systems range 2 to 3:1 (Hall et al., 2014), which would translate into overcapacities of 50% to 100%. Hence, accounting for the EROI factor would substantially increase the land requirements obtained in this analysis.

4.5. PV potential in buildings

As pointed out in Section 2.4, there is substantial heterogeneity in the literature in relation to the methods applied (achieving a different geographical coverage and levels of spatial resolution) and the results obtained. Our study incorporates assumptions about storage, seasonal variability and competing uses that are rarely taken into account in research in this field. It is therefore challenging to compare our results (see Appendix C) with those of other studies. The estimated PV rooftop potential seems to be in accordance with the GIS-based studies considered (e.g., for Spain, Izquierdo et al. (2011) having found that rooftop PV could cover around 4% of the total electricity demand, which is within our range, 2.2-7.4%, including hydro), while our figures are substantially lower than those obtained by constant-value methods (e.g., Defaix et al. (2012) and Paidipati et al. (2008) having reported potential shares of over 20% of the annual electricity demand for the EU-27 and USA). Further research is required to characterize the variability in these methods to reduce the uncertainties in current estimates, as has already been done, for example, for PV and CSP technologies (Horner and Clark, 2013). Further, the method applied does not escape the fact that there is a large uncertainty in the estimation of urban/built-up areas, with differences of an order of magnitude (Schneider et al., 2009). In relation to this, the GAEZ database (FAO/IIASA, 2011) used is the most recent attempt to provide a consistent estimate across different countries, and the global built-up area is in the upper range of the literature (around 1.5 million km^2) (Schneider et al., 2009).

5. Conclusions

In this work, we have analyzed the biophysical feasibility and potential vulnerabilities in the transition to renewable energies focusing on the land requirements for 100% solar energy scenarios for 40 countries considering two issues that are not usually considered in the literature: (1) the need to cope with the variability of the solar resource, and (2) the real land occupation of solar technologies. The exercise performed shows that, for many advanced capitalist economies, the land requirements over the total terrestrial surface area to supply current electricity consumption would be substantial, the situation being especially challenging for those located in northern latitudes with high population densities and high electricity consumption per capita such as the Netherlands, Belgium, the UK, Luxembourg, South Korea, Germany, Finland, Taiwan, Denmark and Japan (10-50%). Moreover, accounting for the electricity footprint, i.e., for the net energy embodied in international trade, tends to worsen the situation of these countries, increasing the land requirements to 11-60%. To assess the implications in terms of land competition, we have defined a land availability factor based on current land use and including a biodiversity buffer. With this indicator, the list of vulnerable countries enlarges substantially (e.g., the EU-27 would require around 50% of their available land), while few advanced capitalist economies would require low shares of the estimated available land (e.g., Canada and Australia, < 1%).

Specifically, the consideration of circumstances not usually taken into account in the literature such as the need for redundant capacity to ensure sufficient winter supply and the real land-occupation factor of solar power plants produces results more challenging in terms of land requirements than previously found (Denholm and Margolis, 2008; Jacobson and Delucchi, 2011; Šúri et al., 2007). In particular, assertions about the practical unlimited nature of the solar potential should be reconsidered (e.g., (IPCC, 2011; Rogner et al., 2012)). In fact, our results help to explain why, when solar is scaled up, parks are often being located in agricultural areas and biodiversity hotspots, namely, that this is a palpable example of the finiteness of the biosphere, i.e., of the “full world” to use the popular expression coined by Daly (2005).

The explorative exercise to examine the implications of a 100% solar energy mix for the same set of countries reveals the marked implications of the transition from concentrated fossil energies (i.e., “mines”) to distributed (over the Earth’s surface) RES. The results, that must be interpreted as order of magnitude estimates, due to the limitations and uncertainties of the analysis, indicate that the transition to domestically produced RES maintaining the current levels of energy consumption could be physically unfeasible for many countries: in particular, the Netherlands, Luxembourg, Belgium, the UK, Denmark, Germany, South Korea, Taiwan, Finland, Japan, Ireland, Czech Republic, Sweden, Poland, Estonia and Italy would require over 30% of their total land area (over 50% for the whole EU-27). Due to the biophysical restrictions on solar, these countries will have to rely on other domestic renewable sources (mainly wind and eventually biomass) or imports in their path to a 100% RES system. Although concerns over the potential land scarcity provoked by a full transition to RES have been already pointed out from a theoretical point of view (Johansson, 2013; Rao and Sastri, 1987; Scheidel and Sorman, 2012), currently available energy models are unable to properly capture the trade-offs between energy and food security, as well as biodiversity conservation, in the context of 100% RES scenarios. We attempt to contribute to the discussion by a rough quantification of potential implications. Specifically, by providing a ranking, we identify countries with particularly high vulnerabilities.

In this context, emerging countries might seem less vulnerable. However, if the projections of electricity and energy consumption growth, on the one hand, and the population increase, on the other, prove to be correct, such countries may suffer similar land pressures in the future to those currently on the advanced capitalist economies. Indeed, the pressures might be even greater, if the current structure of international trade, where they export substantial amounts of embodied energy, is not modified.

Thus, the transition to RES maintaining the current levels of energy consumption might create new vulnerabilities and/or reinforce existing ones in terms of biodiversity conservation, energy (and food) security and sovereignty, with the potential to intensify imperialist geopolitics to grab land and seize resources from other countries. It seems likely that, without profound changes in the level and management of energy demand (adaptation to the natural fluctuations in the availability of renewables, consumption reduction and equity at the global level) and the socio-economic system (i.e., the growth paradigm), the transition to renewables will substantially increase the competition for land globally.

Finally, we recall that the analysis performed must be understood as a vulnerability study of the unavoidable path to a 100% RES system for all countries. Future work could be focused on (1) dynamic developments, (2) expanding the potential constraints that may further reduce PV feasibility (e.g., material availability (García-Olivares et al., 2012; Lo Piano and Mayumi, 2016)), (3) analyzing the feasibility and land requirements of different 100% RES mixes, which has to be approached at a country level and with a different methodology,[21] and (4) improving the methods to represent the land availability and competition between different uses in existing energy models. In particular, GIS-based methods or integrated assessment models that include the interaction between the energy system and land-use changes could substantially contribute to advance in these directions.

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Appendix A: Electricity and final energy consumption by country for 2009

	Electricity use MWh/year/person	**Electricity footprint** MWh/year/person	**Final energy use** MWh/year/person	**Final electricity footprint** MWh/year/person
Australia	11.9	12.5	51.0	59.1
Austria	7.6	9.0	41.3	50.7
Belgium	8.2	8.9	52.0	48.7
Brazil	2.6	2.6	13.5	13.6
Bulgaria	4.9	4.3	15.1	15.2
Canada	16.9	16.3	79.2	75.6
China	2.8	2.2	14.6	12.5
Cyprus	6.6	9.1	32.7	42.9
Czech Republic	6.5	6.1	31.8	30.0
Denmark	6.2	8.4	53.7	47.8

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[21] The methodology applied here cannot straightforwardly be extended for wind since bottom-up analyses violate the Principle of Conservation of Energy (de Castro et al., 2011; Miller et al., 2011).

Estonia	6.6	6.0	28.8	29.0
Finland	15.8	14.2	62.4	59.9
France	7.9	9.1	31.0	40.2
Germany	7.0	7.7	37.6	44.0
Greece	5.8	7.9	28.9	35.1
Hungary	4.1	4.5	22.4	24.2
India	0.8	0.8	4.6	4.8
Indonesia	0.7	0.8	7.6	7.7
Ireland	6.4	8.3	36.4	46.3
Italy	5.6	6.6	27.3	35.0
Japan	8.2	8.9	35.0	38.8
South Korea	9.4	7.9	43.7	34.5
Latvia	3.2	4.0	20.9	25.5
Lithuania	3.5	4.2	20.4	23.9
Luxembourg	13.3	13.0	121.9	91.6
Malta	5.2	6.3	30.4	24.3
Mexico	2.3	2.5	14.7	15.8
Netherlands	7.0	8.0	51.8	44.7
Poland	3.9	4.0	21.6	21.7
Portugal	5.1	5.8	23.5	26.3
Romania	2.5	2.7	13.4	15.4
Russia	6.7	5.1	41.0	32.1
Slovakia	5.0	5.2	26.5	27.4
Slovenia	6.6	6.8	28.3	35.4
Spain	6.2	6.9	26.6	32.6
Sweden	15.2	13.3	47.2	47.8
Taiwan	9.7	6.6	44.3	27.1
Turkey	2.7	2.8	13.7	15.7
United Kingdom	6.1	7.4	30.1	37.6
USA	13.7	14.9	60.1	66.7
Rest of the world	1.4	1.5	10.1	9.9
WORLD	2.9	2.9	15.9	15.9
EU-27	6.4	7.1	31.2	36.0
BRIIC	2.0	1.7	11.3	10.1
EAS	8.7	8.4	38.2	36.4
Developed	9.4	10.0	42.8	46.7

Table A1: Electricity and final energy consumption (use and footprint) by country for the year 2009.

Appendix B: CRC and SV values per country

	Lat	Lon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann	Min/Ann (SV)	$f_{overcapacity}$
CRC	(º)	(º)	We/m²/year													%	%
Australia	-20	133	282	251	262	267	255	239	257	274	275	268	265	286	265	90%	129%
Austria	47	14	104	142	166	176	187	178	184	181	155	122	93	81	148	55%	212%
Belgium	50	5	59	92	125	157	183	180	182	178	140	103	66	48	126	38%	308%
Brazil	-10	-41	240	248	230	230	220	220	228	255	271	265	253	246	243	91%	128%
Bulgaria	42	23	130	148	173	178	195	217	230	227	201	160	117	108	174	62%	188%
Canada	52	-74	97	155	205	239	205	193	175	166	126	102	93	81	153	53%	219%

China	30	96	233	242	225	220	228	220	214	213	217	219	229	233	224	95%	123%
Cyprus	35	27	163	193	244	268	288	303	309	313	300	258	185	151	248	61%	191%
Czech Republic	49	18	75	115	136	158	180	171	178	179	141	100	67	62	130	48%	243%
Denmark	55	9	51	91	129	175	205	193	193	186	141	92	58	48	130	37%	315%
Estonia	58	25	51	93	147	177	210	206	201	183	141	88	55	36	133	27%	430%
Finland	61	25	37	88	147	181	207	198	197	172	136	78	49	22	126	17%	675%
France	45	6	120	150	184	187	203	218	232	221	198	154	117	98	174	57%	205%
Germany	50	12	66	105	126	157	178	170	177	177	133	100	61	52	125	42%	279%
Greece	38	21	143	155	194	209	230	262	264	257	229	188	130	114	198	58%	202%
Hungary	47	17	88	131	154	180	199	193	197	197	161	119	83	67	148	45%	256%
India	17	76	255	272	274	258	261	216	188	178	205	226	241	242	235	76%	153%
Indonesia	-8	112	198	198	203	210	214	208	220	238	252	244	220	208	218	91%	128%
Ireland	52	-7	47	77	105	148	168	163	162	152	128	89	60	42	112	37%	312%
Italy	41	14	121	144	178	188	210	232	247	240	204	164	114	102	179	57%	204%
Japan	35	138	173	193	203	213	197	173	178	194	160	177	171	173	184	87%	133%
South Korea	36	129	185	194	205	225	215	191	163	167	167	187	170	175	187	87%	134%
Latvia	56	27	58	103	150	173	200	192	188	182	134	91	58	46	131	35%	330%
Lithuania	55	26	65	106	148	173	201	191	190	185	139	94	60	55	134	41%	283%
Luxembourg	50	6	60	98	123	160	180	176	181	176	137	96	63	49	125	39%	296%
Malta	36	13	164	200	248	265	277	285	296	293	265	231	179	151	238	64%	183%
Mexico	20	-101	248	282	300	284	261	265	253	238	231	243	257	230	258	89%	130%
Netherlands	52	6	54	93	119	155	180	171	171	169	133	88	58	43	120	36%	321%
Poland	51	24	71	111	145	169	193	181	180	185	138	104	66	59	134	44%	263%
Portugal	38	-8	162	183	223	231	237	265	277	275	241	188	155	138	215	64%	181%
Romania	45	24	130	150	173	166	181	184	193	195	170	144	114	100	158	63%	184%
Russia	55	112	95	143	208	234	219	213	202	189	165	143	100	78	166	47%	247%
Slovakia	48	20	83	124	151	169	183	183	185	188	155	115	78	66	140	47%	247%
Slovenia	46	14	109	150	178	184	197	193	200	196	167	123	96	82	156	52%	222%
Spain	39	0	187	208	246	266	260	275	285	278	254	219	178	164	235	70%	167%
Sweden	58	15	46	88	141	175	200	198	195	180	147	88	52	34	129	26%	443%
Taiwan	23	120	153	150	172	187	200	228	228	214	207	205	177	156	190	79%	147%
Turkey	38	37	155	180	206	213	239	264	279	274	259	200	160	137	214	64%	182%
United Kingdom	53	-1	47	84	110	144	168	162	165	156	125	92	57	40	113	36%	324%
USA	35	-107	208	224	260	274	272	261	239	232	244	242	214	201	239	84%	138%

Table B1: Latitude tilt radiation values (We/m²/year) for each country central reference coordinate (CRC). The last column shows the ratio between the value for the month with the lowest irradiance and the annual average, i.e., the seasonal variability (SV) factor. Minor adjustments due to cloudiness influence for Brazil and Indonesia were made to ensure that the CRC annual average irradiance is higher than the country average: we selected a different longitude associated with the CRC_{lat} with a SV difference lower than 3% compared to the most favorable longitude. $f_{overcapacity}$ refers to the overcapacity factor considered in order to deal with the intermittence of the solar resource and storage (see Section 2.3).

Appendix C: Potential electricity produced by rooftop PV

	Ert_min	**Ert_max**
	%total	
Australia	5.2%	17.4%
Austria	4.2%	13.9%
Belgium	1.2%	3.9%
Brazil	45.0%	150.2%
Bulgaria	4.4%	14.7%
Canada	2.2%	7.3%
China	8.6%	28.7%

Cyprus	3.1%	10.4%
Czech Republic	1.6%	5.5%
Denmark	1.6%	5.5%
Estonia	1.2%	4.1%
EU-27	1.9%	6.3%
Finland	0.3%	1.0%
France	1.9%	6.2%
Germany	1.4%	4.5%
Greece	2.1%	7.1%
Hungary	3.7%	12.3%
India	20.6%	68.5%
Indonesia	27.8%	92.7%
Ireland	1.1%	3.6%
Italy	2.5%	8.2%
Japan	1.4%	4.7%
South Korea	0.9%	3.1%
Latvia	5.7%	19.1%
Lithuania	3.6%	12.1%
Luxembourg	0.6%	1.9%
Malta	2.5%	8.4%
Mexico	8.9%	29.6%
Netherlands	1.0%	3.2%
Poland	2.4%	8.0%
Portugal	3.6%	12.0%
Romania	9.8%	32.5%
Russia	1.9%	6.3%
Slovakia	2.4%	7.9%
Slovenia	2.7%	9.1%
Spain	2.4%	8.1%
Sweden	1.0%	3.4%
Taiwan	2.5%	8.4%
Turkey	5.9%	19.7%
United Kingdom	1.0%	3.4%
USA	2.6%	8.8%

Table C1: Rooftop PV production per country as a share of the electricity use minus the hydroelectricity production.

Appendix D: Share of electricity consumption covered by hydro generation

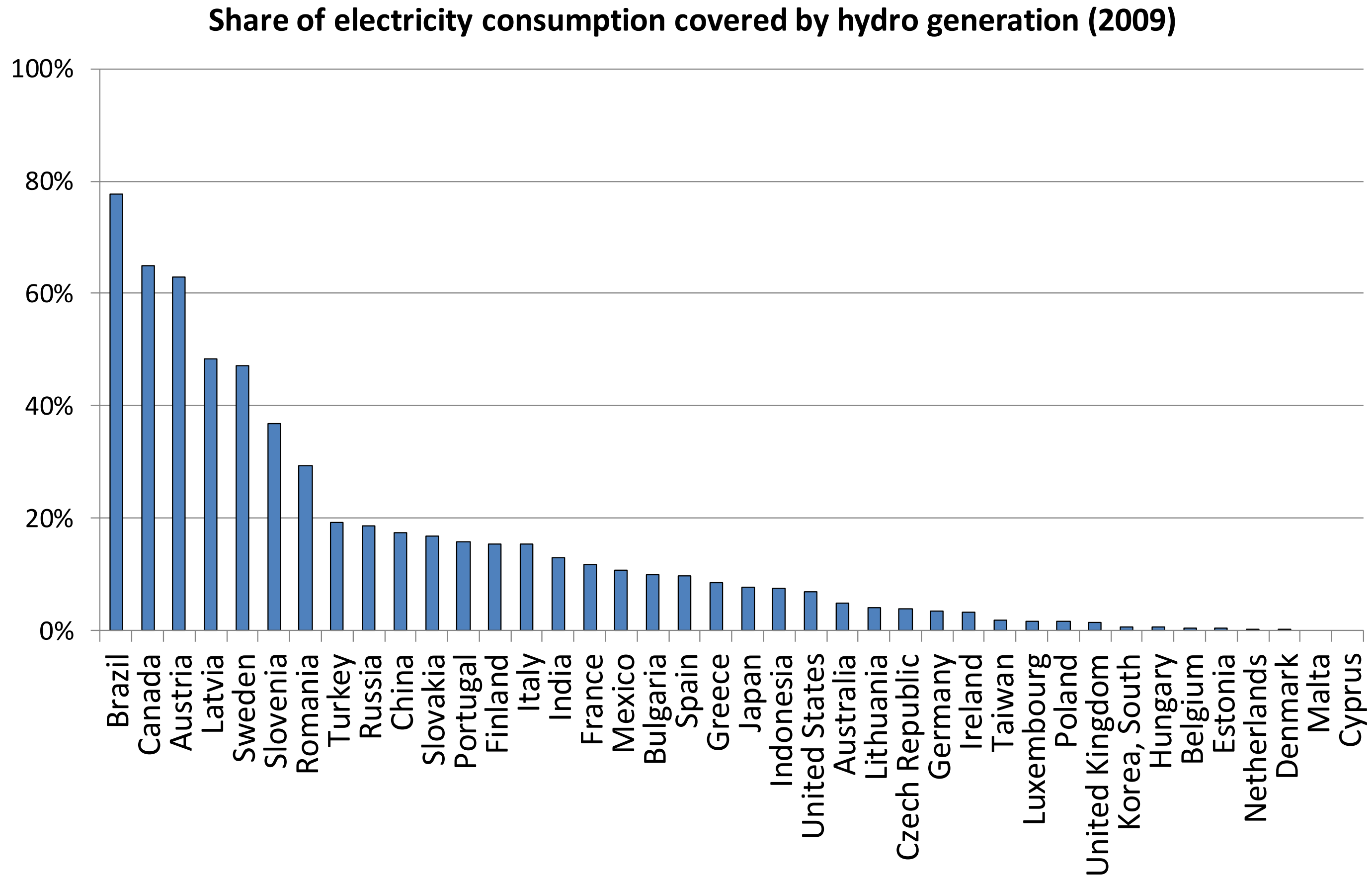

Figure D1: Share of electricity consumption covered by hydro generation by country in 2009 (US EIA db, 2015).

Appendix E: Total land and land per capita by scenario

	Land area (km^2)				**Land per capita (m^2/person)**			
	Elec-use	Elec-F	Total land	Built-up area	Elec-use	Elec-F	Total land	Built-up area
Australia	3,638 ± 1,140	3,837 ± 1,202	7,609,834	11,299	168 ± 53	177 ± 55	354,159	521
Austria	1,402 ± 420	2,078 ± 622	82,161	2,268	168 ± 50	249 ± 75	9,877	272
Belgium	9,054 ± 2,382	9,835 ± 2,587	30,061	3,879	839 ± 221	911 ± 240	2,805	359
Brazil	700 ± 700	705 ± 705	8,222,763	49,313	4 ± 4	4 ± 4	43,197	255
Bulgaria	1,531 ± 463	1,326 ± 401	107,975	2,635	206 ± 62	178 ± 54	14,583	354
Canada	19,998 ± 5,497	18,052 ± 4,962	8,032,228	12,221	595 ± 163	537 ± 148	270,410	363
China	72,209 ± 26,146	54,287 ± 19,656	9,338,610	265,005	54 ± 20	41 ± 15	7,080	199
Cyprus	155 ± 44	215 ± 62	8,318	184	142 ± 41	197 ± 57	8,473	169
Czech Republic	5,241 ± 1,407	4,963 ± 1,332	77,223	3,166	502 ± 135	475 ± 128	7,397	303
Denmark	4,698 ± 1,261	6,324 ± 1,698	37,223	2,128	851 ± 228	1,145 ± 307	7,682	385
Estonia	2,575 ± 679	2,327 ± 613	38,591	573	1,929 ± 509	1,743 ± 460	31,764	430
EU-27	302,221 ± 80,518	327,999 ± 87,547	4,039,667	141,887	605 ± 161	656 ± 175	8,373	284

Finland	38,273 ± 9,689	33,924 ± 8,588	278,053	1,974	7,169 ± 1,815	6,354 ± 1,609	56,922	370
France	26,372 ± 7,147	30,670 ± 8,312	539,687	18,134	408 ± 110	474 ± 128	8,463	280
Germany	52,369 ± 13,894	57,727 ± 15,316	344,330	26,270	639 ± 170	705 ± 187	4,256	321
Greece	2,751 ± 755	3,826 ± 1,050	114,916	2,199	246 ± 67	342 ± 94	11,522	197
Hungary	2,907 ± 853	3,164 ± 929	89,978	4,136	290 ± 85	316 ± 93	9,033	413
India	11,481 ± 7,069	11,454 ± 7,053	2,909,644	206,231	10 ± 6	10 ± 6	2,498	173
Indonesia	1,283 ± 1,136	1,494 ± 1,322	1,705,727	40,029	5 ± 5	6 ± 6	7,628	169
Ireland	4,409 ± 1,155	5,721 ± 1,498	63,581	1,289	972 ± 255	1,261 ± 330	15,189	284
Italy	13,998 ± 3,893	17,063 ± 4,745	283,927	12,887	237 ± 66	289 ± 80	4,977	218
Japan	34,031 ± 9,050	37,145 ± 9,878	338,211	17,741	266 ± 71	290 ± 77	2,847	139
South Korea	14,539 ± 3,786	12,128 ± 3,158	89,621	4,960	296 ± 77	247 ± 64	1,974	101
Latvia	762 ± 244	1,121 ± 359	60,857	873	356 ± 114	524 ± 168	29,033	408
Lithuania	1,351 ± 396	1,656 ± 485	62,217	1,418	427 ± 125	523 ± 153	19,816	448
Luxembourg	659 ± 169	641 ± 164	2,590	137	1,324 ± 339	1,287 ± 330	5,203	276
Malta	65 ± 18	78 ± 22	165	62	157 ± 44	188 ± 52	776	150
Mexico	3,329 ± 1,219	3,575 ± 1,309	1,906,300	19,018	29 ± 10	31 ± 11	16,697	163
Netherlands	16,595 ± 4,328	19,047 ± 4,968	31,687	4,408	1,004 ± 262	1,152 ± 301	2,040	267
Poland	16,923 ± 4,693	17,305 ± 4,799	304,164	11,358	444 ± 123	454 ± 126	8,028	298
Portugal	1,718 ± 502	1,985 ± 580	89,322	2,381	163 ± 48	188 ± 55	8,667	225
Romania	1,732 ± 659	1,902 ± 724	228,614	7,410	85 ± 32	93 ± 36	11,295	364
Russia	91,315 ± 24,777	64,517 ± 17,506	15,964,790	47,848	643 ± 175	455 ± 123	115,404	337
Slovakia	1,779 ± 493	1,874 ± 519	48,063	1,581	330 ± 92	348 ± 96	8,928	293
Slovenia	530 ± 149	554 ± 156	20,072	546	260 ± 73	272 ± 76	9,874	268
Spain	9,383 ± 2,608	10,663 ± 2,964	488,354	8,588	202 ± 56	230 ± 64	10,759	185
Sweden	26,022 ± 6,799	19,808 ± 5,175	383,445	4,805	2,798 ± 731	2,130 ± 557	44,130	517
Taiwan	4,824 ± 1,345	3,227 ± 900	35,410	6,829	209 ± 58	140 ± 39	1,532	295
Turkey	5,746 ± 1,854	5,954 ± 1,921	753,637	13,664	81 ± 26	84 ± 27	10,803	192
United Kingdom	58,967 ± 15,418	72,206 ± 18,879	224,095	16,596	947 ± 248	1,159 ± 303	3,885	266
USA	132,026 ± 37,005	144,969 ± 40,633	8,896,353	130,919	430 ± 121	473 ± 132	29,818	427

Table E1: Land area (km^2) and land per capita (m^2/person) for each WIOD country for: electricity use, electricity footprint, total land and built-up area. 100% solar electricity mix scenario.

	Land area (km^2)				Land per capita (m^2/person)			
	Elec-use	Elec-F	Total land	Built-up area	Elec-use	Elec-F	Total land	Built-up area
Australia	17,499 ± 4,605	20,306 ± 5,343	7,609,834	11,299	807 ± 212	936 ± 246	354,159	521
Austria	19,815 ± 5,023	24,950 ± 6,325	82,161	2,268	2,375 ± 602	2,990 ± 758	9,877	272
Belgium	58,863 ± 14,834	55,133 ± 13,894	30,061	3,879	5,452 ± 1,374	5,107 ± 1,287	2,805	359
Brazil	38,369 ± 10,596	38,739 ± 10,699	8,222,763	49,313	198 ± 55	200 ± 55	43,197	255
Bulgaria	5,375 ± 1,424	5,395 ± 1,429	107,975	2,635	722 ± 191	725 ± 192	14,583	354
Canada	233,732 ± 58,931	221,384 ± 55,817	8,032,228	12,221	6,950 ± 1,752	6,583 ± 1,660	270,410	363
China	513,445 ± 136,455	436,849 ± 116,098	9,338,610	265,005	386 ± 103	328 ± 87	7,080	199
Cyprus	808 ± 208	1,060 ± 272	8,318	184	741 ± 190	972 ± 250	8,473	169
Czech Republic	27,109 ± 6,874	25,594 ± 6,490	77,223	3,166	2,596 ± 658	2,451 ± 621	7,397	303
Denmark	41,584 ± 10,483	37,058 ± 9,342	37,223	2,128	7,529 ± 1,898	6,710 ± 1,691	7,682	385
Estonia	11,469 ± 2,902	11,513 ± 2,914	38,591	573	8,594 ± 2,175	8,627 ± 2,183	31,764	430
EU-27	1,649,098 ± 417,238	1,836,022 ± 464,704	4,039,667	141,887	3,300 ± 835	3,674 ± 930	8,373	284
Finland	172,195 ± 43,169	164,913 ± 41,344	278,053	1,974	32,253 ±	30,889 ±	56,922	370

					8,086	7,744		
France	115,289 ± 29,376	150,786 ± 38,421	539,687	18,134	1,782 ± 454	2,330 ± 594	8,463	280
Germany	295,588 ± 74,699	346,026 ± 87,446	344,330	26,270	3,609 ± 912	4,225 ± 1,068	4,256	321
Greece	15,151 ± 3,855	18,422 ± 4,687	114,916	2,199	1,354 ± 345	1,647 ± 419	11,522	197
Hungary	16,841 ± 4,336	18,170 ± 4,679	89,978	4,136	1,680 ± 433	1,813 ± 467	9,033	413
India	110,934 ± 31,932	114,193 ± 32,871	2,909,644	206,231	93 ± 27	96 ± 28	2,498	173
Indonesia	32,005 ± 8,816	32,234 ± 8,879	1,705,727	40,029	135 ± 37	136 ± 37	7,628	169
Ireland	26,055 ± 6,566	33,250 ± 8,379	63,581	1,289	5,745 ± 1,448	7,331 ± 1,848	15,189	284
Italy	81,310 ± 20,721	104,987 ± 26,755	283,927	12,887	1,376 ± 351	1,777 ± 453	4,977	218
Japan	156,828 ± 39,749	173,939 ± 44,086	338,211	17,741	1,225 ± 310	1,358 ± 344	2,847	139
South Korea	68,680 ± 17,321	54,226 ± 13,676	89,621	4,960	1,396 ± 352	1,103 ± 278	1,974	101
Latvia	9,748 ± 2,490	12,071 ± 3,084	60,857	873	4,552 ± 1,163	5,636 ± 1,440	29,033	408
Lithuania	8,640 ± 2,218	10,136 ± 2,602	62,217	1,418	2,732 ± 701	3,205 ± 823	19,816	448
Luxembourg	6,183 ± 1,550	4,642 ± 1,164	2,590	137	12,422 ± 3,114	9,326 ± 2,338	5,203	276
Malta	391 ± 100	312 ± 80	165	62	949 ± 242	758 ± 193	776	150
Mexico	26,782 ± 7,083	28,759 ± 7,605	1,906,300	19,018	230 ± 61	247 ± 65	16,697	163
Netherlands	124,808 ± 31,382	107,570 ± 27,047	31,687	4,408	7,550 ± 1,898	6,507 ± 1,636	2,040	267
Poland	98,715 ± 25,141	99,048 ± 25,226	304,164	11,358	2,587 ± 659	2,596 ± 661	8,028	298
Portugal	9,557 ± 2,462	10,712 ± 2,759	89,322	2,381	904 ± 233	1,014 ± 261	8,667	225
Romania	14,279 ± 3,796	16,494 ± 4,385	228,614	7,410	701 ± 186	810 ± 215	11,295	364
Russia	677,796 ± 171,397	526,625 ± 133,170	15,964,790	47,848	4,776 ± 1,208	3,711 ± 938	115,404	337
Slovakia	11,285 ± 2,870	11,670 ± 2,968	48,063	1,581	2,095 ± 533	2,167 ± 551	8,928	293
Slovenia	3,369 ± 859	4,303 ± 1,097	20,072	546	1,652 ± 421	2,110 ± 538	9,874	268
Spain	45,224 ± 11,568	55,660 ± 14,238	488,354	8,588	975 ± 250	1,201 ± 307	10,759	185
Sweden	129,493 ± 32,667	131,685 ± 33,220	383,445	4,805	13,926 ± 3,513	14,162 ± 3,573	44,130	517
Taiwan	23,169 ± 5,931	14,142 ± 3,620	35,410	6,829	1,002 ± 257	612 ± 157	1,532	295
Turkey	38,290 ± 9,990	43,906 ± 11,455	753,637	13,664	537 ± 140	616 ± 161	10,803	192
United Kingdom	299,953 ± 75,664	374,462 ± 94,459	224,095	16,596	4,816 ± 1,215	6,013 ± 1,517	3,885	266
USA	637,851 ± 163,461	708,860 ± 181,659	8,896,353	130,919	2,079 ± 533	2,311 ± 592	29,818	427

Table E2: Land area (km^2) and land per capita (m^2/person) for each WIOD country for: electricity use, electricity footprint, total land and built-up area. 100% solar final energy mix scenario.

Appendix D: Land availability at country level

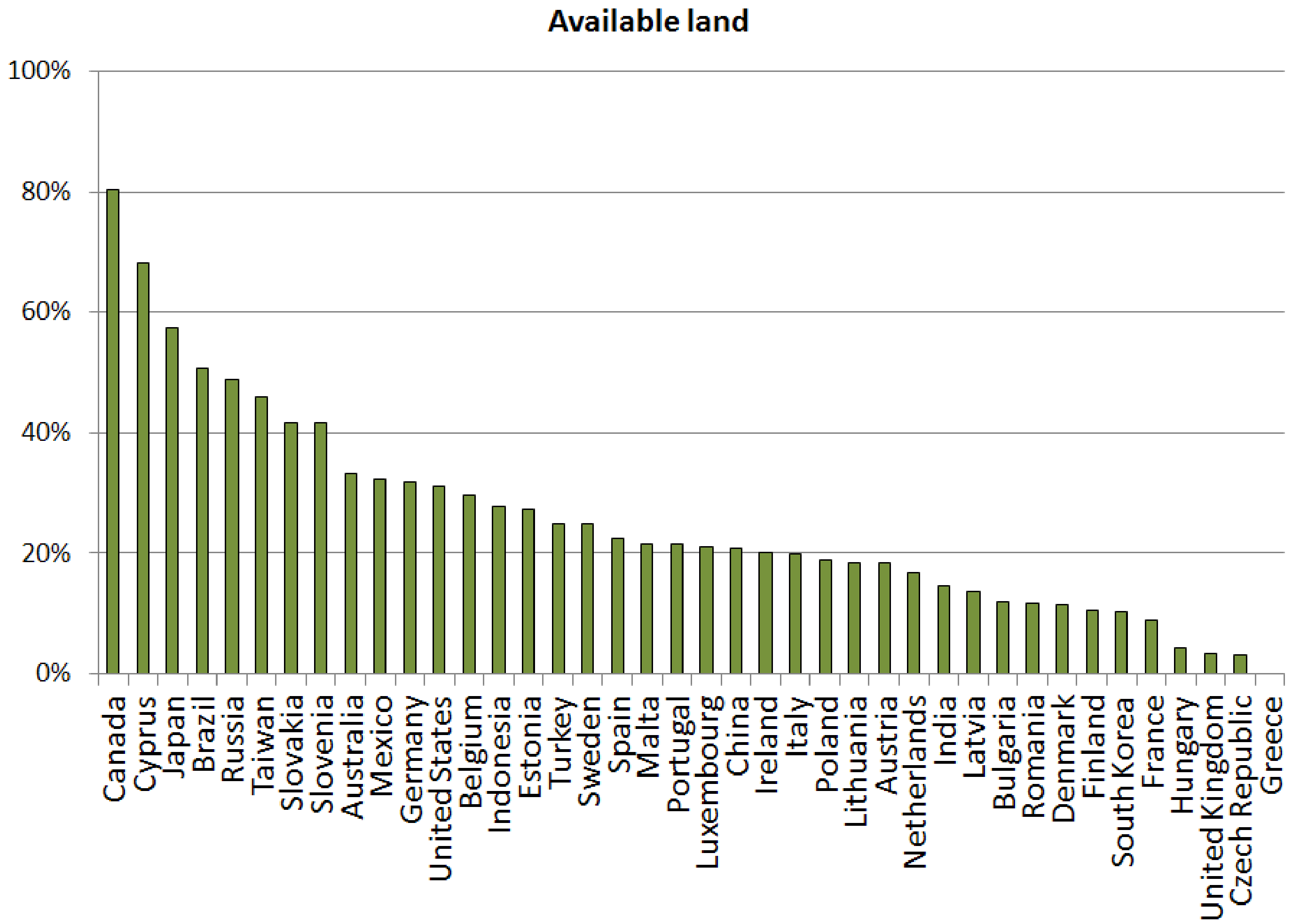

Figure D1: Land availability at country level as defined in Section 3.1.

References

Alston, J.M., Beddow, J.M., Pardey, P.G., 2009. Agricultural Research, Productivity, and Food Prices in the Long Run. Science 325, 1209–1210. doi:10.1126/science.1170451

Armaroli, N., Balzani, V., 2011. Towards an electricity-powered world. Energy Environ. Sci. 4, 3193–3222. doi:10.1039/C1EE01249E

Arto, I., Capellán-Pérez, I., Lago, R., Bueno, G., Bermejo, R., 2016. The energy requirements of a developed world. Energy Sustain. Dev. 33, 1–13. doi:10.1016/j.esd.2016.04.001

Arto, I., Genty, A., Rueda-Cantuche, J.M., Villanueva, Andreoni, V., 2012. Global Resources Use and Pollution: Vol. I, Production, Consumption and Trade (1995-2008). Institute for Prospective and Technological Studies, Joint Research Centre.

Baiocchi, G., Minx, J.C., 2010. Understanding changes in the UK's CO2 emissions: a global perspective. Environ. Sci. Technol. 44, 1177–1184. doi:10.1021/es902662h

Bergamasco, L., Asinari, P., 2011. Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surface area: Application to Piedmont Region (Italy). Sol. Energy 85, 1041–1055. doi:10.1016/j.solener.2011.02.022

Bocca, A., Chiavazzo, E., Macii, A., Asinari, P., 2015. Solar energy potential assessment: An overview and a fast modeling approach with application to Italy. Renew. Sustain. Energy Rev. 49, 291–296. doi:10.1016/j.rser.2015.04.138

Breyer, C., Bogdanov, D., Komoto, K., Ehara, T., Song, J., Enebish, N., 2015. North-east Asian super grid: renewable energy mix and economics. Jpn. J. Appl. Phys. 54, 08KJ01.

Briner, G., 2009. The climate change mitigation potential of the solar PV industry: a life cycle perspective. M Sc thesis, Centre for Environmental Policy, Imperial College London, London, UK.

Brower, M., Barton, M., Lledó, L., Dubois, J., 2013. A study of wind speed variability using global reanalysis data. AWS Truepower.

Byrne, J., Taminiau, J., Kurdgelashvili, L., Kim, K.N., 2015. A review of the solar city concept and methods to assess rooftop solar electric potential, with an illustrative application to the city of Seoul. Renew. Sustain. Energy Rev. 41, 830–844. doi:10.1016/j.rser.2014.08.023

Cansino, J.M., Pablo-Romero, M. del P., Román, R., Yñiguez, R., 2011. Taxes incentives to promote res deployment: the Eu-27 case, in: Sustainable Growth and Applications in Renewable Energy Sources. INTECH Open Access Publisher.

Connolly, D., Lund, H., Mathiesen, B.V., Leahy, M., 2011. The first step towards a 100% renewable energy-system for Ireland. Appl. Energy, The 5th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems, held in Dubrovnik September/October 2009 88, 502–507. doi:10.1016/j.apenergy.2010.03.006

Daly, H.E., 2005. Economics In A Full World. Sci. Am. 293, 100–107. doi:10.1038/scientificamerican0905-100

de Castro, C., Carpintero, Ó., Frechoso, F., Mediavilla, M., de Miguel, L.J., 2014. A top-down approach to assess physical and ecological limits of biofuels. Energy 64, 506–512. doi:10.1016/j.energy.2013.10.049

de Castro, C., Mediavilla, M., Miguel, L.J., Frechoso, F., 2013. Global solar electric potential: A review of their technical and sustainable limits. Renew. Sustain. Energy Rev. 28, 824–835. doi:10.1016/j.rser.2013.08.040

de Castro, C., Mediavilla, M., Miguel, L.J., Frechoso, F., 2011. Global wind power potential: Physical and technological limits. Energy Policy 39, 6677–6682. doi:10.1016/j.enpol.2011.06.027

Defaix, P.R., van Sark, W.G.J.H.M., Worrell, E., de Visser, E., 2012. Technical potential for photovoltaics on buildings in the EU-27. Sol. Energy 86, 2644–2653. doi:10.1016/j.solener.2012.06.007

Deng, Y.Y., Haigh, M., Pouwels, W., Ramaekers, L., Brandsma, R., Schimschar, S., Grözinger, J., de Jager, D., 2015. Quantifying a realistic, worldwide wind and solar electricity supply. Glob. Environ. Change 31, 239–252. doi:10.1016/j.gloenvcha.2015.01.005

Denholm, P., Kulcinski, G.L., 2004. Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. Energy Convers. Manag. 45, 2153–2172. doi:10.1016/j.enconman.2003.10.014

Denholm, P., Margolis, R.M., 2008. Land-use requirements and the per-capita solar footprint for photovoltaic generation in the United States. Energy Policy 36, 3531–3543. doi:10.1016/j.enpol.2008.05.035

DESERTEC, 2003. The DESERTEC project [WWW Document]. URL http://www.desertec.org/ (accessed 10.25.15).

Deutsche Bank, 2015. Deutsche Bank Markets Research. Solar 2015 Outlook.

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., de Vries, G., 2013. The Construction of World Input–Output Tables in the Wiod Project. Econ. Syst. Res. 25, 71–98. doi:10.1080/09535314.2012.761180

European Commission, 2014. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A policy framework for climate and energy in the period from 2020 to 2030 /* COM/2014/015 final */.

FAO/IIASA, 2011. Global Agro-ecological Zones (GAEZ v3.0). FAO Rome and IIASA Laxemburg, Italy and Austria.

FAOSTAT, 2015. Statistics Division of the FAO. Food and Agriculture Organization of the United Nations, Rome (Italy).

Farthing, A., Carbajales-Dale, M., Mason, S., Carbajales-Dale, P., Matta, P., 2016. Utility-Scale Solar PV in South Carolina: Analysis of Suitable Lands and Geographical Potential. Biophys. Econ. Resour. Qual. 1, 8. doi:10.1007/s41247-016-0009-5

François, B., Hingray, B., Raynaud, D., Borga, M., Creutin, J.D., 2016. Increasing climate-related-energy penetration by integrating run-of-the river hydropower to wind/solar mix. Renew. Energy 87, Part 1, 686–696. doi:10.1016/j.renene.2015.10.064

Fthenakis, V., Kim, H.C., 2009. Land use and electricity generation: A life-cycle analysis. Renew. Sustain. Energy Rev. 13, 1465–1474. doi:10.1016/j.rser.2008.09.017

García-Olivares, A., 2016. Energy for a sustainable post-carbon society. Sci. Mar. 80, 257–268. doi:10.3989/scimar.04295.12A

García-Olivares, A., Ballabrera-Poy, J., García-Ladona, E., Turiel, A., 2012. A global renewable mix with proven technologies and common materials. Energy Policy 41, 561–574. doi:10.1016/j.enpol.2011.11.018

Grassini, P., Eskridge, K.M., Cassman, K.G., 2013. Distinguishing between yield advances and yield plateaus in historical crop production trends. Nat. Commun. 4, 2918. doi:10.1038/ncomms3918

Greenpeace, GWEC, SolarPowerEurope, 2015. Energy [R] evolution-A sustainable world energy outlook 2015. Greenpeace, GWEC, SolarPowerEurope.

GSE, 2015. Rapporto Statistico "Energia da fonti rinnovabili" Anno 2013. Gestore Servizi Energetici.

Gulagi, A., Bogdanov, D., Fasihi, M., Breyer, C., 2017. Can Australia Power the Energy-Hungry Asia with Renewable Energy? Sustainability 9, 233. doi:10.3390/su9020233

Hagos, D.A., Gebremedhin, A., Zethraeus, B., rn, 2014. Solar Water Heating as a Potential Source for Inland Norway Energy Mix. J. Renew. Energy 2014, e968320. doi:10.1155/2014/968320

Hall, C.A.S., Lambert, J.G., Balogh, S.B., 2014. EROI of different fuels and the implications for society. Energy Policy 64, 141–152. doi:10.1016/j.enpol.2013.05.049

Hernandez, R.R., Hoffacker, M.K., Murphy-Mariscal, M.L., Wu, G.C., Allen, M.F., 2015. Solar energy development impacts on land cover change and protected areas. Proc. Natl. Acad. Sci. 201517656. doi:10.1073/pnas.1517656112

Horner, R.M., Clark, C.E., 2013. Characterizing variability and reducing uncertainty in estimates of solar land use energy intensity. Renew. Sustain. Energy Rev. 23, 129–137. doi:10.1016/j.rser.2013.01.014

IEA, 2016a. Energy balances statistics. IEA/OCDE.

IEA, 2016b. Global EV Outlook 2016. Beyond one million electric cars. OECD/IEA, Paris.

IEA, 2006. Barriers to Technology Diffusion: The Case of Solar Thermal Technologies (No. C/IEA/SLT(2006)9). International Energy Agency, Paris (France).

Instituto de Estadísticas de Andalucía, 2015. Instituto de Estadísticas de Andalucía. Instituto de Estadísticas de Andalucía.

IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Fifth Assess. Rep. Intergov. Panel Clim. Change.

IPCC, 2011. Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, United Kingdom and New York (USA).

ISE, 2014. Photovoltaics Report. Fraunhofer ISE.

Izquierdo, S., Montañés, C., Dopazo, C., Fueyo, N., 2011. Roof-top solar energy potential under performance-based building energy codes: The case of Spain. Sol. Energy 85, 208–213. doi:10.1016/j.solener.2010.11.003

Jacobson, M.Z., Delucchi, M.A., 2011. Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Policy 39, 1154–1169. doi:10.1016/j.enpol.2010.11.040

Jacobson, M.Z., Delucchi, M.A., Bazouin, G., Bauer, Z.A., Heavey, C.C., Fisher, E., Morris, S.B., Piekutowski, D.J., Vencill, T.A., Yeskoo, T.W., 2015. 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. Energy Environ. Sci. 8, 2093–2117.

Jo, J.H., Otanicar, T.P., 2011. A hierarchical methodology for the mesoscale assessment of building integrated roof solar energy systems. Renew. Energy 36, 2992–3000. doi:10.1016/j.renene.2011.03.038

Johansson, B., 2013. Security aspects of future renewable energy systems–A short overview. Energy 61, 598–605. doi:10.1016/j.energy.2013.09.023

Juffe-Bignoli, D., Burgess, N., Bingham, H., Belle, E., de Lima, M., Deguignet, M., Bertzky, B., Milam, A., Martinez-Lopez, J., Lewis, E., others, 2014. Protected planet report 2014. UNEP-WCMC Camb. UK.

La Gennusa, M., Lascari, G., Rizzo, G., Scaccianoce, G., Sorrentino, G., 2011. A model for predicting the potential diffusion of solar energy systems in complex urban environments. Energy Policy 39, 5335–5343. doi:10.1016/j.enpol.2011.05.031

Laborde, D., 2011. Assessing the land use change consequences of European biofuel policies. Int. Food Policy Inst. IFPRI.

Lenzen, M., 2010. Current State of Development of Electricity-Generating Technologies: A Literature Review. Energies 3, 462–591. doi:10.3390/en3030462

Li, X., Zhong, S., Bian, X., Heilman, W.E., 2010. Climate and climate variability of the wind power resources in the Great Lakes region of the United States. J. Geophys. Res. Atmospheres 115, D18107. doi:10.1029/2009JD013415

Lilliestam, J., Ellenbeck, S., 2011. Energy security and renewable electricity trade—Will Desertec make Europe vulnerable to the "energy weapon"? Energy Policy 39, 3380–3391. doi:10.1016/j.enpol.2011.03.035

Lo Piano, S., Mayumi, K., 2016. Toward an integrated assessment of the performance of photovoltaic power stations for electricity generation. Appl. Energy. doi:10.1016/j.apenergy.2016.05.102

Lund, H., Mathiesen, B.V., 2009. Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. Energy 34, 524–531.

Luque, A., Hegedus, S., 2011. Handbook of photovoltaic science and engineering. John Wiley & Sons, Chichester, West Sussex, United Kingdom.

MacKay, D.J.C., 2013. Solar energy in the context of energy use, energy transportation and energy storage. Philos. Trans. R. Soc. Lond. Math. Phys. Eng. Sci. 371, 20110431. doi:10.1098/rsta.2011.0431

Mainzer, K., Fath, K., McKenna, R., Stengel, J., Fichtner, W., Schultmann, F., 2014. A high-resolution determination of the technical potential for residential-roof-mounted photovoltaic systems in Germany. Sol. Energy 105, 715–731. doi:10.1016/j.solener.2014.04.015

MEA, 2005. Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Scenarios, Global Assessment Reports. Island Press, Washington DC (USA).

Melius, J., Margolis, R., Ong, S., 2013. Estimating Rooftop Suitability for PV: A Review of Methods, Patents, and Validation Techniques. National Renewable Energy Laboratory (NREL), Golden, CO.

Miller, L., Gans, F., Kleidon, A., 2011. Estimating maximum global land surface wind power extractability and associated climatic consequences. Earth Syst Dynam 2, 1–12.

MIT, 2015. The future of solar energy. Energy Initiative Massachusetts Institute of Technology, Cambridge (USA).

Moriarty, P., Honnery, D., 2016. Can renewable energy power the future? Energy Policy 93, 3–7. doi:10.1016/j.enpol.2016.02.051

NABCEP, 2012. Photovoltaic (PV) Installer Resource Guide v.5.3. North American Board of Certified Energy Practitioners, http://www.nabcep.org/wp-content/uploads/2012/08/NABCEP-PV-Installer-Resource-Guide-August-2012-v.5.3.pdf.

NASA SSE, 2008. NASA Surface meteorology and Solar Energy (SSE) Release 6,0 Data Set (Jan 2008). NASA, https://eosweb.larc.nasa.gov/sse/.

Nonhebel, S., 2003. Land-Use Changes Induced by Increased Use of Renewable Energy Sources, in: Dolman, A.J., Verhagen, A., Rovers, C.A. (Eds.), Global Environmental Change and Land Use. Springer Netherlands, pp. 187–202.

NREL, 2014. Dataset: Solar Resources by Class and Country. National Renewable Energy Laboratory, Golden, CO, USA.

NREL, 2012. Renewable Electricity Futures Study (Entire Report) (4 vols. No. NREL/TP-6A20-52409). National Renewable Energy Laboratory, Golden, CO, USA.

Ong, S., Campbell, C., Denholm, P., Margolis, R., Heath, G., 2013. Land-use requirements for solar power plants in the United States. Gold. CO Natl. Renew. Energy Lab.

Ordóñez, J., Jadraque, E., Alegre, J., Martínez, G., 2010. Analysis of the photovoltaic solar energy capacity of residential rooftops in Andalusia (Spain). Renew. Sustain. Energy Rev. 14, 2122–2130. doi:10.1016/j.rser.2010.01.001

Otto, S.A.C., Gernaat, D.E.H.J., Isaac, M., Lucas, P.L., van Sluisveld, M.A.E., van den Berg, M., van Vliet, J., van Vuuren, D.P., 2015. Impact of fragmented emission reduction regimes on the energy market and on CO2 emissions related to land use: A case study with China and the European Union as first movers. Technol. Forecast. Soc. Change 90, Part A, 220–229. doi:10.1016/j.techfore.2014.01.015

Paidipati, J., Frantzis, L., Sawyer, H., Kurrasch, A., 2008. Rooftop photovoltaics market penetration scenarios. National Renewable Energy Laboratory, Golden, Colorado (USA).

Prieto, P.A., Hall, C.A.S., 2013. Spain’s Photovoltaic Revolution: The Energy Return on Investment, 2013th ed. Springer.

Rao, G.L., Sastri, V.M.K., 1987. Land use and solar energy. Habitat Int. 11, 61–75. doi:10.1016/0197-3975(87)90020-8

Raskin, P., Banuri, T., Gallopín, G., Gutman, P., Hammond, A., Kates, R., Swart, R., 2002. Great Transition: The Promise and Lure of the Times Ahead. Stockholm Environment Institute.

REE, 2016. Series Estadísticas del sistema eléctrico español. Red Eléctrica de España, http://www.ree.es/es/estadisticas-del-sistema-electrico-espanol/indicadores-nacionales/series-estadisticas.

REN21, 2015. Renewables 2015. Global Status Report. REN 21, Paris.

Rogner, H.-H., Aguilera, R.F., Bertani, R., Bhattacharya, S.C., Dusseault, M.B., Gagnon, L., Haberl, H., Hoogwijk, M., Johnson, A., Rogner, M.L., Wagner, H., Yakushev, V., 2012. Chapter 7 - Energy Resources and Potentials, in:

Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 423–512.

Sands, R.D., Jones, C.A., Marshall, E., others, 2014. Global drivers of agricultural demand and supply. Econ. Res. Rep. 174.

Scheidel, A., Sorman, A.H., 2012. Energy transitions and the global land rush: Ultimate drivers and persistent consequences. Glob. Environ. Change, Global transformations, social metabolism and the dynamics of socio-environmental conflicts 22, 588–595. doi:10.1016/j.gloenvcha.2011.12.005

Schneider, A., Friedl, M.A., Potere, D., 2009. A new map of global urban extent from MODIS satellite data. Environ. Res. Lett. 4, 044003. doi:10.1088/1748-9326/4/4/044003

Smil, V., 2015. Power Density: A Key to Understanding Energy Sources and Uses. The MIT Press, Cambridge, Massachusetts.

Smil, V., 2010. Energy Transitions: History, Requirements, Prospects. Praeger, Santa Barbara, California, USA.

Smil, V., 2008. Energy in nature and society: general energetics of complex systems. MIT Press, Cambridge, Massachusetts, USA.

Smil, V., 1984. Views: On Energy and Land: Switching from fossil fuels to renewable energy will change our patterns of land use. Am. Sci. 72, 15–21.

Smith, P., Gregory, P.J., Vuuren, D. van, Obersteiner, M., Havlík, P., Rounsevell, M., Woods, J., Stehfest, E., Bellarby, J., 2010. Competition for land. Philos. Trans. R. Soc. B Biol. Sci. 365, 2941–2957. doi:10.1098/rstb.2010.0127

Sorensen, B., 1999. Long-term scenarios for global energy demand and supply: four global greenhouse mitigation scenarios (No. 359). Roskilde Universitet, Roskilde, Denmark.

Soulé, M.E., Sanjayan, M.A., 1998. ECOLOGY: Conservation Targets: Do They Help? Science 279, 2060–2061. doi:10.1126/science.279.5359.2060

Squatrito, R., Sgroi, F., Tudisca, S., Trapani, A.M.D., Testa, R., 2014. Post feed-in scheme photovoltaic system feasibility evaluation in Italy: Sicilian case studies. Energies 7, 7147–7165.

Šúri, M., Huld, T.A., Dunlop, E.D., Ossenbrink, H.A., 2007. Potential of solar electricity generation in the European Union member states and candidate countries. Sol. Energy 81, 1295–1305. doi:10.1016/j.solener.2006.12.007

Trainer, T., 2013a. Can Europe run on renewable energy? A negative case. Energy Policy 63, 845–850. doi:10.1016/j.enpol.2013.09.027

Trainer, T., 2013b. Can the world run on renewable energy? A revised negative case. Humanomics 29, 88–104. doi:10.1108/08288661311319166

Trainer, T., 2012. A critique of Jacobson and Delucchi’s proposals for a world renewable energy supply. Energy Policy 44, 476–481. doi:10.1016/j.enpol.2011.09.037

Trainer, T., 2010. Can renewables etc. solve the greenhouse problem? The negative case. Energy Policy 38, 4107–4114. doi:10.1016/j.enpol.2010.03.037

Turner, J.A., 1999. A Realizable Renewable Energy Future. Science 285, 687–689. doi:10.1126/science.285.5428.687

UN, 2015. World Population Prospects: The 2015 Revision. United Nations, Department of Economic and Social Affairs Population Division. ST/ESA/SER.A/313.

UN Comtrade, 2015. UN Comtrade Database.

US ACT, 2007. Energy Independence and Security Act of 2007 (No. PUBLIC LAW 110–140—DEC. 19, 2007).

US EIA db, 2015. International Energy Statistics (Database). US Energy Information Administration, http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm.

Vačkář, D., 2012. Ecological Footprint, environmental performance and biodiversity: A cross-national comparison. Ecol. Indic., The State of the Art in Ecological Footprint: Theory and Applications 16, 40–46. doi:10.1016/j.ecolind.2011.08.008

Valin, H., Peters, D., van den Berg, M., Frank, S., Havlik, P., Forsell, N., Hamelinck, C., Pirker, J., Mosnier, A., Balkovic, J., others, 2015. The land use change impact of biofuels consumed in the EU: Quantification of area and greenhouse gas impacts.

Wackernagel, M., Schulz, N.B., Deumling, D., Linares, A.C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., Randers, J., 2002. Tracking the ecological overshoot of the human economy. Proc. Natl. Acad. Sci. 99, 9266–9271. doi:10.1073/pnas.142033699

Wagner, F., 2014. Considerations for an EU-wide use of renewable energies for electricity generation. Eur. Phys. J. Plus 129, 1–14. doi:10.1140/epjp/i2014-14219-7

Ward, D.J., Inderwildi, O.R., 2012. Global and local impacts of UK renewable energy policy. Energy Environ. Sci. 6, 18–24. doi:10.1039/C2EE22342B

WCED, 1987. Our common future (Report of the World Commission on Environment and Development). United Nations.

Weber, C.L., 2009. Measuring structural change and energy use: Decomposition of the US economy from 1997 to 2002. Energy Policy 37, 1561–1570. doi:10.1016/j.enpol.2008.12.027

Weitemeyer, S., Kleinhans, D., Vogt, T., Agert, C., 2015. Integration of Renewable Energy Sources in future power systems: The role of storage. Renew. Energy 75, 14–20. doi:10.1016/j.renene.2014.09.028

WEO, 2014. World Energy Outlook 2014. OECD / IEA, Paris.

Wiginton, L.K., Nguyen, H.T., Pearce, J.M., 2010. Quantifying rooftop solar photovoltaic potential for regional renewable energy policy. Comput. Environ. Urban Syst., Geospatial Cyberinfrastructure 34, 345–357. doi:10.1016/j.compenvurbsys.2010.01.001

Wirth, H., 2015. Recent facts about photovoltaics in Germany. Fraunhofer Institute for Solar Energy Systems, Germany.

WWF, 2011. The energy report: 100% renewable energy by 2050. WWF, Ecofys, OMA.