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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 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 to 29 months EPT depending on used materials [6,7], and a prospective assessment of silicon heterojunction solar cells found a 0.9 to 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

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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 to 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 (Hsu et al. 2012). 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 technological landscape in the solar industry [23]. A second cut-off is the exclusion of solar panels below a size of 75 Wattpeak as these are a-typical older modules not representative of today's technology. The size cut-off resulted in the removal of two studies from the dataset [24,25], which led to a twenty-nine study dataset with fourty-three energy metric values.

2.2 Data quality indicators

The retrieved studies were analysed for their data quality. To establish a complete energy metric analysis an understanding is necessary of all the direct and indirect processes involved to manufacture, operate, and dispose of the solar-PV system across its life cycle. The manufacturing system is complex, technologically evolving, and energy throughputs are influenced by geography due to variation in process input sourcing, technological setups, and transport distances. The data quality indicator approach seeks to provide insights in how well these characteristics are captured by individual studies. For life cycle inventories a system has been developed based on reliability, completeness, temporal age, geographical correlation, and technological correlation [21]. This system is still used commonly, such as by the US Environmental Protection Agency [26] and in the Eco-Invent LCA database [27]. In this study an adjusted indicator set including system completeness and facility level completeness is added.

The approach provides for the following set of indicators:

- **Reliability**, the sourcing method of data used in the analysis as an indicative approach on the occurrence of data errors.
- **System completeness**, the extent to which inputs outside of direct solar PV manufacturing are taken into account such as operation, installation, transportation, higher-order manufacturing inputs, and auxiliary services.
- **Facility completeness**, the extent to which key manufacturing stages which can spatially be separated are included. In case of solar-PV these are quartz mining, quartz to silicon chunks refining, silicon ingot forming, wafer production, cell, manufacturing, and module production.
- **Data age**, the age of the data in relation to the publication date of the study.
- **Geographical conditions**, the extent to which process data comes from a uniform set of areas, or is extracted from different sites with varying production conditions.
- **Technological uniformity**, the extent to which data comes from processes of the same or different companies, as well as from technologies specific to the output of study or borrowed from similar industries.

The information from these indicators can be used to assess key differences in results and direct additional data collection. Another considered indicator was the completeness of individual or unit processes within facilities such as etching of wafers. This level of unit process completeness could not be analysed because existing studies only focus on the aggregate level of a system or facility in their data reports and supply chain descriptions.

The quality indicators need to be scaled and criteria are required for categorization. In [21] a scale from 1 to 5 was proposed for five categorisation criteria, which is adopted here in reverse order (higher is better). In this study an alternative set of criteria is used, as summarised in Table 1 below, as the criteria in [21] were found to be too generic to enable a transparent and explicit estimation. Each study was analysed based on the table 1 criteria at a supply chain facility level for all criteria, except system completeness. The estimation of quality indicators for reliability, technology, and data age, was based on averaging individual quality values for each facility in the supply chain, whereas for the other indicators a single score was assigned. If study data was not measured directly but taken from other sources, secondary or original data was traced and analysed for the categorisation analysis. Data was also analysed for congruence in copying data from the original study to the borrowing study to categorize reliability. The results of the quality indicator assessment are presented in results section 3.1 and the underlying calculation details are in the Supplementary Materials A available on the internet.

Table 1 Quality indicator criteria applied in this study as amended from [21].

Indicator score	**1**	**2**	**3**	**4**	**5**
Reliability	Non-qualified estimate or non-referenced estimate	Qualified estimate (e.g. by industrial expert)	Data from measurements from other sources adjusted without stating assumptions	Data from measurements from other sources adjusted stating assumptions*	Data from measurements or other studies measurements without adjustments
System completeness	The value is set by awarding 0.5 points for each item covered under operation, maintenance, raw material transport, recycling/landfill transport, transport to installation site, installation, decommissioning, auxiliary services, balance of system inclusion, and higher order manufacturing stages calculated with LCA software.**				
Facility completeness	<50% of facilities covered or no description	50 to 65% of facilities covered	65 to 80% of facilities covered	80 to 90% of facilities covered	90 to 100% of facilities covered
Data age	age of data unknown or >10 years difference	10,9,8,7 years difference in age of data to year of study	6 or 5 years difference in age of data to year of study	4 or 3 years difference in age of data to year of study	2 to 0 years difference in age of data to year of study
Geographical conditions	Process data from unknown areas	Process data from multiple areas per facility for individual sub-processes in dataset	Process data from multiple locations varying by facility	Multiple sets of process data uniform across regions averaged for the dataset	Process data from a single region for all facilities (no averaging)
Technological uniformity****	No description of processing route and not traceable through sources	Process data non-matching technologies and outputs across supply chain***	Process data matches outputs but based on non- standard technologies****	Process data for slightly different outputs and technologies	Process data matches outputs and technological route

*Data taken from measurements either from the study itself or from another study are adjusted either with explicitly stating what adjustments and why or without mentioning the underlying assumptions and procedure.

**Higher-order upstream stages of the production process include inputs to produce the machinery and deliver it to a facility, inputs to produce the machinery that produces the machinery, and so on. Normally in a life cycle inventory a truncation takes place at a 0th or 1st order stage. Such truncation errors have been found to be significant up to the order of 50% (Lenzen 2000).

***An example of slightly different material and technologies would be semiconductor silicon ingot manufacturing at 10 levels of purity versus solar ingot manufacturing at 6 or 7 degrees of purity.

****Standard from an overall market perspective. An example of non-standard technologies is the use of float-zone based versus the standard Bridgeman process to produce polysilicon ingots.

2.3 Study harmonization

The qualitative indicator assessment was complemented with a quantitative inventory for both energy inputs and outputs for purposes of comparison and harmonization. The baseline for the harmonization was established by verifying the inventory through assessment of energy input and output data and meta-data, which were used to reproduce energy metric results for each study. If only aggregate values for a solar module were published, yet referenced studies contained any disaggregate data matching the aggregate value, then disaggregate values were included in the analysis.

After establishing the baseline a harmonization was carried out using the following nine adjustments:

- Studies which only publish energy payback values were complemented with net energy return calculations and vice versa.
- Studies lacking energy input values within the solar module production chain were complemented with mean values from the inventory.
- Studies lacking energy input values for BOS, installation, installation transportation, operation & maintenance, and decommissioning were complemented with mean values from the inventory. Also for decommissioning recently published silicon module thermal treatment electricity costs were incorporated [28].
- Energy input values for batteries, auxiliary services, and power lines operation and restructuring were removed from studies incorporating these.
- Energy input values for labour and capital investment cost based on conversions via the energy intensity of economies were removed from studies incorporating these. Wages in the view of this author represent an allocation of energy surplus, not an energy consumption on-site), and including capital expenditures causes double counting of embodied material and direct energy costs in manufacturing of solar-PV.
- Electricity output values were recalculated using a 1700 kWh/m2/year radiation value.
- A systems efficiency rate of 0.8%, and a degradation rate of 0.7%/year was applied to all studies based on average values across 2000 solar systems found in the literature [74-75].
- Solar module packing factors to adjust for non-cell module area were assumed at 0.94 for polysilicon and 0.8 for mono-silicon modules.
- A plant lifetime of 25 years for all systems.

The missing components in a studies inventory were filled based on mean values across studies with the respective components with the constraint of data published since 2004 to reflect more up-to-date quantities. The complete harmonized dataset is presented in results section 3.2 and underlying calculation details are available on the internet in the supplementary Materials B.

2.3.1 Harmonized Energy Metric Analysis

The energy metrics were calculated using the mathematical bottom-up approach to distinguish flows developed by [29] briefly summarized here. The approach divides the supply chain or project up in a set of process stages $s = 1,2,3, \dots n$ from initial resources to end-of-life. Each stage represents a transformation at the same spatial location of energy and material flows. At each stage a distinction is made between, internal, external, and indirect energy flows:

- **Flow input internal self-consumption**, Xi_s, representing the portion of energy in a fuel used in the conversion process. For instance, the ~10% of crude oil used up in a refinery in the conversion to petroleum products.
- **Flow output internal self-consumption**, $Xo_{s,u}$, where $u = 1,2,3, \dots n$ is an output flow index. This represents the proportion of outputs diverted back at the end of a process stage or stages into it for energy conversion purposes, for instance waste heat obtained from a curing proces redirected back for use in ingot growing processes.
- **External energy flows**, $E_{s,p}$, where $p = 1,2,3, \dots n$ denotes flow pathways wherein direct non-internal input energy is produced. An example is the external input of electricity used in the operation of solar-PV facilities.
- **Indirect energy flows**, $I_{s,c}$, where $c = 1,2,3, \dots n$ denotes the sector wherein the flow was consumed. The indirect consumption can consist of i) 'embodied' energy used to produce material inputs at higher-order stages, ii) energy used in the provisioning of labour associated with the project, and iii) energy used in the production of external energy inputs at higher-order stages.

Since a portion of produced output after each stage, F_s, can end up in indirect energy flows a subtraction from the output itself is necessary to obtain a net value of energy generated to society. For this purpose a parameter r is introduced to enable calculation of this fraction of indirect energy inputs, as $rI_{s,c}$, which provides the sum of energy reverting back into a stage.

The distinction between several types of outputs and inputs is used to reproduce net energy return values using equation (1) and energy payback using equation (2) below. The produced output of a solar module F_s is adjusted by a module degradation rate δ as incorporated in analysed studies and for harmonization to produce a degradation corrected value F_s^* using equation (3).

$$NER = \frac{F_s - \sum_{s,u} Xo_{s,u} - r_c \sum_{c,s} I_{c,s}}{\sum_s Xi_s + \sum_{s,u} Xo_{s,u} + \sum_{s,p} E_{s,p} + \sum_{c,s} I_{c,s}} \quad (1)$$

$$EPB = \frac{\sum_t F_t / t}{\sum_s Xi_s + \sum_{s,u} Xo_{s,u} + \sum_{s,p} E_{s,p} + \sum_{c,s} I_{c,s}} \quad (2)$$

$$F_{s,t}^* = F_{s,t-1}(1 - \delta) \quad (3)$$

2.3.2 Study data trends

The quality indicator and harmonization study values can be combined to analyse the occurrence of trends across studies. A set of four analyses were carried out to infer key aspects to take into consideration in study interpretation. First, the year of study publications was compared with the asserted average year wherein the original data was obtained, so as to gain an overview on data to study time-lags. Second, harmonized Energy Metrics values from this study were plotted against the asserted year wherein original data was obtained, to assess if a discernable trend over time is visible. Third, the mean values for EPT and NER were estimated from studies with sourced data estimated to be derived from the year 2009 or later, and compared with those with data obtained in period 2004-08, and before 2004. Fourth, data on module size and power output in watt for each study was compared against the Energy Metrics values and Energy input per kWp of module capacity, for assessment of resource economy of scale effects as a factor in energy cost. Less components are necessary for the same m^2 of module such as aluminium frames, cells are packed more efficiently in a module, and the capacity per cell has increased. The results of the trend analysis are provided in section 2.3.1.

2.4 Data interval sensitivity analyses

Sensitivity analyses aim to systematically estimate the influence in a computer model of one parameter or value on the outcome of another parameter or overall value [30]. A standardized approach is to employ intervals and assess the effects of minimum and maximum values on the outcome, or apply a distribution Monte-Carlo or sampling based uncertainty propagation technique. In this study a minimum to maximum value interval approach is selected due to a lack of available data within a technological supply chain specification necessary to establish a non-arbitrary distribution.

Effects of variation in known manufacturing values, key existing technological improvements, and solar radiation, is examined on the aggregate metrics of energy payback time and energy return. Solar radiation variation is taken based on a geographic range between 700 and 2700 kWh/m2/year [31]. Data variability in energy cost of manufacturing steps for each facility was estimated by using minimum to maximum energy cost values from the literature, restricted to data established after 2004. In addition estimated efficiency improvements stemming from new technologies already in operation under commercial conditions were incorporate to examine the effect of using more recent data that reflect current technologies. The recently developed technologies are described in section 3.2.1 within the context of the present solar-PV supply chain from mine-mouth to module. The baseline for the sensitivity analysis was the harmonized dataset developed as per the methodology described in section 2.2, in particular the external energy flow, $E_{s,p}$, to which a differential between old and new technology, $T^n - T^o$, was applied. Results are presented in energy payback and net energy return sensitivity scale plots in section 3.3.

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2.4.1 Solar-PV supply chain technological improvements

The technology sensitivity analysis demonstrates the implication of using outdated data and effects of novel commercialised technologies on the energy metric evaluation. The analysis was carried out on fourty-two study results with one study omitted as this study provided a combined mono-silicon and polysilicon value which could not be disentangled [32]. The data age effect was assessed based on changes in wafer thickness as per the industry average reduction from 320 to 175 μm between 2003 and 2013 [23]. The energy costs of each study for metallurgical silicon to ingot production were adjusted for changes in wafer thickness up to 2013. The adjustment was based on assessed processing costs on a GJ input cost per m^2 of cell area in relation to the study date age. For example, if average data related to 2006, the effect on energy input reduction stemming from a wafer thickness reduction occurring from 2006 to 2013 was taken into account. New technology effects were assessed for wafer sawing slurry recycling, diamond wire based wafer sawing, and the metallurgical silicon refining technology of Elkem Solar in operation in Norway (Wild-Scholten and Gløckner 2012). Studies with data published prior to 2008 were assumed to not incorporate wafer sawing slurry recycling, as this process has gained substantial prominence since in factory expansion by leading firms including CRS processing and Metallkraft. Diamond wire wafer sawing was applied to all studies, as this technology is still only used for 18% of mono-silicon panels, and 1% of polysilicon panels at present (Forstner et al. 2014). Similarly, metallurgical silicon refining from the Elkem Solar process was applied to all data, in a 50:50 ratio with the standard Siemens Process for silicon supply, as this process only recently was commercially introduced in 2014 in the Norwegian plant. A summary of the four technology innovations and references is given in Table 2 below. In the online supplementary materials B quantitative details for individual studies and technologies related to the sensitivity analysis are available.

Table 2 Technology data as applied in the sensitivity analysis.

New Technology	Processing facility	Replaces commonplace technology	Existing external energy input (m2 cell area)	New technology external energy input (m2 cell area)	Established geographic location and output	References
Metallurgical refining of silicon to solar grade quality (Elkem process)	Metallurgical to polysilicon chunks	Bell jar reactor silicon purification & deposition from TCS gas (Siemens process)	173 (kWh/kg)	40 (kWh/kg)	Norway / 7500 Million tonnes per year	[33,34]
Wafer Sawing Slurry Recycling*	Polysilicon Ingot & Wafer Production	Wafer Sawing Without Slurry Recycling	0.17 GJ	0.07 GJ	Several / 210+ BT per year	[35]
Diamond wire wafer sawing*	Polysilicon ingot & wafer production	Slurry based wafer sawing with recycling	0.07 GJ	0.02 GJ	Meyer-Burger DW288	[23,36,37]
Wafer thickness reduction by 145 μm between 2003 and 2013	Metallurgical silicon to ingot production	Glass thickness 3 mm	0.37 GJ (320 μm polysilicon wafers) 0.52 GJ (320 μm monosilicon wafers)	0.20 GJ (320 μm polysilicon wafers) 0.28 GJ (320 μm monosilicon wafers)	Average global estimate for thickness reduction	[20,23]

*Energy values based on slurry value only (silicon carbide powder in diethylene glycol) for recycling versus non-recycling and replacement by recycled water (water with additives)

3 Results

3.1 Quality indicator literature meta-analysis

The quality indicator scoring overview is shown in Table 3 below for both mono- and polysilicon modules. The majority of assessed studies investigated energy payback time only with only four net energy return values published.

The quality indicator assessment values, based on the methodology outlined section 2.2, resulted in a score range from 10.5 to 26.5 between the lowest and highest study. In case of reliability of twenty-nine studies thirteen were found to provide data from either original measurements or directly traceable from referenced studies. A total of twelve studies took data from other studies and modified the datasets, of which ten studies without properly stating assumptions as examined by comparing original data with the borrowed data study, such that only incomplete data adjustment reconstructions could be made. In four cases the lowest reliability value was assigned due to a lack of any information on where the data was obtained [38,39], because a reverse calculation was performed using an assumed net energy metric value for solar module manufacturing (Prieto and Hall 2003), or because the actual data reference in the study was a meta-data analysis for referencing purposes only, as instead the data could only be traced via a secondary grey literature publication of the authors [40,41]

The completeness of 10 system aspects, as outlined in table 1, is minimal in a large number of cases. Four or less aspects were covered in twelve studies and five or six aspects in fifteen studies. Coverage primarily includes operation, transport to the installation site, the installation of the modules, and the balance of system, and to a lesser extent decommissioning. Only one study incorporates eight [32], and another nine aspects [42] including detailed analyses of maintenance, transport, recycling/landfill transportation, and auxiliary services. The embodied energy cost in higher order manufacturing stages, I.E. the embodied energy in the machinery and input used to produce the materials that go into the solar module supply chain, are only covered in a minority of cases using LCA software [42–45]. Similarly, raw material transports between facilities in the solar module supply chain were covered in only one study [46], whilst possible to specify this aspect in LCA software this was not described in studies employing the LCA approach. In general many system completeness components were not qualitatively described, and the extent of inclusion had to be based on a textual description which could not be verified. Facility completeness in seventeen studies included 6 out of 7 and in another eight studies 5 out of 7 facilities within the solar module supply chain, of which primarily quartz to metallurgical silicon chunks processing and quartz mining was missing. In one study all facilities including quartz mining were taken into account, whilst in two study results it was not clear which facilities were included, and in three studies 4 out of 7 facilities were included.

The average age of data in relation to the study publication date varies substantially from 18 years to 2 years prior to publication with a mean age of 7 years, based on a weighted value for the entire solar-PV manufacturing supply chain from quartz to module. A total of eight out of twenty-nine studies were reliant on data more than 10 years older as the publication date, another eight studies utilised data between 6 and 10 years old, four studies were based on data 4 or 5 years old, and only six studies used data obtained within 3 years prior to publication. Another perspective is to look at the age of data versus current time of all existing publications, based on which it was found that only five publications use data from the year 2009 or later on average [45,47–50], whilst fourteen out of twenty-nine where published since 2010.

Geographical conditions varied substantially. In five out of twenty-nine studies no region or country of facilities was mentioned, nine studies used data from facilities located in different geographies, and fourteen studies described their data as coming from a uniform region or country. The geographical differentiation is relevant in relation to the absence of facility to facility material transportation, plus variation in energy inputs due to different energy mixes per country.

Technological precision was difficult to establish due to an across the board lack of detail in describing the module supply chain and technologies used therein. In many cases the processing route had to be established using the referenced data. In eight studies no technological description was given, and in another five studies the outputs and processes are not properly matching, such as when using novel pilot silicon cells for outputs whilst using inputs related to producing standard silicon modules. For six studies only minor mismatches between modules produced and technology data was found, and in ten studies congruence between modules and technologies was established. The underlying scoring information for each study and indicator can be found in supplementary materials A available on the internet.

Table 3 Quality indicator scoring of energy metric studies for mono-and polysilicon modules.

Study		Silicon solar panel type	Panel rating (Wpeak)	Energy payback (years)	Net energy (ratio)	Estimated Average year of original data collection	Quality indicator score: Reliability	System Completeness	Facility Completeness	Data Age	Geographical conditions	Technological precision	Total score
Amor et al. (2010)	[43]	Mono	140	3.40	-	2007	3.0	3.0	4.0	4.0	5.0	5.0	24.0
Chen et al. (2016)	[48]	Mono	305	0.42 to	-	2009	5.0	1.0	2.0	2.0	3.0	4.0	17.0
Ferroni and Hopkirk (2016)	[41]	Mono	-	-	0.82	1998	5.0	3.0	4.0	1.0	1.0	1.0	15.0
Francke et al. (2015)	[47]	Mono	337	0.76	-	2009	4.0	3.0	4.0	4.0	3.0	2.0	20.0
Fthenakis and Kim (2011)	[2]	Mono	165	2.70	-	2004	5.0	0.5	3.0	2.0	3.0	4.0	17.5
Garcia-Valverde et al. (2009)	[51]	Mono	106	9.08	-	1996	4.0	3.0	4.0	1.0	1.0	2.0	15.0
Hou et al. (2016)	[50]	Mono	240	1.70	14.60	2014	5.0	2.5	4.0	5.0	5.0	4.0	25.5
Ito et al. (2011)	[52]	Mono	160	3.00	-	2007	5.0	2.0	3.0	4.0	5.0	5.0	22.0
Ito et al. (2016)	[42]	Mono	254	1.70	-	2006	3.0	4.0	4.0	2.0	1.0	1.0	15.0
Jungbluth et al. (2004)	[53]	Mono	185	4.50	-	2002	5.0	2.5	4.0	5.0	5.0	5.0	26.5
Kabakian et al. (2015)	[54]	Mono	75	16.10	-	2002	3.0	0.5	4.0	1.0	1.0	1.0	10.5
Kannan et al. (2006)	[55]	Mono	75	6.74	-	1998	5.0	2.5	2.0	2.0	5.0	5.0	21.5
Kim et al. (2014)	[56]	Mono	253	4.65	-	2007	3.0	2.0	4.0	2.0	3.0	5.0	19.0
Knapp and Jester (2001)	[57]	Mono	75	4.10	-	1998	5.0	0.5	3.0	4.0	5.0	5.0	22.5
Laleman et al. (2011)	[58]	Mono	240	4.90	-	2006	4.0	1.0	4.0	3.0	1.0	1.0	14.0
Meijer et al. (2003)	[59]	Mono	152	3.50	-	1997	3.0	1.0	3.0	3.0	1.0	2.0	13.0
Muneer et al. (2006)	[60]	Mono	90	8.00	-	2002	5.0	1.5	4.0	4.0	5.0	2.0	21.5
Nawaz and Tiwari (2006)	[61]	Mono	75	22.00	-	1996	3.2	1.5	4.0	2.0	3.0	4.0	17.7
Sumper et al. (2011)	[62]	Mono	180	8.37	-	1995	3.0	2.5	3.0	1.0	3.0	2.0	14.5
Wetzel and Borchers (2015)	[49]	Mono	243	1.09	-	2013	5.0	1.5	3.0	5.0	1.0	4.0	19.5
Wild-Scholten (2013)	[45]	Mono	240	1.96	-	2009	5.0	1.5	5.0	4.0	5.0	5.0	25.5
Wild-Scholten (2013)	[45]	Mono	240	2.34	-	2009	5.0	1.5	5.0	4.0	5.0	5.0	25.5
Prieto and Hall (2013)	[32]	Mo&Po	-	-	2.46	2004	1.0	4.0	3.0	2.0	1.0	1.0	12.0
Alsema (2000)	[63]	Poly	140	3.50	-	1995	4.0	1.0	4.0	3.0	1.0	1.0	14.0
Battisti and Corrado (2005)	[44]	Poly	80	3.30	-	1997	3.0	3.0	3.0	2.0	1.0	1.0	13.0
Amor et al. (2010)	[43]	Poly	132	3.90	-	2007	3.0	3.0	4.0	4.0	5.0	5.0	24.0
Celik et al. (2008)	[64]	Poly	120	7.90	-	1997	3.0	0.5	4.0	1.0	3.0	1.0	12.5
Fthenakis and Kim (2011)	[2]	Poly	165	2.20	-	2004	5.0	0.5	2.0	2.0	3.0	4.0	16.5
Hou et al. (2016)	[50]	Poly	240	1.60	15.80	2014	5.0	2.5	4.0	5.0	5.0	4.0	25.5
Ito et al. (2003)	[38]	Poly	120	1.70	-	2001	1.0	2.5	2.0	5.0	5.0	1.0	16.5
Ito et al. (2008)	[46]	Poly	120	1.90	-	1996	3.0	3.0	3.0	1.0	5.0	4.0	19.0
Ito et al. (2008)	[46]	Poly	152	1.50	-	1996	3.0	3.0	3.0	1.0	5.0	4.0	19.0
Ito et al. (2011)	[52]	Poly	180	2.30	-	2007	5.0	2.0	3.0	4.0	5.0	5.0	22.0
Ito et al. (2016)	[42]	Poly	240	1.50	-	2006	3.0	4.0	4.0	2.0	1.0	1.0	15.0
Jungbluth et al. (2004)	[53]	Poly	166	4.50	-	2002	5.0	2.5	3.0	5.0	5.0	5.0	25.5
Kim et al. (2014)	[56]	Poly	237	3.68	-	2007	3.0	2.0	4.0	2.0	3.0	5.0	19.0
Laleman et al. (2011)	[58]	Poly	240	4.30	-	2006	4.0	1.0	4.0	3.0	1.0	1.0	14.0
Pacca et al. (2007)	[65]	Poly	120	7.50	2.70	1996	4.0	1.0	4.0	1.0	5.0	4.0	19.0
Sumper et al. (2011)	[66]	Poly	270	4.36	-	1995	3.0	2.5	3.0	1.0	3.0	2.0	14.5
Tripanagnostopoulos et al. (2005)	[39]	Poly	75	2.90	-	1992	1.0	2.0	4.0	1.0	3.0	4.0	15.0
Wetzel and Borchers (2015)	[49]	Poly	260	0.93	-	2013	5.0	1.5	3.0	5.0	1.0	4.0	19.5
Wild-Scholten (2013)	[45]	Poly	225	1.24	-	2009	3.0	1.5	5.0	4.0	5.0	5.0	23.5
Wild-Scholten (2013)	[45]	Poly	225	1.45	-	2009	3.0	1.5	5.0	4.0	5.0	5.0	23.5

3.2 Energy metric indicator study reproduction and harmonization

A total of nineteen studies and twenty-eight study energy metric value results were assessed from the total of twenty two assessed studies. As described in the methodology in the collective overview two values were omitted due to a solar panel size below the 75 MW panel size cut-off, and one value was omitted in the collective results also as both poly- and mono-silicon were jointly analysed without separation possibilities [32]. See Table 4 for a study by study overview, and Figures 1 and 2 for a boxplot summary of fourty-two energy payback and net energy values.

The range of results found for the twenty-two energy payback time values of **monosilicon-PV** were:

- **The original study**: a mean energy payback time value of 5.5 years within a min-max range of 0.8 to 22 years.
- **This study reproduced**: the reproduced values yielded a mean energy payback time value of 5.1 years within a min-max range of 0.4 to 31 years.
- **This study harmonized**: the harmonized values yielded a mean energy payback time value of 3.9 years within a min-max range of 0.8 to 9.3 years.

The range of results found based on the twenty energy payback times values of **polysilicon-PV** were:

- **The original studies**: values yielded a mean energy payback time value of 3.1 years within a min-max range of 0.9 to 7.9 years.
- **This study reproduced**: the reproduced values yielded a mean energy payback time value of 2.7 years within a min-max range of 1.0 to 6.9 years.
- **This study harmonized**: the harmonized values yielded a mean energy payback time value of 2.9 years within a min-max range of 1.8 to 5.3 years.

The range of results based on the twenty-two Net Energy Ratio values for monosilicon-PV over the module's lifetime were:

- **The original studies**: the published values included a 0.82 ratio from [41] and 14.6 ratio from [50]
- **This study**: the reproduced and created values from original study data gave a mean net energy ratio of 12.5 within a min-max range of 0.8 to 60.3.
- **This study**: the harmonized values gave a mean net energy ratio of 8.6 within a min-max range of 2.7 to 30.6.

The range of results based on the twenty Net Energy Ratio values of Polysilicon-PV over the module's lifetime were:

- **The original studies**: in the published values included a 2.7 ratio from [62] and a 15.8 ratio from [50].
- **This study**: the reproduced and created values from original study data, gave a mean net energy ratio of 12.9 within a min-max range of 2.9 to 31.0
- **This study:** the harmonized values gave a mean net energy ratio of 9.3 within a min-max range of 4.8 to 13.7.

The discrepancies between reproduced and original study values were also assessed. In twenty-seven out of fourty-three values the reproduced outcome was within range of the original study published results, or with only minor deviations below 10%. In ten cases medium sized discrepancies were found ranging from 10% to 40% deviation between the reproduced and original value, with causes traceable due to varying boundaries such as inclusion of all energy in reproduced value, versus only fossil in the original value (ignoring hydropower inputs), or due to omission of heat retention glazing in the reproduced value. In seven cases major discrepancies were found above 50% relative to this study values, primarily caused by a lack of correction for thermal to electric values (or vice versa) in the original studies or discrepancy between large battery systems in-or exclusion.

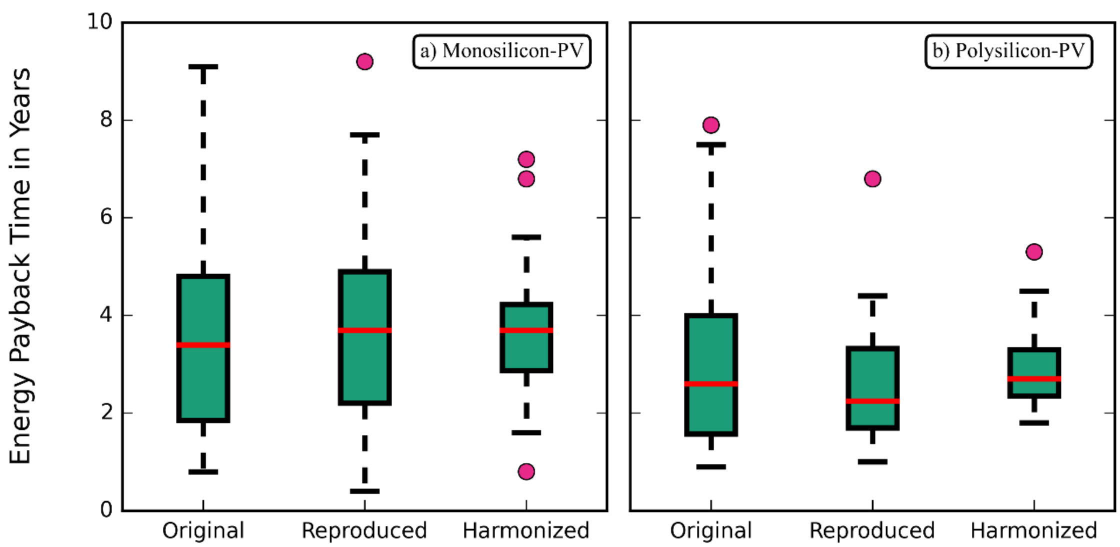

Fig. 1 Boxplot of original, reproduced, and harmonized Energy Payback Time values for a) monosilicon-PV on the left and b) polysilicon-PV on the right. The red line indicates the median and whiskers displayed at 1.5 interquartile values. The mono-silicon EPT outlier values of 22 from [61], 16.1 from [54], and 30.8 generated from [41] are not shown for display scaling purposes.

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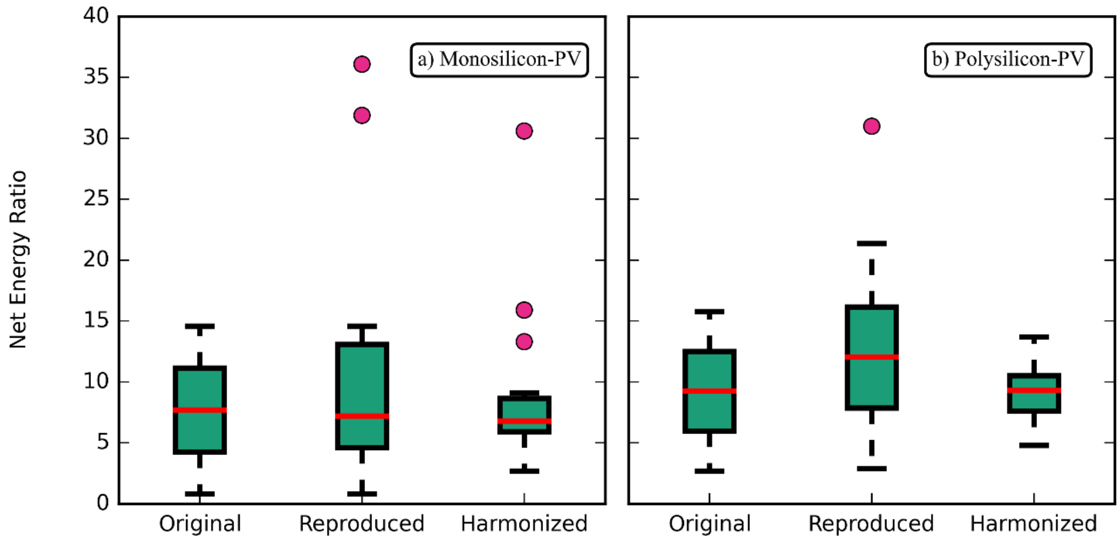

Fig. 2 Boxplot of original, reproduced, and harmonized Net Energy Ratio values for a) monosilicon-PV on the left and b) polysilicon-PV on the right. The red line indicates the median and whiskers displayed at 1.5 interquartile values. The mono-silicon NER reproduced study outlier value of 60 from [47] is not shown for display scaling purposes

Table 4 Energy metrics original, reproduced, and harmonized values.

Study		Silicon solar panel type	Energy payback time (years)			Net energy ratio		
			Original study	Reproduction (this study)	Harmonized value (this study)	Original study	Reproduction (this study)	Harmonized value
Amor et al. (2010)	[43]	Mono	3.4	4.1	3.8	-	7.3	6.7
Chen et al. (2016)	[48]	Mono	0.4 to 0.9	0.4	1.6	-	60.3	15.9
Ferroni and Hopkirk	[41]	Mono	-	30.8	9.3	0.8	0.8	2.7
Francke et al. (2015)	[47]	Mono	0.8	0.8	0.8	-	36.1	30.6
Fthenakis and Kim	[2]	Mono	2.7	2.3	2.7	-	13.1	9.1
Garcia-Valverde et al.	[51]	Mono	9.1	9.2	4.3	-	2.2	5.8
Hou et al. (2016)	[50]	Mono	1.7	1.7	1.9	14.6	14.5	13.3
Ito et al. (2011)	[52]	Mono	3.0	2.8	3.1	-	10.6	8.0
Ito et al. (2016)	[42]	Mono	1.7	2.2	5.6	-	13.6	4.5
Jungbluth et al. (2004)	[53]	Mono	4.5	4.4	4.0	-	6.8	6.3
Kabakian et al. (2015)	[54]	Mono	16.1	5.7	3.8	-	4.4	6.6
Kannan et al. (2006)	[55]	Mono	6.7	6.7	6.8	-	3.7	3.7
Kim et al. (2014)	[56]	Mono	4.7	4.6	5.2	-	6.5	4.8
Knapp and Jester (2001)	[57]	Mono	4.1	4.1	7.2	-	7.3	3.5
Laleman et al. (2011)	[58]	Mono	4.9	4.9	3.8	-	6.1	6.5
Meijer et al. (2003)	[59]	Mono	3.5	3.5	3.4	-	7.2	7.2
Muneer et al. (2006)	[60]	Mono	8.0	7.6	3.9	-	4.0	6.4
Nawaz and Tiwari	[61]	Mono	22.0	7.7	3.6	-	4.6	6.9
Sumper et al. (2011)	[62]	Mono	8.4	3.7	3.1	-	6.7	8.2
Wetzel and Borchers	[49]	Mono	1.1	0.9	1.6	-	31.9	15.9
Wild-Scholten (2013)	[45]	Mono	2.0	2.1	2.8	-	14.6	8.8
Wild-Scholten (2013)	[45]	Mono	2.3	2.5	3.3	-	12.1	7.6
Mean value			**5.5**	**5.1**	**3.9**		**12.5**	**8.6**
Alsema (2000)	[63]	Poly	3.5	3.1	3.6	-	8.0	7.0
Battisti and Corrado	[44]	Poly	3.3	3.3	3.2	-	7.5	7.8
Amor et al. (2010)	[43]	Poly	3.9	3.4	2.9	-	8.9	8.7
Celik et al. (2008)	[64]	Poly	7.9	6.8	3.8	-	2.9	6.6
Fthenakis and Kim	[2]	Poly	2.2	1.7	2.8	-	17.2	9.1
Hou et al. (2016)	[50]	Poly	1.6	1.6	1.8	15.8	15.8	13.7
Ito et al. (2003)	[38]	Poly	1.7	2.8	2.6	-	10.5	9.5
Ito et al. (2008)	[46]	Poly	1.9	1.9	2.6	-	15.6	9.7
Ito et al. (2008)	[46]	Poly	1.5	1.5	2.6	-	19.6	9.5
Ito et al. (2011)	[52]	Poly	2.3	2.3	2.2	-	13.3	11.2
Ito et al. (2016)	[42]	Poly	1.5	2.2	5.3	-	13.5	4.8
Jungbluth et al. (2004)	[53]	Poly	4.5	4.0	3.0	-	7.5	8.3
Kim et al. (2014)	[56]	Poly	3.7	3.7	4.5	-	8.2	5.6
Laleman et al. (2011)	[58]	Poly	4.3	4.4	3.9	-	6.9	6.4
Pacca et al. (2007)	[65]	Poly	7.5	2.8	3.0	2.7	7.1	8.2
Sumper et al. (2011)	[66]	Poly	4.4	1.9	2.4	-	12.8	10.2
Tripanagnostopoulos et	[39]	Poly	2.9	2.2	2.4	-	11.3	10.3
Wetzel and Borchers	[49]	Poly	0.9	1.0	1.9	-	31.0	13.3
Wild-Scholten (2013)	[45]	Poly	1.2	1.4	1.9	-	21.4	13.4
Wild-Scholten (2013)	[45]	Poly	1.5	1.7	2.1	-	17.9	11.8
Mean value Polysilicon		**Poly**	**3.1**	**2.7**	**2.9**	**-**	**12.9**	**9.3**
Prieto and Hall (2013)	[32]	Mono & Poly	-	9.9	6.5	2.5	2.5	3.8

3.2.1 Energy metric indicator trend analyses

The analysis of time lags demonstrated a mean delay of 7 years between the year in which the original data was obtained and study publication for the fourth-three study values. The minimum delay is 2 years and the maximum 18 years, as shown in Figure 3 below for mono- and polysilicon.

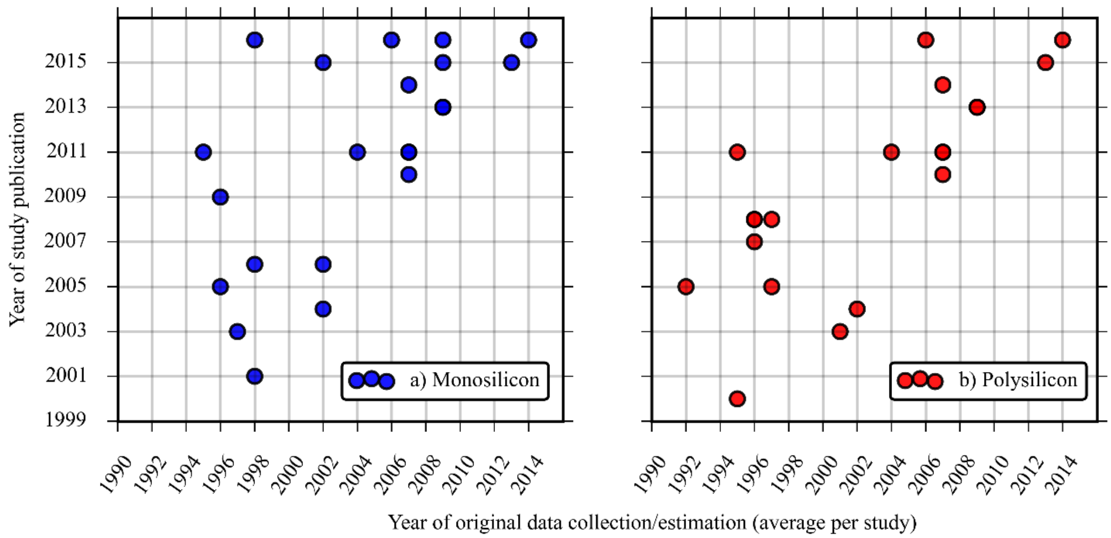

Fig. 3 Year wherein original data was obtained (x-axis) plotted against year of study publication (y-axis) for a) monosilicon (blue, left) and b) polysilicon (red, right).

The comparison between the year in which study data was obtained and Net Energy Metrics based on harmonized values only shows a weak trend over time (see Figure 4). The lowest harmonized Energy Payback value at 0.82 comes from a study published in 2016, of which the data was obtained around 2014 for cell, wafer, and module manufacturing, and 1997 and 2009 for processes up to Silicon Ingot production [47]. In contrast the highest harmonized energy payback value at 9.3 comes from a study published in 2016 with the estimated average year of sourced data as 1998 [40,41].

If we compare the time-periods of data themselves we find the following average harmonized values for mono- and polysilicon solar-PV:

- Studies with data obtained after 2008 the EPT equals 2.0 and 1.9, and NER of 15 and 13.
- Studies with data from 2004-08 an average EPT of 4.0 and 3.6, and NER of 6.6 and 7.5.
- Studies with data obtained before 2004 an average EPT of 5.0 and 2.9, and NER of 5.7 and 8.8.

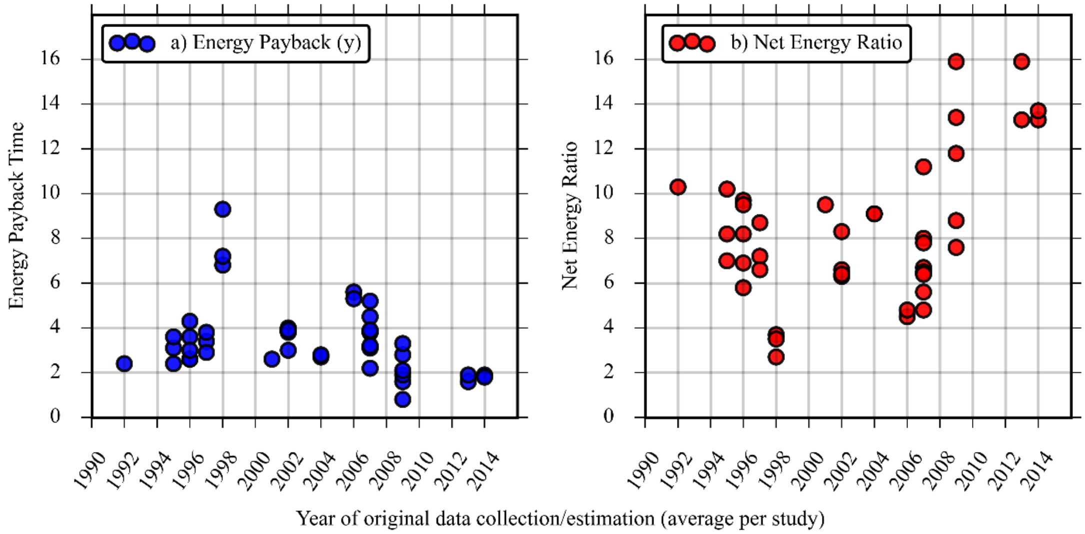

Fig. 4 Year wherein data was obtained (x-axis) versus harmonized Energy Metric values (y-axis) including a) Energy Payback time (blue, left) and b) Net Energy Ratio (red, right).

The results of the economy of scale assessment by means of module size and power output per module is shown in Figure 5 and 6 below. A clear scaling effect for the amount of power output per module surface area can be discerned in Figure 5 as an increase in 20 to 30 Watt capacity per m^2 per doubling of overall module capacity. Similarly, a scaling effect can be found on increasing module power capacity on Energy input and Energy Metric values. As displayed in Figure 6 a reduction in energy input per kWp module capacity of 5 to 10 GJ is discernable when scaling from 75 to 240 Watt modules, and another 5 GJ when scaling further to 300+ Watt modules, with a corresponding improvement in Energy Payback Time and Net Energy Ratio's.

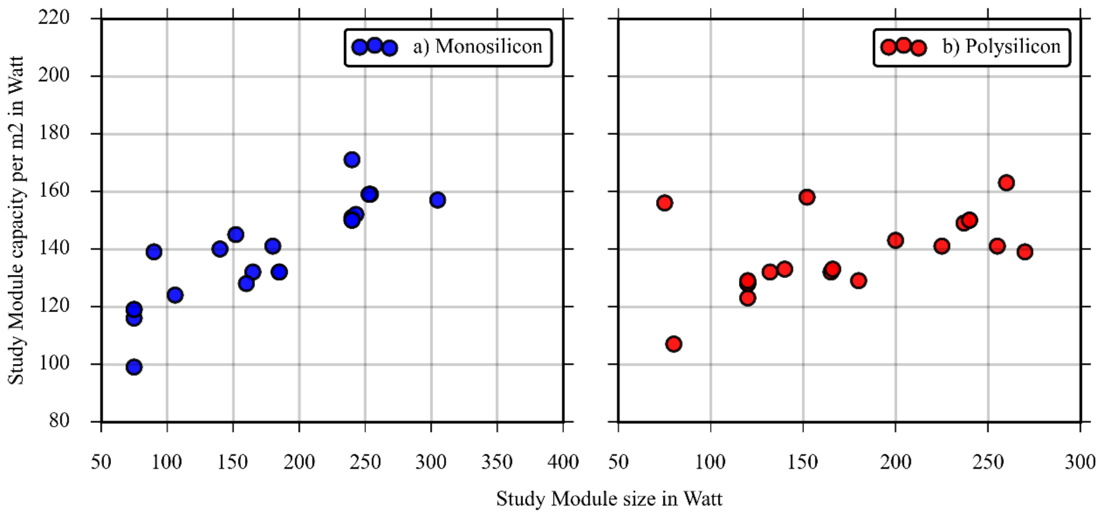

Fig. 5 Study module size in Watt (x-axis) plotted against the module size in Watt per m2 (y-axis) differentiated between a) monosilicon (blue, left) and b) polysilicon (red, right).

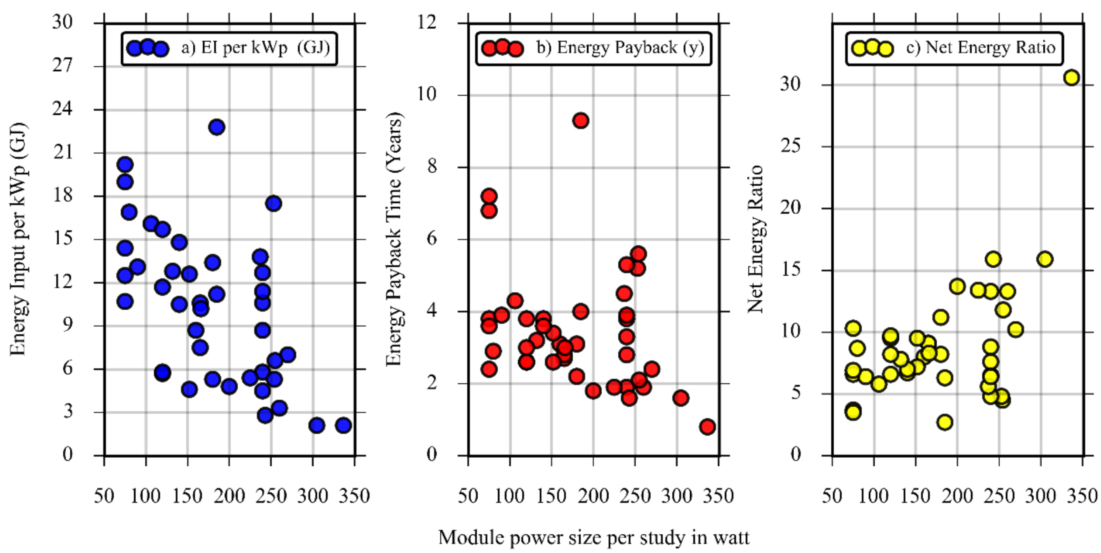

Fig. 6 Module power size in watt for each study (x-axis) plotted against a) Energy input in GJ per kWp module (blue, left) b) Energy Payback Time (red, center), c) Net Energy Ratio (yellow, right).

3.3 Data interval sensitivity analysis

The sensitivity of energy metric values to solar radiation and energy input variation was analysed for a solar radiation interval between 700 and 2600 kWh/m^2/year, and life cycle energy input variation as published in literature studies since 2004, as described in section 2.4. The analysis yielding the following ranges for monosilicon and polysilicon systems:

- A **net energy ratio range** between 2 and 22 years for **Monosilicon solar-PV systems**, based on an energy input range between 1.5 and 5.5 GJ per m2 of module cell area, plus a solar radiation range between 976 and 2600 kWh/m2/year (figure 7a top left).
- A **net energy ratio range** between 5 and 27.5 years for **Polysilicon solar-PV systems**, based on an energy input range between 1.0 and 2.6 GJ per m^2 of module cell area, plus a solar radiation range between 976 and 2600 kWh/m2/year (figure 7b top right)
- An **energy payback time** range between 2 and 22 years for **Monosilicon solar-PV systems**, based on an energy input range between 1.5 and 5.5 GJ per m^2 of module cell area, plus a solar radiation range between 732 and 2500 kWh/m2/year (figure 7c bottom left)
- An **energy payback time** range between 1.5 and 10.5 years for **Polysilicon solar-PV systems**, based on an energy input range between 1.0 and 2.6 GJ per m^2 of module cell area, plus a solar radiation range between 732 and 2500 kWh/m2/year (figure 7d bottom right).

The harmonized values of analysed studies were placed within these interval ranges in the colour gradient charts of Figure 7, based on their original study solar radiation energy input, and harmonized energy output value and energy metrics.

Also the interval sensitivity of energy metric values to technology developments was assessed including wafer thickness reduction, wafer sawing slurry recycling, diamond wire based wafer sawing, and metallurgical silicon refining technology, as described in section 2.4.1. The analysis yielded the following ranges for monosilicon and polysilicon system studies :

- A **life cycle energy input reduction** for the twenty-two study values for monosilicon **solar-PV systems** ranging from 0.10 to 0.44 GJ per m2 with a mean value of 0.30 GJ per m2.
- A **life cycle energy input reduction** for the twenty study values for polysilicon **solar-PV systems** ranging from 0.10 to 0.40 GJ per m2 with a mean value of 0.29 GJ per m2.
- A **net energy ratio** value increase for the twenty-two study values for monosilicon **solar-PV systems** ranging between 0.1 and 6.8 with a mean increase of 1.1 in ratio value (figure 8a top left). Thereby the mean net energy ratio value across studies increased from 8.6 to 9.7.
- A **net energy ratio** value increase for the twenty study values for polysilicon **solar-PV systems** ranging between 0.4 and 6.2 with a mean increase of 2.1 in ratio value (figure 8b top right). Thereby the mean net energy ratio value across studies increased from 9.3 to 11.4.
- An **Energy Payback Time** value decrease for the twenty-two study values for **monosilicon solar-PV systems** ranging between 0.1 and 0.7 years with a mean decrease of 0.4 years

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(figure 8c bottom left). Thereby the mean energy payback time across studies decreased from 3.9 to 3.5 years.

- An **Energy Payback Time** value decrease for the twenty study values for **polysilicon solar-PV systems** ranging between 0.2 and 0.9 years with a mean decrease of 0.5 years (figure 8d bottom right). Thereby the mean energy payback time across studies decreased from 2.9 to 2.4 years.

The interval analysis for technologies yields a mean improvement in the energy metric values of 10% and 20% for respectively mono- and polysilicon Solar-PV values relative to the harmonized data values.

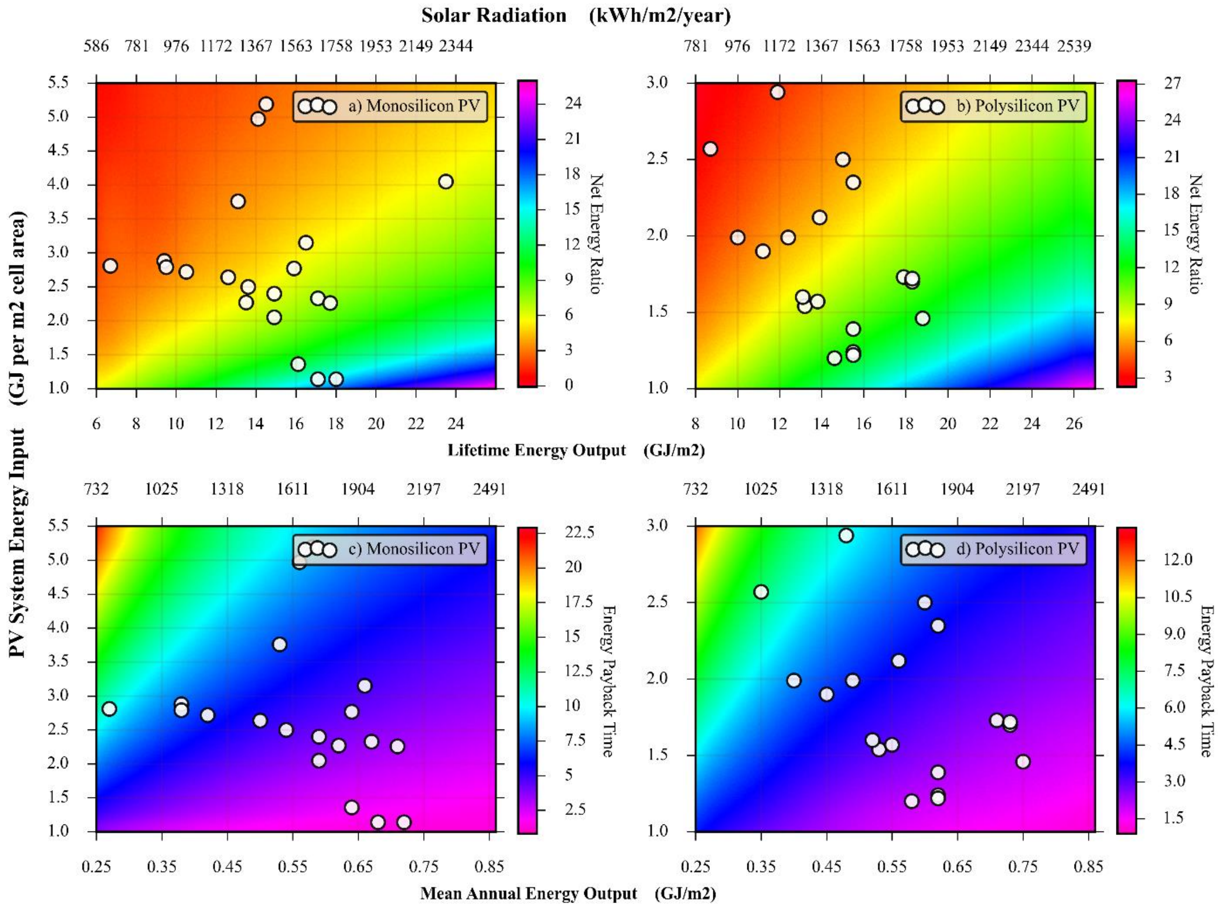

Fig. 7 Data interval sensitivity plots for a) monosilicon PV net energy ratio, b) polysilicon PV net energy ratio, c) monosilicon PV Energy Payback Time, d) polysilicon PV Energy Payback Time. Individual data points of assessed studies are included in the plots.

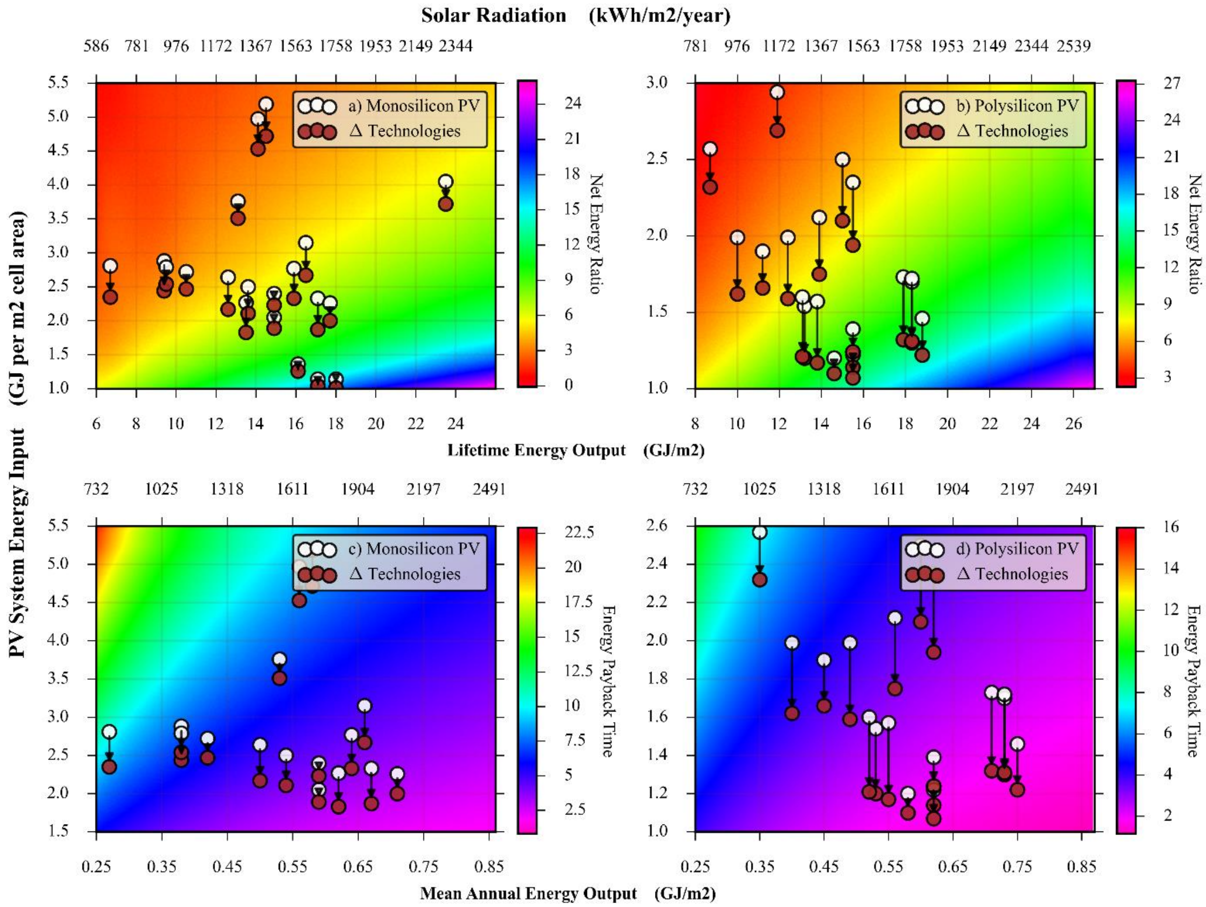

Fig. 8 Effects on study Energy Payback Time and Net Energy Ratio values due to technology variation adjustment, as described in section 2.3.1, within data interval sensitivity plots for a) monosilicon PV net energy ratio, b) polysilicon PV net energy ratio, c) monosilicon PV Energy Payback Time, d) polysilicon PV Energy Payback Time.

4 Discussion

The study aim was to examine the variability in existing energy metrics studies with a focus on data quality aspects. In this section in sequence discussed are the applied methodology in this study, how data is reported in examined studies looking at reproducibility, what is reported in examined studies, and finally a discussion of the overall data trends. The underlying basis of all methodologies in this study was the examination of a data from each individual study as necessary to construct the external study net energy metric analysis, as well as to infer meta-data to examine quality aspects. The analysis in certain cases was fairly straightforward, for instance in the categorization of data reliability, but in other cases a time consuming effort, for instance in examining data age or system completeness. The selective effort stems from the lack of meta-data reported on certain elements, such as in most cases the absence of solar module technicalities like packing factors and wattage, or technology process chain configuration information underlying the data, due to which analysing congruence of technological uniformity is challenging. To make this ambiguity more transparent quality indicator criteria were adjusted to reflect a lack of reported meta-data. The time consuming nature of the effort stems from the lack of clear reporting, such that individual studies had to be carefully read to understand key data points, data had to be indirectly inferred from diagrams, and data calculation was required from various values based on assumed congruence. For example, in certain cases the wattage of a solar module had to be calculated based on the reported total capacity figure for the solar park and the reported total square m^2 figure. In many cases individual values were not reported such as the packing factor necessary to analyse cell area per module surface area. In the absence of such values an effort was made to retrieve these indirectly, in this case through tracing the type of module used in a study and retrieving the manufacturer's specifications. The ability to assess the quality of studies is thereby limited except by means of a time consuming effort. It was also found that in four studies large methodological errors were made by comparing energy inputs on a thermal basis with energy outputs on an electricity basis [61,54,62,65]. Possibly caused by a lack of standardised structure in conducting a study, which increases the likelihood of occurrence such errors. Additional details on dealing with energy conversions can be found in the extensive discussion in [67,68]. If studies are to be conducted such that their quality can be easily verified, and for reproducibility following standard scientific conduct, a significant improvement in reporting efforts and transparency is necessary. In case practitioners wish to pursue this aim efforts should be made to closely follow and report according to the International Standards Organisation (ISO) such as ISO14040 and ISO14044, and IEA-PVPS T12 for LCA [69], by including in a study boundary descriptions in a more rigorous manner including what is not included, what key assumptions were made, what adjustments were made to utilised data from other sources, and which calculation methods were applied. The latter especially for electric to thermal conversions and vice versa. Furthermore, these aspects need to be reported in a clear and transparent manner to remove ambiguities as well as to facilitate the reader in the interpretation of results.

The assessment of individual data quality aspects highlighted a number of features typically absent yet necessary to carry out appropriate data quality analysis. Notwithstanding a significant number of studies with good data practices on reliability of data collection, the practice of obtaining data from secondary studies was found to be problematic. In many studies adjustments were made to borrowed data without properly outlining the exact procedure of the adjustment, as necessary to explain the difference in original datasets and published or inferred data from the borrowed data study. The omission of data handling practices was found to be one of the main challenges in study reproducibility, which can be addressed either by outlining the exact data adjustment procedures or by providing the datasets used in the study as supplementary materials, inclusive of original datasets taken without adjustments. In a limited number of cases no information on data sourcing was included altogether, which puts the quality of study review into question. The completeness of studies was also found to vary highly in terms of supply chain and life cycle coverage. More importantly, from a quality perspective the reporting of completeness is not carried out in a standardised manner. It is often necessary to carefully interpret the study text to find out study boundaries, as opposed to a transparent table outlining what is and what is not included such that direct interpretation becomes feasible. This also includes the lack of boundaries reported in the operation of LCA software for aspects of embodied energy in materials. Furthermore, the description in the text of incorporated life cycle components is mostly limited to a qualitative statement without specifying exact quantitative information of the boundary. A key example is the representation of transportation without explication which part of transportation in the supply chain and which distances.

The analysis of data age yielded significant differences between studies with authors of about half of the analysed studies choosing to utilise data 6 years or older since the publication date, and in an extreme case up to 18 years. The practice indicates a lack of rigour in data selection also for recent studies, based on that rapid technological change in the solar industry results in rapidly outdated data. In several cases it was found that studies cite older studies which again cite older studies [41,61,65,64]. This view is further reinforced by the public availability of reasonably up to date datasets in the literature which could have been taken instead of outdated sources. As a consequence it cannot be automatically assumed if a study is published in recent years that a studies values reflect up to date information, given the lack of adherence to quality standards. Also the average value from the literature is not as representative, as the filtering of five studies with recent data based on collection since 2009 found an improvement of approximately half the EPT and double the NER relative to studies with older data.

In the examination of a given study an evaluation of the original data sources is necessary for quality assessment and study interpretation purposes, at least under current limited reporting practices. On that basis it can be argued that more rigorous standards are required in the use of borrowed data and data-age. As an example of transparent, comprehensive, yet easy to interpret reporting the energy metric study of [51] can be consulted.

The aspect of technological configuration was difficult to establish because of the lack of reporting on the processing route, plausibly caused by the overall lack of information of technological configuration of facilities from which data is obtained in case of direct estimates, given the proprietary nature of this meta-data. A potential route for improvement is to deepen the analytical framework to a individual process per facility level using process engineering principles. As a basis energy and material balances can be incorporated, following accounting methodologies such as published by [1,70], and specific solar-PV analyses of technology configuration such as published by [71]. As an example for solar-PV module assembly the life cycle sustainability analysis by [72] and for silicon wafer processing the study by [73] can be consulted. Whilst significantly more complicated the need for a greater technological understanding of the process chain was established by the non-trivial result of a 10% to 20% improvement in energy metric values, as established from a sub-set of historic and current technological progress. Once such a technological understanding is developed in the context of energy metrics and LCA the impact of individual technology components, such as solar panel cleaning robots, can also be assessed in a more direct and transparent manner.

Beyond data quality aspects this study also evaluated a limited number of technical causes of variation in energy metric results. In general the chosen energy output parameters of solar radiation and absorption efficiency were found to be larger contributors to study value variation than energy input values. The study also found a clear relationship between module power size and lower energy payback and higher net energy ratio metrics, whose underlying dynamic was found to be caused by lower energy input values per module. Studies with smaller wattage modules thus produce poorer energy metric results and vice versa. The effect is indicative of economies of scale based on the logic that larger modules can be produced more efficiently with less material waste and cost and thereby less overall energy input requirements. Factors explain the difference can include less components necessary for the same m^2 of module such as aluminium frames, more efficient packaging of cells in a module, and greater capacity per cell over time. Knowledge of the technological configuration of the process chain and differences in produced modules over time could be used in unison with energy metric analysis and LCA to further explore the precise contribution of economy of scale factors to improved solar-PV energy metric values.

5 Conclusions

The analysis was based on a review, reproduction, and harmonization of thirty-four studies that investigated for solar-PV systems the energy payback time in years and energy return, in solar energy output gain per energy input. The study showed that the mean harmonized EPT values for mono-and polysilicon solar-PV was 3.8 and 2.9 years, and the mean NER 2.7 and 9.2 times. An analysis of the meta-data yielded that the data used to produce these results is on average 7 years old, with a range of 2 to 18 years. The impact of this publication to data-delay was quantified in two analyses. First, a comparison of five studies with only recent data collected since 2009, versus twenty-nine using data collected before, showed that in studies with recent data the harmonized EPT halved, and the harmonized NER doubled. Second, a data-age correction for a sub-set of technological improvements yielded an improvement in the harmonized EPT from 3.5

to 2.4 years, and in the harmonized NER from 9.7 to 11.4 years. Based on these conclusions three recommendations are made:

- **First**, in the interpretation of any study the data-sources including secondary data should be scrutinized on their data age and if they reflect recent technological standards in solar-PV manufacturing.
- **Second**, in future studies an effort should be made to utilise available primary or secondary data, that reflect more recent technological standards, as opposed to harken back to copying older data.
- **Third,** that the year wherein the original data as collected is reported, regardless of whether it is primary or secondary data from other sources.

The analysis also found that the quality of study reporting to interpret and accurately reproduce existing study results was challenging, due to limited transparent reporting of meta-data, especially technical system specifications, data-handling procedures, and solar supply chain descriptions. Also in four studies an error was found where primary inputs were directly compared with final electricity outputs, and smaller discrepancies were established to plausibly also be due to electric to thermal energy conversions in the manufacturing supply chain.

Based on these conclusions five recommendations are made to improve study transparency and comparability:

- **First,** to include in the reporting tables relevant meta-data on solar module specifications (e,g, dimensions, rate Wpeak output, packing factor, cell and module efficiency,
- **Second,** to report in a table the energy inputs broken-down per module manufacturing supply chain component (e.g. each facility or unit process from quartz to module), including a distinction between direct process and embodied materials energy.
- **Three,** to report in a table the additional energy inputs, which can include transportation, operation & maintenance, disposal/recycling, auxiliary, transmission, Balance of System (BOS), higher order embodied energy, and other inputs.
- **Fourth**, when collecting original data to specifically include reporting of both primary and final energy values, and when carrying out conversions to explicate the conversion procedure in the paper.
- **Fifth,** if any adjustments are made of secondary data, such as combining sources, averaging, or technological adjustments, to include the adjustments in quantitative form in the study.

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