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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 lead 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