Comments on: Land use for United States power generation: A critical review of existing metrics with suggestions for going forward (Renewable and Sustainable Energy Reviews 2021; 143: 110911)

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1. Introduction

Recently, a review paper titled "Land use for United States power generation: A critical review of existing metrics with suggestions for going forward" by Wachs and Engel was published in *Renewable and Sustainable Energy Reviews* [1]. We argue that this review was not fully objective in identifying "the most influential" papers and suffered from methodological flaws. The authors discuss the shortcomings of a "lack of transparency" and "inconsistent methodologies" of papers on land use associated with energy systems, but the paper itself does not adequately describe nor justify the review methods used to identify the most influential papers from which important conclusions are drawn. Wachs and Engel [1] report a 1) guide of commonly used metrics used to describe energy-land relationships, and 2) comparative analysis of land-use intensity across different energy systems, in which the methods for calculating commonness and land-use intensity are absent. Thus, this article itself may perpetuate the inconsistencies and biases present in the energy-land interactions literature.

We strongly agree with the need to address the research problem identified by Wachs and Engel [1], namely, that there exists striking inconsistencies in metrics used in the literature quantifying energy and land relationships; however, we assert that such concerns should be assessed using quantitatively rigorous approaches aligning with current methodological standards of bibliometric and/or systematic reviews (e.g. Refs. [2,3]) and particularly for outcomes related to metrics [2–5]. We argue that the analytical results presented in the review by Ref. [1] should be considered with the utmost caution.

2. Reviews on metrics that measure or quantify trends need to be methodologically sound

In an era of increasing scientific information, there is consensus on baseline standards for literature and systematic reviews. Such standards include defined characteristics and methodology, especially for systematic reviews that identify and measure phenomena and trends to answer a specific question [6]. In a rapid global energy transition, literature and systematic reviews can play an increasingly critical rolein the development and standardization of metrics and their associated terms, especially across diverse energy types. For example, outcomes from reviews may guide real-world siting and land management decisions from local development to domestic policy. Reviews on energy-land relationships are needed to address critical knowledge gaps, including those related to renewable energy siting, public acceptance, and conflicts with wildlife [7], but such reviews must be methodologically sound [8].

An essential, albeit relatively recently defined, characteristic of a properly implemented bibliometric and/or systematic review is the creation of a selection protocol, including explicit screening criteria for an article to be excluded or included in the final review corpus (i.e., all the articles considered and/or included). This criteria helps to ensure a review is both repeatable and as unbiased as possible [9–11]. According to Ref. [12], there are four broad coverage types used in literature reviews: 1) exhaustive, 2) exhaustive review with selective citation, 3) representative sample, and 4) purposive sample. It is widely accepted by researchers that although examining a subset of the literature is more convenient, the rigor of such a review can be diminished [13]. Further, reporting article selection methods for an interdisciplinary review topic, like energy-land relationships, is necessary because relevant articles may exist beyond the typical "field of view" of reviewers' core disciplines [14]. Lastly, when the objective of a review is to measure commonness, a specific type of review, called a systematic review, is needed such that the measurement is based on empirical text and/or data from the corpus.

Wachs and Engel [1] use a literature review to identify the most common metrics used to describe energy-land relationships but present results without methodological content on how articles were selected and how commonness was measured. For example, to ensure repeatability, it would be useful for Wachs and Engel [1] to describe how instances of metric terms were counted within a single article (e.g., is more than one instance counted?) and how these numbers were analyzed to measure commonness.

Thus, the reader is left uninformed as to how the authors identified the three most common metrics (i.e., ecological footprint, land use intensity, and power density) and what type of analysis (if any) the authors conducted to come to this conclusion.

The temporal boundaries that authors establish as criteria in article selection can be an important determinant of trends observed in metrics used in the literature. Wachs and Engel [1] report, “The literature frequently relies heavily on assessments that are decades old, many dating from the 1980's,” but they do not describe the temporal boundaries they used to constrain the corpus of literature for their review. The authors contradict themselves by indicating that certain studies, such as Gagon et al. [15], published in 2002, are too dated to be included as an influential study, while one of the three most “influential” papers demonstrating the ecological footprint metric and aggregate indicator (i.e. [16]) was originally published six years prior to Ref. [15]. This is evidence of an arbitrary use of temporal exclusion criteria or a lack of criteria altogether.

Overall, Wachs and Engel [1] also do not state the coverage type they selected to identify these metrics nor the search terms and engines they used to develop their initial review corpus, the types of documents they considered (e.g., peer-reviewed journal articles, reports, white papers), the years that their review is limited to, and the journals they restricted their search to. These issues present an initial and possibly unrecoverable problem with the article itself. Specifically, the lack of methods compromises the review's analytical outcomes, namely in stating which metrics in the literature are most common and the subsequent analyses. It is possible that the authors simply neglected to report the methods, and this could be resolved, in part, by publishing them as a corrigendum.

3. Inaccuracies and errors in the description of the three “most common” metrics

We agree that the arbitrary and inconsistent use of metrics leads to confusion in the study of energy and land relationships but Wachs and Engel [1] may add to the confusion. A metric, in its simplest form, is a quantitative (but sometimes qualitative [17]) measurement of an entity through a repeatable method, described with a specific combination of term(s) and unit(s). For example, in a systematic review of metrics used to assess sustainability in supply chains in the peer-reviewed literature, [5] found 113 unique metric terms in the literature corpus evaluated and across 20 different journals.

3.1. Issues with the use of ecological footprint as a land-use indicator and metric

Wachs and Engel [1] define ecological footprint and contend that it is one of the three most commonly used metrics to describe energyland interactions. However, it is difficult for the reader to understand exactly how ecological footprint is calculated as Wachs and Engel [1] do not give the reader a clear example demonstrating this. Broadly, ecological footprint is a metric used to quantify aggregate human demand on natural capital, the latter typically expressed in units of land and water area required from nature to support the human demand (e.g., global hectares [gHa] per capita) [18]. Owing to this omission, the reader is not well equipped to understand conceptually and quantitatively how ecological footprint is applied nor how it relates to other metrics used for quantifying energy-land relationships (but see Ref. [18]). Further, ecological footprint may not be the most applicable (given that it does not have an explicit energy unit: gHa/per capita [16] or most frequently used metric for all energy types. The metric, ecological footprint, may hold relatively greater value in other fields, including, for example, corporate sustainability ([19–21]), but the metric has also been the source of ferment and critique over its incompleteness when measuring environmental pressures and the oversimplification of processes, namely carbon sequestration potential [22].

Another shortcoming in this section is Wachs and Engel [1] referring to “carbon sequestration land” and “sequestration land use impact” when referencing the potential shortcomings of the ecological footprint metric. These two terms are not commonly employed in the vernacular of landscape ecology, climate change, or energy systems but more importantly these terms are imprecise and confusing.

3.2. Misinterpretation of land-use intensity metric

To describe the metric “land-use intensity,” Wachs and Engel [1] cite a paper they regard as common in the literature, Fthenakis and Kim [23]. However, by doing so, they misrepresent [23] by misstating the metric term reported in this study. While Wachs and Engel [1] are accurate in that [23] is commonly cited, [23] did not report the term land-use intensity explicitly. Instead, [23] present their findings as two metrics: 1) *land transformation* (the total area altered from a reference state [m^2/GWh]), and (2) *land occupation* (the land area occupied by an energy generating facility as a function of time [m^2

year/GWh]). It is important to note that the term occupation is relatively common in the field of life cycle analysis compared to other disciplines where it may also have other meanings.

The metric term “land-use intensity” itself has been used inconsistently to represent both capacity and generation-based relationships between energy and land, including both applications in the technical report by Ref. [24] to depict land use per unit of capacity and generation. Further muddling communication, various metric terms have been reported in the literature with slightly different verbiage to represent the same unit (e.g., “land use intensity of energy” and “land useenergy intensity” [24,25]. Indeed, the use of the word “intensity” has been used in multiple variations of metric terms to define the same metric unit [25–27]. Thus, despite the relatively high occurrence of the term land-use intensity in the literature, it is equally important to acknowledge that, to date, there is no consensus yet on its definition. We encourage scholars to explore trends in the use of metrics using repeatable approaches and be specific when describing metrics and outcomes related to energy-land relationships until fair and open standardization is reached.

3.3. *Use of power density without context and with incorrect discussion of the definition of power*

The authors of this article also present power density as a viable metric to represent land use associated with power-generating technologies, specifically as presented by Ref. [28]. Power density, as a metric in this context, is defined as the installed generating capacity (Watt) of a technology as a function of area (square meters) and is typically reported in units W/m^2. In this context, it is converted from rated capacity to generating capacity using an assumed capacity factor. Power density as a capacity-based metric of land use has documented use in the literature [29,30]. Unfortunately, Wachs and Engel [1] fail to mention different applications of the metric “power density” as it may pertain to land-based observations of power generating technologies. In the engineering literature, power density is sometimes used as a metric relating the output of solar cells as a function of cell size [31]. Power density (in W/m^2) is also the favored evaluation method of energy converters, calculating the flux of energy through their working surface areas [32]. If researchers conflate the power density of a given technology with relationships related to land use when publishing on the topic of land-energy interactions, it may present a misleading interpretation of what is being quantified: the working surface area of a technology or the associated land use of a particular technology [32,33]. Authors must clearly state what is being quantified by the power density metric to allow for the accurate use of the metric in any type of land-based application outside of strict engineering research. Wachs and Engel [1] present land use intensity (m^2/MWh) as a simple inverse of power density (W/m^2), and this is not correct or at best not clear as described as the units are incommensurate [32,33].

Additionally, the concepts of power and energy are misrepresented in the review by Wachs and Engel [1]. For example, the authors state “… land use intensity and power density metrics seek to provide a measure of actual generation of electricity or energy use with respect to area of land needed” when, by their own definition, their land-use intensity metric explicitly is used to quantify actual generation whereas the units for power density presented by Wachs and Engel [1] explicitly measures power capacity as a function of land area (using capacity factor; W/m^2) [1]. The units for power density presented by Wachs and Engel [1], W/m^2, also do not align with their definition for power density being “annual power generated,” as annual electricity production is a function of electricity generated (Wh), not a function of power capacity (W). Power, by definition, is quantified in Watts (W), or Joules per second (J/s) and represents an instantaneous power output whereas energy generation refers to the amount of electricity output over a given period of time, measured in Watthours (Wh) [34]. It is particularly critical to be clear about temporal scope because life cycle studies examine the electricity generated over the life of a plant (e.g., 30 years) versus one year. The differences between actual energy generation and capacity are major differences between the two metrics and are used to describe unique land-energy interactions. By using the units and terms to describe power and energy interchangeably, Wachs and Engel [1] may be introducing the type of incomparability they seek to reduce in this article. We clarify how such assumptions may lead to incommensurate results in Section 5. Assumptions of temporal lifespan for both generation and impacts on land require diligent detail and clarity.

4. Words matter when using metrics: landscape ecology terms are oversimplified

The authors oversimplify landscape ecology terms in describing relationships between energy and land. Wachs and Engel [1] state: “Land use affects ecosystems, biodiversity, and geochemical cycles…” but this is more veracious if they clarified that “land use” is being used here as an umbrella term for land-use and land-cover change, such that these drivers of change are also represented. Land-cover change occurs when there is a modification to the biophysical characteristics of land, including its vegetation, soil, and other natural attributes [35]. Land-use change is an alteration in the manner in which land is being managed by humans (e.g., farmland to pasture [35]), and this, as Wachs and Engel [1] correctly stated, does impact ecosystems, biodiversity, and geochemical cycles, if, for example, intensification occurs or practices change [36].

We use examples from renewable energy-land relationships to demonstrate the importance of specificity when using these terms. Global concerns about ground-mounted renewable energy infrastructure point to documented *land-cover changes* (e.g., loss of desert scrubland habitat) as evidence of adverse ecological impacts [37–39]. Concerns about renewable energy development have also been raised over *land-use changes*, including the abandonment of agricultural production to solar energy development

[37,40,41]. That said, *land use*, the human use of land, is germane too; the construction of a wind farm may not cause *land-use and land-cover change* but its *land use* may be useful to predict and understand impacts on avian species (e.g., injuries, mortality). Overall, siting concerns about energy development may be raised over land use but also owing to *changes* in land-use and land-cover change.

Further, Wachs and Engel [1] state, “Land metrics include an implicit time factor.” This statement is slightly misleading but likely stems from the frequent documented absence of a time factor where they are necessary. Many metrics (and their respective units) in landscape ecology used to assess impacts do not include an explicit or implicit time factor (e.g., patch area [e.g., km^2], distance [e.g., km], adjacency [e.g., km] [42]). There are also useful metrics specific to the study of energy-land relationships that do not include time and simply answer the question: how much land does energy infrastructure (in nameplate capacity) require, even if the power plant fails to become operational? For example, land-use efficiency (LUE; e.g., Wm^{-2}) is a metric used to describe the relationship between the capacity (e.g., megawatts) of the energy infrastructure and the area that installation requires [4,43,44]. This metric, LUE, is irrespective of the time it will exist on the land and is useful for estimating how much land is required to install a certain amount of power and in comparing or predicting infrastructural impacts across different energy types and landscapes, respectively [4,44]. We believe Wachs and Engel [1] were likely making the point that time should often be explicitly documented but often isn't, which we completely agree with, but this was not articulated clearly.

5. Comments on analyses of major generation technologies

The comparisons of land use of electricity generation technologies presented in Figure 3 and 4 of Wachs and Engel [1] have methodological flaws. We note that the authors correctly refer to the importance of temporal assumptions. Ultimately, if the results are truly to be used in any meaningful comparison that considers life cycle implications, the lifetime of electricity generation of each technology should also be considered explicitly. What is lacking from the analyses in Wachs and Engel [1] is adequate differentiation between land-use and land-cover change for finite activities and facilities (e.g., new land converted for the extraction of non-renewable resources, mining activities, etc. [45] and persistent land use specific to other activities and facilities (e.g., power plant infrastructure) [46]. Instead, the results for land-use intensity presented in the paper appear to be merely the inverse of the power density results and vice versa. It is thus critical to clarify if the assumptions about energy extraction and electricity generation represent the lifetime energy throughout of the facility (or over shorter timeframes) and whether new land is required for fuel extraction.

Such challenges are exemplified by statements such as: “Natural gas has lowest land use but there is potential for renewables to improve land use profile via mixed-use development.” This conclusion overlooks the important fact that natural gas wells are often not reclaimed, resulting in compounding land use over time [46,47]. Importantly, the discussion of natural gas pipelines does not differentiate between gathering and transmission pipelines. Gathering pipelines collect natural gas from individual wells for transportation to more central facilities and transmission pipelines. Transmission pipelines transport natural gas across large geographic areas, including both inter and intra-state destinations. Pointing to the importance of ensuring robust review methods, numerous papers have already found that gathering pipelines are important contributors to land use [45,46] (not the transmission pipelines that are well reported by The US Department of Transportation's Pipeline and Hazardous Materials Safety Administration). Indeed, gathering pipelines have been found to dominate landscape impacts [46], with orders of magnitude greater land requirements compared to transmission pipelines alone [45].

The crucial concept of “time to equivalency” is similarly overlooked over time, the use of the same parcels of land by renewable technologies will become equivalent to fossil fuels, which require new land for extraction [46,48,49]. We interpret that the authors’ statement (transcribed directly) “If the (temporal) factor is long enough, renewables always best conventionals,” refers to times to equivalency [48]. Their analysis, however, shows the opposite, which adds confusion to general scientific understanding and contribution of the paper. The inclusion of relevant literature and important concepts presented in the literature that was cited could have provided additional clarity [48].

Robust results require an examination of uncertainty and variability both of which are critical to understanding the relationships between energy technologies and land. The authors state that, “Estimates of land use by power generation technologies vary by orders of magnitude.” We agree that such differences can be problematic if equations used to calculate results are inconsistent. Regardless, accurate assessments of energy-land relationships actually can vary by orders of magnitude owing to a number of factors (the nature of the energy technology, geological reserves, or even the vintage of the project, to name a few). In fact, we expect large variability in results for each energy technology: large variability sometimes spanning an order of magnitude has already been demonstrated in data-driven facility-level analyses [27,29,50,51]. Indeed, results being presented as singular points ignores known variability for each technology.

We note other serious oversights in the analyses of specific technologies that are critical to advancements in this field. It is unclear whether run-of-river hydro is considered, which would account for thousands of MW of installed hydro capacity in the United States. Even if run-of-the-river is considered, we expect the results to be substantially different than conventional dams (preliminary calculations demonstrate as much [49]). Pumped hydro storage “typically affects pristine greenfields”; however, the authors neither provide supporting data nor define a pristine greenfield. As a result, the percentage of proposed pumped storage projects that would actually affect pristine greenfields remains unsubstantiated. Lastly, it is unclear whether other energy technologies are developed on already impacted or pristine landscapes, which the latter under climate change, arguably no longer exist. Overall, questions related to energy siting are of critical importance, including the land implications of each option, and knock-on effects on ecosystems and their services.

We note that the discussion of nuclear excludes land requirements associated with disposal for nuclear material post-generation. The authors correctly note that most of the spent fuel is stored on site; however, the duration of the land use in this context becomes of critical importance. The land essentially will be occupied for thousands or tens of thousands of years after plants are decommissioned unless along term waste management plan is put in place [53]. Also, citation of the proposed plant is not accessible due to a mistyped citation and thus the reader cannot compare or validate findings proposed in this section (citation 44 in Ref. [1]).

6. Conclusion

At the high level, we found that the content of Wachs and Engel [1] may perpetuate the information bias and methodological pitfalls common to poorly conducted literature reviews, notably those that include analytical elements. Essential details are needed to describe metrics clearly and communicate methods used to identify those "most common" in systematic reviews. Energy scholars need to be mindful of time as a factor and distinguish carefully among land use, land cover, and land-use and land-cover change to provide credible and robust comparative analysis of the land requirements across energy types. Lastly, the methods in Wachs and Engel [1] overlook critical factors that would truly pave the way for realistic and representative comparisons in this field: a nuanced approach to land needed for energy infrastructure, reclamation, project lifetimes, and adequate consideration of important uncertainty and known variabilities.

Amidst the flaws we note in Wachs and Engel [1], it does embody some accurate observations and we do not want to discount these contributions. The authors are correct in observing that energy-land metrics, with standardized definitions, terms, and units, are critical for many reasons including, but not limited to quantifying ecological and environmental justice impacts from energy generation. The authors also point out some gaps in the literature that represent opportunities for improving our understanding of both energy-land and energy-water metrics, including the need for:

- Offshore energy-water metrics
- Energy-land metrics for renewables with storage
- Greater rigor for energy-land studies of geothermal
- Standardized metrics based on sound methodological approaches for energy-land analyses, including those that are comparable across energy types

We argue that the application of systematic review to understand energy-land metrics in the literature is one approach to converge on universal metrics in a manner that recognizes and can overcome historical, disciplinary, and geographical differences. In Cagle et al., *in review* [4] we systematically reviewed 608 publications to identify the full suite of metrics that scholars employ to describe solar energy-land interactions. We found and identified three distinct categories of solar energy-land metrics: capacity (nominal)-based metrics, generation based metrics, and population-based metrics. We used the most frequently reported terms (and units of measure) in each category to inform a globally standardized suite of metrics, which are: land-use efficiency (W/m^2), annual land transformation ($m^2/Wh/y$), lifetime land transformation (m^2/Wh), and solar footprint (m^2/capita). Land-use efficiency refers to the operational power output of a given solar installation per unit of land whereas land transformation refers to the area of land associated with a solar installation to produce a given unit of energy. The solar footprint metric refers to the land area of a solar energy installation necessary to provide electricity to a person in a defined area based on local resource potential and energy demand. While this review focused solely on solar energy-land interactions, the methods embody a widely applicable quantitative approach to identifying the most commonly used metrics in the published literature. The global scope of the systematic review was intentional with the aim to increase representation of scholars and other stakeholders that may be marginalized owing to socio-economic constraints. That said, our analysis was ultimately limited to documentation in peer reviewed literature and this is likely disproportionately greater in developed economies [7]. Future studies seeking to achieve greater representation may wish to perform a standardized review followed by an expert elicitation (or similar activity). This approach may build a more equitable framework for standardized metrics—one based on rigorous quantitative analysis and formalized by consensus of diverse stakeholders.

1 Credit author statement

R.R.H., S.M.J. – Conceptualization, Writing. A.C., G.E., S.M.G. – Writing.

2 Declaration of competing interest

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