LAND-USE REQUIREMENTS OF SOLAR AND WIND POWER

Olga Turkovska[1], Katharina Gruber, Michael Klingler[1], Claude Klöckl[1], Luis Ramirez Camargo[2], Peter Regner[1], Sebastian Wehrle[1], Johannes Schmidt[1]

[1] Institute of Sustainable Economic Development, University of Natural Resources and Life Sciences, Gregor-Mendel-Straße 33, 1180, Vienna, Austria

[2] Copernicus Institute of Sustainable Development - Utrecht University, Princetonlaan 8a, 3584, CB Utrecht, Netherlands

This review paper is a non-peer reviewed preprint submitted to EarthArXiv.

It was submitted to One Earth for peer review.

SUMMARY

Rising shares of wind power and solar power in energy systems raises concerns over their land-use requirements (LURs) and associated impacts. Although abundant literature is available on LURs of solar and wind power, existing estimates exhibit a large variance, if not even inconsistency. This systematic review therefore evaluates published LURs for these technologies in the English scientific literature until early 2023, in total 2,286 estimates. The choice of LUR estimates for renewable energies causes significant variance in projections of total land required for the energy transition. In some cases, the associated variance is as large as variations due to scenario-based projections on the future deployment capacities of these technologies globally, thus, implying additional uncertainties for decarbonization. We find that methodological differences can explain the variance partly, but data documentation is poor. We therefore call for improved standards in reporting LURs and provide guidelines for developing and applying LURs.

1. INTRODUCTION

The energy sector is undergoing a rapid transition towards a low-carbon system, and renewable energies are seen as key decarbonization options in this context. Among all renewable energy technologies, solar photovoltaics (PV) and wind power are expected to experience the strongest growth, while concentrated solar power may have an important niche role[1]. However, deploying these low-carbon technologies requires significant land resources, integrating these technologies into existing land-use systems as well as altering them, which could inevitably lead to undesired conflicts and impacts on biodiversity, ecosystems, and livelihoods[2–10]. A large strand of literature assesses therefore land-use requirements (LURs) of renewable energies. One consistent result of studies, such as by Fthenakis & Kim[11], is that renewable energies have a larger land occupation than fossil fuels in a life-cycle perspective, except for coal power using surface mining, while land-use intensity of solar PV is lower than wind power when considering the spacing area in-between the infrastructural elements, but higher if infrastructure only is included[11,12]. As a consequence, McDonald et al.[6] and Lovering et al.[13], who studied the land-use impacts of the expansion of the US energy system, showed that a transition to renewable energies may increase the land footprint of the energy sector. Both conclude that the subject of land-use may become a major constraint in the energy transition. Capellán-Pérez et al.[14] showed that land-use could be problematic for some global regions, when aiming at 100% solar PV systems, e.g., the EU-27 might require more than 50% of the land that is not occupied by agriculture, forestry and build-up areas to host these capacities, and for some countries such as Greece, UK, or the Netherlands even more than 100% of available land would have to be used. Therefore, inconsistencies between policy goals, such as Sustainable Development Goal 7 (Affordable and clean energy) and Sustainable Development Goal 15 (Life on land), may be introduced, complicating their implementation.

Understanding the extent of land resources necessary to accommodate renewable energy facilities is therefore important to correctly assess policy related trade-offs and conflicts. Precise estimates and their correct application may also help in learning how LURs can be lowered by improving regulation, technological choices, or siting decisions. Furthermore, planning of energy systems has to accurately assess LURs of renewable technologies, as over- or underestimating the amount of renewables that can be deployed may lead to suboptimal system configurations.

However, published LURs estimates show high variance, or even inconsistencies, making available assessments subject to large uncertainties. The scale of this challenge is made explicit once we assess the total land-use required to accommodate installed capacities aligned with decarbonization goals (figure 1). In particular, we compare the variability in total required land-use introduced by either fixing capacity expansion and using LURs at the level of single parks or the mean of LURs per publication obtained in this review, compared to fixing the LUR value at the mean of all publications and varying capacity expansion values. Capacity expansions are obtained from decarbonization scenarios for the year 2040, which are consistent with the 1.5°C limit from the IPCC's sixth assessment report[15]. For wind power, variability introduced by using different LURs, either for single parks or when using publication means, is higher than the variability introduced by differences in capacity expansion scenarios. For solar PV, variability due to expansion scenarios is higher than due to variability in LURs. However, the range of total required land-use, when varying single-park LURs and fixing expansion, is still between 0.2 Mkm^2 and 1.2 Mkm^2, and 0.2 Mkm^2 and 0.6 Mkm^2 of global land-use if means from publications are used. This is a striking uncertainty implied by variability in LURs only.

Understanding the source of the high variability in LURs estimates is therefore of crucial importance. However, the terminology used in different assessments is inconsistent. There are a variety of different methods applied to measure the land required by renewables, and it is often unclear which land is considered to be required by renewables. These factors may explain a substantial part of the variability in estimates, but a comprehensive assessment is currently lacking.

Several review articles have partly addressed these issues before, but empirical comparisons and an analysis of the underlying methodological differences remain scattered across several publications.

Harrison-Atlas et al.[16] reviewed capacity density for wind power in the US and the most common assumptions for its quantification. Wachs & Engel[17] analysed in detail three types of LUR metrics for renewable and fossil-based technologies — ecological footprint, land-use intensity, and power density. Harrison-Atlas et al[18] provided definitions for land-use intensity as well as for capacity, power, and energy densities. Although some of the most commonly used metrics are described and even some recommendations on their use are given[17], a study that systematises definitions and assumptions underlying those and other, less frequently used metrics, or quantitatively compares the differences is absent.

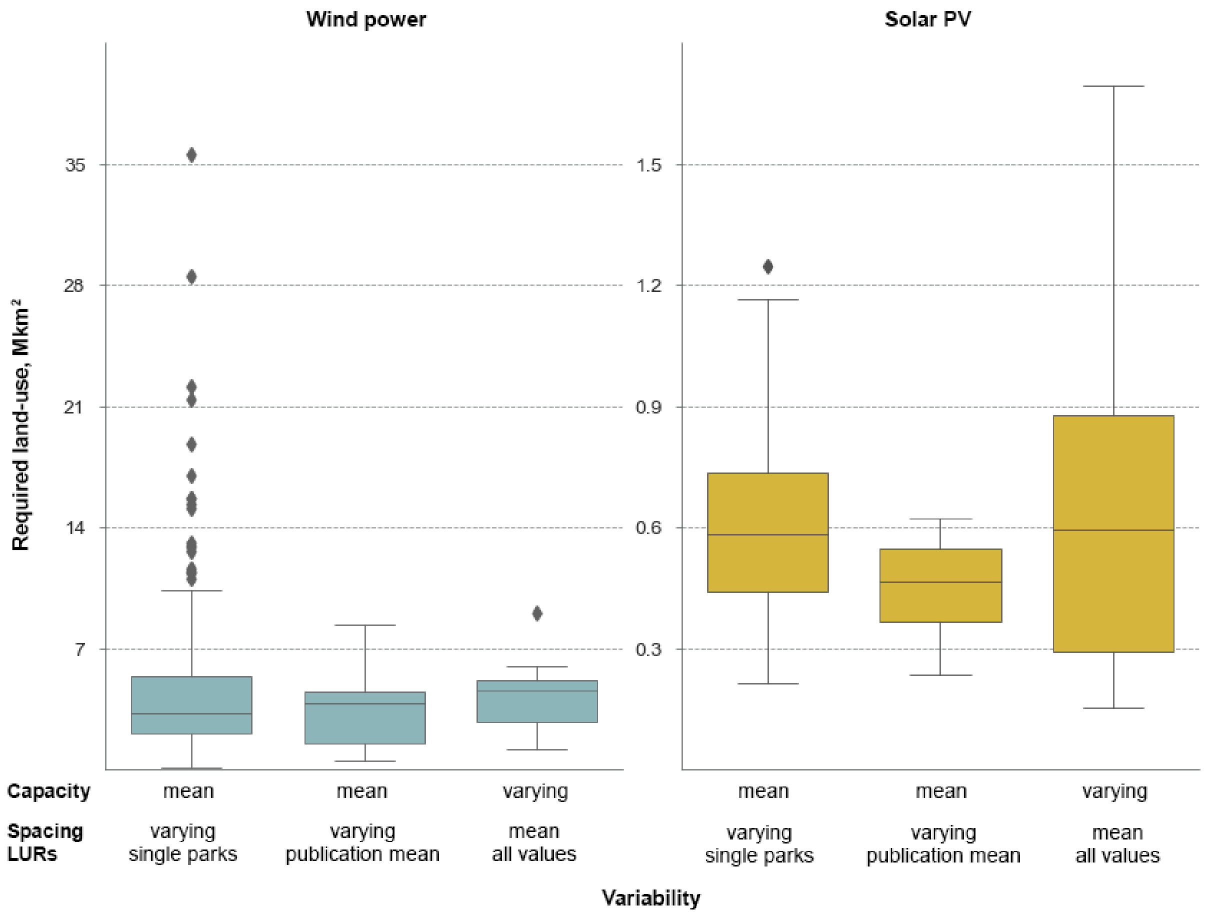

Figure 1. Total global land-use for solar PV and wind power, comparing 59 scenarios from IIASA's AR6 scenario explorer for the year 2040 consistent with the 1.5°C limit. We either fix total installed capacity at the mean value from all scenarios for the year 2040 and vary LURs calculated for single parks, which explicitly consider spacing area (left boxplot), vary LURs by publication (i.e., taking the mean of spacing LURs by publication, middle boxplot), using all applicable spacing LUR estimates from this review, or we fix LURs at the mean of all spacing values in this review and vary total installed capacities, covering the whole range of scenarios for the year 2040 (right boxplot).

Other studies highlighted that land-use, location-related and technological factors contribute to the variability of LURs[19,20]. As metrics treat the power component of LURs, i.e., how generation or capacity is measured, differently, some studies harmonised available LURs in terms of their technological and location-specific factors under one single metric[20,21]. However, the respective comparisons are limited to major types of technologies, such as wind power with solar PV. Technological subtypes, such as fixed vs tracking solar PV systems, are less studied except for

Hornet & Clark[20], who accounted for sub-technologies of solar PV and CSP in their harmonisation of a limited number of plants. Furthermore, in all assessed reviews of LURs, the investigation of the land-use component of LURs gets considerably less attention than the power component. Although differences in defining the spacing and physical infrastructure area can be high, particularly for wind power, the variability introduced by different approaches to measuring land-use has not been reviewed so far.

In conclusion, existing studies and reviews do not fully assess and harmonise the applied metrics, methods and definitions of land-use and do not fully control for sub-technologies. Therefore, uncertainties related to LURs cannot be comprehensively assessed in studies that use LURs, and incomplete and inconsistent data standards limit attempts to narrow them down and understand the driving factors of LURs. Consequently, LURs estimates may be off significantly, implying inaccurate inputs to policy decisions.

This paper addresses these significant knowledge gaps and provides a comprehensive systematic literature review of the state of the art on LURs of wind power, solar PV and CSP technologies. In section 2, we discuss the state of the literature on LURs and their geographical scope. Section 3 discusses LUR terminology and harmonises it into standard meta-metrics groups. Section 4, 5, 6 assesses how methodologies and underlying assumptions affect the uncertainties and variabilities of LURs for wind power, solar PV and CSP, respectively. Major research gaps regarding LURs are outlined in section 7. Moreover, as a first step towards addressing these gaps, we offer a best-practice guide for the development and reporting of LURs as well as a guide for selecting and using LURs in the study. To facilitate future studies, we openly publish our resulting database of LURs estimates with complete metadata for use by our peers.

Overall, the paper provides a comprehensive overview of LURs for the most important renewable energy technologies, offering insights and guidance for researchers, policymakers, and stakeholders: a more comprehensive and detailed understanding of LURs will improve the quality of knowledge exchange to make better-informed policy decisions and guide the deployment of low-carbon technologies.

2. REGIONAL AND TEMPORAL COVERAGE OF LURs

The literature does not provide a strict definition of *land-use requirements* (LURs) of renewable energy technologies. Commonly this concept is understood as an indicator quantifying the land area necessary to accommodate a facility of a given installed capacity or amount of power generation, or an amount of power that can be installed or generated on a given area of land. Here, we use LURs as an umbrella term for a broad range of terms that, in their essence, fit into the aforementioned definition. Therefore, our search string during our literature research (see table S1 of SI for details) included this umbrella term and a pre-assembled list of terminologies identified by the authors that fit the above definition. Furthermore, generic terms such as *land-use* and *area* that allowed us to discover terms outside of our pre-assembled list were included.

Our review process consisted of a five-stage selection process combining a systematic literature review including a snowball approach and a final error evaluation (for details see *Methodology* section of the SI). The review considers references published until February 2023. Out of 582 potential publications, 99 publications were selected, reporting a total of 2,286 different LURs. The data corpus consists mainly of peer-reviewed articles (70 publications), as well as grey literature such as technical reports, conference papers, and an online database. Among the selected publications, LURs of solar PV plants are by far the most studied (43% of all publications). LURs of CSP plants are reported in 22% of all publications, followed by LURs for onshore wind technology assessed in 20% of all publications. The remaining 15% of LURs are not fully considered in this review as they represent a mix of technologies or offshore wind parks.

LURs of renewable technologies have been discussed in the literature for a while. The earliest article included in this review was published in 1977, assessing the LURs of solar photovoltaics[22], however, quantitative assessments of LURs are rarely found in the literature before the 2000s. Yet, the interest towards assessing LURs of renewables has been increasing quickly: in the past five years, on average seven publications per year provided LUR estimates. In comparison, over the period of 2003-2007, on average, there was only one publication per year (see temporal dynamics in fig. S1 of SI).

LURs identified in the literature unevenly cover major geographical regions (figure 2). North America has the highest coverage for all technologies among all global regions. In total, LURs for North America are provided in 40[11,14,16,18,22–56] publications. Only four of these publications provide LURs outside of the US[40,41,46,51]. The remaining publications contain data for the US providing 1284 LUR estimates there. The large number of different LURs for the US is also explained by two important reports by NREL, one for wind power[23] and another one for ground-mounted solar PV[24]. In total, both reports provide 51% of the US LURs for large-scale renewable facilities. Although these reports investigate LURs for plants that were built two decades ago or even earlier, their results are highly influential in the field. Our analysis showed that LURs from these reports are most frequently used by other publications in our list of screened references (figure S2 in SI).

Europe is the second most represented region in literature, i.e., 29 publications cover this region[12,14,28,31,36,39,46,51,57–76]. LURs for solar PV technology are geographically diverse. Although Spain and Germany are considerably better represented than other European countries, estimates are available for 28 countries, which are provided in 18 publications[12,14,28,36,46,58,59,61,62,66–74]. LURs for wind power were reported only for eight European countries in eight publications[12,25,39,60,63–65,75]. The UK has by far the best coverage for wind technologies (139 values in four publications)[12,25,64,65] where publications by MacKay[65] and Noland et al.[12] provided 80% of the LURs for wind technologies in the UK. LURs for CSP technologies are covered in five publications[28,31,43,51,76] with Spain as the most represented country (116 values in four publications)[28,31,57,76]. As the global number of CSP installations is significantly lower compared to wind and solar PV technologies, in total there are limited LUR estimates for CSP globally.

23 publications cover Asian countries[12,14,28,31,39,58,59,77–92]. Comparably to Europe, solar PV LURs are available for a broader range of countries than those for CSP and onshore wind power. LURs for solar PV technology are available for 14 countries with India being the most frequent[12,14,28,58,59,78,80,84,88–92]. Wind power LURs are found for five countries in 4 publications[39,78,84,86]. There are eight publications on CSP LURs that cover seven countries, with a main focus on China and India[31,77,79,81–83,85,87].

In contrast to the aforementioned regions, South America, Australia & Oceania, and Africa are significantly less represented. LURs for South America were found in ten publications[12,14,31,39,93–98], eight of them provided data for solar PV LURs covering three countries with data on Brazil prevailing[12,14,93–98]. Wind power LURs were provided in four publications for four countries[12,39,97,98]. LURs for the CSP technology are only available for Chile[31]. LURs for Australia and Oceania are reported in five reviewed references[12,14,25,31,39] that cover all technologies in Australia and one publication providing LURs for New Zealand[25]. Five publications reported LURs for five countries in Africa[12,31,99–101]. LURs for CSP technologies are provided for four countries[31,99–101], solar PV LURs are reported only for Zambia[99], and one publication provided a wind power LUR for Egypt and South Africa[3], respectively.

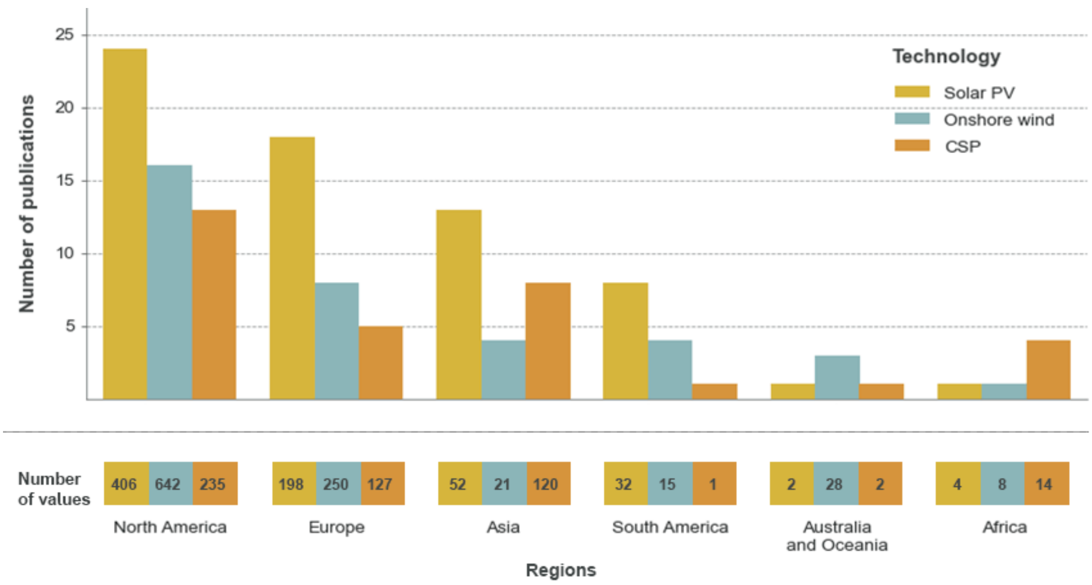

Figure 2. Regional representation of LURs in the reviewed publications by technology type. The numbers below the bars report the total number of LUR estimates provided per region. This figure does not account for LURs that were reported as averages for subregions (e.g., EU, a group of countries in Asia) or global averages.

3. LURs TERMINOLOGY AND METRICS

The terms used to describe LURs found in the reviewed literature are not self-explanatory in all cases, i.e., some parameters essential for accurately interpreting LURs are not evident from the terminology. In the following discussion, we will explore key terms based on our systematic literature review and discuss crucial parameters that must be understood to interpret the associated LUR estimates correctly.

We encountered 22 different terms for LURs across 55 publications[11,12,16,23,25,26,28–30,32–36,38–41,41–44,46,49,50,59–61,63–65,65–68,71,72,74,79,82,84,85,89,91,92,96–98,102–109]. It should be noted that the remaining publications contained measurements or estimates of how much area was used by renewables and how much capacity was installed or how much power was generated, but they do not combine these values to report an actual LUR and therefore do not add to LUR terminology. From those publications that introduce a LUR term, almost every second publication uses a different term. Such variety cannot be explained solely by actual differences between the definitions of LURs, i.e., different terms clearly point to the same LUR definition. As shown in figure 3a), the most frequently used terms are *power density*[18,34–36,38,44,46,64,65,65,109,110], *capacity density*[16,18,26,34,35,42,60,61,67,97,105], and *area requirements*[40,71,79,84,102,106,107]. In the category *others*, we compiled terms reported only once — this was the case for 18% of publications. These terms include *energy yields*[108], *footprints*[98], and *surface performance ratio*[67], among others (see table S3 in SI).

A detailed analysis of all these LURs showed that — regardless of the term used — each LUR consists of two strictly required elements: the land-use of the facility and a power-related component (figure 3b)). The land-use of the facility describes how much land is occupied by a given facility. The power-related component refers to the amount of installed or generated power of that facility. Furthermore, assumptions regarding time periods have to be made. Power-related components can be *installed capacity*, *power output* or *energy generated per time period*. All LURs have some time period assumption, frequently implicit, even though the time period is explicitly incorporated into the LUR calculation in some publications. Therefore, we grouped all terms into seven meta-metrics groups (figure 3a). Six groups were derived depending on the chosen power-related component and its relation to the facility's land-use that is expressed as area. Capacity-based groups report either capacity per area or area per capacity. Power-based groups include either power output per area or area per power output, while energy-based groups refer to either energy per area per time period or area per energy per time period. The seventh group refers to LURs that explicitly consider the duration of land occupation by the facility. Such an approach is commonly associated with life cycle assessments[11,32].

The Sankey diagram and bar plot in the middle of figure 3a) show the correspondence between the original terminology and the seven meta-metric groups. Overall, most terms that appear in at least two publications (except *land-use* and *capacity density*) belong to at least two meta-metrics groups, i.e., the same term is used for two different metrics. This implies a lack of standard terminology to quantify LURs. In some cases, the same term was used to refer to two different meta-metrics in a single publication. For some terms, it is hard to directly derive which meta-metric group they belong to. This is the case for metric names such as *land-use intensity*, *area requirements*, and *land transformation*, among others. From the terms alone, it is hardly possible to understand how LURs were quantified, and we had to resort to an assessment of the applied methodology to categorise them. In contrast, terms such as *capacity-*, *power-*, and *energy density* seem self-explanatory, as *density* generally relates to a quantity per unit of area, e.g., comparably to population density. However, an explicit reference to *power* in the term does not necessarily indicate that *power output* was used to quantify LURs. E.g., in the case of *power density*, either *installed capacity* or *power output* was used in quantifications. Therefore, we propose to simplify the wide variety of terms to these LUR meta-metrics that describe how the chosen power component relates to the facility's land-use. This avoids potential confusion rooted in the diversity of terminology.

The seven meta-metrics assist our understanding of parameters underlying LURs. Furthermore, the available LURs can partly be numerically converted to other meta-metrics. Firstly, metrics based on *energy* are, in principle, convertible to power-based metrics as *energy generation per time period* (e.g., MWh/year) corresponds to average power output. However, some studies might consider energy-based meta-metrics more suitable contextually. *Area-time-energy* LURs can be converted to *area-energy* — if the considered time period is provided — and then to *area-power*. Therefore, following these conversions, the data can be further aggregated into four meta-metrics. Moreover, most of the data that belongs to *capacity-* and *power-area* can be converted to *area-capacity* and *-power* meta-metrics or vice versa. However, in cases, when mean values of various single estimates are reported this conversion would not be correct as the reciprocal mean does not equal the mean of reciprocal values, in general. Even if the conversion is numerically feasible, i.e., for single installations, it changes the interpretation of LURs. Therefore, studies may choose the meta-metric depending on the research purposes. For this review, we performed the described numerical conversions and split the data between *capacity-area* and *power-area* meta-metrics. This allowed us to preserve and compare most values we found in the literature review, to better understand the factors that affect these estimates.

Solely the meta-metrics categories are not sufficient to describe all differences between LUR estimates. Therefore, we show how elements of quantifying LURs — i.e., the facility's land-use and the power-related component, as well as assumed time period — can be further differentiated (see figure 3b)).

The definition of a facility's land-use is surprisingly complex and depends on which components of the facility are considered in an assessment — and which methodology is applied to delineate the boundaries of the facility. The land used by the facility can be split into two groups. The first group refers to the area physically occupied by a facility's infrastructure. This typically includes the core facility elements (e.g., solar PV panels, turbine pads, CSP mirrors and towers), transmission towers[50], access roads[23,98], storage devices[99], and substations[11,23,46,50]. In some cases, even remote infrastructure can be included, such as land needed to mine materials and produce power plant components[11,32,82]. The second group refers to land required to ensure the operation of the infrastructure, which is however not physically occupied by the infrastructure. In this context, publications often mention the terms *spacing area*[11,12,16,18,25,26,29,29,34–36,38,39,44–46,49,57,58,61,62,64,71,74,79,79,86,87,96,98,99,101,105,109,111,112], *project area*[22–24,28,31,33,37,40,41,46,53,63,66,69,73,78,82,92], and *construction area*[23].

It is essential to know which aforementioned area elements were included in a LUR measurement or estimate to control for differences between different LUR quantifications accurately. However, publications often do not fully report these components. For 32% of publications, we could not infer how the facility's land-use was determined. In some cases, the value of the area is extracted from official documentation provided by facility developers or from reports such as environmental assessment reports[23]. In this case, the land-use usually represents the *project area*. In other cases, the area is measured or estimated, sometimes automatically following some geometrical rules or manually using ortho-photos of the facility[27,49,65]. The area of the facility can be estimated by applying geometrical rules to the core elements of the facility, e.g., determining the convex hull of a project [12,18,57,62,63,73], drawing Voronoi polygons[34,35], or applying setback distances[12,39]. The area can also be estimated by applying theoretical rules without relying on actual locations of a facility. For example, the diameter of the rotor is often used to estimate the spacing area for wind parks[36,45,64,86,109]. Also, a buffer of a given size can be applied to estimate the area of a facility[65]. In rare cases, the estimated area results from optimisation to maximise power output[58,99]. However, this method was applied to the planning of new facilities only.

The power-related component can either represent *installed capacity* or *power output*. As indicated above, the latter is either reported as average power output or energy generation over time. The power output is determined using different methods, for example through measuring generation[28,47], simulating generation from climate data[87,105], or applying average capacity factors[27,57,78].

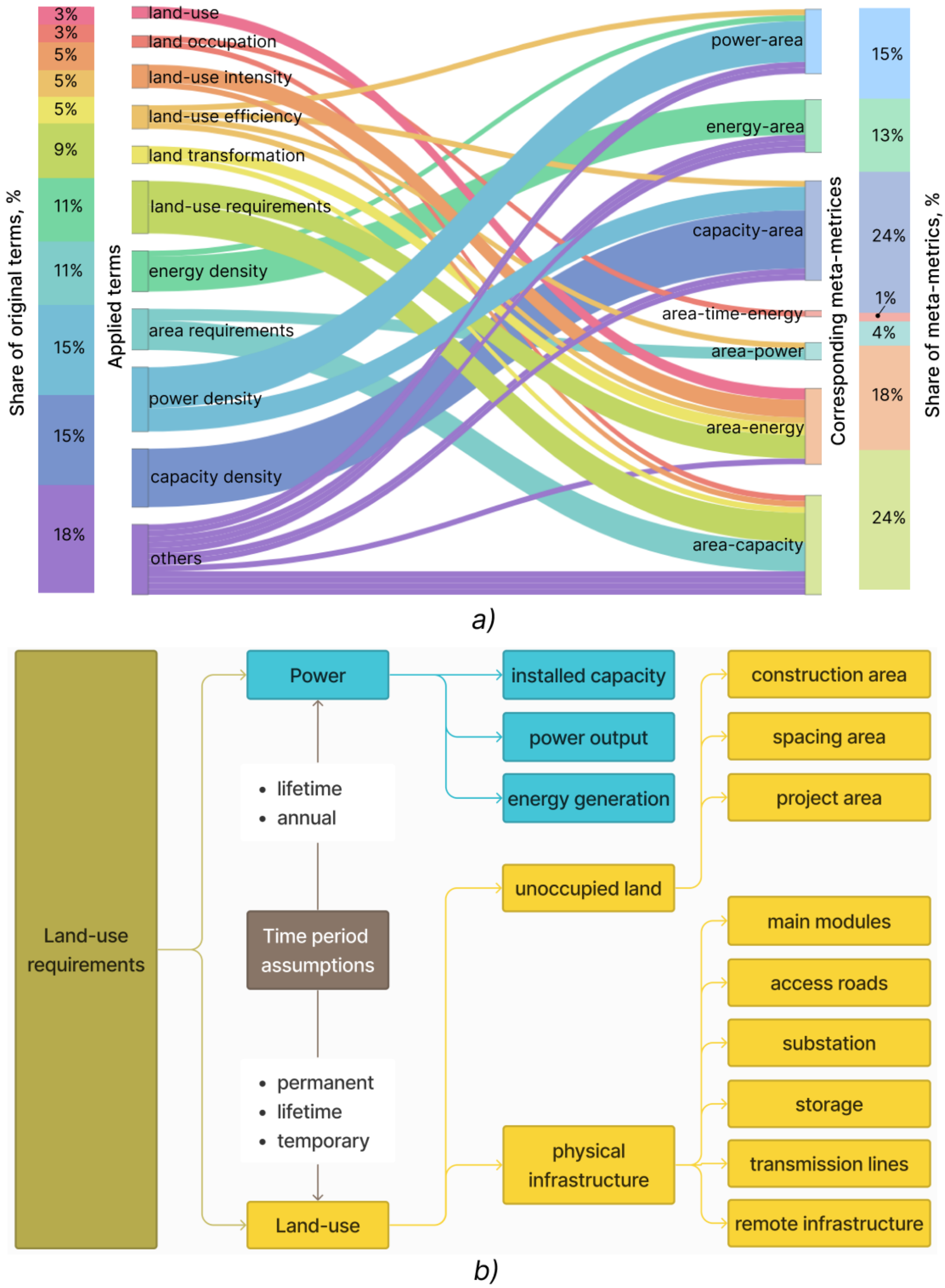

Figure 3. Representation of LURs in the current literature: *a)* the leftmost bar plot shows the frequency of LURs terms in literature. The Sankey diagram demonstrates how those terms can be aggregated into seven meta-metrics, whereas the rightmost bar plot on its right displays the representation of these meta-metrics in literature., *b)* the diagram displays the most relevant components of LURs.

Finally, the assumed time period is rarely explicit in LURs. In the case of capacity-based meta-metrics, it is implicitly assumed that a renewable facility stays at its location permanently or over its lifetime. In the case of all power-based meta-metrics, the time period is embedded in the calculation of average power generation. Commonly, it is calculated on an annual basis and less frequently over the facility's lifetime[32,49,70,82,95]. Explicit assumptions regarding time are made by publications which consider the land-use of a facility as temporary, i.e., they average area and power generation over the lifetime of the facility to obtain annual LURs[32]. Another example of explicit time assumption is reporting LURs for the period of facility's construction[23]. This implies that the land is used for the facility's purposes only over a limited time, particularly during construction.

Figure 4 demonstrates the variability of *capacity-area* and *power-area* LURs of each major technology, i.e., onshore wind, solar PV, and CSP. In each case, LURs vary by at least one order of magnitude. Understanding factors that influence estimates of LURs is crucial to disentangle the uncertainties introduced by methodology from factual differences due to e.g. technology, location, or regulation in observed LURs. Reducing the variability that stems from methodological differences will allow gaining a better understanding of the latter factors and make more informed choices of LURs in subsequent analyses. To do so, we comprehensively describe each LUR in terms of methodology in the following: we differentiate by the definition of land-use type and the approach to delineate facility's boundaries, and underlying characteristics, in particular the sub-types of major renewable technologies. We separately focus on each major technology, i.e., onshore wind, solar PV, and CSP.

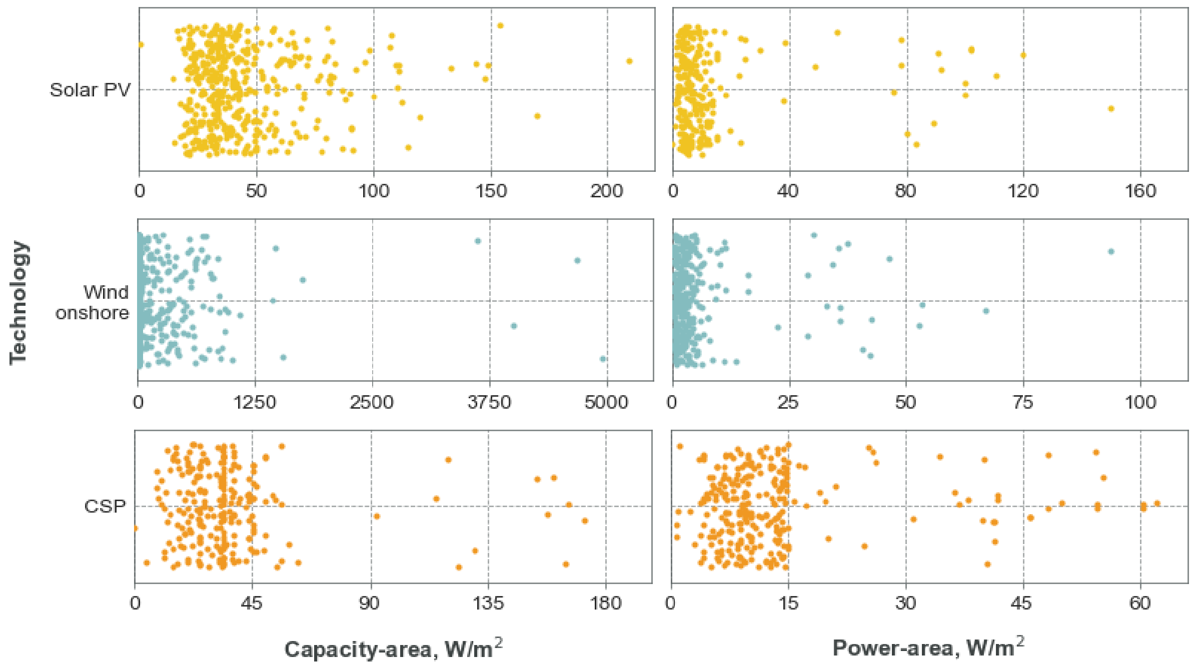

Figure 4. The variability of capacity-area and power-area LURs for solar PV, wind power, and CSP technologies. Each data point represents one LUR estimate reported by one of the reviewed publications — directly or indirectly via reporting power and land-use components separately.

4. LURs FOR ONSHORE WIND TECHNOLOGY

LURs for wind power had the highest internal variability among all assessed technologies; the range is 0.4-4950 W/m^2 for *capacity-area* LURs and 0.1-93.5 W/m^2 for *power-area* LURs. In the following, we gradually explain factors that affect LURs and report the median value after each step to demonstrate the changes after accounting for each factor.

A large part of the variability stems from the definition of the facility's land-use as demonstrated by both meta-metrics: *power-area* and *capacity-area* (figure 5). We differentiated LURs by three definitions of the wind park's land-use, i.e., land-use as the area taken by *i)* the physical infrastructure of the project exclusively, *ii)* the construction and other temporary activities necessary to complete the project, and *iii)* spacing between the turbines that accounts for the physical infrastructure and the land necessary to ensure that parks operate at reasonable efficiencies.

The median *capacity-area* LURs based on spacing area (3.9 W/m^2) differ from those based on the physical or temporary areas (485.9 W/m^2 and 200.4 W/m^2) by two orders of magnitude. In the case of *power-area*, the difference between physical infrastructure and spacing LURs is reduced to one order of magnitude, i.e., 35.7 W/m^2 and 2.4 W/m^2 respectively. Here, the smaller quantitative difference between the two definitions is due to a considerably lower — than in the case of *capacity-area* — number of values for each definition. Furthermore, the methodology chosen for measuring the boundaries of the facility affects the magnitude of LURs. For *capacity-area* LURs, based on physical infrastructure, two approaches were found in the literature. One extracts the area from reports or official documentation, and the other one manually delineates boundaries of the physical infrastructure based on aerial images and quantifies the area. Reported LURs yield higher land-use efficiency than manually measured LURs, in particular reported LURs have a median *capacity-area* of 443.8 W/m^2, whereas it drops to 96 W/m^2 for manually measured LURs. Manually measuring the area of the physical impact of wind parks poses some specific challenges that can reduce the accuracy of the result. Solely aerial images are not enough to infer about the spread of the facility's access roads, thus, the decision about which roads belong to the park might be arbitrary. In addition, the quality of the image might be insufficient to precisely mark the boundaries of infrastructural elements. High precision of boundaries is important for measuring the extent of wind park infrastructure, e.g., changing the width of a road by 1m can alter its total area by 14% (based on Ramirez Camargo et al[98]). These challenges in manually delineating wind park infrastructure may explain the difference in observed efficiency between the approaches.

For measuring spacing area, methodological diversity is even higher. We found seven approaches used to quantify the spacing area of the facility (table 1 and figure 5). Overall, the seven approaches can be clustered into empirical and theoretical approaches: empirical approaches rely on the actual location of turbines. The convex hull, reported, Voronoi polygons, buffered, and buffer-spacing-cluster approaches belong to this category. As the buffered approach was used for a very specific park layout, i.e., a single string wind park, and buffer-spacing-cluster does not fully account for spacing of the facility, they yield LURs that are not representative of average wind parks. The remaining three methods of the empirical estimates yield results of a similar order of magnitude and more conservative estimates compared to those of theoretical estimates. The latter rely on geometrical relations between the rotor diameter and turbine distances, but do not take into account specific locations of turbines. Land-use for future renewable systems can be easily derived without explicitly spatially allocating the turbines, however, we found that the literature applying these approaches chooses parameters (e.g., distance factors) that are likely underestimating LURs. In contrast, the location-based, empirical methods implicitly consider the influence of context-dependent factors on land requirements. However, due to context specific variability, single location-based LURs for individual parks can be outliers (e.g., spacing area for string layout wind parks). Therefore, individual values using location-based methods can gravely distort the outcomes of analyses applying them.

Table 1. Approaches used to delineate the boundaries of wind parks and their median LURs.

Approach	**Definition**	**Median *capacity-area***	**Median *power-area***
Empirical approaches			
buffered[12]	The boundaries of the park area are based on the location of the utmost turbines and an additional buffer of the size of the rotor diameter has been applied to a string wind park layout only.	42.8 W/m^2	12.6 W/m^2
buffer-spacing-cluster[39]	A buffer of the radius of the hub height is determined around each turbine. Afterwards, areas of buffered turbines are merged into one cluster if the distance in-between them is at most three maximum hub heights. The area of all determined clusters constitutes the land-use of the facility.	30 W/m^2	7.2 W/m^2
convex hull [12,18,63]	Land-use is defined as the convex hull area of the utmost turbines of the facility.	4.6 W/m^2	1.5 W/m^2
reported[23,37]	The project area reported in the official documentation of the park.	3.4 W/m^2	-
Voronoi polygons[34,35]	The area per wind turbine is estimated using Voronoi triangulation and the median polygon area is multiplied by the number of turbines.	2.8 W/m^2 (mean)	0.9 W/m^2
Theoretical approaches			
spacing-diameter[36,45,64,86,109]	The spacing required between the turbines is calculated as rotor diameter multiplied by a given coefficient that mostly often varies in the range of five to nine.	7.2 W/m^2	3.7 W/m^2
diameter-buffer[65]	A buffer is applied with a radius equal to five rotor diameters around each turbine.	-	2.9 W/m^2

The suitability of LURs derived from official documentation, i.e., estimates using the reported methodology, has been questioned as likely to overestimate the required land-use area[18,23], but we find estimates of similar magnitude to the other two empirical approaches that explicitly report spacing. We furthermore validated reported LURs by comparing reported and convex-hull estimates for seven wind parks, where LURs for each park were quantified by both approaches. Noland et al.[12] applied the convex hull approach to measure spacing land-use, whereas Denholm et al.[23] extracted the land-use of the same parks from official documentation. The comparison showed a minor difference between their means: the average *capacity-area* of convex-hull-based LURs was 4.15 W/m^2, whereas project-based LURs yielded 4.18 W/m^2. Therefore, project-based LURs appear to be in-line with the location-based estimate, although estimates for single parks can differ significantly between the two approaches.

After controlling variability for differences in methodology and land-use definitions, there remains considerable variability in wind power LURs. These differences most likely can be explained by location specific factors but would require additional meta-data for a full assessment. In particular, LURs reporting physical infrastructure or temporary areas vary within two orders of magnitude within each group. Data that includes the facility's capacity, the land area and the number of turbines showed that generating capacities of plants and the number of turbines both strongly correlate with the occupied land area (defined as the physical infrastructure area). However, in some cases the land-use area of two plants with the same capacity and number of turbines can vary by up to 50%. This might be attributed to the layout, climatic conditions, technological developments, legal or administrative conditions or other context-dependent factors. Although the literature mentions the potential influence of these factors, the reviewed publications do not report location-specific conditions comprehensively. When the land-use is defined by the temporary area of the facility, no correlation between capacity and the temporary area used by the plant could be observed. Thus, the role of context-dependent factors in explaining the variability in LUR estimates is even stronger for this type of land-use.

There is a strong bias in the number of publications available per different land-use definitions of onshore wind technology. Mostly, land-use is defined by spacing area. 52% of the reviewed publications define their land-use by spacing area, 16% of all publications by physical infrastructure, and only one publication reported temporary areas. Furthermore, the remaining 28% of publications that provided LURs for onshore wind technology did not provide any clear documentation regarding the areas included in the estimates, indicating that improved data documentation can decrease uncertainties considerably.

We finally show that mean *capacity-area* LURs from the report by Denholm et al.[23], which was most often cited as source for capacity-area spacing LURs in our sampled publications, differ significantly from other publications: estimates vary by -30%[34,35] to +1000%[12] relative to Denholm et al[23]. The potential for wind power will linearly scale with the assumptions taken for those values, thus implying a major source of uncertainty. Interestingly, although the report was released more than two decades ago, some recent publications estimated lower LURs, i.e., 30% lower *capacity-area* values[16,34,35], than the ones found in the report.

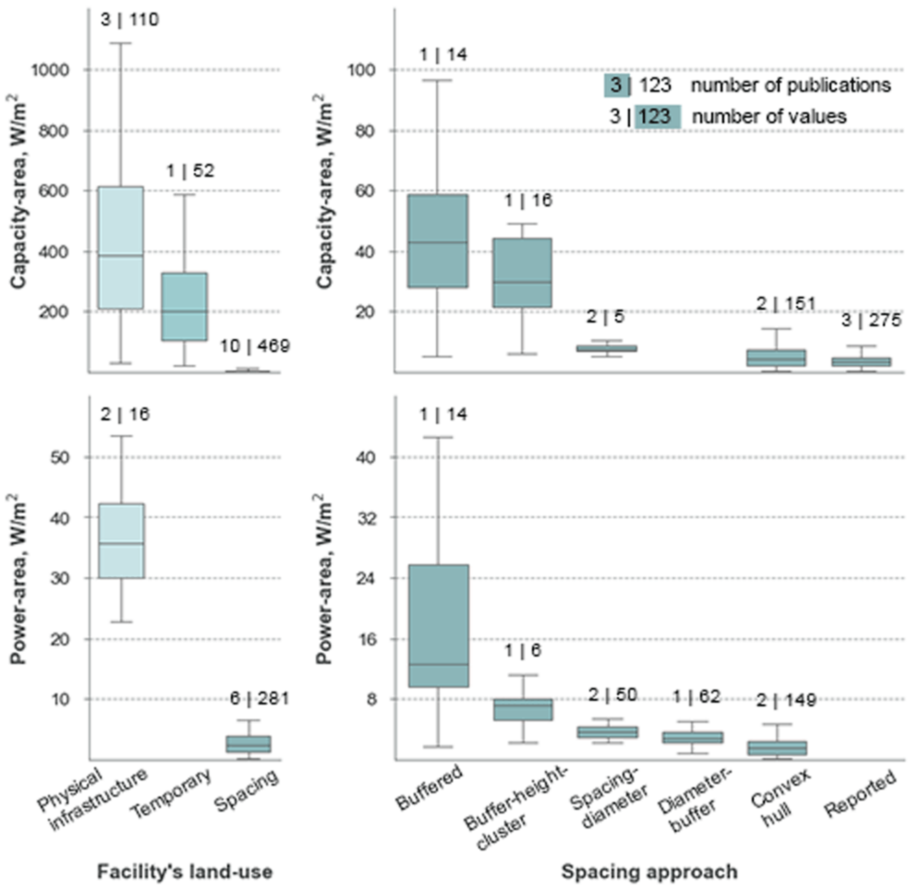

Figure 5. LUR per land-use and spacing approach for wind power: a) median LURs depending on different types of facility's land-use, b) the difference across different spacing approaches to quantify spacing of the facility. Outliers are excluded in both figures. Total number of spacing LURs on the right side are not equal to the number of spacing LURs on the left side as the box plots on the right exclude spacing LURs that did not report the spacing approach.

5. LURs FOR SOLAR PV TECHNOLOGIES

The internal variability of LURs for solar PV technology is considerably lower than for onshore wind technology: its *capacity-area* varies from 0.6 to 209.2 W/m^2, and the range for *power-area* is between 0.1 and 150 W/m^2. Similarly to onshore wind technology, we accounted for the definition of the facility's land-use and the methodology used for obtaining its boundaries to disentangle the variability of LURs for solar PV technology. In addition, we took into account the main types of solar PV technology, i.e., fixed axis, single- and double-tracking axes. Unfortunately, 24% of publications reporting solar PV LURs did not provide the type of PV technology and therefore were discarded from the further analysis. This also reduced the pool of analysed definitions, as the discarded LURs estimates defined the facility's land-use not only by including physical infrastructure and spacing area, but also assessing temporary and remote areas. The physical infrastructure area includes only PV modules or arrays and other infrastructural elements in the land-use of the facility. The spacing area, in addition to the PV modules or arrays of PV modules, includes the area between the arrays necessary for servicing the facility and minimising shading. Sometimes this area is defined through the legal, fenced or leased land officially declared as belonging to the facility[46,58,74]. Fixed solar PV LURs are most frequently reported in the literature (50% of values), followed by single-tracking PV (22%), and double-tracking PV (5%). The corresponding LURs included either physical infrastructure or spacing areas.

Changes in variability are explained by gradually including explanatory factors and reporting the corresponding median. Firstly, we analyse how the definition of the facility's land-use contributes to variability. The majority of solar PV LURs define a facility's area as the spacing area of the facility. Only LURs for fixed solar PV were defined using a physical infrastructure definition[46,94] (figure 6). The median *capacity-area* LURs for fixed solar PV defined by physical infrastructure are 2.8 times larger than those defined by spacing area, i.e., 110.4 W/m^2 and 39.4 W/m^2, respectively. Although this is a much lower difference between land-use definitions for physical infrastructure and spacing area than is the case for wind power, it still suggests that the spacing area required for solar PV panels is significant. The median physical infrastructure LURs and the spacing area for the *power-area* of fixed solar PV, are 4.8 W/m^2 and 3.7W/m^2, respectively. As the data on *power-area* LURs is scarce regardless of the definition, we cannot conclude about the underlying reasons for the small difference between these two values.

We found a lower variety of approaches to obtain the boundaries for LURs of solar PV technologies compared to wind power. They include (a) manual delineation on ortho-photos[12,24,28,38,46,49,98], (b) automated detection[42], (c) extraction from documentation[29,30,40,41,48,53,68,71,74,78,89,90,94,96], and (d) theoretical assessments[28,58,59,80]. Once we consider only LURs that explicitly mention the type of solar PV technology, the list of approaches reduces to three, as LURs derived by automated detection have to be excluded. When comparing across solar PV technologies, we compared only LURs using the manual detection method, assessing spacing area. For the other methods, insufficient data was available. Nevertheless, controlling for the type of technology considerably reduces variability. As the flexible tilt requires more spacing land for the shading adjustment, the median *capacity-area* LURs for fixed solar PV (40.1 W/m^2) is higher than for single- and double-tracking ones (31.2 W/m^2 and 30.9 W/m^2). The tracking panels require more space between the rows for their tilt to adjust during operation. However, the variability across different facilities within the same technology type is lower for tracking solar PV. *Capacity-area* LURs for fixed solar PV ranges from 18.9 W/m^2 to 110 W/m^2, whereas for single-tracking solar PV the range reduces to 19.1-65.7 W/m^2 and to 17.1-49.4 W/m^2 for double-tracking solar PV.

Once *power-capacity* is considered, the difference between the median of fixed and single-tracking solar PV is very low, i.e., 3.6 W/m^2 and 3.9 W/m^2, as tracking PV has higher output per capacity. The variability of single-tracking PV LURs is within the range of fixed PV that has a wider spread due to a higher number of data points.

The report by Ong et al.[24] was the most often cited source for PV LURs in our sample of literature. The average *capacity-area* LUR for fixed solar PV parks equals 43 W/m^2. All other values are higher than the LURs provided by Ong et al.[24], indicating lower solar PV land-use, and range from 4% to 132%[61,69] However, the highest relative difference is for LURs estimated in a semi-theoretical approach, i.e., by applying a factor to estimate the area used by solar PV[61].

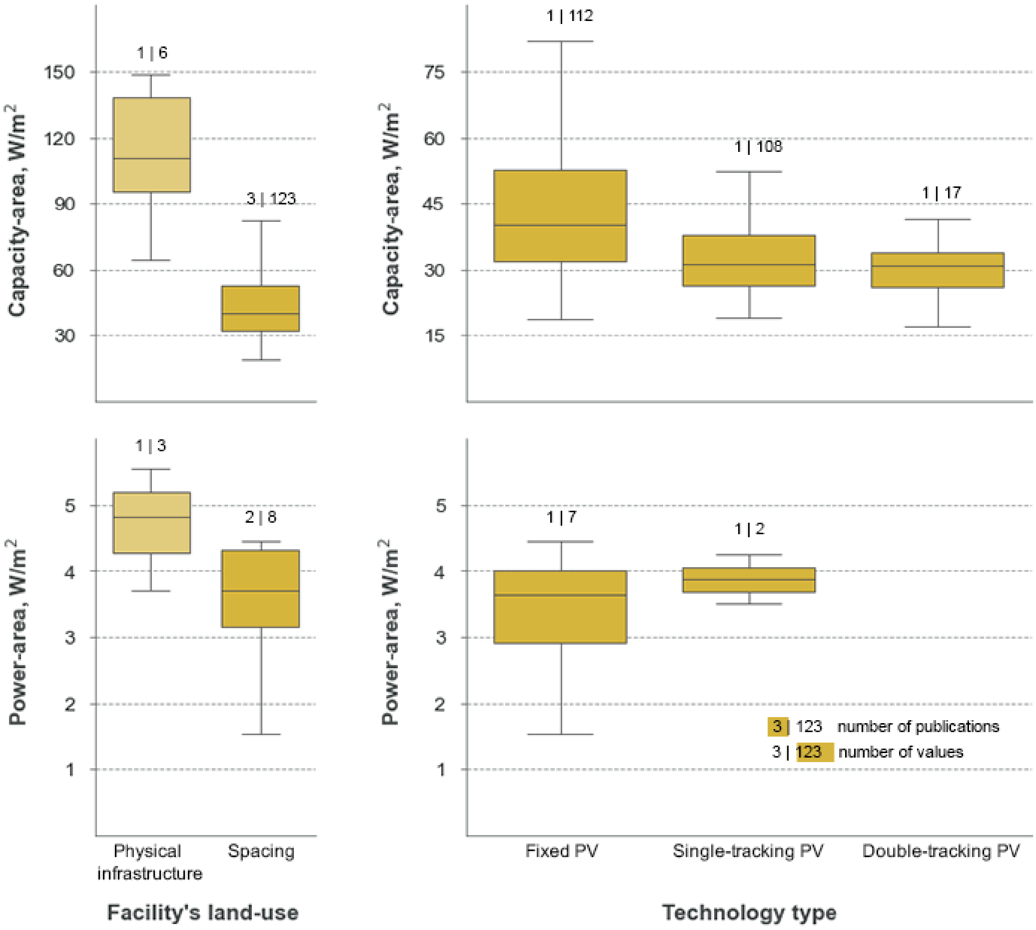

Figure 6. The variability of solar-PV LURs: a) a comparison of LURs for fixed solar PV across a facility's land-use type and b) difference of solar PV LURs across technologies for spacing areas.

6. LURs FOR CSP TECHNOLOGIES

Similar to solar PV, the variability of LURs for CSP technologies is much lower than for wind power. This applies to capacity-area LURs that vary from 4.5 W/m^2 to 172 W/m^2 as well as to power-area LURs that range from 0.8 W/m^2 to 62.1 W/m^2. In total, there are significantly fewer estimates of land-use for CSP than for wind and solar projects, mainly due to the low number of installed plants globally. Nevertheless, the available data is sufficient to explore the variability of CSP LURs. In contrast to solar PV, CSPs are represented by a wider range of technologies, i.e., Stirling dish, trough, hybrid trough, tower, Fresnel. In addition, 6% of CSP LURs data did not provide the type of technology, and hence were excluded.

In the case of CSP technologies it was impossible to explore the effect of various land-use definitions on variability as the facility's land-use type was defined as spacing area exclusively. However, we could assess how variability is affected by the approach used to establish the facility's boundaries (figure 7). Here, we found manually measured values[24,28] and values extracted from reports[22,29–31,77,82,100]. Sufficient data was available to evaluate *capacity-area* LURs quantified with two different methods for three types of CSP technologies — Fresnel, trough and tower. Overall, consistently for these technologies, manually measured LURs show higher LURs than those extracted from reports. CSP Fresnel technology LURs are particularly high in terms of *capacity-area*, with a median of 88.2 W/m^2, when measured manually. LURs of remaining sub-technologies have less of a difference between the two approaches. LURs of the other two technologies, in contrast, are similar and do not exceed 60 W/m^2. Once the LUR is measured in terms of power output, only LURs extracted from reports are available. All technologies demonstrate quite low variability and remain within the same range relative to each other. In this case, the CSP trough LUR has the highest median of 9.1 W/m^2, while CSP Fresnel has 8 W/m^2 and CSP tower has 6.6 W/m^2. Overall, the values are however in a similar range.

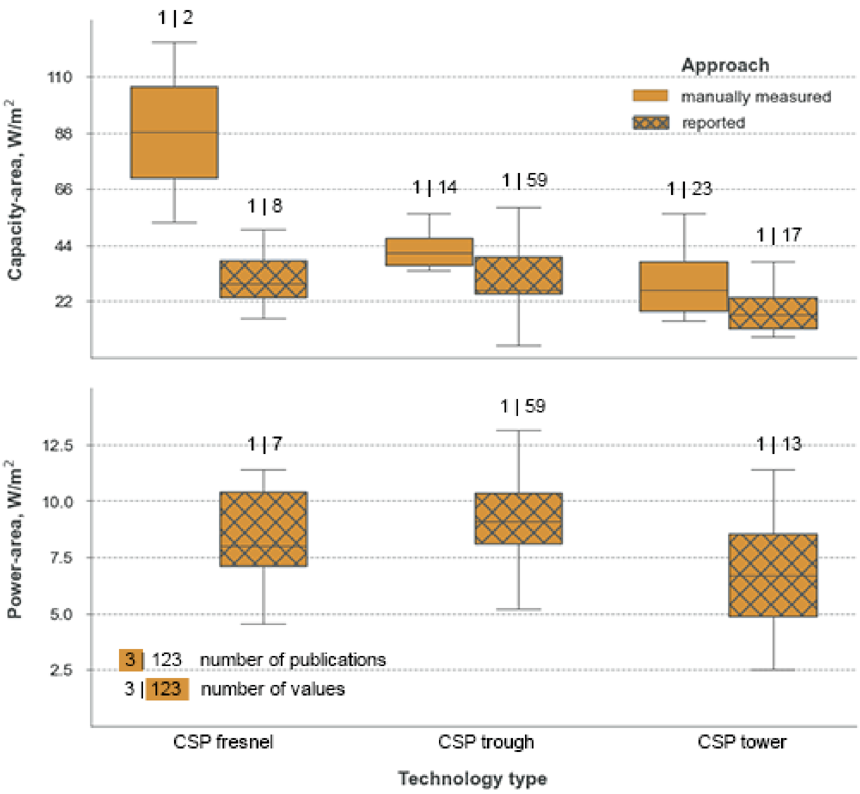

Figure 7. Variability of capacity-area and power-area LURs of CSP, grouped by technology and method used to define LUR.

7. FURTHER RESEARCH AND BEST PRACTICES

Reducing the uncertainties of LURs of renewable energy technologies and gaining better understanding of their variability is an overarching research goal, necessary to improve assumptions in energy system models, improve the planning of future renewable energy systems, and manage the related socio-environmental impacts. In the following, we discuss several research directions that assist attaining this goal.

Our literature search resulted in more than 2000 data points on LURs for all three technologies, however this body of literature is regionally strongly biased towards the US, and towards wind power and solar PV technologies. The low diversity in regional coverage makes it impossible to consistently compare different regions in terms of LURs, and how LURs dynamically developed in different regions. Future research should therefore focus on facilities installed in regions outside of the US and the EU. Such knowledge would improve the planning of future facilities as well as assist in studying the potential influence of regionally specific factors, such as legislative and administrative rules, on LURs globally.

Currently, little is known on how LURs have transformed over time, e.g., through the impact of technological development and context-specific factors. Some research analysed dynamic changes in LURs, e.g., van Zalk et al.[21] assessed changes in power density over time based on a very limited review of LURs in existing publications, whereas Harrison-Atlas, et al.[18] analysed changes in LURs for wind power on a large pool of US facilities, but did not provide the single LURs derived in the analysis. In this review, we were therefore unable to obtain sufficient data to consistently assess changes of LURs over time. Therefore, future work should evaluate the temporal development of LURs, using a larger pool of data from different global regions.

A variety of methods exist to delineate the boundaries of a facility's land-use, and these methodological choices do affect final estimates. In particular for the spacing area of wind power, results can vary substantially due to different methods, but we observed substantial variability for solar PV and CSP too. To reduce uncertainties and improve existing methods, we encourage to conduct comparisons of LURs estimated using different methodological approaches for a large pool of the same facilities. This would also increase our understanding why areas extracted from reports showed lower LURs than those estimated with other methods for CSP. Although we found that reported LURs are quite close to ones derived using the convex hull approach for wind parks, this conclusion should be verified for a larger pool of data.

Understanding real-world factors that influence the variability of LURs is essential for all technologies but in particular for wind power. Physical infrastructure LURs for wind parks show very high variability even after accounting for methodological differences. The assumption that context-dependent factors explain these differences has to be verified. In this context, accounting for the spatial layout of the facility will be necessary.

For solar PV and CSP, the extent of difference between physical infrastructure and spacing area is uncertain when comparing the existing literature. Thorough assessments, which empirically measure both quantities are necessary to reduce these uncertainties. In particular, determining the outer boundaries of parks in detail is crucial, as these are often hard to derive from the available data.

Sub-technologies of Solar PV and CSP affect the respective LURs. However, due to high uncertainty ranges for different technologies, LURs across sub-technologies must be investigated in more detail using consistent methodology for both solar PV and CSP. Also, in the case of solar PV, it should be further explored why the variability of LURs for single-tracking PV is lower than for fixed PV.

SUGGESTIONS TO ESTIMATE AND REPORT LURs

The choice of a term for LURs in a study usually follows the naming conventions of a particular scientific field. Nevertheless, these terms might lead to misinterpretations by readers unfamiliar with the field. Using one of the **meta-metrics** proposed by us to additionally name LURs is recommended to simplify their interpretation.

To reduce uncertainties arising from methodological choices, we recommend to indicate explicitly how the **land-use of the facility** was defined (physical infrastructure only, spacing area, temporary or remote infrastructure). Here, we provide indicative definitions for each type of the facility's land-use, however each study should adapt it to its own conditions (figure 8). For assessments of physical infrastructure area, exact infrastructural elements included should be reported, while reporting the purpose of the temporary land-use by the facility when deriving temporary areas. Reporting remote areas should mention which kind of considered remote infrastructure is crucial. For spacing areas, a thorough description of the approach to its estimation and reporting the infrastructural elements covered by the approach is important.

The approach to delineate the **boundaries of the facility** mainly depends on the study design and the pool of the available facilities. Deriving LURs of existing renewable facilities or estimating them for future — theoretical — facilities sometimes uses simple assumptions on how chosen technologies and LURs interact (e.g., determining spacing of wind parks by multiple of the rotor diameter or a packing factor and centroid buffering for solar PV). In these cases, spacing area LURs are derived. While in principle we recommend using empirically observed LURs over such theoretical ones, sometimes this is not possible: e.g., studies may assess technologies which currently do not exist (such as very large wind turbines), and which therefore require the application of theoretical approaches. We observed, however, that the parameters chosen in theoretical approaches underestimate LURs when compared to empirical estimates. Therefore, we recommend validating chosen parameters against existing facilities, if possible in the case-study area (e.g., assess if the used multiple of rotor diameters or buffer diameter can explain LURs of existing parks before applying it to a new technology).

Deriving LURs for physical infrastructure areas is a tedious task, both if done manually or automatically by means of remote sensing. Luckily, some recent studies provide land-use areas for wind and solar parks globally[113,114]. Matching these datasets with accurate locally available data on capacity or generation can constitute a rapid way of deriving LURs. We recommend partial — manual — validation against manual delineation however. Also, the physical infrastructure area as well as temporary and remote areas can often be found in the documentation or in reports on existing facilities.

For determining spacing areas for wind power, the choice of approaches is more versatile. If the location of the turbines is given, the empirical approaches shown in figure 8 are suitable. Note that while the spacing area of a wind park can be extracted from official documentation, it is worth comparing extracted values with existing LURs or conducting visual checks on the overlap between the reported land-use area and the turbines. The buffer-spacing-diameter approach tends to considerably underestimate spacing area and overestimate physical infrastructure area. Therefore, we advise applying this method with great caution. For solar PV and CSP facilities, manual and automatic detection as well as reports are frequently used to delineate the spacing area. We observed — also from our own experience — that manual detection captures well the area in-between the arrays of panels, however the area around the facility might be less certain. Potentially, reports can provide more accurately delineated boundaries, for instance when the fenced area is reported. However, one should carefully study available documentation to verify which areas are in fact reported.

Finally, we would like to underline the importance of clear and accurate documentation for estimating LURs. This is highly valuable for the further usage and assessment of LURs. In particular, this concerns the facility's land-use type and approaches to delineate the boundaries. These two parameters have been frequently neglected in the literature, yet, appear to be responsible for a great deal of uncertainties identified in the literature. Our suggestion on explicit reporting of LUR’s parameters is shown in figure S3 in the SI.

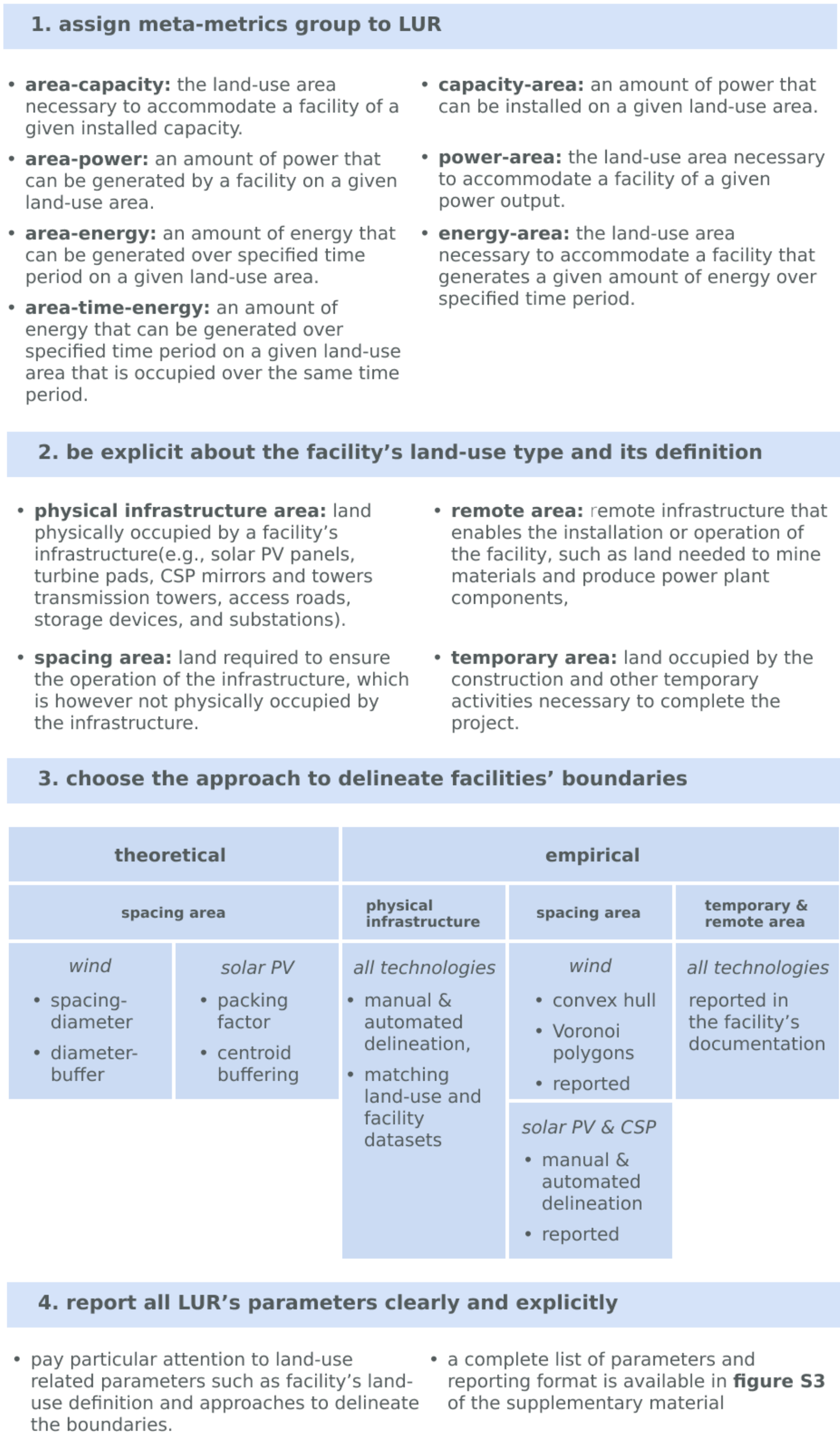

Figure 8. Recommendations' summary to estimate and report LURs

RECOMMENDATIONS TO SELECT AND USE LURs

As we demonstrated here, a large pool of LURs exist in literature, however they have plenty of nuances that must be considered once applying LUR data in a study. The following recommendations help to make a more informed choice of LURs for applications from the existing literature and our own database.

The type of application determines which LUR should be used. Direct land-use change of renewable infrastructure is best measured by LURs which are based solely on physical infrastructure and exclude the spacing of facilities. Biodiversity and ecosystem impacts, potentials for future renewable development, and economic and social impacts[3,5,9] are — in most cases — best studied with spacing area LURs, as they consider all land necessary for operating a facility. Some of such applications might also need to consider temporary or remote LURs in their analysis, depending on the scope. For solar PV and wind power, estimates for all these categories are available, but there are no LUR estimates for physical infrastructure for CSP at the moment.

In terms of the power component, we recommend choosing LURs that rely on capacity instead of power generation. Power generation depends highly on local climatic conditions. If independent estimates of power generation for the location of interest are available, these should therefore be combined with LUR estimates from literature based on capacity. Thus, much more specific estimates of land-use can be derived, than using more generic power generation based LURs.

It is also highly relevant to consider how the boundaries of facilities were delineated when choosing LURs. For physical infrastructure LURs for wind and solar PV, the most common approaches are manual or automated delineation of land occupation of facilities or values reported in official documentation. All approaches are in principle suitable, if however legal conditions such as land tenure are relevant for the study, we recommend focusing on reported LURs. It is more likely that these contain legal boundaries of the facility, e.g., fenced area. For spacing LURs, more approaches to delineation exist and they differ depending on technology. For wind power, location-based methods such as convex hull, Voronoi polygons and reports agree on the spacing requirements and therefore likely capture existing patterns of wind turbine siting well. We recommend avoiding LURs based on methods such as spacing-diameter or buffered or buffered-spacing-cluster as they are highly dependent on the choice of uncertain parameters. Existing assessments tend to use parameters which underestimate LURs. In the case of PV and CSP, the range of methods found in literature is smaller. For these technologies, manual delineation and reports were used in the literature to obtain spacing land-use.

Sometimes, wind parks and solar PV LURs are estimated based on certain geometrical assumptions regarding spacing of the facility. Such theoretical approaches are more uncertain and are not based on existing facilities, therefore we suggest avoiding these LURs. If that is the only available option, we recommend estimating your own LURs, verifying your assumptions against empirical observations (see recommendations for LUR developers).

If possible, we recommend to use LURs that are as close as possible to the context of the case-study in terms of technology, time and location. In particular for solar PV and CSP — technologies that have pronounced variability across sub-technologies — it is important to choose LURs quantified for that type of sub-technology.

Furthermore, we recommend using statistical aggregates such as medians or means when using LURs to understand land-use requirements of renewable energies in a larger context, as the variability of LURs is high, even when controlling for differences in methodology and area assessed. Furthermore, we recommend showing spreads of results depending on different assumptions for LURs.

8. CONCLUSIONS

This review consists of more than 2000 LUR values found in literature and comprehensively analyses the state-of-the-art of LUR assessments for renewable technologies. We assessed definitions of LURs and methodologies used to quantify them to explain variabilities and reduce uncertainties when comparing different LUR approaches. Despite a fuzzy terminology, we were able to aggregate and harmonise all estimates to four major meta-metrics that facilitate understanding the meaning and purpose of the respective LUR estimates. Any LUR consists of two major components: power or capacity and land-use. As methodologies to measure or estimate power and capacity are well understood, we focused on assessing the land-use component of LURs. Land-use of renewable facilities is defined in almost all cases as either physical infrastructure area only, spacing area or project area of the facility. This definition, as well as methodologies used to determine the respective boundaries, significantly impact the extent of LURs. For wind power, we showed that determining spacing area by convex hulls, Voronoi polygons or project area yields similar results when comparing average or median values. Other approaches to defining spacing areas may show higher land-use efficiency, potentially underestimating the required spacing areas. In particular, the buffer-height-cluster method seems to yield too optimistic estimates. Furthermore, we showed that land-use of solar PV sub-technologies (tracking vs fixed) is comparable once a facility's generation is considered but differs strongly when only capacities are regarded. For CSP, manual measurements of land-use are more efficient than values taken from reports, i.e., project areas.

Although we gathered many different LUR estimates, their in-depth systematic assessment was limited due to lacking meta-data. The reviewed publications frequently did not provide information on the type of land-use included, methodologies to quantify the LURs, or the type of sub-technologies, among others. Such a lack of meta-data implies that, first, the current understanding of LURs is still superficial and, second, researchers that use LURs in their applications might risk misusing them. Additionally, data were strongly skewed towards US and Europe, hence, very much limiting the possibility of exploring regional differences. Furthermore, our stylized experiment showed that variability stemming from LURs is as large as the variability found in decarbonization scenarios, implying that those assessments may wrongly inform policy decisions. Therefore, we recommend that any studies using LURs should comprehensively assess the inherent variability, including environmental and technological factors, the type of facility land-use considered and the methodologies to quantify them. Consistent and thorough reporting of LUR's metadata is essential to enable such assessments in the future. Therefore, we offer an approach to standardise reporting for the newly quantified LURs and a concise guide for researchers who need to navigate LURs with little prior knowledge.

ACKNOWLEDGMENTS

We gratefully acknowledge support from the European Research Council (''reFUEL'' ERC-2017-STG 758149).

DECLARATION OF INTERESTS

The authors declare no competing interests.

AUTHORS CONTRIBUTIONS

O.T., conceptualization, methodology, investigation, formal analysis, writing – original draft, visualization, writing – original draft; K.G., investigation, writing – review & editing; M.K., writing – investigation, review & editing; C.K., writing – investigation, review & editing; L.R.C., methodology, investigation, writing – review & editing; P.R., investigation, writing – review & editing; S.W., investigation, writing – review & editing; J.S., funding acquisition, conceptualization, methodology, investigation, writing – original draft.

REFERENCES

1. Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2023). (Cambridge University Press) 10.1017/9781009157926.
2. Palmer-Wilson, K., Donald, J., Robertson, B., Lyseng, B., Keller, V., Fowler, M., Wade, C., Scholtysik, S., Wild, P., and Rowe, A. (2019). Impact of land requirements on electricity system decarbonisation pathways. Energy Policy *129*, 193–205. 10.1016/j.enpol.2019.01.071.
3. Akella, A.K., Saini, R.P., and Sharma, M.P. (2009). Social, economical and environmental impacts of renewable energy systems. Renewable Energy *34*, 390–396. 10.1016/j.renene.2008.05.002.
4. Schmidt, J., Gruber, K., Klingler, M., Klöckl, C., Ramirez Camargo, L., Regner, P., Turkovska, O., Wehrle, S., and Wetterlund, E. (2019). A new perspective on global renewable energy systems: why trade in energy carriers matters. Energy Environ. Sci. *12*, 2022–2029. 10.1039/C9EE00223E.
5. McKenna, R., Pfenninger, S., Heinrichs, H., Schmidt, J., Staffell, I., Bauer, C., Gruber, K., Hahmann, A.N., Jansen, M., Klingler, M., et al. (2022). High-resolution large-scale onshore wind energy assessments: A review of potential definitions, methodologies and future research needs. Renewable Energy *182*, 659–684. 10.1016/j.renene.2021.10.027.
6. McDonald, R.I., Fargione, J., Kiesecker, J., Miller, W.M., and Powell, J. (2009). Energy Sprawl or Energy Efficiency: Climate Policy Impacts on Natural Habitat for the United States of America. PLOS ONE *4*, e6802. 10.1371/journal.pone.0006802.
7. Trainor, A.M., McDonald, R.I., and Fargione, J. (2016). Energy Sprawl Is the Largest Driver of Land Use Change in United States. PLoS ONE *11*, e0162269. 10.1371/journal.pone.0162269.
8. Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky, B.L., Boer, H.S. de, Fricko, O., Hejazi, M., Humpenöder, F., Iyer, G., et al. (2019). Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. Nat Commun *10*, 1–13. 10.1038/s41467-019-13067-8.
9. Holland, R.A., Scott, K., Agnolucci, P., Rapti, C., Eigenbrod, F., and Taylor, G. (2019). The influence of the global electric power system on terrestrial biodiversity. PNAS *116*, 26078–26084. 10.1073/pnas.1909269116.
10. Rahman, A., Farrok, O., and Haque, M.M. (2022). Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal,

ocean, and osmotic. Renewable and Sustainable Energy Reviews *161*, 112279. 10.1016/j.rser.2022.112279.

11. Fthenakis, V., and Kim, H.C. (2009). Land use and electricity generation: A life-cycle analysis. Renewable and Sustainable Energy Reviews *13*, 1465–1474. 10.1016/j.rser.2008.09.017.
12. Nøland, J.K., Auxepaules, J., Rousset, A., Perney, B., and Falletti, G. (2022). Spatial energy density of large-scale electricity generation from power sources worldwide. Sci Rep *12*, 21280. 10.1038/s41598-022-25341-9.
13. Lovering, J., Swain, M., Blomqvist, L., and Hernandez, R.R. (2022). Land-use intensity of electricity production and tomorrow's energy landscape. PLOS ONE *17*, e0270155. 10.1371/journal.pone.0270155.
14. Capellán-Pérez, I., de Castro, C., and Arto, I. (2017). Assessing vulnerabilities and limits in the transition to renewable energies: Land requirements under 100% solar energy scenarios. Renewable and Sustainable Energy Reviews *77*, 760–782. 10.1016/j.rser.2017.03.137.
15. Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J., Lamboll, R., Nicholls, Z., Sandstad, M., Smith, C., et al. (2022). AR6 Scenarios Database. Version 1.1 (Zenodo). 10.5281/ZENODO.5886911 10.5281/ZENODO.5886911.
16. Harrison-Atlas, D., Maclaurin, G., and Lantz, E. (2021). Spatially-Explicit Prediction of Capacity Density Advances Geographic Characterization of Wind Power Technical Potential. Energies *14*, 3609. 10.3390/en14123609.
17. Wachs, E., and Engel, B. (2021). Land use for United States power generation: A critical review of existing metrics with suggestions for going forward. Renewable and Sustainable Energy Reviews *143*, 110911. 10.1016/j.rser.2021.110911.
18. Harrison-Atlas, D., Lopez, A., and Lantz, E. (2022). Dynamic land use implications of rapidly expanding and evolving wind power deployment. Environ. Res. Lett. *17*, 044064. 10.1088/1748-9326/ac5f2c.
19. Chiabrando, R., Fabrizio, E., and Garnero, G. (2009). The territorial and landscape impacts of photovoltaic systems: Definition of impacts and assessment of the glare risk. Renewable and Sustainable Energy Reviews *13*, 2441–2451. 10.1016/j.rser.2009.06.008.
20. Horner, R.M., and Clark, C.E. (2013). Characterizing variability and reducing uncertainty in estimates of solar land use energy intensity. Renewable and Sustainable Energy Reviews *23*, 129–137. 10.1016/j.rser.2013.01.014.
21. van Zalk, J., and Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. Energy Policy *123*, 83–91. 10.1016/j.enpol.2018.08.023.
22. Nadler, A.D. (1977). Planning Aspects of Direct Solar Energy Generation. Journal of the American Institute of Planners *43*, 339–351. 10.1080/01944367708977897.
23. Denholm, P., Hand, M., Jackson, M., and Ong, S. (2009). Land Use Requirements of Modern Wind Power Plants in the United States 10.2172/964608.
24. Ong, S., Campbell, C., Denholm, P., Margolis, R., and Heath, G. (2013). Land-Use Requirements for Solar Power Plants in the United States 10.2172/1086349.
25. Area Used by Wind Power Facilities [AWEO.org] http://www.aweo.org/windarea.html.
26. Renewable Energy Technology Characterizations (1997). (Electric Power Research Institute, Inc. and U.S. Department of Energy).

27. Ciliberti, C., Jordaan, S.M., Smith, S.V., and Spatari, S. (2016). A life cycle perspective on land use and project economics of electricity from wind and anaerobic digestion. Energy Policy *89*, 52–63. 10.1016/j.enpol.2015.11.015.

28. MacKay, D.J.C. (2013). Solar energy in the context of energy use, energy transportation and energy storage. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences *371*, 20110431. 10.1098/rsta.2011.0431.

29. Hernandez, R.R., Hoffacker, M.K., and Field, C.B. (2014). Land-Use Efficiency of Big Solar. Environ. Sci. Technol. *48*, 1315–1323. 10.1021/es4043726.

30. SunShot Vision Study (2012). (National Renewable Energy Laboratory).

31. CSP.guru 2021-07-01 10.5281/zenodo.5094290.

32. Turney, D., and Fthenakis, V. (2011). Environmental impacts from the installation and operation of large-scale solar power plants. Renewable and Sustainable Energy Reviews *15*, 3261–3270. 10.1016/j.rser.2011.04.023.

33. Kalogirou, S.A. (2013). Solar thermoelectric power generation in Cyprus: Selection of the best system. Renewable Energy *49*, 278–281. 10.1016/j.renene.2012.01.014.

34. Miller, L.M., and Keith, D.W. (2018). Observation-based solar and wind power capacity factors and power densities. Environ. Res. Lett. *13*, 104008. 10.1088/1748-9326/aae102.

35. Miller, L.M., and Keith, D.W. (2019). Corrigendum: Observation-based solar and wind power capacity factors and power densities (2018 Environ. Res. Lett. 13 104008). Environ. Res. Lett. *14*, 079501. 10.1088/1748-9326/aaf9cf.

36. Smil, V. (2015). Power density: a key to understanding energy sources and uses (The MIT Press).

37. Final Programmatic Environmental Impact Statement on on BLM-Administered Lands in the Western United States (2005). (U.S. Department of the Interior Bureau of Land Management).

38. Bolinger, M., and Bolinger, G. (2022). Land Requirements for Utility-Scale PV: An Empirical Update on Power and Energy Density. IEEE Journal of Photovoltaics *12*, 589–594. 10.1109/JPHOTOV.2021.3136805.

39. Enevoldsen, P., and Jacobson, M.Z. (2021). Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide. Energy for Sustainable Development *60*, 40–51. 10.1016/j.esd.2020.11.004.

40. Calvert, K.E. (2018). Measuring and modelling the land-use intensity and land requirements of utility-scale photovoltaic systems in the Canadian province of Ontario. Canadian Geographies / Géographies canadiennes *62*, 188–199. 10.1111/cag.12444.

41. Calvert, K., and Mabee, W. (2015). More solar farms or more bioenergy crops? Mapping and assessing potential land-use conflicts among renewable energy technologies in eastern Ontario, Canada. Applied Geography *56*, 209–221. 10.1016/j.apgeog.2014.11.028.

42. Assessing the Potential for Renewable Energy on National Forest System Lands (2005). (National Renewable Energy Laboratory, Golden, CO (US)).

43. Gagnon, L., Bélanger, C., and Uchiyama, Y. (2002). Life-cycle assessment of electricity generation options: The status of research in year 2001. Energy Policy *30*, 1267–1278. 10.1016/S0301-4215(02)00088-5.

44. Dabiri, J.O. (2011). Potential order-of-magnitude enhancement of wind farm power density via counter-rotating vertical-axis wind turbine arrays. Journal of Renewable and Sustainable Energy *3*, 043104. 10.1063/1.3608170.

45. Lu, X., McElroy, M.B., and Kiviluoma, J. (2009). Global potential for wind-generated electricity. PNAS *106*, 10933–10938. 10.1073/pnas.0904101106.

46. de Castro, C., Mediavilla, M., Miguel, L.J., and Frechoso, F. (2013). Global solar electric potential: A review of their technical and sustainable limits. Renewable and Sustainable Energy Reviews *28*, 824–835. 10.1016/j.rser.2013.08.040.

47. Bernardi, M., Ferralis, N., Wan, J.H., Villalon, R., and Grossman, J.C. (2012). Solar energy generation in three dimensions. Energy Environ. Sci. *5*, 6880–6884. 10.1039/C2EE21170J.

48. Hernandez, R.R., Hoffacker, M.K., Murphy-Mariscal, M.L., Wu, G.C., and Allen, M.F. (2015). Solar energy development impacts on land cover change and protected areas. PNAS *112*, 13579–13584. 10.1073/pnas.1517656112.

49. Jordaan, S.M., Lee, J., McClung, M.R., and Moran, M.D. (2021). Quantifying the ecosystem services values of electricity generation in the US Chihuahuan Desert: A life cycle perspective. Journal of Industrial Ecology *25*, 1089–1101. 10.1111/jiec.13111.

50. Diffendorfer, J.E., and Compton, R.W. (2014). Land Cover and Topography Affect the Land Transformation Caused by Wind Facilities. PLOS ONE *9*, e88914. 10.1371/journal.pone.0088914.

51. Wolpert, J.L., and Riffat, S.B. (1996). Solar-powered Rankine system for domestic applications. Applied Thermal Engineering *16*, 281–289. 10.1016/1359-4311(95)00032-1.

52. Allen, M.F., and McHughen, A. (2011). Solar Power in the Desert: Are the current large-scale solar developments really improving California's environment?

53. Mount Signal Solar Power Plant, Imperial County, California Power Technology. https://www.power-technology.com/projects/mount-signal-solar-power-plant-imperial-county-california/.

54. Pletka, R., Block, S., Cummer, K., Gilton, K., O'Connell, R., Roush, B., Stoddard, L., Tilley, S., Woodward, D., and Hunsaker, M. (2007). Arizona Renewable Energy Assessment.

55. BrightSource (2014). IVANPAH Project facts.

56. Webster, I.A. (2010). National Brownfields Association Conference, Sacramento, CA.

57. Noone, C.J., Torrilhon, M., and Mitsos, A. (2012). Heliostat field optimization: A new computationally efficient model and biomimetic layout. Solar Energy *86*, 792–803. 10.1016/j.solener.2011.12.007.

58. Aronova, E.S., Grilikhes, V.A., and Shvarts, M.Z. (2008). Optimization of arrangement of photoelectric power plants with radiation concentrators in solar electric power plant design. Appl. Sol. Energy *44*, 237–242. 10.3103/S0003701X08040014.

59. Hyder, F., Baredar, P., Sudhakar, K., and Mamat, R. (2018). Performance and land footprint analysis of a solar photovoltaic tree. Journal of Cleaner Production *187*, 432–448. 10.1016/j.jclepro.2018.03.249.

60. Nitsch, F., Turkovska, O., and Schmidt, J. (2019). Observation-based estimates of land availability for wind power: a case study for Czechia. Energy, Sustainability and Society *9*, 45. 10.1186/s13705-019-0234-z.

61. Wirth, H. (2021). Recent Facts about Photovoltaics in Germany.

62. Trommsdorff, M., Kang, J., Reise, C., Schindele, S., Bopp, G., Ehmann, A., Weselek, A., Högy, P., and Obergfell, T. (2021). Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany. Renewable and Sustainable Energy Reviews *140*, 110694. 10.1016/j.rser.2020.110694.

63. Bakken, T.H., Aase, A.G., Hagen, D., Sundt, H., Barton, D.N., and Lujala, P. (2014). Demonstrating a new framework for the comparison of environmental impacts from small- and large-scale hydropower and wind power projects. Journal of Environmental Management *140*, 93–101. 10.1016/j.jenvman.2014.01.050.

64. Christie, D., and Bradley, M. (2012). Optimising land use for wind farms. Energy for Sustainable Development *16*, 471–475. 10.1016/j.esd.2012.07.005.

65. MacKay, D.J.C. (2013). Could energy-intensive industries be powered by carbon-free electricity? Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences *371*, 20110560. 10.1098/rsta.2011.0560.

66. Scognamiglio, A. (2016). 'Photovoltaic landscapes': Design and assessment. A critical review for a new transdisciplinary design vision. Renewable and Sustainable Energy Reviews *55*, 629–661. 10.1016/j.rser.2015.10.072.

67. de Simón-Martín, M., Alonso-Tristán, C., and Díez-Mediavilla, M. (2014). Sun-trackers profitability analysis in Spain. Progress in Photovoltaics: Research and Applications *22*, 1010–1022. 10.1002/pip.2347.

68. Prieto, P.A., Prieto, P.A., and Hall, C.A.S. (2013). Methods: Calculating the Energy Input. The Energy Invested (EI or Ein): Analyzing the Total Energy Costs of Photovoltaic Systems in Spain. In Spain's Photovoltaic Revolution SpringerBriefs in Energy. (Springer New York), pp. 61–113. 10.1007/978-1-4419-9437-0_6.

69. Kymakis, E., Kalykakis, S., and Papazoglou, T.M. (2009). Performance analysis of a grid connected photovoltaic park on the island of Crete. Energy Conversion and Management *50*, 433–438. 10.1016/j.enconman.2008.12.009.

70. Jungbluth, N., Stucki, M., Flury, K., Frischknecht, R., and Büsser, S. (2012). Life Cycle Inventories of Photovoltaics (Swiss Federal Office of Energy).

71. Schindele, S., Trommsdorff, M., Schlaak, A., Obergfell, T., Bopp, G., Reise, C., Braun, C., Weselek, A., Bauerle, A., Högy, P., et al. (2020). Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications. Applied Energy *265*, 114737. 10.1016/j.apenergy.2020.114737.

72. MacKay, D.J.C. (2011). Sustainable energy - without the hot air repr. (UIT Cambridge).

73. Poggi, F., Firmino, A., and Amado, M. (2018). Planning renewable energy in rural areas: Impacts on occupation and land use. Energy *155*, 630–640. 10.1016/j.energy.2018.05.009.

74. Valera, F., Bolonio, L., La Calle, A., and Moreno, E. (2022). Deployment of Solar Energy at the Expense of Conservation Sensitive Areas Precludes Its Classification as an Environmentally Sustainable Activity. Land *11*, 2330. 10.3390/land11122330.

75. European Environment Agency (2009). Europe's onshore and offshore wind energy potential : an assessment of environmental and economic constraints (Publications Office).

76. Solar Millennium AG (2008). The parabolic trough power plants Andasol 1 to 3 (Solar Millennium AG).

77. Ling-zhi, R., xin-gang, Z., Xin-xuan, Y., and Yu-zhuo, Z. (2018). Cost-benefit evolution for concentrated solar power in China. Journal of Cleaner Production *190*, 471–482. 10.1016/j.jclepro.2018.04.059.

78. Rej, S., and Nag, B. (2021). Energy crossroads and prioritization of energy choices: the case of India. OPEC Energy Review *45*, 135–158. 10.1111/opec.12201.

79. Reddy, K.S., and Kumar, K.R. (2012). Solar collector field design and viability analysis of stand-alone parabolic trough power plants for Indian conditions. Energy for Sustainable Development *16*, 456–470. 10.1016/j.esd.2012.09.003.

80. Kazim, A., and Veziroglu, T.N. (2001). Utilization of solar–hydrogen energy in the UAE to maintain its share in the world energy market for the 21st century. Renewable Energy *24*, 259–274. 10.1016/S0960-1481(00)00199-3.

81. Son, I.W., Jeong, Y.H., Choi, Y.J., and Lee, J.I. (2021). Feasibility study of solar-nuclear hybrid system for distributed power source. Energy Conversion and Management *230*, 113808. 10.1016/j.enconman.2020.113808.

82. Wu, X., Shao, L., Chen, G., Han, M., Chi, Y., Yang, Q., Alhodaly, M., and Wakeel, M. (2021). Unveiling land footprint of solar power: A pilot solar tower project in China. Journal of Environmental Management *280*, 111741. 10.1016/j.jenvman.2020.111741.

83. Venegas, R., Kuravi, S., Kota, K., and McCay, M. (2018). Comparative Analysis of Designing Solar and Geothermal Power Plants: A Case Study. International Journal of Renewable Energy Research (IJRER) *8*, 625–634.

84. Abd, M.K., Abdullah, H.N., Sun, H., and Cheng, S. (2018). Techno-economic Viability and Energy Conversion Analysis of RHES with Less Weight/Area. TELKOMNIKA (Telecommunication Computing Electronics and Control) *16*, 2331–2341. 10.12928/telkomnika.v16i5.8897.

85. Desai, N.B., and Bandyopadhyay, S. (2015). Integration of parabolic trough and linear Fresnel collectors for optimum design of concentrating solar thermal power plant. Clean Techn Environ Policy *17*, 1945–1961. 10.1007/s10098-015-0918-9.

86. Giani, P., Tagle, F., Genton, M.G., Castruccio, S., and Crippa, P. (2020). Closing the gap between wind energy targets and implementation for emerging countries. Applied Energy *269*, 115085. 10.1016/j.apenergy.2020.115085.

87. Reddy, K.S., and Veershetty, G. (2013). Viability analysis of solar parabolic dish stand-alone power plant for Indian conditions. Applied Energy *102*, 908–922. 10.1016/j.apenergy.2012.09.034.

88. Ludin, N.A., Mustafa, N.I., Hanafiah, M.M., Ibrahim, M.A., Asri Mat Teridi, M., Sepeai, S., Zaharim, A., and Sopian, K. (2018). Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review. Renewable and Sustainable Energy Reviews *96*, 11–28. 10.1016/j.rser.2018.07.048.

89. Spivey, H. (2020). Governing the Fix: Energy Regimes, Accumulation Dynamics, and Land Use Changes in Japan’s Solar Photovoltaic Boom. Annals of the American Association of Geographers *110*, 1690–1708. 10.1080/24694452.2020.1740080.

90. Manna, J., Jha, P., Sarkhel, R., Banerjee, C., Tripathi, A.K., and Nouni, M.R. (2021). Opportunities for green hydrogen production in petroleum refining and ammonia synthesis industries in India. International Journal of Hydrogen Energy *46*, 38212–38231. 10.1016/j.ijhydene.2021.09.064.

91. Raman, P., Murali, J., Sakthivadivel, D., and Vigneswaran, V.S. (2012). Opportunities and challenges in setting up solar photo voltaic based micro grids for electrification in rural areas of India. Renewable and Sustainable Energy Reviews *16*, 3320–3325. 10.1016/j.rser.2012.02.065.

92. Mohan, A. (2017). Whose land is it anyway? Energy futures & land use in India. Energy Policy *110*, 257–262. 10.1016/j.enpol.2017.08.025.

93. Kulik, A.C., Tonolo, É.A., Scortegagna, A.K., da Silva, J.E., and Urbanetz Junior, J. (2021). Analysis of Scenarios for the Insertion of Electric Vehicles in Conjunction with a Solar Carport in the City of Curitiba, Paraná—Brazil. Energies *14*, 5027. 10.3390/en14165027.

94. Dias, C.L. de A., Castelo Branco, D.A., Arouca, M.C., and Loureiro Legey, L.F. (2017). Performance estimation of photovoltaic technologies in Brazil. Renewable Energy *114*, 367–375. 10.1016/j.renene.2017.07.033.

95. de Jong, P., Kiperstok, A., and Torres, E.A. (2015). Economic and environmental analysis of electricity generation technologies in Brazil. Renewable and Sustainable Energy Reviews *52*, 725–739. 10.1016/j.rser.2015.06.064.

96. Carvalho, P.C.M., Machado, L.A., Vitoriano, C.T., and Fernández Ramírez, L.M. (2018). Land requirement scenarios of PV plants in Brazil. In Renewable Energy and Power Quality Journal, pp. 170–174. 10.24084/repqj16.252.

97. Ramirez-Tovar, A.M., Moreno-Chuquen, R., and Moreno-Quintero, R. (2022). Land-use in the Electric Colombian System: Hidden Impacts and Risks of Large-scale Renewable Projects. International Journal of Energy Economics and Policy *12*, 127–134. 10.32479/ijeep.11631.

98. Ramirez Camargo, L., Castro, G., Gruber, K., Jewell, J., Klingler, M., Turkovska, O., Wetterlund, E., and Schmidt, J. (2022). Pathway to a land-neutral expansion of Brazilian renewable fuel production. Nat Commun *13*, 3157. 10.1038/s41467-022-30850-2.

99. Maronga, A., Nyoni, K.J., Tuohy, P.G., and Shane, A. (2021). Evaluation of PV and CSP Systems to Supply Power in the Zimbabwe Mining Sector. Energies *14*, 3740. 10.3390/en14133740.

100. Relloso, S., and Gutiérrez, Y. (2017). SENER molten salt tower technology. Ouarzazate NOOR III case. AIP Conference Proceedings *1850*, 030041. 10.1063/1.4984384.

101. Mucci, J.M.H. (2015). Khi Solar One Project Overview and Economic Analysis.

102. Dahle, D., Elliott, D., Heimiller, D., Mehos, M., Robichaud, R., Schwartz, M., Stafford, B., and Walker, A. (2008). Assessing the Potential for Renewable Energy Development on DOE Legacy Management Lands 10.2172/924989.

103. Denholm, P., and Margolis, R. (2007). Regional Per Capita Solar Electric Footprint for the United States 10.2172/921203.

104. Fritsche, U., Berndes, G., Cowie, A., Dale, V.H., Kline, K.L., Johnson, F., Langeveld, H., Sharma, N., Watson, H., and Woods, J. (2017). Energy and land use (United Nations Convention to Combat Desertification and International Renewable Energy Agency).

105. Computing America's Offshore Wind Energy Potential Energy.gov. https://www.energy.gov/eere/articles/computing-americas-offshore-wind-energy-potential.

106. Kurt, M., Aksoy, A., and Sanin, F.D. (2015). Evaluation of solar sludge drying alternatives by costs and area requirements. Water Research *82*, 47–57. 10.1016/j.watres.2015.04.043.

107. Masters, G.M. (2004). Renewable and efficient electric power systems (Wiley).

108. Nonhebel, S. (2005). Renewable energy and food supply: will there be enough land? Renewable and Sustainable Energy Reviews *9*, 191–201. 10.1016/j.rser.2004.02.003.

109. Rinne, E., Holttinen, H., Kiviluoma, J., and Rissanen, S. (2018). Effects of turbine technology and land use on wind power resource potential. Nature Energy *3*, 494–500. 10.1038/s41560-018-0137-9.

110. Agostini, A., Colauzzi, M., and Amaducci, S. (2021). Innovative agrivoltaic systems to produce sustainable energy: An economic and environmental assessment. Applied Energy *281*, 116102. 10.1016/j.apenergy.2020.116102.

111. Barron-Gafford, G.A., Pavao-Zuckerman, M.A., Minor, R.L., Sutter, L.F., Barnett-Moreno, I., Blackett, D.T., Thompson, M., Dimond, K., Gerlak, A.K., Nabhan, G.P., et al. (2019). Agrivoltaics

provide mutual benefits across the food–energy–water nexus in drylands. Nature Sustainability *2*, 848–855. 10.1038/s41893-019-0364-5.

112. Patel, B., Gami, B., Baria, V., Patel, A., and Patel, P. (2018). Co-Generation of Solar Electricity and Agriculture Produce by Photovoltaic and Photosynthesis—Dual Model by Abellon, India. Journal of Solar Energy Engineering *141*. 10.1115/1.4041899.

113. Dunnett, S., Sorichetta, A., Taylor, G., and Eigenbrod, F. (2020). Harmonised global datasets of wind and solar farm locations and power. Sci Data *7*, 1–12. 10.1038/s41597-020-0469-8.

114. Kruitwagen, L., Story, K.T., Friedrich, J., Byers, L., Skillman, S., and Hepburn, C. (2021). A global inventory of photovoltaic solar energy generating units. Nature *598*, 604–610. 10.1038/s41586-021-03957-7.