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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.

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 [44,51,81,113]. Among renewables, wind and solar are estimated to have the greatest potential [16,45,87], with projections often assuming that the resource base provides no practical limitation if adequate investments are forthcoming (e.g., [45]).

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 [86]. Hence, for delivering the same power, RES are substantially more land intensive. 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 [15,61,86]. 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 [47,53,74,91].

Hence, the transition to RES will add to the pressure in the global competition for land, which is already driven by many factors [90]. In

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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 [23,81]. Thus, this transition could aggravate existing vulnerabilities and create new ones in terms of energy security, biodiversity loss, and food sovereignty, among others [51,61,70,78,84,89]. 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 led to the ban of incentives for this technology on agricultural soil [93].

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., [48,116,49,95,31]), 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., [61]). 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 [16,45].

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 [21] for the states of the USA and Šúri et al. [94] 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 [21,61,66,94,100], and by Jacobson and Delucchi [48] at a global level, while other studies have focused on comparisons with other energy technologies [30]. 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, Šúri et al. [94] 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 [21] 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 [61,96,98,99].
- The real land occupation of solar technologies is five to ten times higher than the estimates usually considered, which are based on ideal conditions [16,61,73,86].

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 [15,61,86]. 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 [2,88]. In the period 1990–2007, 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 [113]. 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 [111,5]. This shift of economic activities between countries has also had consequences in terms of energy use. Arto et al. [3] 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 [24].

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 [113]. 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” [61]. 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 [51,57,67,97].

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:

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

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 [111,5]. 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 [24], 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. [3]. 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 [40]. 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 Fig. 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 MW h/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 MW h/person/year, with differences between the electricity footprint and 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 (Fig. 1a).

In relation to per capita final energy consumption, similar trends can be observed (Fig. 1b). The advanced capitalist economies consume over 20 MW h/person/year, while emerging and developing economies consume below the world average of 16 MW h/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 [3].

2.2. Solar power density at country level (ρ_e^i)

The net solar power density per country i (ρ_e^i) is estimated following the top-down approach from de Castro et al. [16] and Smil [86]. 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:

$$\rho_e^i = I^i \cdot f_1 \cdot f_2^i \cdot f_3^i \quad (2)$$

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 [15,20]. 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 [16,60,61]. 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 [16,73,86]. 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 [19,38]. 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 [69] (latitude tilt radiation, 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

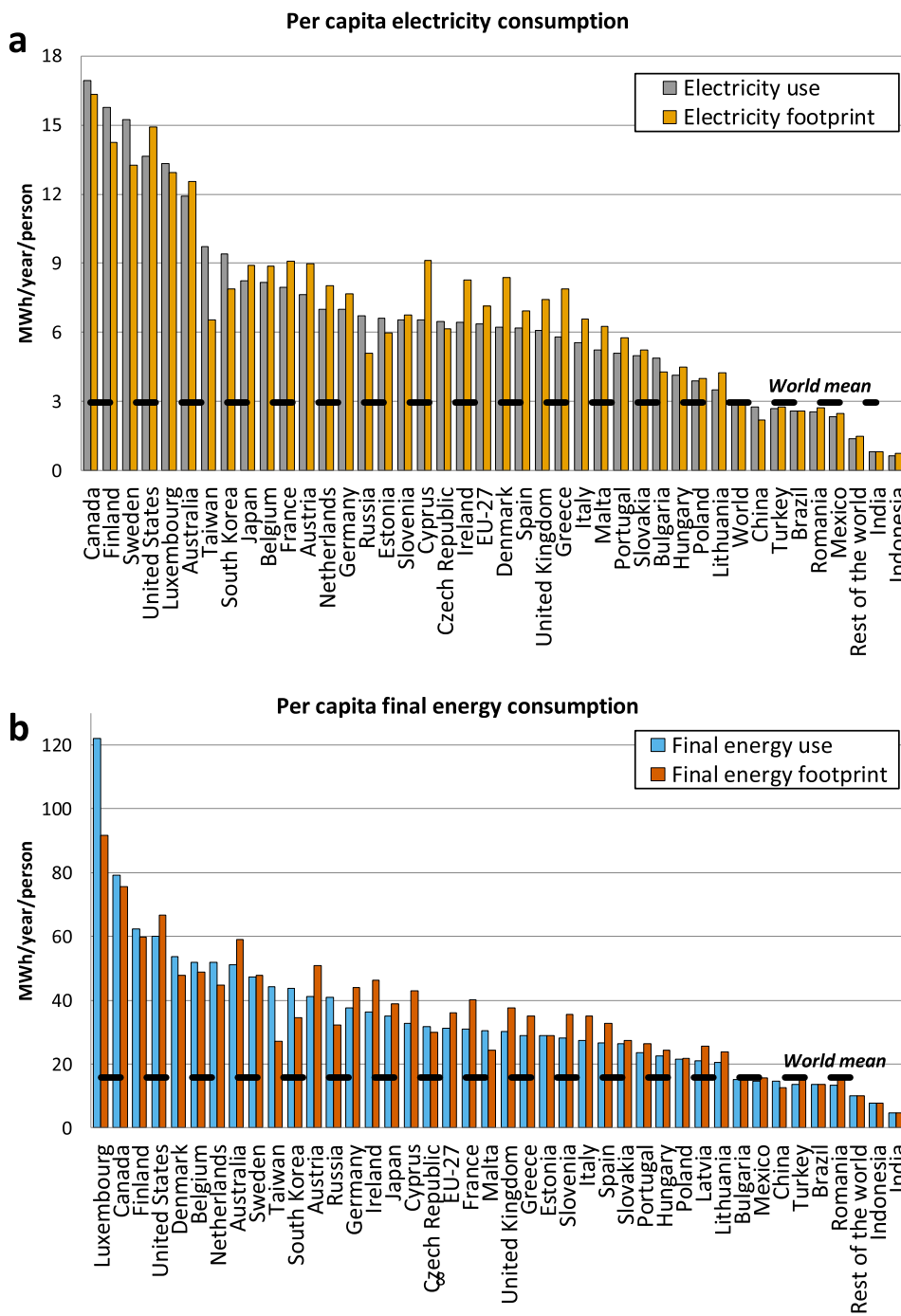


Fig. 1. (a) Per capita electricity use (in white) and footprint (in red), and (b) per capita final energy use (in white) and footprint (in blue); both in MWh/person/year by country (decreasing order) for 2009. The world mean is depicted by a dotted black line. For the numbers, see Table A1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

obtained can be seen in Table 1. This table also reports the coefficient of variation¹ (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%).

2.2.2. Cell efficiency conversion (f_1)

Current average efficiencies from single and polycrystalline silicon

¹ CV is a standardized measure of dispersion of a frequency distribution. It is the ratio between the standard deviation and the average.

cells are between 10% and 12% [16,86]. The best current research cell efficiencies under standard test conditions (STC)² 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 [86]. Although future technologies will improve on current efficiencies, it is unclear whether future parks will increase average efficiencies

² 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 1kW/m² of insolation power of a certain standard spectrum (corresponding to bright sunlight) while the cell temperature is fixed at 25°C and air mass at 1.5 spectrum). An array of modules is rated by summing up the watts peak of all the modules [60].

Table 1

Estimates of the annual average solar irradiance and coefficient of variation (CV) for the countries in the WIOD database from NREL [71]. 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).

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%
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%

beyond 20%. For example, thin film technologies (currently representing roughly 10% of the share [46]) might lead the way in the future due to their economic advantage [61]. 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 [60].

Further, material constraints might emerge at significant solar power deployment levels (e.g., copper, silver) [16,32]. 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 15–25% to be a plausible range for the future average cell efficiency conversion of installed PV capacity [16]. At the lower limit, simpler and cheaper technologies such as thin-film or amorphous silicon would 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 [81].

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 [16,60]. 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. [16] estimated a PR value of 0.67. Prieto and Hall [77] 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 [60] 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.³ 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 Fig. 2 in de Castro et al. [16]). For multi-row commercial systems, row-to-row shading is inevitable, but designers have the ability to choose array geometry to 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 Fig 2) [60]. 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

³ 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% [60].

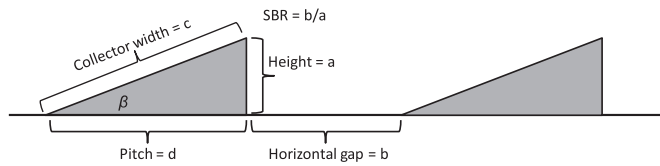


Fig. 2. Row spacing geometry with module facing to the left at tilt angle β . Adapted from Luque and Hegedus [58].

Table 2
Land-occupation factors from de Castro et al. [16] from locations that lie between the parallels 23.5° and 51°.

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 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. f_3 from the geographical region Temperate 1 as the reference.
Source: NABCEP [68].

Geographical region	SBR	f_3
Tropics	< 23.5°	0.34
Temperate1	23.5° < x < 51°	0.23
Temperate2	51° < x < 56°	0.17
Temperate3	> 56°	0.11

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. [16] (see Table 2).

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 ([68], 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).⁴

Table 4 summarizes the estimates of the likely ranges of the parameters f_1 , f_2 and f_3 , and Fig. 3 shows the estimated range of solar power density by WIOD country applying Eq. (2). The whole range is 1.1–12.1 $W_e/m^2/year$ (Fig. 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

⁴ The results from de Castro et al. [16] 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 the infrastructure in the field (and sometimes the shape of the field itself (see, for example, the Olmedilla plant in [16]) are found to be critical to maximize the solar power density of each plant.

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.

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 Rest	0.60 0.65
f_3	Ad	Land-occupation ratio	Tropics Temperate 1 Temperate 2 Temperate 3	0.34 0.23 0.17 0.11

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 $W_e/m^2/year$).

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 [86] 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. [16] and Ong et al. [73] 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. [73] 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 requirements⁵ 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 [21], 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. [73]. 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 the other hand, only 15% of the projects analyzed by Ong et al. [73] 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 [16].⁶

In terms of land use energy intensity (the inverse of ρ_e), our equivalent range is 9.4–99.8 $m^2/yr/MW$ h. 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 [39]. However, this review only included one study at typical Scandinavian solar irradiance (see Ref. [5] in Horner and Clark [39]) without taking into account the additional shadowing in these latitudes ($f_3=0.33$).

⁵ 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.

⁶ 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 $W_e/m^2/year$, which are all values lower than the reported average (8.3 $W_e/m^2/year$).

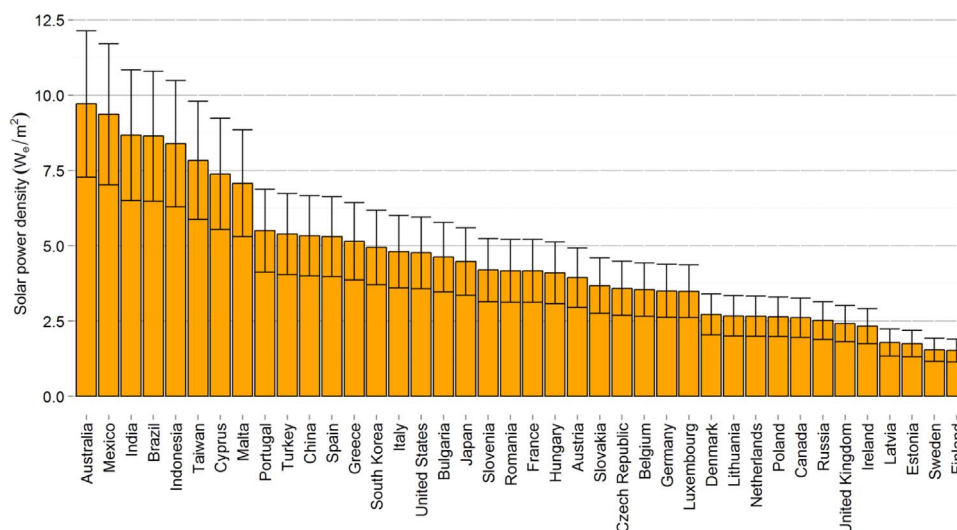


Fig. 3. Estimated average solar power density per country ($W_e/m^2/year$) considering uncertainty in the efficiency of future PV modules and specific geographical characteristics..

2.3. 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 [2,55]. 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 [21]. Although electric batteries might also address the short-term variability,⁷ 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 [2]. 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 Eq. (8)), i.e., a round-trip storage efficiency of 75% [20,21,61]. 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., [108], 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 [21] 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 [98]. For example, MacKay [61] 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 [96] estimated for Europe that generation from pumped storage would have to be scaled up by a factor approaching 20.⁸ 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 [80].

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 [86,98]. 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% [69]. 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.⁹ 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., [21,94], 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 [98,99].

Apart from hydro pumping storage, 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 [108]. 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.¹⁰ This process consists of the following steps:

- 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”,

⁷ In particular, electric cars may act as storage devices. The IEA [41] estimates that “125,000 cars could be equivalent to 300MW of flexibility – a medium size pump storage plant or a successful stationary demand side response program”.

⁸ However, the identified total technical potential for hydropower in Europe only doubles current installed capacity [45].

⁹ <http://www.solarwirtschaft.de/en/photovoltaic-market.html>.

¹⁰ 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.

- CRCⁱ) with longitude CRC_{lg}ⁱ and latitude CRC_{lat}ⁱ.
- b) CRC_{lat}ⁱ was taken at approximately¹¹ +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 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, 1/2, 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 [73], 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).¹² 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):

$$f_{\text{overcapacity}}^i = \frac{1 + X_{\text{stor}}^f}{SV^i} \quad (3)$$

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. [112] 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.¹³

Fig. 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 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.

¹¹ 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.

¹² 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 [80]).

¹³ 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" [112].

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/m² to below 200 W_e/m².

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 Eq. (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 [96].

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.¹⁴ Studies that evaluate this potential at a regional or country level are very common in the literature (e.g., [11,114,47,50,53,6,74,76]). 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 [64]. 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 [62,64].

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 [53,91], since existing urban and architectural designs were not conceived to incorporate solar modules and are poorly compatible with them. Ordóñez et al. [74] 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 [43]). 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

¹⁴ Other studies such as that of Šúri et al. [94] did not consider the land-use requirements for solar plants by assuming a priori that all the PV power would be roof-mounted panels.

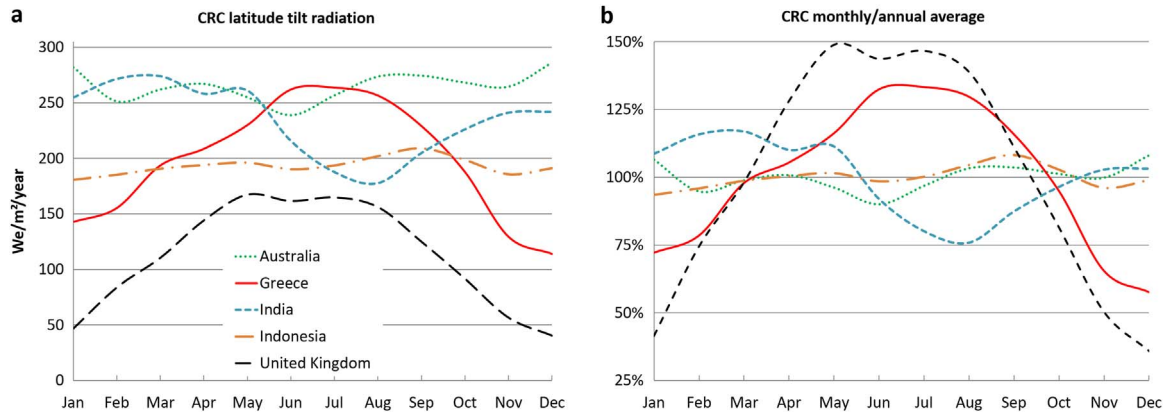


Fig. 4. Seasonal variations in solar irradiance (latitude tilt) at the estimated CRC for 5 countries: Australia, Greece, India, Indonesia and the UK. a) Monthly evolution ($W_e/m^2/year$) and b) the ratio between each month and the annual average value (%).

a promoted and competitive technology already occupying many suitable locations [12,81] (including in high latitude regions [36]), 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 [42]. Globally, solar thermal already accounts for about 1.2% of water and space heating in buildings [81]. 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 [47].

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 Eq. (2) but with the land-occupation ratio ($f_{3,rt}$) corresponding to the range 1–2%,¹⁵ and with $f_{2,rt}$ less than the performance ratio in Eq. (2) taking into consideration the lower relative efficiency of rooftop PV systems over ground-mounted systems (see Eq. (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).

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

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 [86] 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 [34] (see Table 5). The Cp for < 20 kW plants (mainly rooftop) is around 80% of the Cp for $\geq 1,000$ 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, [115], and therefore the efficiency of the solar system of Germany is $0.53/0.66 \approx 0.80$ 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. [74], a region with a very good average irradiance ($\sim 200 W_e/m^2$) 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

¹⁵ 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.

Table 5

Solar PV capacity factor depending on the capacity of the installed plant for the year 2013 in Italy [34].

Capacity of installed plants	Cp (%)
< 20 kW	12.2
< 200 kW	12.7
< 1,000 kW	14.0
$\geq 1,000$ kW	15.1

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 [77]), then the performance ratio of rooftop/ground mounted would be $f_{2,rt}/f_2 < 0.5$. The study of Ordóñez et al. [74] 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.

Hence, Eq. (4) can be rewritten as:

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

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 [26]. 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.¹⁶

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 Fig. D1) [104]. In any case, since the power density of hydropower is similar to solar ($0.5\text{--}7 W_e/m^2$ [86]), 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

¹⁶ With this hypothesis, we expect to compensate for developments not taken into account such as PV potential on facades.

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.¹⁷

$$E_{rt}^i = BU^i \cdot \rho_e^i \cdot \frac{SV^i}{1 + \chi \cdot f_{stor}} \quad (6)$$

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

Thus, with ρ_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:

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

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 (220–380·10³ km²), the USA (95–170·10³ km²), Russia (65–115·10³ km²) and China (45–100·10³ km²), and those with the smallest size and populations are at the bottom: Malta (50–85 km²), Cyprus (110–200 km²) and Luxembourg (490–830 km²).¹⁸ Hence, to comprehend the implications in terms of land use for each country, a relative perspective must be taken. Fig. 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 [26]. 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% to 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).

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 [66] (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 [21] 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 Šúri et al. [94] for UE-28+5 EU countries.

¹⁷ 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.

¹⁸ 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).

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 [108] found that around 540,000 km² (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 km²). Further, a study focusing on supplying a level of electricity for the USA similar to current levels of consumption demand 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" [72], which is again a higher figure than our range for 100% RES for that country of 1.1–1.9%. 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 Fig. 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 [27]) nor built-up [26]. 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 [107,110]. This value is a conservative lower bound, which has been strongly criticized as being unable to ensure an effective protection of biodiversity [105]. For example, the UNEP and IUCN give 17% as a reference value [52], while Soulé and Sanjayan [92] 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. [19] and Farthing et al. [28]). The estimated land availability per country is depicted in Fig. 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 Fig. 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

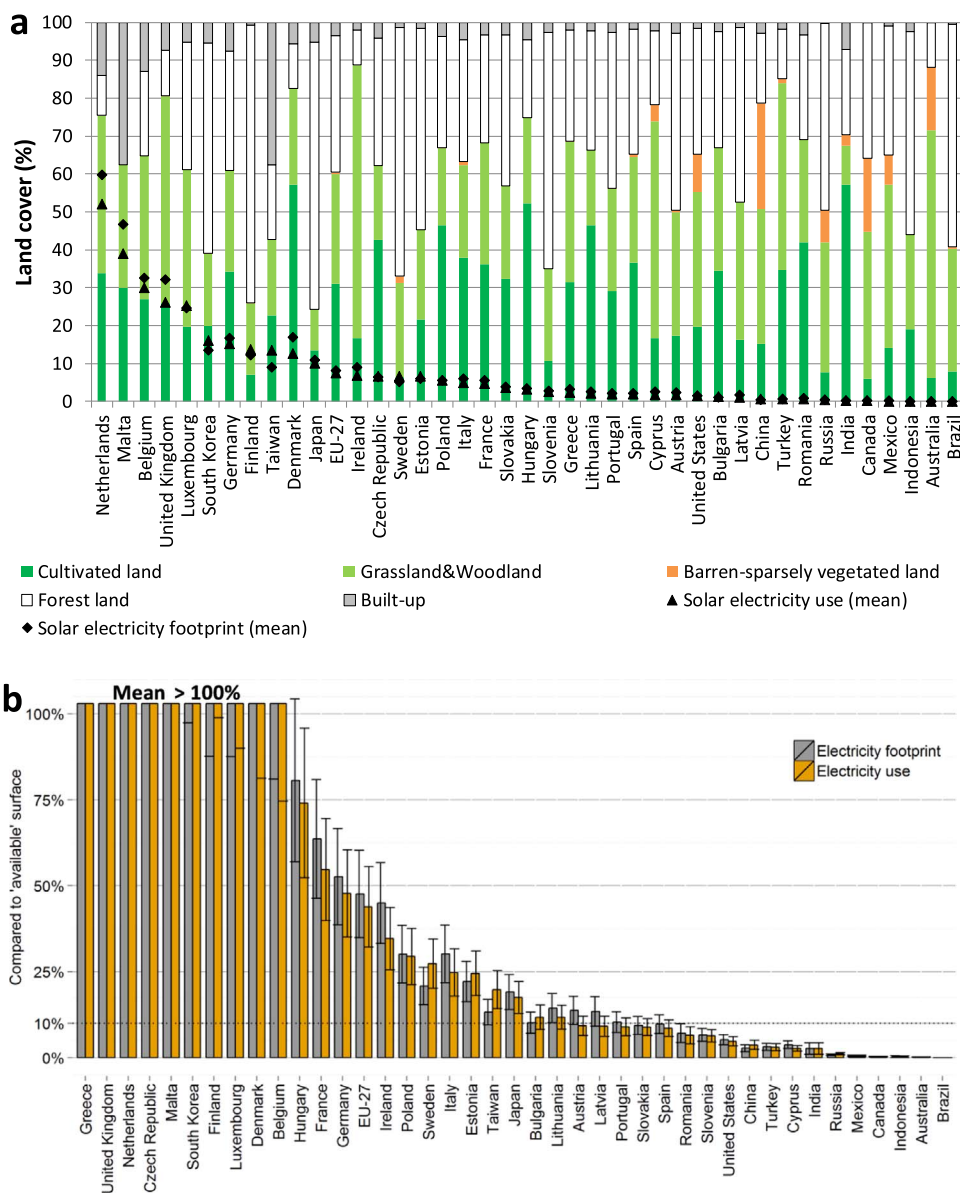


Fig. 5. (a) Land associated with the solar electricity footprint and use (mean values) for each WIOD country as a share of the total land. Different land uses are depicted: cultivated, grassland and woodland and barren/sparsely vegetated, built-up and forest. The countries are ranked from the highest 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 [26] and own calculations. Land-use data for Taiwan extracted from the CIA World Factbook: <https://www.cia.gov/library/publications/the-world-factbook>.

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%¹⁹ 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 Fig. 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., [38,7,93].

¹⁹ 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.

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 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

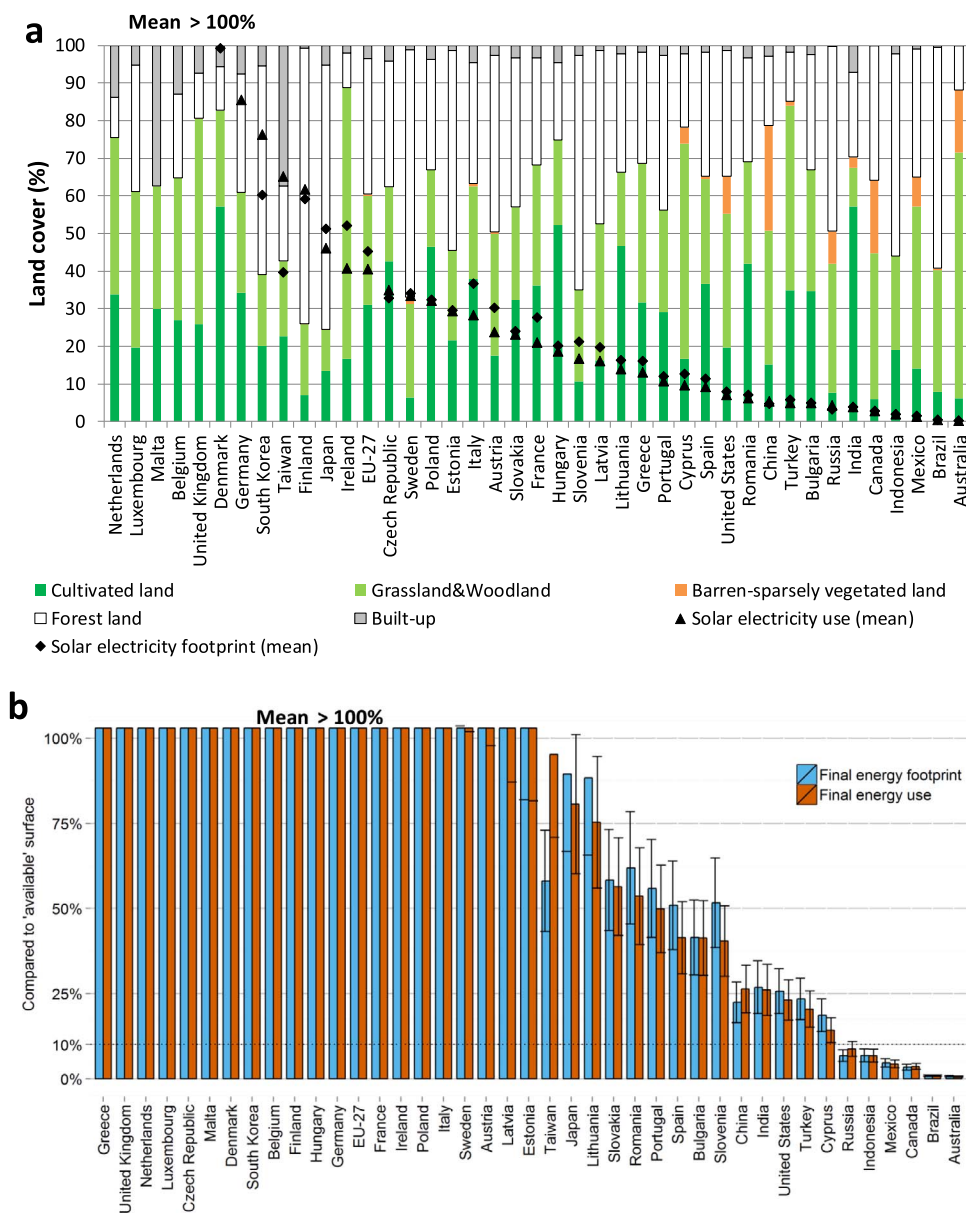


Fig. 6. (a) Land associated with the solar final energy footprint and use (mean values) for each WIOD country as a share of the total land. Different land uses are depicted: cultivated, grassland and woodland and barren/sparsely vegetated, built-up and forest. The countries are ranked from the highest 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 [26] and own calculations. Land-use data for Taiwan extracted from the CIA World Factbook: <https://www.cia.gov/library/publications/the-world-factbook>.

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 (Fig. 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 [61] 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 (km²) occupied by solar facilities per country and the associated land per capita (m²/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 below 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 (Fig. 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).

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 greater 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. [44]). 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 [59] 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 [13]. 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 [4]. 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 [109]. 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 [106,54]. 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 [75].

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 [116,31,48,95]. For example, Jacobson and Delucchi [48] 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 [31] 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 invested (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 [102]. 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 [103,51]. 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”) [25], 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 [108].

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 [2,32,48,96]. Although several projects have been proposed, none is currently under way [8,23,35]. 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 [22]. Its connection with the electricity generated by PV, wind, hydro, geothermal and biomass in European countries would lead to an integrated regional framework [2]. 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 [86]. 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 [63,79]. 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 [57].

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 [108,112,2,29]. 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 [56,10]. With hydroelectricity covering currently a mere 15% of the current global electricity consumption and already being close to its technical potential in many countries [45], 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 [55] and biophysical limitations [17,65] 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 [61,98]. 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 [96], 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 [98].

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 [21,94], 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 [113,2]. 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 ($0.4\% \pm 0.2$) and final energy ($3.8\% \pm 1.1$) 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 Fig. 5a) or built up (~7%). Hence, in terms of land availability the situation worsens substantially, especially in terms of final energy ($26.1\% \pm 7.5$). Population growth (projected to be +30% to 2050 [101]) combined with the expected increase in energy consumption (currently around a third of the global average, see Fig. 1) are likely to drive land requirements to unfeasible levels. Similar reasoning could be applied to other emerging countries such as China and Nigeria [19].

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 [1,33,83].

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}) (see eq. 9). 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 $1+r^2+r^3+\dots$, which is the Taylor series of $1/(1-r)$ (see eq. 11).

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

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

$$Total\ capacity = 1 + r^2 + r^3 + \dots = \frac{1}{1-r} = \frac{EROI}{EROI-1} \quad (11)$$

An examination of the EROI literature on solar PV energy generation shows differences in the assumptions, parameters and methodologies employed [37]. Assuming a conventional value of 10:1 and applying the Eq. (11), an overcapacity of $1/(1+10) \approx 11\%$ 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 [9]), 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 [37], 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. [47] 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. [18] and Paidipati et al. [76] 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 [39]. 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. In relation to this, the GAEZ database [26] 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 km²) [85].

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 [21,48,94]. In particular, assertions about the practical unlimited nature of the solar potential should be reconsidered (e.g., [45,82]). 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 [14].

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 [51,78,84], 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 [32,58]), (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,²⁰ 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

²⁰ The methodology applied here cannot straightforwardly be extended for wind since bottom-up analyses violate the Principle of Conservation of Energy [17,65].

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

See [Table A1](#).

Table A1

Electricity and final energy consumption (use and footprint) by country for the year 2009 (MWh/year/person).

	Electricity use	Electricity footprint	Final energy use	Final electricity footprint
	MW h/year/ person	MW h/year/ person	MW h/ year/ person	MW h/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
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
BRIC	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

Appendix B. CRC and SV values per country

See Table B1.

Table B1

Latitude tilt radiation values $((W_e/m^2/year)^2/W_e/m^2/year)$ 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).

CRC	Lat (°)	Lon (°)	Jan $W_e/m^2/year$	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann	Min/Ann (SV) %	$f_{overcapacity}$ %
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%

Appendix C. Potential electricity produced by rooftop PV

See Table C1.

Table C1

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

	Ert_min %total	Ert_max
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%

(continued on next page)

Table C1 (continued)

	Ert_min %total	Ert_max
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%

Appendix D. Share of electricity consumption covered by hydro generation

See Fig. D1.

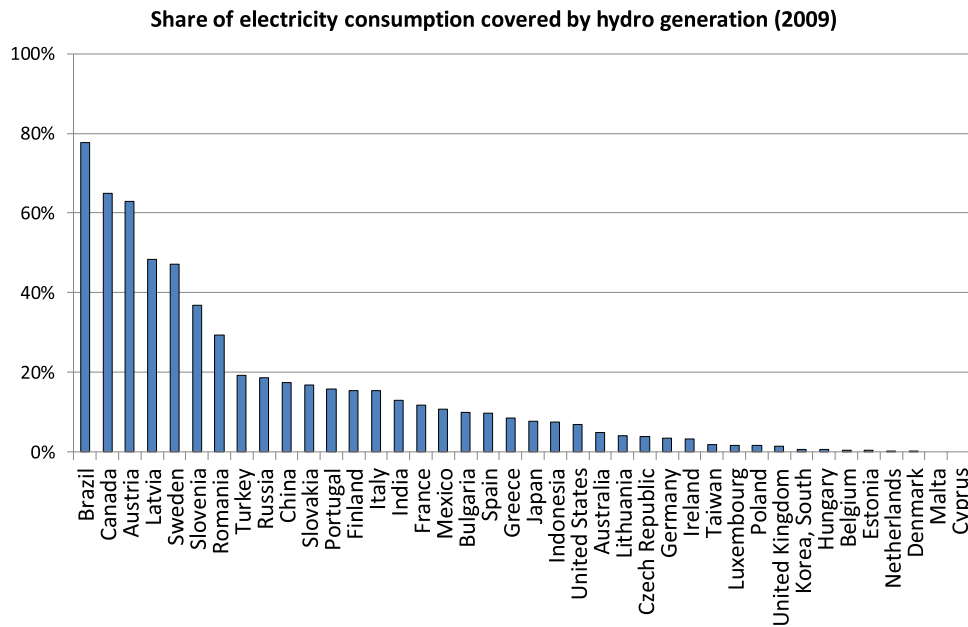


Fig. D1. Share of electricity consumption covered by hydro generation by country in 2009 [102].

Appendix E. Total land and land per capita by scenario

See Tables E1 and E2.

Table E1

Land area (km²) and land per capita (m²/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)			
	Electricity use	Electricity footprint	Total land	Built-up area	Electricity use	Electricity footprint	Total land	Built-up area
Australia	3638 ± 1140	3837 ± 1202	7,609,834	11,299	168 ± 53	177 ± 55	354,159	521
Austria	1402 ± 420	2078 ± 622	82,161	2268	168 ± 50	249 ± 75	9877	272
Belgium	9054 ± 2382	9835 ± 2587	30,061	3879	839 ± 221	911 ± 240	2805	359
Brazil	700 ± 700	705 ± 705	8,222,763	49,313	4 ± 4	4 ± 4	43,197	255
Bulgaria	1531 ± 463	1326 ± 401	107,975	2635	206 ± 62	178 ± 54	14,583	354
Canada	19,998 ± 5497	18,052 ± 4962	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	7080	199
Cyprus	155 ± 44	215 ± 62	8318	184	142 ± 41	197 ± 57	8473	169
Czech Republic	5241 ± 1407	4963 ± 1332	77,223	3166	502 ± 135	475 ± 128	7397	303
Denmark	4698 ± 1261	6324 ± 1698	37,223	2128	851 ± 228	1145 ± 307	7682	385
Estonia	2575 ± 679	2327 ± 613	38,591	573	1929 ± 509	1743 ± 460	31,764	430
EU-27	302,221 ± 80,518	327,999 ± 87,547	4,039,667	141,887	605 ± 161	656 ± 175	8373	284
Finland	38,273 ± 9689	33,924 ± 8588	278,053	1974	7169 ± 1815	6354 ± 1609	56,922	370
France	26,372 ± 7147	30,670 ± 8312	539,687	18,134	408 ± 110	474 ± 128	8463	280
Germany	52,369 ± 13,894	57,727 ± 15,316	344,330	26,270	639 ± 170	705 ± 187	4256	321
Greece	2751 ± 755	3826 ± 1050	114,916	2199	246 ± 67	342 ± 94	11,522	197
Hungary	2907 ± 853	3164 ± 929	89,978	4136	290 ± 85	316 ± 93	9033	413
India	11,481 ± 7069	11,454 ± 7053	2,909,644	206,231	10 ± 6	10 ± 6	2498	173
Indonesia	1283 ± 1136	1494 ± 1322	1,705,727	40,029	5 ± 5	6 ± 6	7628	169
Ireland	4409 ± 1155	5721 ± 1498	63,581	1289	972 ± 255	1261 ± 330	15,189	284
Italy	13,998 ± 3893	17,063 ± 4745	283,927	12,887	237 ± 66	289 ± 80	4977	218
Japan	34,031 ± 9050	37,145 ± 9878	338,211	17,741	266 ± 71	290 ± 77	2847	139
South Korea	14,539 ± 3786	12,128 ± 3158	89,621	4960	296 ± 77	247 ± 64	1974	101
Latvia	762 244	1121 ± 359	60,857	873	356 ± 114	524 ± 168	29,033	408
Lithuania	1351 ± 396	1656 ± 485	62,217	1418	427 ± 125	523 ± 153	19,816	448
Luxembourg	659 ± 169	641 ± 164	2590	137	1324 ± 339	1287 ± 330	5203	276
Malta	65 ± 18	78 ± 22	165	62	157 ± 44	188 ± 52	776	150
Mexico	3329 ± 1219	3575 ± 1309	1,906,300	19,018	29 ± 10	31 ± 11	16,697	163
Netherlands	16,595 ± 4328	19,047 ± 4968	31,687	4408	1004 ± 262	1152 ± 301	2040	267
Poland	16,923 ± 4693	17,305 ± 4799	304,164	11,358	444 ± 123	454 ± 126	8028	298
Portugal	1718 ± 502	1985 ± 580	89,322	2381	163 ± 48	188 ± 55	8667	225
Romania	1732 ± 659	1902 ± 724	228,614	7410	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	1779 ± 493	1874 ± 519	48,063	1581	330 ± 92	348 ± 96	8928	293
Slovenia	530 ± 149	554 ± 156	20,072	546	260 ± 73	272 ± 76	9874	268
Spain	9383 ± 2608	10,663 ± 2964	488,354	8588	202 ± 56	230 ± 64	10,759	185
Sweden	26,022 ± 6799	19,808 ± 5175	383,445	4805	2798 ± 731	2130 ± 557	44,130	517
Taiwan	4824 ± 1345	3227 ± 900	35,410	6829	209 ± 58	140 ± 39	1532	295
Turkey	5746 ± 1854	5954 ± 1921	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	1159 ± 303	3885	266
USA	132,026 ± 37,005	144,969 ± 40,633	8,896,353	130,919	430 ± 121	473 ± 132	29,818	427

Table E2Land area (km²) and land per capita (m²/person) for each WIOD country for: electricity use, electricity footprint, total land and built-up area. 100% solar final energy mix scenario.

	Land area (km ²)				Land per capita (m ² /person)			
	Electricity use	Electricity footprint	Total land	Built-up area	Electricity use	Electricity footprint	Total land	Built-up area
Australia	17,499 ± 4605	20,306 ± 5343	7,609,834	11,299	807 ± 212	936 ± 246	354,159	521
Austria	19,815 ± 5023	24,950 ± 6325	82,161	2268	2375 ± 602	2990 ± 758	9877	272
Belgium	58,863 ± 14,834	55,133 ± 13,894	30,061	3879	5452 ± 1374	5107 ± 1287	2805	359
Brazil	38,369 ± 10,596	38,739 ± 10,699	8,222,763	49,313	198 ± 55	200 ± 55	43,197	255
Bulgaria	5375 ± 1424	5395 ± 1429	107,975	2635	722 ± 191	725 ± 192	14,583	354
Canada	233,732 ± 58,931	221,384 ± 55,817	8,032,228	12,221	6950 ± 1752	6583 ± 1660	270,410	363
China	513,445 ± 136,455	436,849 ± 116,098	9,338,610	265,005	386 ± 103	328 ± 87	7080	199
Cyprus	808 ± 208	1060 ± 272	8318	184	741 ± 190	972 ± 250	8473	169
Czech Republic	27,109 ± 6874	25,594 ± 6490	77,223	3166	2596 ± 658	2451 ± 621	7397	303
Denmark	41,584 ± 0,483	37,058 ± 9342	37,223	2128	7529 ± 1898	6710 ± 1691	7682	385
Estonia	11,469 ± 2902	11,513 ± 2914	38,591	573	8594 ± 2175	8627 ± 2183	31,764	430
EU-27	1,649,098 ± 417,238	1,836,022 ± 464,704	4,039,667	141,887	3300 ± 835	3674 ± 930	8373	284
Finland	172,195 ± 43,169	164,913 ± 41,344	278,053	1974	32,253 ± 8086	30,889 ± 7744	56,922	370
France	115,289 ± 29,376	150,786 ± 38,421	539,687	18,134	1782 ± 454	2330 ± 594	8463	280
Germany	295,588 ± 74,699	346,026 ± 87,446	344,330	26,270	3609 ± 912	4225 ± 1068	4256	321
Greece	15,151 ± 3855	18,422 ± 4687	114,916	2199	1354 ± 345	1647 ± 419	11,522	197
Hungary	16,841 ± 4336	18,170 ± 4679	89,978	4136	1680 ± 433	1813 ± 467	9033	413
India	110,934 ± 31,932	114,193 ± 32,871	2,909,644	206,231	93 ± 27	96 ± 28	2498	173
Indonesia	32,005 ± 8816	32,234 ± 8879	1,705,727	40,029	135 ± 37	136 ± 37	7628	169
Ireland	26,055 ± 6566	33,250 ± 8379	63,581	1289	5745 ± 1448	7331 ± 1848	15,189	284
Italy	81,310 ± 20,721	104,987 ± 26,755	283,927	12,887	1376 ± 351	1777 ± 453	4977	218
Japan	156,828 ± 39,749	173,939 ± 44,086	338,211	17,741	1225 ± 310	1358 ± 344	2847	139
South Korea	68,680 ± 17,321	54,226 ± 13,676	89,621	4960	1396 ± 352	1103 ± 278	1974	101
Latvia	9748 ± 2490	12,071 ± 3084	60,857	873	4552 ± 1163	5636 ± 1440	29,033	408
Lithuania	8640 ± 2218	10,136 ± 2602	62,217	1418	2732 ± 701	3205 ± 823	19,816	448
Luxembourg	6183 ± 1550	4642 ± 1164	2590	137	12,422 ± 3114	9326 ± 2338	5203	276
Malta	391 ± 100	312 ± 80	165	62	949 ± 242	758 ± 193	776	150
Mexico	26,782 ± 7083	28,759 ± 7605	1,906,300	19,018	230 ± 61	247 ± 65	16,697	163
Netherlands	124,808 ± 31,382	107,570 ± 27,047	31,687	4408	7550 ± 1898	6507 ± 1636	2040	267
Poland	98,715 ± 25,141	99,048 ± 25,226	304,164	11,358	2587 ± 659	2596 ± 661	8028	298
Portugal	9557 ± 2462	10,712 ± 2759	89,322	2381	904 ± 233	1014 ± 261	8667	225
Romania	14,279 ± 3796	16,494 ± 4385	228,614	7410	701 ± 186	810 ± 215	11,295	364
Russia	677,796 ± 171,397	526,625 ± 133,170	15,964,790	47,848	4776 ± 1208	3711 ± 938	115,404	337
Slovakia	11,285 ± 2870	11,670 ± 2968	48,063	1581	2095 ± 533	2167 ± 551	8928	293
Slovenia	3369 ± 859	4303 ± 1097	20,072	546	1652 ± 421	2110 ± 538	9874	268
Spain	45,224 ± 11,568	55,660 ± 14,238	488,354	8588	975 ± 250	1201 ± 307	10,759	185
Sweden	129,493 ± 32,667	131,685 ± 33,220	383,445	4805	13,926 ± 3513	14,162 ± 3573	44,130	517
Taiwan	23,169 ± 5931	14,142 ± 3620	35,410	6829	1002 ± 257	612 ± 157	1532	295
Turkey	38,290 ± 9990	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	4816 ± 1215	6013 ± 1517	3885	266
USA	637,851 ± 163,461	708,860 ± 181,659	8,896,353	130,919	2079 ± 533	2311 ± 592	29,818	427

Appendix F. Land availability at country level

See Fig. F1.

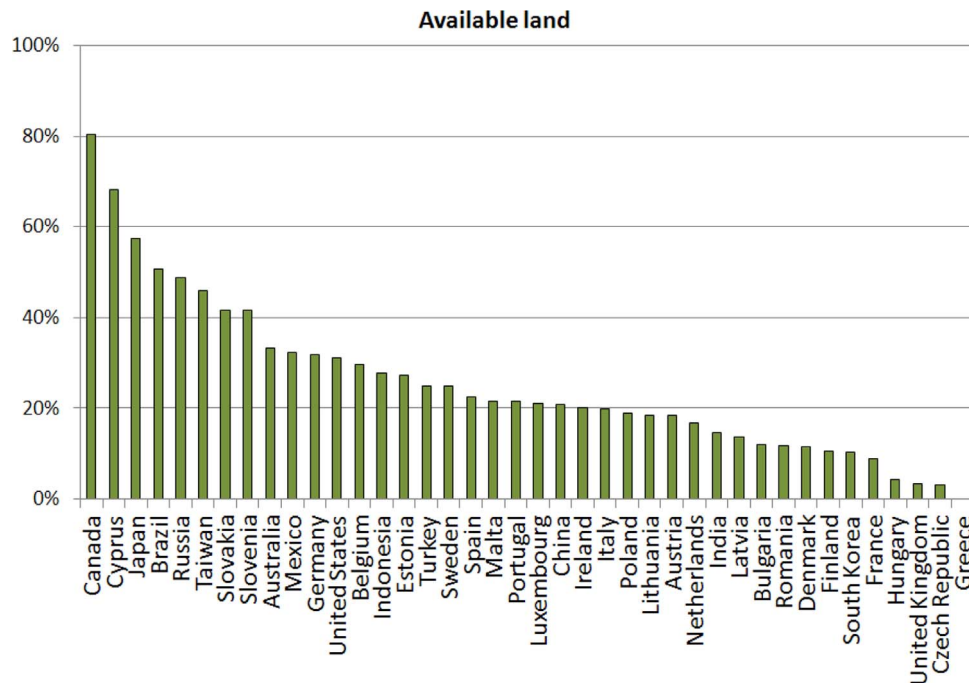


Fig. F1. Land availability at country level as defined in Section 3.

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