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Solar-PV energy payback and net energy: Meta-assessment of study quality, reproducibility, and results harmonization

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ABSTRACT

Numerous analyses of mono- and polysilicon Solar-Photovoltaic (PV) modules provide an Energy Payback Time (EPT) or Net Energy Ratio (NER) value. Few are directly comparable due to differences in annual solar radiation, supply-chain technologies, life-cycle boundaries, and system specifications. The purpose of this paper is to reproduce and harmonize twenty-nine studies, and to examine the influence of data age, system boundaries, and technological configurations.

The results include:

- The study harmonization yielded a mean EPT for mono- and polysilicon solar-PV of 3.9 and 2.9 years, and a mean NER of 8.6 and 9.2 times, as expressed in solar energy output gain per unit of energy input, respectively.
- The average time between study publication and sourced data was established at 7 years within a 2–18 year range, due to which energy input costs are typically overestimated as recent technological improvements are not captured.
- When filtering for studies with manufacturing data collected after 2008, the harmonized average EPT for mono- and polysilicon was found to be approximately half (e.g. 2.0 instead of 3.9) and NER double (e.g. 14.4 instead of 7), relative to studies with data from 2008 or older.
- An input correction with recent technological improvements for all studies resulted for mono- and polysilicon solar-PV in an adjusted mean harmonized EPT of 3.5 and 2.4 years and NER of 9.7 and 11.4 times, respectively.
- Few studies in their system boundaries considered energy costs for embodied material, maintenance, decommissioning, and auxiliary services.

It is recommended in future studies to use recent data reflecting up-to-date technological standards and include the collection year of any used datasets. And to strictly follow existing ISO14040, ISO14044, and IEA-PVPS T12 standards, especially by transparent reporting of: solar module specifications, energy inputs for individual facilities and non-module components, technology assumptions, and electric/thermal conversions.

1. Introduction

The calculation of energy flows across the life cycle of energy generating technologies serves to identify the net energy delivered and environmental impacts from these sources. Several metrics are used to establish how energy inputs relate to energy outputs of an energy technology, of which two are most prominent. First, the net energy return value (NER), expressed as a ratio, which evaluates the amount of energy an energy source contributes to society over its life-cycle, relative to the inputs required to establish the technology. A standard

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way of calculation is by taking delivered life-time outputs, and dividing these by the inputs necessary to produce, operate, maintain, and dismantle an energy technology, with appropriate boundary levels as specified [1]. Second, energy payback time (EPT), an estimate of the duration of time expressed in months or years at which an energy source has "paid back" its initial energy input. It is expressed by taking the energy input necessary to produce and operate the energy technology and dividing by the outputs produced over a fixed period of time [2]. In a similar manner the impact of carbon emissions are studied across their life cycle, using metrics based on greenhouse gas emissions per unit of energy output, whereas the GHG emissions figure is partially or fully derived from energy inputs [3,4].

The NER and EPT metrics can be used for purposes of energy planning in several ways as described in [5]. First, by assessing the energy impacts of energy transition pathways due to large shifts between energy systems, including the need for upfront energy investment in scaling new infrastructure, and trade-offs such as intermittent solar storage versus curtailment. Net energy metrics can be used to calculate whether the net energy delivered to society by the energy sector grows sufficiently in such a transition, as financial and generation values only do not deliver this information. Second, by comparison between energy technologies on the net output delivered to society in complement to financial values. If technology A has a larger total energy input for the same amount of output versus B, yet costs less (for instance due to less labour input and additional market price of risk), then typically B will be built since it has the lowest dollar per unit of energy delivered to its owner, yet technology A is preferable from a lowest dollar per total energy available to society perspective. And third, for assessment of technologies by themselves at early laboratory stages, in terms of whether they deliver net energy input at all, how much, and what improvements are feasible. The assessment indicates at an early stage if an energy technology, and which configurations thereof, has large potential. For example, recent perovskite solar cell studies calls for a 2–29 months EPT depending on used materials [6,7], and a prospective assessment of silicon heterojunction solar cells found a 0.9–1.2 EPT by 2020 [8].

In this study a meta-analysis of quality aspects of existing energy metrics studies for solar-photovoltaic (solar-PV) is carried out. The purpose is to identify quality variation, study shortcomings, and the ability to reproduce existing results, to carry out a harmonization of studies, and to assess methodological improvements for assessments of the energy component of solar-PV using life cycle analysis (LCA), material flow analysis (MFA), or other methods. In 2015 the total installed grid-connected capacity for solar-PV was 230 GigaWatts, which provided for approximately 1% of electricity use, or 0.9 out of 86 ExaJoules of electricity generated, showing its growing importance in energy systems [9–12].

The variability in net energy was studied prior in several meta-analyses. A wide variation in study results has been established. For example for polycrystalline systems an EPT between 1.5 and 5.7 years [13], and for monocrystalline systems a NER of 5.2–12.3 times output versus input [14]. The variation has been stated to be caused by variability in the operational environment of solar-PV installations, technical performance and life expectancy assumptions, in- or exclusion of balance of system (BOS) components, installation methods, and the manufacturing processes to produce the cells [13,15,16]. Similarly, a 397 harmonization meta-analysis for solar-PV on Greenhouse Gas emission (GHG) metrics found key variation due to solar irradiation, operating lifetime, module efficiency, and performance ratios [74]. All these factors relate to technical aspects and thereby available meta-analyses are limited in scope in the discussion of data quality issues affecting results. Individual energy metric assessments do refer the results being affected by outdated data [2,14], missing data [17], quality of collected data [18], and reliability and verifiability of data [19], but implications thereof have to the awareness of the author not been assessed. The influence of data quality remains an uncertain parameter in relation to the variability of outcomes.

Data in the literature is primarily derived from Life Cycle Inventory (LCI) databases, especially Eco-Invent, because of its frequent updates for solar-PV data [20]. Data in LCI databases is obtained by a life cycle inventory approach using a variety of methods which can include company data surveys, direct measurements, expert assessments, and theoretical calculations. The LCI data is used either directly for a system component in an energy metric assessment, such as the energy input required to produce a silicon wafer, or indirectly, by estimating component material mass and multiplication with an associated embodied energy data value from an LCI database, such as for the aluminium frame. In addition to LCI data other data sources used in energy metric analyses can include manufacturer's technical specifications, market surveys from solar industry magazines, indirect estimates for technological processes, and data directly obtained from industry sources outside of LCI. It is also common in the majority of studies to borrow data from other studies to cover a part of the LCA supply chain.

In this paper a meta-analysis of twenty studies which calculate solar-PV energy metrics is carried out with a focus on the aspect of data quality, data age, and verifiability and reporting.

The following aspects are examined:

- **First**, the **data quality** of each study is analysed using a framework based on the indicator approach developed by [21]. The indicator quality framework is outlined in Section 2.2 and results are presented in Section 3.1.
- **Second**, the ability to **accurately reproduce** each study is analysed to examine scientific standards of reliability and verifiability of used data. Also a subsequent study harmonization step is carried out to create similar boundary conditions for purposes of comparability. The reproduction and harmonization methodology is outlined in Section 2.3 and results are presented in Section 3.2.
- **Third**, **trends in reported energy metrics** values in relation to age of data, size of studied modules, and changes in module power capacity per m^2 are examined. The effort serves to deepen the analysis of the relevance of data age and solar panel types. The trend methodology is presented in Section 2.3.2 and results are presented in Section 3.2.1.
- **Fourth**, an **interval sensitivity analysis** is carried out in relation to solar radiation, reported life cycle energy input values, as well as technology development. The technology analysis serves to understand the impact of using outdated data without correcting for technology improvements. The interval sensitivity methodology is outlined in Section 2.4, and results are presented in Section 3.3.

The paper subsequently discusses results in Section 4 and ends with conclusions and recommendations in Section 5. The study is carried out as an individual piece of work which aims to contribute to advancing net energy metrics, as part of an open collaboration between the Institute of Integrated Economic Research and Stanford University (Prof. Adam Brandt), for purposes of creating a net energy calculator tool.

2. Methodology

2.1. Literature Survey

The literature search for solar-PV energy metric studies was conducted via Google Scholar, Elsevier Sciencedirect, and Web of Science using combinations of the keywords "solar-PV", "embodied energy", "net energy", "energy payback", "energy return", "solar cells", "solar modules", "life cycle analysis". Also references in previous meta-assessments of solar-PV were taken into account [14–17,22]. In total thirty-one studies assessing solar-PV net energy metrics for polysilicon and monosilicon modules were assessed published since 2000. The temporal cut-off was selected because of the rapidly changing techno-