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Characterizing variability and reducing uncertainty in estimates of solar land use energy intensity

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ABSTRACT

Estimates of the amount of land used for a defined amount of utility-scale electricity generation in the solar power industry, referred to here as *solar land use energy intensity* (LUEI), are important to decision makers for evaluating the environmental impact of energy technology choices. However, these estimates for solar LUEI are calculated using three difficult-to-compare metrics and vary by as much as 4 orders of magnitude (0.042–64 m^2/MWh) across the available literature. This study reduces, characterizes, and explicates the uncertainty in these values for photovoltaic (PV) and concentrated solar power (CSP) technologies through a harmonization process. In this harmonization process, a common metric is identified and data existing in other forms are converted to the metric, where possible; standard algorithms for calculating solar LUEI are developed; gaps and deficiencies in the literature calculations are identified and remedied; and differences among the resulting estimates are characterized and analyzed. The resulting range of harmonized solar LUEI estimates is reduced to 2 orders of magnitude [5–55 (m^2y)/MWh]. Due to variables such as technology and location, there is a significant amount of irreducible variability in general solar LUEI estimates. However, this variability does not necessarily represent uncertainty, as most of it can be explained by choices in calculation input parameters. This study finds that key solar technology- and location-dependent parameters such as insolation, packing factor, system efficiency, and capacity factor all vary widely across studies, and thus all share in the overall variability of solar LUEI. Only land use at the site of solar electricity generation facilities is considered because lifecycle land use beyond the site (for manufacturing, disposal, etc.) is not widely accounted for in the existing literature. This study provides a basis for moving forward with standardized and comparable solar land use studies and for filling gaps in lifecycle solar LUEI.

Contents

Abbreviations: CSP, Concentrating solar power; PV, Photovoltaic; LUEI, Land use energy intensity

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1. Introduction

Concerns about the potential environmental impacts of utility-scale solar energy technologies, including the amount of land used, can present a barrier to solar energy development. To inform decision making, it is necessary to compare the land areas required for solar energy development with the land needs of other energy technologies. To accomplish this comparison, the spatial intensity with which each technology generates electrical energy must be known. However, no single definitive source for land use energy intensity (LUEI) exists for solar energy. Current published studies on land use for solar electricity generation present a wide range of intensity values—covering 4 orders of magnitude—and use several different metrics of measurement. They use differing data, study boundaries, calculation methods, and assumptions about location and technology to arrive at divergent results.

This study explicates the differences among the existing solar energy LUEI estimates across both photovoltaic (PV) and concentrating solar power (CSP), or solar thermal, technologies and reconciles as many of them as possible through a harmonization process. Harmonization is a meta-analytical method for bringing divergent study results into closer agreement through the reduction of inconsistencies in data, calculations, and assumptions. The overall goal of harmonization is to develop a robust understanding of the variation in existing study results [1]. Because the amount of land used to produce a certain amount of electricity from solar power will always depend on variables such as location and technology, this study proposes two standard algorithms, or meta-models, for calculating solar LUEI. This study does not use harmonization to eliminate all variability in LUEI values. Instead, it intends to preserve the natural variability present among different technologies and locations while reducing error caused by inappropriate assumptions and inconsistent calculation techniques.

The analysis of land use in this study is limited to the site of the deployed solar energy technology. While the preponderance of existing literature on the subject only addresses onsite land use, several authors [2–6] have explored land use in other stages of the solar energy technology lifecycle, including land used for construction, material acquisition, and generation of the energy used in manufacturing. However, these sources do not always clearly communicate what lifecycle stages they account for, and when they do, the stages accounted for are not always consistent between studies. Due to the limited availability of upstream and downstream land use information and the inconsistency with which it is covered, this analysis concentrated on land use at the site of the power plant.

2. Methods

To examine the differences among solar LUEI estimates, first a comprehensive set of estimates was aggregated from the literature. Those estimates were examined for assumptions, study boundaries, and methods of calculation. Then, estimates gathered from the literature that failed to include adequate information for the harmonization process were screened from further study. Finally, in an iterative harmonization process, standard algorithms for calculating LUEI were developed and used, along with supporting information from the literature, to reduce and explicate discrepancies in the aggregated LUEI estimates.

2.1. Data aggregation

To identify data for aggregation, a literature review was conducted. Studies containing LUEI estimates and solar specifications such as rated capacity[1], energy output, site area, capacity factor[2], packing factor[3], insolation[4], PV cell efficiency[5], and system efficiency[6] were included in the review. Of 115 articles identified as potentially useful, 29 contained solar LUEI data useful for our study, and are thus included in this report.

The solar LUEI estimates gathered from these studies were aggregated according to their metric of measurement. All supporting information, including the specific technology modeled, calculation method for the estimate, data or specifications used to make the calculation, boundaries of analysis, sources, and date of study, was also collected.

2.2. Screening

Unfortunately, many of the sources identified by the literature review fail to include any calculations or data to support the solar LUEI values they provide. Absent information that can be used to compare and contrast one calculation with another, or identify gaps in calculation methodology, these LUEI values cannot be harmonized (see Section 2.3 for information on this process). For example, estimates of insolation and capacity factor are highly dependent on the specific solar technology being used and its location. Both of these factors affect the calculated LUEI. If these (and other) assumptions are not communicated, it is not possible to determine the reason for differences among LUEI estimates.

[1] Capacity is the electrical load that a plant is rated to be able to supply (the maximum power output) [7].

[2] Capacity factor is ratio of a plant's average power output over a specified period of time (normally a year for the solar industry) to its rated capacity [7].

[3] Packing factor is the ratio of a plant's solar collector array area (the area actually covered by the PV panels or CSP mirrors) to the total land area occupied by the array [7]. This includes land area left open to avoid shading and to allow access for maintenance [2].

[4] Insolation is the solar power density incident on a surface [7]. This varies by location due to differences in latitude and climate.

[5] PV cell efficiency is the ratio of electrical energy produced by the cell to the solar energy incident on the cell [7].

[6] System efficiency is the ratio of the energy produced by the power plant to the solar energy incident on the solar collectors [7].