BioPhysical Economics and Resource Quality (2017) 2:15
https://doi.org/10.1007/s41247-017-0033-0

ORIGINAL PAPER

An Exploration of Divergence in EPBT and EROI for Solar Photovoltaics

Graham Palmer[1] · Joshua Floyd[2]

Received: 19 September 2017 / Accepted: 16 November 2017 / Published online: 22 November 2017

Abstract

Solar photovoltaics (PV) is widely regarded as one of the most promising renewable energy technologies. Net energy analysis (NEA) is a tool to evaluate the energetic performance of all energy supply technologies, including solar PV. Results across studies can appear to diverge sharply, which leads to contestation of NEA's relevance to energy transition feasibility assessment and contributes to ongoing uncertainty in relation to the critical issue of the sustainability of PV. This study explores how PV NEA approaches differ, including in relation to goal definitions, methodologies and boundaries of analysis. It focuses on two principal NEA metrics, energy return on investment (EROI) and energy payback time (EPBT). Here we show that most of the apparent divergence between studies is accounted for by six factors—life-cycle assessment methodology, age of the primary data, PV cell technology, the treatment of intermittency, equivalence of investment and output energy forms, and assumptions about real-world performance. The apparent divergence in findings between studies can often be traced back to different goal definitions. This study reviews the differing approaches and makes the case that NEA is important for assessing the role of PV in future energy systems, but that findings in the form of EROI or EPBT must be considered with specific reference to the details of the particular study context, and the research questions that it seeks to address. NEA findings in a particular context cannot definitively support general statements about EROI or EPBT of PV electricity in all contexts.

Keywords Solar PV · EROI · EPBT · Net energy

Introduction

Summary

Net energy analysis (NEA) is a tool used to evaluate the energetic performance of energy supply technologies. The two net-energy metrics commonly applied to electricity generation technologies are the energy return on investment (EROI) and energy payback time (EPBT). EROI for electricity generation has been widely studied, especially coal-fired electricity, including carbon capture (Wu et al. 2016; White and Kulcinski 2000), wind power (Kubiszewski et al. 2010), solar photovoltaics (Bhandari et al. 2015; Koppelaar 2016; Louwen et al. 2016) and gas-fired generation (Moeller and Murphy 2016). The boundaries and types of analysis vary between studies, but all those just cited adopt the electricity busbar or inverter output as the EROI numerator—electricity distribution and management of the grid system as a whole is typically excluded from the analysis boundary.

Net energy analyses for solar photovoltaic (PV) systems have mostly conformed to mainstream life-cycle assessment (LCA) guidelines, with different values often assumed for key performance parameters, such as insolation and operating life. Further reinforcement of a standard methodology was provided by the IEA PV Power Systems Programme (IEA-PVPS) guidelines (Frischknecht et al. 2016). Since the IEA-PVPS guidelines are seen by many investigators as the consensual outcome of debate over methodology, this study adopts them as its reference point for standard practice.

The principal benefit of standard guidelines is that they permit like-for-like comparison between different types of solar PV system (e.g. between systems employing different cell technologies), and assessment of the variance between different production contexts for systems of the same type. Many of the differences in findings between conventional analyses can be accounted for via meta-analyses that harmonise for key performance parameters (e.g. Bhandari et al. 2015; Koppelaar 2016; Louwen et al. 2016).

✉ Graham Palmer
graham.palmer@climate-energy-college.org

1 Australian-German College of Climate and Energy, The University of Melbourne, Parkville 3010, Australia

2 The Rescope Project, Melbourne, Australia

The limitation of a standardised methodology is that studies are then restricted to answering the range of research questions to which that methodology is suited. An emphasis on improved harmonisation between studies may come at the cost of excluding energy investments that are important for understanding the broader socio-economic consequences of providing an increasing proportion of final energy supply via PV electricity. Furthermore, considerations relating to the engineering-systems view of electricity supply, which are critical to establishing the value of solar PV at higher grid penetration, are generally treated as lying outside the domain of conventional life-cycle research.

This study explores the differing approaches to understand why there is apparently such divergence in EROI findings. We show that much of the difference between studies can be attributed to six factors—life-cycle assessment methodology, age of the primary data, PV cell technology, the treatment of intermittency, equivalence of investment and output energy forms, and assumptions about real-world performance.

Definition of EROI and EPBT

EROI is a unitless ratio, defined as the ratio of the gross energy output over the operating lifetime for an energy supply system, and the sum of the energy for manufacture, construction, operation and maintenance, decommissioning and disposal/recycling over the system's project life-cycle (Murphy et al. 2011, Eq. 1). Murphy and Hall (2010) state that 'EROI is the ratio of how much energy is gained from an energy production process compared to how much of that energy (or its equivalent from some other source) is required to extract, grow, etc., a new unit of the energy in question.' EPBT is the length of time, in years, for a PV system to generate the same amount of energy (in terms of primary energy equivalent) that was used to produce the system itself (Frischknecht et al. 2016, Sect. 3.4.2). The energy invested (embodied energy) is established by LCA. For a PV *system*, this is the same as the cumulative energy demand (CED). However, the CED of PV *electricity* differs markedly depending on whether the 'energy harvested' or the 'energy harvestable' concept is applied (see "Output Energy form Equivalence in the Context of PV NEA" section). Energy investment and output can be expressed in different forms depending on the goal of the study, as discussed in detail in "Equivalence of Investment and Output Energy Forms" section.

$$EROI = \frac{E_{out}}{E_{inv}} \tag{1}$$

$$EPBT = \frac{E_{inv}}{E_{out_{yr}}}, \tag{2}$$

where E_{out} is the life-cycle electrical energy delivered by the PV system at the inverter output, E_{inv} is the life-cycle energy investment and $E_{out_{yr}}$ is the annual primary energy equivalent output (see "Equivalence of Investment and Output Energy Forms" section).

Goal Definitions

Defining LCA Goal and Scope

ISO 14040 (ISO 2006) sets out the requirements for LCA goal and scope definition. The scope definition reflects the underlying purpose of the LCA. Since EROI is defined as the ratio of 'energy out' to 'energy investment', the goal and scope may sometimes be interpreted as self-evident. Studies published in the LCA-specific literature generally adopt more explicit goal and scope definitions than has been typical for EROI-focused NEA studies.

Goal Definition in the Context of NEA

Carbajales-Dale et al. (2015) identified three applications of NEA with distinctly different goal definitions:

1. descriptive assessment of the viability of a particular technology (e.g., solar PV satellite);
2. comparative assessment of alternative energy technologies; and
3. calculation of the (minimum) EROI to support an industrial society, or alternatively assessing the feasibility of some technology to (single-handedly) support an industrial society.

For the present study, we reframe and expand on these applications and their respective goal definitions as follows:

1. Energy in, lifetime energy out. Most life-cycle-focused EROI analyses adopt the 'basic net-energy' goal definition of 'lifetime energy out' versus 'life-cycle energy in'. The functional unit is typically 1 kWh (or alternatively, 1 MJ) of AC electricity delivered to the grid. Furthermore, most adopt a process-based LCA methodology, which focuses on the energy-intensive production processes. Within this broad category, there are slightly different approaches to boundaries. System-level considerations, such as the functional role of PV within an electricity grid treated as a whole, lie outside of the scope. Examples: Fthenakis and Kim (2011), Alsema (2000), Leccisi et al. (2016).
2. Energy in, dispatchable equivalent out. Considers an expanded role beyond the lifetime electricity generation. Includes PV overbuild and storage to provide an equiva-

lent role to dispatchable generation such as gas turbine or hydro. Does not consider system-level requirements within a broader suite of generation, including geographic and technology diversity. Defining the magnitude of PV overbuild and storage that provides an 'always available' role is fraught, and understates the value of PV in other contexts. Example: Weißbach et al. (2013), see also Weißbach et al. (2014), Raugei (2013), Raugei et al. (2015).

3. Comparative assessment in relation to substitution of generation capacity. Considers an expanded role beyond the lifetime electricity generation. Includes the embodied energy of storage and solar PV overbuild. Considers the value of generated electricity and the degree to which solar PV substitutes for generation power capacity. The functional unit is 1 kWh of AC electricity delivered to the grid, but concern for the energy cost of 1 kW of supply capacity is implicit in the study context. Permits a trade-off between storage capacity and power capacity substitution. Considers the role of solar PV within a suite of different generation types. Requires technical and reliability analysis of electricity systems and geographic and technology diversity. Examples: Palmer (2013, 2017).
4. Comparative assessment in relation to fossil-fuel consumption. Compares the life-cycle embodied energy with the fossil fuels displaced over the lifetime of the PV system. The focus is on the substitution of fuels rather than substitution of capital infrastructure. The functional unit is 1 kWh of AC electricity delivered to the grid, though this is implicitly a proxy for an equivalent quantity of fossil fuel displaced from conventional thermal generation. No weighting applied to energy out on the basis of system-level considerations. Examples: Raugei et al. (2012), Dale and Benson (2013).
5. Comparative assessment in relation to greenhouse gas emissions. The greenhouse gas emissions embodied in the manufacture of solar PV systems are estimated using life-cycle inventories. Most greenhouse-focused analyses adopt a similar framework to approach (1). Functional unit is CO_2-equivalent emissions per kWh, with no weighting of lifetime energy out. Example: Nugent and Sovacool (2014).
6. Comparative assessment in relation to substituting for all primary energy. A conceptually and technically demanding goal definition, based on the functional unit of 1 MJ of final energy service (e.g. work or heat of various forms, or some mix of these) delivered to the 'rest of the economy' by the overall economy's energy supply sub-system. Hypothesises the substitution of solar PV electricity for incumbent fuels and their associated supply infrastructure. May include, for example, consideration of solar PV electricity as a transport fuel including conversion to liquid fuels, and possibly broader electrification of final energy uses currently reliant on direct use of liquid, gaseous or solid fuels.

Analysis Boundaries

Figure 1 provides a conceptual overview of the range of boundary definitions used across PV NEA studies. Boundary definition varies depending on study goals. As such, it could be considered as a 'meta-factor' in terms of its implications for the apparent divergence in study findings. However, in terms of the range of factors identified in this study, the implications of boundary definition flow through directly to (i) the selection of life-cycle assessment methodology; and (ii) the treatment of intermittency (if this is considered at all). We therefore consider the effects of boundary definition specifically through the consequences for these two factors, rather than treating analysis boundaries as a separate factor in its own right. That said, there is no *essential* relationship between the analysis boundary and LCA methodology. Studies with the same boundary could employ different methodologies, and studies with different boundaries could employ the same methodology. As such, recognising that analysis boundaries differ between studies for legitimate reasons, and taking into account the specific boundary employed in any given study, is essential for accurately interpreting NEA study findings.

In this study, the 'Level 2' boundary from Raugei et al. (2016, Sect. 3.4.4) is adopted as the conventional frame of reference with which to compare alternative definitions. This boundary may be defined either as cradle-to-gate or cradle-to-installation, capturing the most important direct energy inputs of the solar PV panel manufacturing process chain, including the related 'balance of system' (BOS) components, comprising inverter, wiring and support structure, and possibly end-of-life energy inputs. This study focuses on crystalline silicon PV cell technologies because they comprise ~ 94% of global production (IEA 2016b, p. 5).

Detailed Investigation of Factors Contributing to Divergence

Life-Cycle Assessment Methodologies

Process-Based LCA

The most commonly adopted LCA technique, and that recommended by the IEA-PVPS Programme, is attributional, process-based life-cycle assessment (ALCA) (Frischknecht et al. 2016, p. 6). Attributional approaches contrast with consequential approaches. "Attributional Versus Consequential

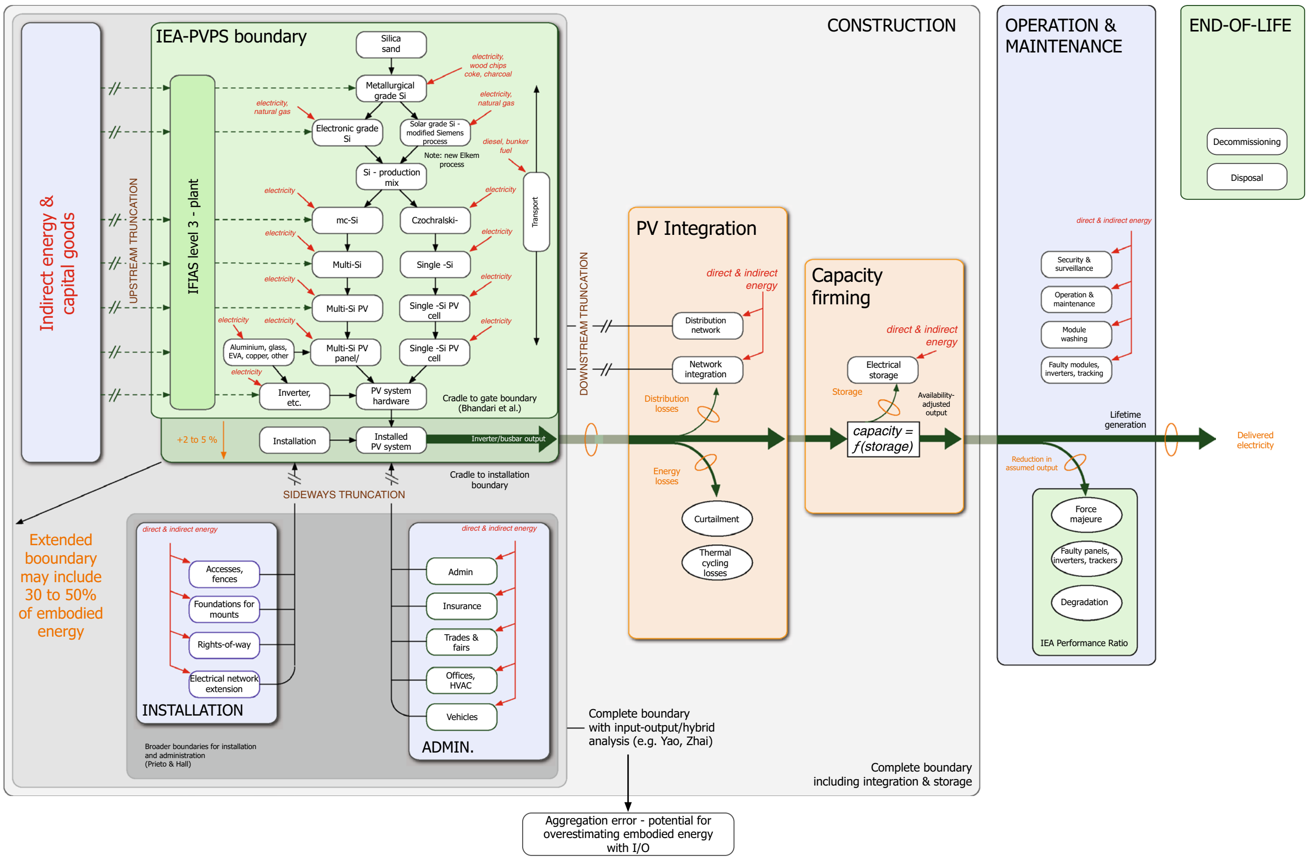

Fig. 1 Definition of boundaries for this study for solar PV life-cycle assessments. Green coloured regions indicate conventional boundaries recommended by the IEA-PVPS Programme. Size of regions not related to magnitude of energy investment

LCA” section discusses the distinction between these, and the contexts for which each is most relevant.

In process analysis, the focus is on identifying the most energy-intensive stages in the process chain. In the case of crystalline silicon, the direct energy inputs for the major production processes are shown in Table 1. For example, silica sand undergoes carbothermic reduction, driven by heat and reducing agents in electric arc furnaces, to produce metallurgical grade silicon, consuming 11 kWh electricity per kg of product. The metallurgical grade silicon is processed via the Siemens process to produce PV grade silicon, and so on. Alternative pathways are also available, including the *Elkem* pathway, which bypasses the Siemens process (Glöckner and de Wild-Scholten 2012).

The researcher steps through the process chain, identifying the process-specific data. Firm-level data are required but are often hard to acquire—a key objective of IEA-PVPS ‘Task 12’ is to gather and compile life-cycle inventory data (Frischknecht et al. 2015a). In the case of PV modules, each of the processes is based on the primary flow of wafer-based materials, but differences in process implementation and operational characteristics from firm to firm will result in

Table 1 Direct energy inputs for major production processes, for mono- and multi-crystalline silicon wafers *Source* Frischknecht et al. (2015a)

Process input	Process output	Major process	Major process energy inputs
Silica sand	Metallurgical grade silicon (MG-Si)	Electric arc furnace at 2000–2200 °C	11 kWh electricity per kg MG-Si
MG-Si	PV grade silicon (SoG-Si)	Siemens process	110 kWh electricity and 185 MJ natural gas per kg SoG-Si
SoG-Si	Mono-Si	Czochralski process (mono-Si)	68 kWh electricity per kg mono-Si
SoG-Si	Multi-Si	Casting and crystallisation process (multi-Si)	56 kWh electricity per kg multi-Si
Mono- or poly-Si	Single wafers	Wafering process	75–93 kWh electricity per m^2 Si

Energy inputs vary depending on region, and change with technology development and production learning variations in material and energy flows at a more detailed level. Depending on time and effort, the researcher continues with a detailed assessment for each process. Ideally, all flows should be followed until they are elementary—i.e. to the boundary between the technical system and the natural system (Tillman 2000). However, since the number of connections in the 'energy flow web' rapidly accumulates as the researcher proceeds through the upstream processes, there is a practical need to 'prune' sub-branches that are deemed insignificant (Suh and Huppes 2002). Furthermore, the importance of each energy flow rapidly diminishes through indirect relations, requiring greater effort for diminishing significance.

Truncation Error

The practical necessity to adopt a finite boundary leads to the omission of contributions that lie outside this boundary. The magnitude of these contributions is termed truncation error. There are broadly three types of truncation error (Crawford 2011):

1. Upstream truncation. This includes higher-order (or background) processes, such as products further up the value chain, or capital goods, including production equipment. PV studies often include an allowance for 'capital plant', but process-based analyses do not comprehensively account for capital goods.
2. Sideways truncation. This includes the omission of minor goods or services that are not part of the main process chain, such as inputs associated with office administrative costs. These costs are generally of low energy intensity and comprise a small (but in aggregate, material) proportion of the overall energy footprint. The IEA-PVPS LCA guidelines (Frischknecht et al. 2016, Sect. 3.2.3) recommend against including administration, marketing, and research and development. Prieto and Hall (2013) investigated such costs, including plant accesses, administration, insurances and promotions among others, and found them to account for a significant proportion of their total inputs.
3. Downstream truncation. This is usually defined as the exclusion of processes in the 'use' and 'end-of-life' phase. In this study, 'downstream' is defined as the additional inputs that lie beyond the busbar or inverter. These are explored further in "Treatment of Intermittency" section.

Energy-intensive products generally carry the lowest truncation error since most of the energy investment is embodied in a limited number of direct and first-order inputs. Services exhibit higher truncation error because much of the energy footprint is in higher-order (or background) paths. Lenzen (2000) notes that most goods carry a truncation error of the order of 50%.

Level of 'Completeness'

Since the ISO 14041 standard for goal and scope definition does not define system boundaries as absolute, but as dependent on the goal of the study (Lenzen 2000), there is no requirement to ensure that the analysis meets a prescribed level of 'completeness'. ISO (1998, Sect. 6.4.5; 2006, Sect. 5.2.3) requires that stages, unit processes or inputs are followed until they 'lack significance' within the given scope. This can be problematic when applied to NEA since a high level of 'completeness' is often assumed by NEA practitioners applying LCA data.

Benefits of Standard Boundaries and Methodology

The consistent treatment of system boundaries is useful for comparison of findings between studies with similar goals. For example, Bhandari et al. (2015) collected 232 references for PV studies published between 2000 and 2013, the vast majority of which adopted conventional LCA-based boundaries. This biases meta-analyses towards conventional boundaries.

If all products within a product class are used within a similar context, the truncation associated with defined boundaries is less important than establishing the differences between products. For example, in considering the life-cycle differences between timber and concrete railway sleepers, it may not be necessary to consider the life-cycle energy of the steel tracks or installation, since these are common to both types of sleepers. However, if the study goal was to compare rail freight to road freight, then much wider boundaries would be required.

The level of completeness need not be a limitation provided the goal definition is stated clearly and results are presented with appropriate qualifications. However, results that have been obtained with a process-based framework are often presented as though they represent a comprehensive inventory of all energy investments. The common use of expressions such as 'cradle-to-grave' and 'full life-cycle' implies a high degree of completeness, but is only accurate in the context of the process-based methodology.

Attributional Versus Consequential LCA

The objective of ALCA is to track energy and material flows using a bottom-up accounting approach, for the purpose of attributing energy and material quantities to a unit of product or service delivered at the analysis boundary (Tillman 2000). This allows comparison of functionally equivalent products and services on the basis of embodied energy, materials and pollutants. Consequential life-cycle assessment (CLCA), on the other hand, involves estimating how flows to and from the environment would be affected by the adoption of particular products or services, or the substitution of alternative products or services for those currently in use. This requires broader boundaries, which may overlap with other LCAs and potentially lead to double counting of energy inputs. The IEA-PVPS LCA guidelines recommend a system boundary ending at the inverter output (Frischknecht et al. 2016, Sect. 3.2.2). The marginal or consequential changes in network costs due to intermittency are not generally included (Jones et al. 2016, Sect. 3.1.2). The guidelines argue that 'aspects of dispatchability or intermittency' should be addressed at a system level rather than at a technology level (Frischknecht et al. 2016, p. 9). The third edition of the IEA-PVPS LCA methodological guidelines has maintained its recommendation of process-based ALCA, but has suggested that a consequential approach should be adopted for investigating a large-scale, long-term energy supply transition (Frischknecht et al. 2016, Sect. 3.2.1.d).

Input–Output and Hybrid LCA

An alternative to the process-based approach is the use of economic input–output (I/O) tables with a satellite energy account, classified as environmentally extended input–output analysis (EEIOA) (Suh and Huppes 2005). I/O analysis connects energy flows to monetary flows using national I/O tables, which are a comprehensive account of national monetary flows. Analyses can be expanded with multi-region I/O tables to account for imports and exports. Since financial data are usually more commonly available than energy-based data, they enable researchers to access industry information that may otherwise be difficult to obtain. Furthermore, EEIOA is systematically complete—all energy within the region/s of the analysis is included. The main weakness is that I/O tables combine products that are heterogeneous in terms of energy inputs, introducing aggregation error. Other weaknesses of I/O analysis include excessive age of data, inconsistent classification schemes and inadequate documentation (UNEP/SETAC 2011).

The respective benefits of process and I/O analysis—specificity for the former and completeness for the latter—can be combined through the use of hybrid analysis. There are three broad types of hybrid analysis (Suh and Huppes 2005):

1. tiered-hybrid approach;
2. IO-based hybrid approach; and
3. integrated hybrid approach.

In a tiered-hybrid approach for example, some important direct requirements are examined with a detailed process analysis, while higher-order requirements that are less easily tracked are covered with an I/O analysis (Crawford 2011, p. 53). In the PV NEA literature, very few studies have adopted a hybrid approach, and for those that do, embodied energy values significantly higher than for comparable process-based analyses are calculated—see Table 2.

We note here that since I/O analysis uses financial costs as the basis for determining energy inputs, results are sensitive to the energy intensities attributed to different cost components. It is sometimes assumed that embodied energy and PV prices (and by inference, the installed cost incurred by PV plant owners) should exhibit a strong positive correlation (Bhandari et al. 2015, p. 140). However, differences between financial costs incurred in manufacture, and prices paid by owners, can lead to anomalous results.

Several factors have contributed to declines in prices that do not reflect corresponding reductions in embodied energy. 'Soft costs' are defined as the costs associated with regulation and compliance (IEA 2016b, pp. 43, 57), and comprise from around 10% of system costs (e.g. Spain), up to around 60% (e.g. the US and Canada) (IEA 2016b, Fig. 26). These costs relate to low energy intensity administrative functions, which are independent of the PV production system and its energy investments. The greater the contribution that soft costs make to overall price reduction over time, the weaker the correlation will be between installed prices and embodied energy. As such, declining cost of ownership may be a poor proxy for embodied energy reduction.

A similar issue arises in relation to the effect of market distortions on PV system price. For instance, overcapacity in Chinese PV production has led to dumping in several markets, starting from around 2011 (European Commission 2017, Sects. 4.7, 3.3.2). Some jurisdictions, including the EU, implemented anti-dumping measures (European

Table 2 Comparison of hybrid versus process-based LCA for the same or comparable projects

Study	Hybrid LCA	Process-based LCA
Building integrated photovoltaic systems		
Crawford et al. (2006, Table 1)	41.0 GJ (total)	18.4 GJ (total)
Major Chinese manufacturers		
Yao et al. (2014, Table 3)	4.7-year EPBT	1.5–2.6-year EPBT
Multi-Si PV System in 2007		
Zhai and Williams (2010, Table 7)	4.4 GJ/m^2	2.7 GJ/m^2

Commission 2017, Sect. 1.1). The further markets deviate from the ideal of perfect competitive behaviour, the weaker the correlation is likely to be between price and embodied energy. Comparison of experience curves for price and CED makes apparent the overall effect of considerations such as these—Louwen et al. (2016, Fig. 3) show a learning rate of 20% for selling price and around 12% for CED. If an LCA methodology makes use of an assumed relationship between cost of ownership and embodied energy in order to calculate energy inputs, different assumptions about the strength of any correlation would contribute to divergence in values for EROI and EPBT.

Primacy of Precision or Comprehensiveness Depends on Study Context

Sonnemann et al. (2013, p. 1171) differentiate between 'traditional' process-based data and 'adaptive' approaches, including I/O and hybrid. While the I/O and hybrid approaches are recognised in the IEA-PVPS LCA guidelines (Frischknecht et al. 2016, p. 6), the guidelines recommend against the I/O approach due to a lack of confidence, citing Sonnemann et al. (2013) and UNEP/SETAC (2011). However, UNEP/SETAC (2011, p. 97) note that 'LCAs should use the most appropriate datasets and modelling approaches to meet the specific goal and scope required to satisfactorily answer the questions posed.'

The IEA-PVPS LCA guidelines endorse the 'traditional' process-based approach, emphasising the primacy of datasets based on 'complete and verifiable documentation' (Sonnemann et al. 2013, p. 1170). Furthermore, process analysis is generally seen to be more accurate (within the given scope) and relevant. A counter argument here is that when the context for NEA is feasibility assessment for large-scale energy transition, providing a comprehensive account of the situation from a net-energy perspective may be a higher priority than data precision, especially if precision necessarily comes at the cost of narrowing the focus for data collection.

Age of Primary Data

Solar PV is a developing technology. Various manufacturing improvements have led to lower energy intensity production, including processing of metallurgical grade silicon to solar grade silicon, and more productive wafering processes. Louwen et al. (2016, Fig. 3) estimated a CED learning rate (per doubling of cumulative capacity) of between 11 and 13%. NEA findings are particularly sensitive to increases in energy output due to improvement in PV cell efficiency over time (Fthenakis, personal communication, 2 February 2017).

Since published studies utilise a mix of primary and secondary data, the publication date may not reflect the age of the primary data. In some cases, studies cite secondary sources that themselves cited earlier primary data. For example, Ferroni and Hopkirk (2016) cited Kannan et al. (2006), who had adopted primary data from studies from 1997 and 2002 (i.e. the primary data were 14–19 years old at the time of publication). The use of older data (see Fig. 2) confounds the age-adjustment process for PV EROI and EPBT meta-analyses, unless the primary data sources are traced and adjusted accordingly (Koppelaar 2016).

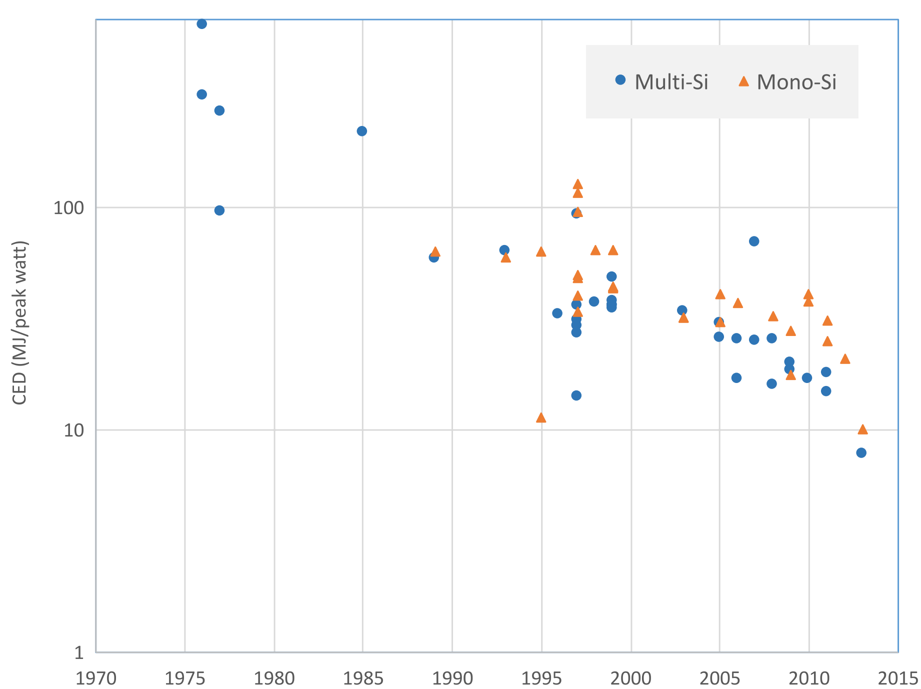

Fig. 2 Reported cumulative energy demand (CED) data by year. Note logarithmic y-axis. Data from Louwen et al. (2016)

Of the factors considered in this study, this stands out as potentially contributing to actual rather than apparent divergence in NEA findings, where studies are otherwise equivalent. If the purpose of a study is to consider present or future PV deployment, then the use of earlier data will lead to errors. If the purpose of a study is to investigate historical performance, then this may require the intentional selection of older data.

PV Cell Technologies

This study focuses on crystalline silicon (mono-Si, multi-Si) cell technologies, which account for ~ 94% of global production (IEA 2016b, p. 5). Most of the remainder comprises thin-film technologies, including amorphous silicon, copper indium gallium selenide (CIGS) and cadmium telluride (CdTe). The so-called III–V semiconductor compounds with gallium arsenide (GaAs) or similar substrates allow production of high-efficiency multi-layer cells, but are currently used in niche applications only. Process analyses for thin-film technologies calculate an EPBT of around half that of crystalline Si (Ito et al. 2016; Fthenakis and Kim 2011). Findings from a meta-study by Bhandari et al. (2015, Fig. 7) indicate mean harmonised PV module plus BOS EROI (factory-gate boundary) for multi-Si approximately 33% higher than for mono-Si.

Treatment of Intermittency

A significant area of difference in NEA goal definition is the treatment of output power quality, specifically the difference between PV electricity when an inverter boundary is assumed, and electricity from dispatchable sources. Since most studies consider the lifetime aggregate energy output only, issues associated with real-time electrical power characteristics are not usually assessed. If such issues are considered in the goal definition though, this can contribute significantly to the apparent divergence in findings.

Defining Reliability

The reliability of large electrical systems is defined by the loss-of-load-expectation (LOLE), which is the primary reliability metric for generation adequacy planning (NERC 2011; OFGEM 2013). The value of the LOLE metric for a given grid is prescribed based on priorities that are particular to the prevailing socio-political-economic values for the territory in question. A developing country may place much less value on a high level of reliability than a developed country, depending on electricity consumers' needs and expectations.

The LOLE is mostly a function of two factors: (i) the 'availability factor' of individual generators; and (ii) the projected demand function of the power system. The availability factor is defined as the inverse of the probability of a forced outage in a given period (Billinton and Allan 1996, Chap. 11). No single generator is completely reliable, but since forced outages are usually uncorrelated between generating units (i.e. the distribution functions are independent random variables), the *system reliability* converges asymptotically towards 100% with a large enough number of generators. Within this conventional framework, the role of energy storage, such as pumped hydro storage (PHS), is to arbitrage between low-cost overnight baseload supply and higher-value peak load supply. The value of PHS is therefore determined by the economics of arbitrage (Yang and Jackson 2011).

In contrast to thermal and hydro generators, PV output exhibits very strong correlation across geographic regions (i.e. it is simultaneously either day-time or night-time everywhere across a region), and therefore individual PV systems cannot be modelled as independent random variables. Instead, since the reliability contribution of PV is dominated by the correlation between PV output and demand on the peak-demand days, PV is often modelled as a demand reducer (Preston 2015b). The potential role of demand management becomes more apparent in this context, since the value of PV is also dependant on the potential to voluntarily shed load or time-shift it to periods of high insolation.

The question of whether or not storage should be defined as falling within the PV system boundary arises because PV systems can be designed to exhibit an availability comparable with conventional generation when sufficient storage and PV overbuild is deployed. The issue then is not, as Leccisi et al. (2016, p. 4) suggest, whether a single generator can 'single-handedly follow the dynamics of societal electricity demand', but how PV, whether considered at the scale of individual systems in isolation, or collectively at the grid-scale, can contribute to system reliability.

Capacity Firming and Storage to Accommodate Temporal and Spatial Output Variability

Solar PV exhibits variability over timescales ranging from seconds to seasons, and at local, regional and national spatial scales (Sayeef et al. 2012). At a regional level, geographic diversity smooths short-term cloud flicker, generally reducing aggregate output variability from all PV systems in a given region. However, weather systems can sometimes extend for thousands of kilometres, reducing output across entire regions (Huva et al. 2016; Sayeef et al. 2012). Sunrise and sunset are each effectively co-incident for different locations at the regional scale. This results in almost simultaneous diurnal ramp-up and ramp-down of output from optimally oriented PV modules across regions.

On a seasonal timescale, the ratio of the average monthly insolation between summer and winter varies greatly across geographic regions and latitudes (NASA 2017; PV Education 2016). Low-latitude regions, such as Singapore, show a relatively small summer-to-winter ratio of 1.3–1.7, rising to 3–4 in the mid-latitudes such as Nevada, USA, and above 10 for higher latitudes, such as London. Latitude is the primary determinant of the seasonal ratio, but regional climate factors, including the cloud index, are also important.

At low penetration, variable output from solar PV is readily integrated into electricity systems (Gross et al. 2006). At higher penetration, maintaining system reliability is more challenging and costly, and, in addition to demand management, will require complementary flexible generation and storage (Sims et al. 2011, pp. 15–16).

Defining Integration Costs

Integration costs are usually defined as additional expenses associated with load following, the provision of ancillary services and curtailment (Kirby et al. 2003; Heptonstall et al. 2017). In most cases, the additional costs are small at low solar PV penetration, but will be material at a higher penetration; however, the relationship between penetration and integration costs is highly context specific (Heptonstall et al. 2017, Sect. 2.3).

Integration costs can also be conceptualised more broadly as the additional buffering, connection and ancillary service costs necessary for PV to provide a substantive role in a transition from fossil fuel to low-carbon electricity supply. The physical characteristics of conventional synchronous generators, including inertia and reactive power response, have provided some ancillary services by default, and so these have traditionally been uncosted. The retirement of synchronous generators will reduce the contribution of these uncosted services. Since solar PV and wind are asynchronous, the substitution of these electricity sources for synchronous generation will require some form of market mechanism or 'security obligation' to ensure that equivalent ancillary services are provided with rising variable renewable energy (VRE) penetration (Finkel et al. 2017, recommendations 2.1, 3.3). Additional energy inputs associated with providing ancillary services by alternative means need to be included in NEA where study goals relate to large-scale energy transition.

Transmission Infrastructure

Transmission infrastructure consists of meshed networks that are shared by multiple supply and demand nodes. As such, high-voltage transmission infrastructure is usually assumed to lie outside the study boundary for electricity generation NEA [for exceptions, see Ito et al. (2008, 2016)].

Sometimes, however, dedicated transmission network extensions are required where new generation assets (whether solar PV or otherwise) are situated geographically outside the existing grid boundary. Many of the most favourable locations for solar PV lie in sparsely inhabited regions. For example, Ito et al. (2008) assumed that 100 km of transmission lines would be required to connect a 100-MW PV system to existing transmission, and found that transmission infrastructure comprised between ~ 10 and 15% of system CED over the lifetime of the project (Ito et al. 2008, Table 8). Furthermore, Ito et al. (2005) estimated losses due to transformer, reactive power compensation and transmission line losses of 5.8–8.2% for a 100 km line in a hot desert.

In such situations, it is legitimate to ask whether the dedicated transmission infrastructure should be treated as falling inside the generation NEA boundary. LCA studies are usually seeking to answer a narrower question than that posed by NEA studies, and therefore the question is resolved by simply stating the scope. However, if the goal of the NEA study is to assess the feasibility of a large-scale energy transition, then the additional transmission costs must be accounted for somewhere, whether attached to a generation asset or considered as part of the broader system-level changes. The lifetimes of transmission assets are usually longer than generation assets. If included within the generation boundary, this would require allocating the transmission CED across multiple PV lifetimes, mitigating the impact on EROI and EPBT.

High-Penetration PV and Storage Scenarios

An estimate for the quantity of storage required to meet a supply–demand balance for a given period can be derived from studies with a high penetration of solar PV. However, much of the electricity system scenario literature avoids the problem of large-scale storage by maintaining a significant share of legacy thermal generation capacity at low capacity factor (Budischak et al. 2012), or by assuming the ready availability of large-scale biomass-fuelled thermal generation (Lenzen et al. 2016). In the context of energy transition feasibility assessment, we note that studies that reduce emissions while retaining legacy generation capacity involve fundamentally different goals to those focused on transition to 100% renewable electricity supply.

For scenarios where conventional thermal generation capacity is not retained (and where this is not replaced by biomass generation), the storage capacity required for a given level of reliability escalates rapidly with increasing VRE penetration, exhibiting a sharply diminishing return in terms of the reliability outcome obtained for each unit of energy investment (Palmer 2017). This is mostly due to the 'big gaps' problem of extended cloudy periods during winter (Lenzen et al. 2016). More generally, the shift from an electricity system based on 'stored sunlight' (i.e. fossil fuels) to the one based mostly on uncontrollably variable energy flows is constrained by the storage capacity required and the quantity of VRE overbuild necessary to maintain energy stores at adequate levels to ride through low insolation periods. Sufficient generation capacity overbuild can substitute to some extent for inter-seasonal variation in PV output. Regardless of storage medium though, in the absence of backup thermal generation capacity, for 100% renewable electricity supply with high PV penetration, some combination of capacity overbuild and large-scale storage sufficient for inter-seasonal balancing of generation and demand is likely to be essential.

For example, in a 100% renewable simulation with wind and solar PV for Germany, 45 days of full-load electricity supply capacity (based on average annual demand) was required (Palzer and Henning 2014, Fig. 3.4). In a study encompassing Canada, USA and Mexico, Aghahosseini et al. (2016) found that around 14 days of supply capacity was required. Both of these studies assumed power-to-gas for inter-seasonal storage. Preston (2015a) modelled a set of wind, solar and storage scenarios for Texas, finding that 21 days of supply capacity was required.

Effect of Storage and Overbuild on NEA Findings

There is no single 'best answer' to the appropriate quantity of storage (if any) and solar PV overbuild. However, it is possible to state some general principles. Summer peaking grids benefit much more from solar PV than winter peaking grids, and a wide latitudinal diversity improves the value of solar PV when interconnected between regions. Relatively modest storage can improve the value of solar PV in some contexts, such as systems that have high air conditioning loads in summer. Palmer (2017) formulated a framework for calibrating EROI based on the generation capacity displaced, which provided a method to trade-off storage capacity versus the value it provided in a specific context. The low capacity factor and seasonality of PV results in strongly diminishing return with increasing solar PV penetration (i.e. the first units are the most valuable but as penetration increases, the marginal value of adding further capacity decreases). In winter peaking grids, the role of PV is restricted to displacing fuel consumption of thermal generators, rather than displacing their contribution to the generating capacity required by the overall system, unless inter-seasonal storage and/or a very high level of PV overbuild is implemented.

With reference to the goal definitions in "Goal Definitions" section, different study contexts explore different questions, and will arrive at different answers in relation to the quantity of storage required. Approaches (1), (4) and (5) do not consider system-level implications at all, and therefore do not consider storage. Approach (2) specifically assumes that 'PV plus storage' substitutes for dispatchable generation, and therefore requires solar overbuild and substantial storage. Weißbach et al. (2013, p. 213) adopted a 2-time solar PV overbuild, resulting in a halving of EROI. The EROI was reduced by a further ~ 20 % due to the inclusion of pumped hydro energy storage.

Approach (3) takes the incumbent system as given and assumes that a supply system transition proceeds by incrementally substituting solar PV and storage for conventional generation capacity. For example, in summer peaking grids, at low PV penetration 2 h of battery storage without solar overbuild improves the network value of PV, but reduces the EROI by a modest 15% (based on data from Palmer 2017, Table 2). But at near 100% wind and solar penetration, the EROI of the *last unit* of solar PV with battery storage is reduced by 98.8% due to the problem of diminishing returns (Palmer 2017, Fig. 7).

Approach (6) considers the complete substitution of the fossil-fuel energy system by renewable sources, including for transport. As such, a range of alternative storage media may be considered, including liquid and gaseous fuels, with NEA accounting for the attendant conversion losses.

Equivalence of Investment and Output Energy Forms

Primary Energy Basis for LCA Energy Input Accounting

For all LCA methodologies, it is conventional to account for each energy input in terms of the primary energy required to make it available at the point where it enters the analysis boundary. In the broadest physical sense, primary energy is considered to be energy that is available from resources as they exist in nature: chemical energy of fossil fuels, gravitational potential energy of water in a reservoir, electromagnetic energy of sunlight, etc. (Nakicenovic et al. 1996). For the purpose of accounting for energy supply and use at the national and global level, the primary energy value of an energy source is typically treated as its 'physical energy content' at the point where it first becomes an economically useful 'energy product' suitable for multiple downstream purposes (IEA 2017). With combustible fuels in the form of wood, biomass and, most significantly, fossil fuels dominating energy trade, by convention, this type of high-level energy accounting has been recorded in thermal energy units, including BTUs or joules. For the purpose of most LCA studies on the other hand, the primary energy input from a given source is defined as that source's life-cycle CED (Frischknecht et al. 2007b, 2015b).

Since electricity is a secondary energy carrier, each electricity input is adjusted to account for the primary energy required for its supply. For instance, if a particular process in the PV production chain requires 1 kWh of electricity sourced from the grid at the point of manufacture, then this is accounted for as $1/\eta_{grid}$ kWh of primary energy, where

η_{grid} is the grid-average life-cycle efficiency. This is calculated as the ratio of the annual electrical energy supplied to the total primary energy (renewable and non-renewable) harvested from the environment for the operation of the grid in the same year (Raugei et al. 2016, p. 8). Where combustion-based thermal generation dominates supply, the life-cycle efficiency is slightly lower than the grid-average thermal efficiency (the ratio of electricity delivered to heating value of all fuel used) since combustion fuels constitute most of the life-cycle primary energy. However, grids composed of greater shares of nuclear and/or renewables may produce a markedly different grid life-cycle efficiency depending on the approach for determining the energy resource inputs.

Output Energy form Equivalence in the Context of PV NEA

While primary energy input accounting is a standard convention across LCA methodologies, there is no universal standard for establishing the energy content equivalence of different energy sources. Within the LCA literature, various conventions are followed for assigning primary energy values to different final energy carriers (Frischknecht et al. 2007b, pp. 31–32). In the case of solar PV, for which the natural resource is unlimited on a human time scale, but for which the conversion efficiency is low, it may be appropriate to register the amount of energy harvested rather than the amount of solar radiation ultimately required (Frischknecht et al. 2007a). Ecoinvent, a widely applied LCA databases, defines the energy harvested by a solar panel as equal to the electrical energy transmitted from the panel to the inverter (Frischknecht et al. 2007b, Sect. 2.2.1). However, several other LCA databases apply the 'energy harvestable' concept to solar PV, for which the renewable energy input is the amount of solar energy needed to produce the electricity generated by the PV module (Frischknecht et al. 2015b). From a LCA perspective, the most important consideration is to clearly state the methodology and assumptions for a given study context. However, where the study context relates to NEA, there is a potential for misalignment between NEA study goals and standard LCA practice.

Among the major agencies that report on national and global energy statistics, there are two conventions for determining the primary energy equivalence of non-thermal renewables (Lightfoot 2007, Sect. 1.A.3; Grubler et al. 2012). A 'substitution method' is used by BP, EIA, IIASA and WEC. This is based on thermal energy equivalence and considers the fossil fuels displaced by renewables, giving a conversion of 1 MJ PV electricity equals ~ 3 MJ primary energy. The 'direct equivalent' method is used by the UN, IEA and Eurostat. It adopts a one-to-one equivalence between electricity and primary energy (i.e. 1 MJ electricity equals 1 MJ primary energy). Within the LCA literature, no method corresponds exactly with the 'direct equivalent' method. However, the 'energy harvested' method used in LCA for determining the primary energy for PV electricity returns a numerically similar result.

Given that the output from solar PV systems is typically in the form of AC electricity delivered to grids supplied by a range of generation types, questions naturally arise in relation to how this output should be treated in terms of its equivalence to other energy sources. There are two distinct contexts in which questions relating to the energy content equivalence of the electricity output from PV can be considered. The first relates to its equivalence to other electricity sources within the context of the grid for which a PV system is deployed. The second relates to the output electricity's equivalence to the full range of energy sources required for manufacture and deployment of the PV system itself, and hence that are accounted for as energy inputs for the purpose of NEA. This includes a range of liquid and solid fuels, and electricity from grids other than that for which the PV system is deployed. This second context is discussed further at the end of this section.

In relation to equivalence questions arising in the first of these contexts, the IEA-PVPS Programme recognises two principal approaches: (i) accounting for the output in terms of the physical energy content of the electrical energy delivered; and (ii) accounting for the output in terms of the equivalent primary energy for the grid to which the PV system is connected (Raugei et al. 2016, p. 5). In the context of grids where combustion-based thermal generation dominates, the second approach returns numerically similar results to the 'substitution method' described above in relation to conventions used by energy reporting agencies. It is, however, a methodologically distinct approach, and results diverge as the contribution of non-combustion generation sources increases. The IEA-PVPS Programme recommends the second approach, on the basis of what it describes as a 'replacement logic', where a unit of electricity from any source is considered equivalent to the primary energy required to produce a unit of electricity from the overall mix of sources for the grid in question (Raugei et al. 2016, p. 5). Where NEA indices are calculated on this basis, their values must be viewed as deployment-context specific, and findings interpreted accordingly.

In the PV NEA literature more broadly, three approaches to treating the equivalence of investment and output energy forms are recognised, as shown in Table 3. The IEA-PVPS Programme's recommended method is shown as Method 1 (Frischknecht et al. 2016, pp. 16–17). Methods 1 and 2 are both forms of the 'substitution method' and give essentially the same result. Method 3 is the most common method in the wind power EROI literature (e.g. Kubiszewski et al. 2010), and is the alternative method recognised by the IEA-PVPS Programme (Raugei et al. 2016, Eq. 2, p. 8). It is also widely adopted in the PV EROI literature. Of the

Table 3 Methods of adjusting for investment and output energy equivalence in the PV and related EROI literature

	Methodology	Examples	Equation
1	Convert electricity output to 'primary energy equivalent'	Frischknecht et al. (2016), Raugei et al. (2012), Bhandari et al. (2015), Fthenakis and Kim (2011), Ito et al. (2016), Louwen et al. (2016)	$EROI_{PE-eq} = \frac{Eout_{PE-eq}}{Einv}$, where $Eout_{PE-eq} = \frac{Eout_{el}}{\eta_{grid}}$
2	Convert primary energy investments to 'electricity equivalent'	Koppelaar (2016), Dale and Benson (2013)	$EROI_{el-eq} = \frac{Eout_{el.}}{Einv_{el-eq}}$, where $Einv_{el-eq} = Einv_{PE} \times \eta_{grid}$
3	Adopt 'direct equivalent' to electricity output	Ito et al. (2003), Fu et al. (2015), Moeller and Murphy (2016), Kubiszewski et al. (2010)	$EROI_{el} = \frac{Eout_{el.}}{E_{inv}}$

PE−eq primary energy equivalent, *el−eq* electricity equivalent, *el* electricity. η_{grid} is the life-cycle energy efficiency of the grid in question (typically 0.29–0.35)

three meta-analyses considered in this study, all apply a 'substitution method' equivalence adjustment to either the investments or output, with primary energy to electricity conversion factors of 0.311 (Louwen et al. 2016) and 0.35 (Bhandari et al. 2015; Koppelaar 2016). A related study adopts 0.30 (Leccisi et al. 2016).

Since PV produces electricity, and most of the direct energy inputs in the manufacturing process are in the form of electricity (see Fig. 3), it could be argued that EROI should be expressed as the ratio of the electrical energy output to the electrical equivalent of all energy investments. Arithmetically, this requires expressing all inputs as *el−eq* (Method 2), or expressing the PV output as *PE−eq* (Method 1)—see Table 3.

On the other hand, some essential non-electrical energy inputs, while smaller in relative magnitude, may not be readily substituted by electricity. If an energy input is essential, but cannot in practice be provided by electricity, then a question arises as to how the scaling for an electricity-equivalent adjustment should be determined. Freight transport provides an interesting case in point. There is no imminent substitute for diesel for heavy vehicles and ocean-going shipping, or jet fuel for air transport (Sims et al. 2014, p. 615). Calculating the electricity equivalent of a given quantity of liquid fuel would require the assumption of a suitable conversion pathway from electricity through to a synthetic fuel, such as hydrogen, and estimation of the 'electricity-to-wheels' (or equivalent, depending on end-use) efficiency for the full fuel cycle.

Implications for Interpreting PV NEA Findings

The appropriate method for treating investment and output energy form equivalence depends on the study context and the questions it seeks to answer. In light of this, our interest is in understanding the different approaches and the contexts in which they might be applied, rather than arguing for a single 'correct' method. For example, goal definitions (4) and (5) from "Goal Definitions" section are exploring the magnitude of displaced fossil fuels within an incumbent system, and therefore Method 1 (convert electricity output to 'primary energy equivalent') may be most appropriate. On the other hand, goal definition (6) considers the potential role for solar PV in providing all energy services, including transport, via renewably generated electricity, and the adoption of a universal energy content scaling factor may be inappropriate given the complex energy conversion pathways involved.

Further to this, we point out that the established conventions discussed here treat equivalence exclusively in terms of a 'physical energy content' criterion. We note that, particularly in light of considerations discussed in "Treatment of Intermittency" section, a broader concept of functional equivalence could provide clearer guidance with respect to the most appropriate scaling adjustment to make to the energy output from a PV system in any given situation. Closer investigation of this seems to be warranted, but is beyond the scope of the present study.

From the point of view of understanding the apparent divergence in PV NEA findings, the particular method for treating investment and output energy form equivalence adopted in any given study context clearly plays a major role. Just by adopting a different reporting convention, the findings of a study can change by a factor of three or more. Being informed about the convention adopted for a particular study, and making appropriate adjustments when comparing findings across studies, is fundamentally important for accurate interpretation of findings.

Differences Between Assumed Values for Key Performance Parameters and Real-World Performance

Actual performance of PV systems depends on many factors, including insolation of the region in question, orientation and shading of panels, and the actual (versus rated) performance of the PV modules. The IEA-PVPS Programme adopts a 'performance ratio' (PR) of 0.75 or

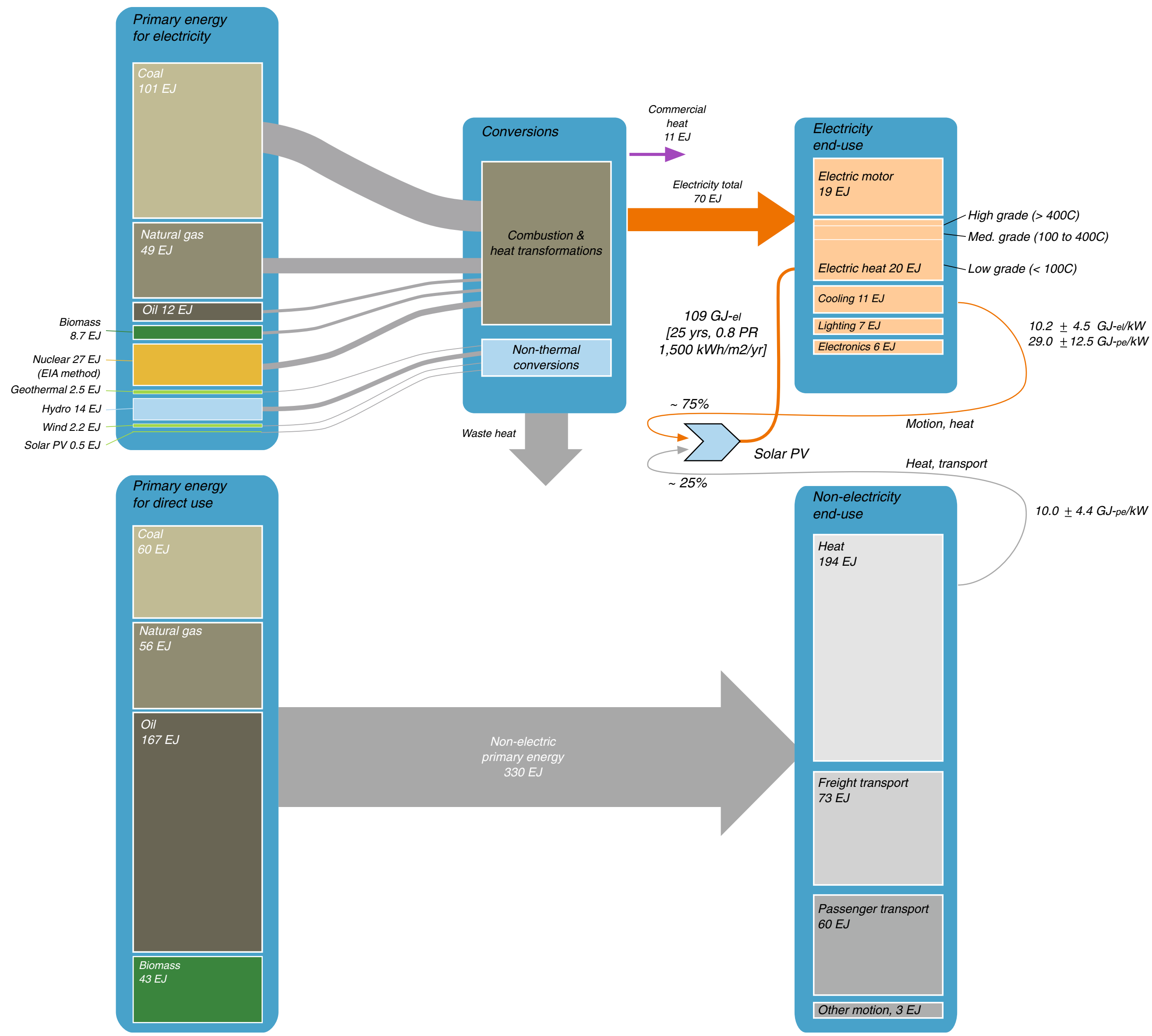

Fig. 3 Sankey diagram of annual global energy flows, focused on electricity. PV output is lifetime output *Source* Adapted from IEA (2016a). Data based on median from Koppelaar (2016). Relative proportion of PV inputs estimated from Frischknecht et al. (2015a). (Color figure online)

0.80 to account for differences between rated performance and actual AC electricity generation (Frischknecht et al. 2016, p. 4). The PR accounts for non-optimal siting and shading, panel degradation, dust, DC to AC conversion losses and other factors. LCAs and NEAs are carried out with assumed factors that are intended to approximate real-world conditions in a given deployment context.

Insolation

The IEA-PVPS LCA guidelines (Frischknecht et al. 2016, Sect. 3.1.2) recognise three approaches for treating insolation, depending on the goal of the study. These are industry average and best-case insolation; insolation with modules optimally orientated and tilted, or with single-axis tracking; and average insolation for installed systems in a grid network. Insolation should be reported with the given orientation and inclination (Frischknecht et al. 2016, Sect. 3.5).

Meta-analyses (e.g. Bhandari et al. 2015; Koppelaar 2016; Louwen et al. 2016) typically adopt a reference in-plane insolation of 1700 kWh/m^2 year. However, there is sometimes ambiguity as to whether the insolation refers to in-plane or global horizontal insolation (GHI). Many LCA studies explicitly identify the insolation as being in-plane (e.g. de Wild-Scholten 2013; Ito et al. 2016, Table 2, Sect. 5; Louwen et al. 2016, Eq. 1). However, some studies also refer to horizontal insolation in relation to an ‘average’ 1700 kWh/m^2 year insolation (e.g. Fthenakis and Kim 2011; Phylipsen and Alsema 1995, p. 42). In other studies, it is unclear whether insolation values are meant to be interpreted as in-plane or horizontal (e.g. Bhandari et al. 2015, Sect. 2.4.3; Koppelaar 2016, Sect. 2.3), although tracing references usually resolves ambiguity. Solar maps usually depict annual solar exposure as the total amount of solar radiation falling on a horizontal surface. From Breyer and Schmid (2010, Appendix), it has been estimated that the in-plane global insolation for an optimally tilted, fixed array is ~ 145–272 kWh/m^2 year greater than the GHI. The actual difference is dependent on the latitude, and the relative contributions from direct versus diffuse insolation at the given region in question.

In principle, for the purpose of comparing the relative performance of different PV systems, any consistently applied in-plane insolation value will suffice. However, for NEA findings to be representative of actual field performance, the reference insolation value must match the actual conditions at the deployment location. EROI and EPBT values must be adjusted accordingly to account for any difference between reference and site-specific values. In this respect, it is interesting to consider also how the reference in-plane insolation of 1700 kWh/m^2 year compares with the average insolation for all PV deployed globally to date, when this is weighted for conditions at the deployment location.

The geographic distribution of solar PV reflects factors including population, wealth, the availability of transmission infrastructure, and historically political support and PV subsidies. Hot, arid regions generate the highest output but do not generally favour high population densities over widespread territories. Figure 4 provides a graphical depiction of the global relationship between installed PV capacity, population, wealth and insolation. It plots representative summer and winter GHI across latitudes versus population and GDP per capita. Insolation plots are averaged across longitudes and are intended to depict differences across latitude rather than between specific regions—there can be significant variation between locations at similar latitude. Also plotted is the estimated distribution of solar PV capacity by latitude. This was calculated from national-level reporting of the regional distribution of solar PV for the 15 leading countries by installed capacity. The distributions were extrapolated for the reported PV capacity at the end of 2015 from IEA (2016b), and for China up to the end of 2016 due to around 34 GW being installed during 2016. IEA (2016b) provides an average country final yield [i.e. annual AC electricity at inverter output in kWh per kW of installed capacity (Frischknecht et al. 2016, Sect. 3.1.3)] and installed capacity, shown in Fig. 5.

Based on these data sources, the deployment-location-weighted average final annual yield (i.e. the ratio of AC electricity out to rated PV capacity) equates to 1204 kWh/kW year. Population-weighted country insolation data from Breyer and Schmid (2010, Appendix) was used to calculate a

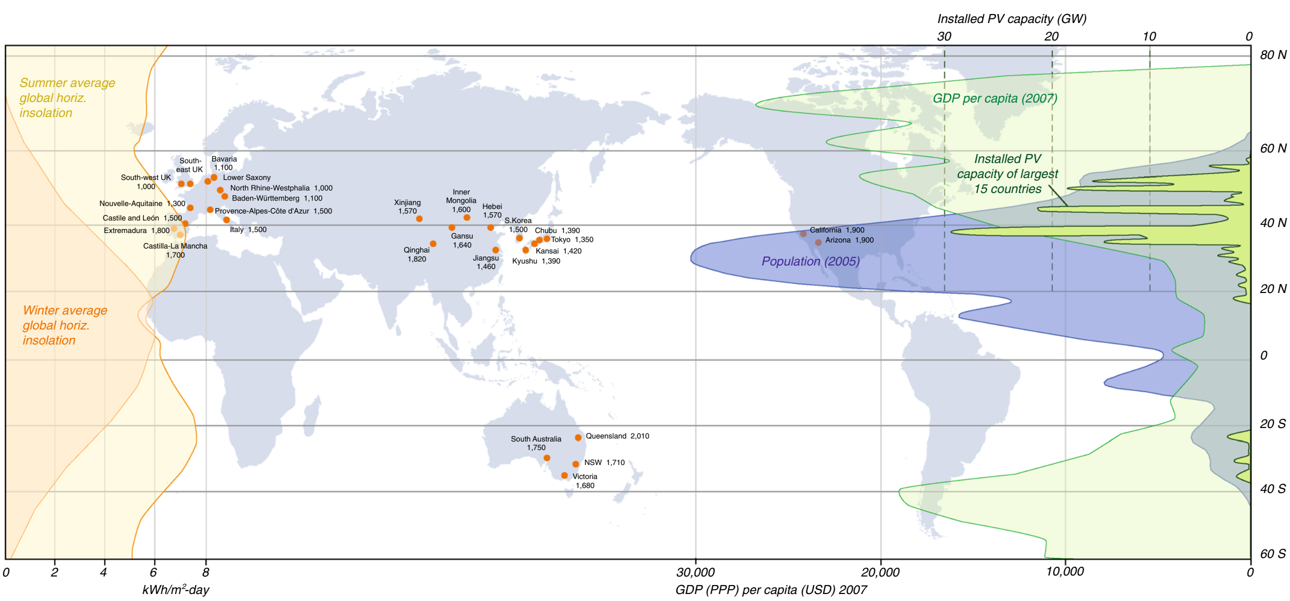

Fig. 4 Population, GDP per capita, and winter and summer average global horizontal insolation by latitude. *Sources* Kummu and Varis (2011); NASA (2017). Insolation values are averaged across all longitudes for 22-year period 1983–2005. Winter uses northern hemisphere January/southern hemisphere July; Summer uses northern July/southern January. Orange dots indicate regions with substantial solar installations, and number is average annual insolation in kWh/m^2. (Color figure online)

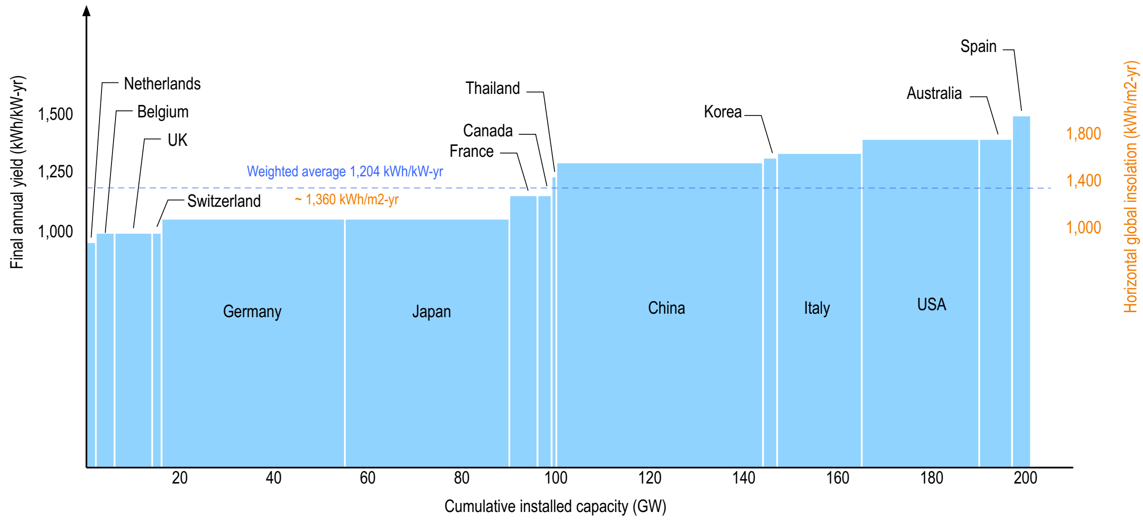

Fig. 5 Installed capacity and final annual yield of countries with greater than 1 GW installed PV capacity. Yield data from IEA (2016b). Horizontal insolation estimated, based on Fig. 4. Note that countries with a higher proportion of on-ground installations and systems with tracking generate a higher yield for a given insolation than countries with a higher proportion of rooftop systems

corresponding deployment-location-weighted average insolation for fixed, optimally tilted PV installations, returning a value of 1550 kWh/m^2 year. We used Breyer and Schmid's population-weighted country insolation data, rather than the area-weighted data that they also provide, on the assumption that geographic distribution of population within countries will act as a proxy for geographic distribution of PV capacity. Dividing the deployment-location-weighted average final annual yield by the fixed optimally tilted insolation returns a corresponding average PR of 0.78. This is in close agreement with the typical PR range of 0.75 (rooftop) to 0.80 (ground-mounted) specified in the IEA-PVPS LCA Methodological Guidelines (Frischknecht et al. 2016, p. 4). The deployment-location-weighted average in-plane insolation (fixed, optimally tilted installations) of 1550 kWh/m^2 year is 9 % below the reference in-plane insolation typically adopted for meta-analyses.

Longevity

The operational lifetime of solar panels can vary significantly. There are reported examples of earlier panels with operational lives well in excess of 25 years, but there are also reports of premature failure and abandonment after only a few years (Jordan et al. 2016). During the 1990s, 5- to 10-year product warranties were common, but almost all manufacturers now offer a 25-year performance warranty, in addition to the 5- to 10-year product failure warranty. The most common standard factory warranty for the leading inverter brands is 5 years.

We observe what seem to be two competing views on system performance. On the one hand, solar PV has proven to be mostly robust and durable, particularly in the emerging period of high-cost panels. High-cost components placed a floor on quality and provided motivation to maintain systems.

In contrast, under-performance has emerged as a significant issue in recent years due to the proliferation of budget-priced rooftop systems, exposing structural problems in some markets (Johnston 2017; Pulsford 2016). It is not yet clear how rooftop systems will be maintained following the failure of minor parts or inverters. The use of net-metering in rooftop systems obscures actual solar generation, making it difficult to establish precise generation statistics. Commercial enterprises are usually better equipped to conduct due diligence and quality assurance. Profit-seeking enterprises have an interest in maintaining systems for the duration of the operational life.

Researchers legitimately hold differing perspectives in relation to the appropriate operating life to assume for PV NEA. Most studies now default to a lifetime of 25 or 30 years for PV modules (20 years was common in the past), reflecting manufacturers' expectations. In the context of life-cycle assessment, the statistically representative operating life based on actual field experience should be used, rather than the manufacturer's anticipated operating life for an individual facility in isolation. Notably, DNV-GL report that 85% of the current installed global PV capacity is less than 5 years old (Meydbray and Dross 2016). Hence, it will be some decades before a clear empirical picture of statistically representative operating life can be determined for PV systems presently being deployed. In the meantime, researchers will be required to make assumptions about the long-term performance of systems.

Discussion of Overall Implications for EROI and EPBT Metrics

A summary of the methodological factors discussed in "Detailed Investigation of Factors Contributing to Divergence" section is shown in Table 4 and Fig. 6. The table provides a heuristic for contextualising studies that investigate different questions and that adopt different methodologies and boundaries. It is not intended as a precise harmonisation tool—the factors can, however, be compounded to compare studies that have adopted different assumptions.

It is apparent that any factor considered in isolation can alter the EROI or EPBT significantly, and that studies conducted in relation to essentially equivalent situations can produce markedly different results. For example, the use of primary data that were sourced 10 years prior to conducting a study would be expected to roughly halve EROI and double EPBT. Choosing between the 'direct equivalent method' versus the 'substitution method' for treatment of investment

Table 4 Methodological factors affecting EPBT and EROI

	Factor	Range of reported values	Comments
1	LCA methodology	Process-based or hybrid I/O	I/O reduces sideways and upstream truncation, increases EPBT ~ 43–100% (reduces EROI ~ 30–50 %)
2	Time between study publication and sourced data	~ 2–19 years	10-year-old data increase EPBT ~ 100 % (reduces EROI ~ 50%), 20 years ~ 400% (reduces EROI ~ 80%) (Louwen et al. 2016)
3	PV technology	Mono-Si, multi-Si, amorphous silicon, CIGS, CdTe	Crystalline silicon (mono/multi-Si) technologies account for ~ 94 % of global production (IEA 2016b, p. 5). Relative to multi-Si, mono-Si has 33 % longer EPBT (25 % lower EROI). Amorphous silicon, CIGS and CdTe, respectively, have 20, 42 and 66 % shorter EPBT than multi-Si (Bhandari et al. 2015, Fig. 7)
4a	Transmission infrastructure	Rarely considered. Only applicable to remote solar farms. Ito et al. (2008) considered 100 km	Inclusion of 100 km transmission to connect 100 MW PV, and including losses, increases EPBT 16–25 % (reduces EROI 14–20 %) over the lifetime of the PV project. Transmission lifetime is longer than PV
4b	Capacity firming	Zero storage up to 10 days. Battery or pumped hydro storage	2-h Li-ion storage increases EPBT ~ 20 % (reduces EROI ~ 17 %). With 2-day Li-ion storage and PV overbuild for off-grid solar, EPBT increases 400 % (reduces EROI ~ 80 %) (Palmer 2013, 2017)
5	Investment and output energy form equivalence	'Direct equivalent method' or 'Substitution method'	Applying the 'Substitution method' adjustment to either investments or output increases EROI ~ 200 %
6a	In-plane insolation	800–2344 kWh/m^2 year	Meta-analyses usually adopt 1700 kWh/m^2 year (Bhandari et al. 2015; Koppelaar 2016; Louwen et al. 2016). Deployment-location-weighted average insolation for fixed, optimally tilted installations is 1550 kWh/m^2 year. Applied globally, an assumed in-plane insolation of 1700, relative to 1550 kWh/m^2 year, reduces EPBT 9 % (increases EROI 10%)
6b	System lifetime	20–30 years	Studies take into account manufacturers' expectations and historic experience. 85% of the current installed global PV capacity is less than five years old (Meydbray and Dross 2016). Future performance is uncertain. An increase from 20 to 30 years reduces EPBT 33% (increases EROI 50%)

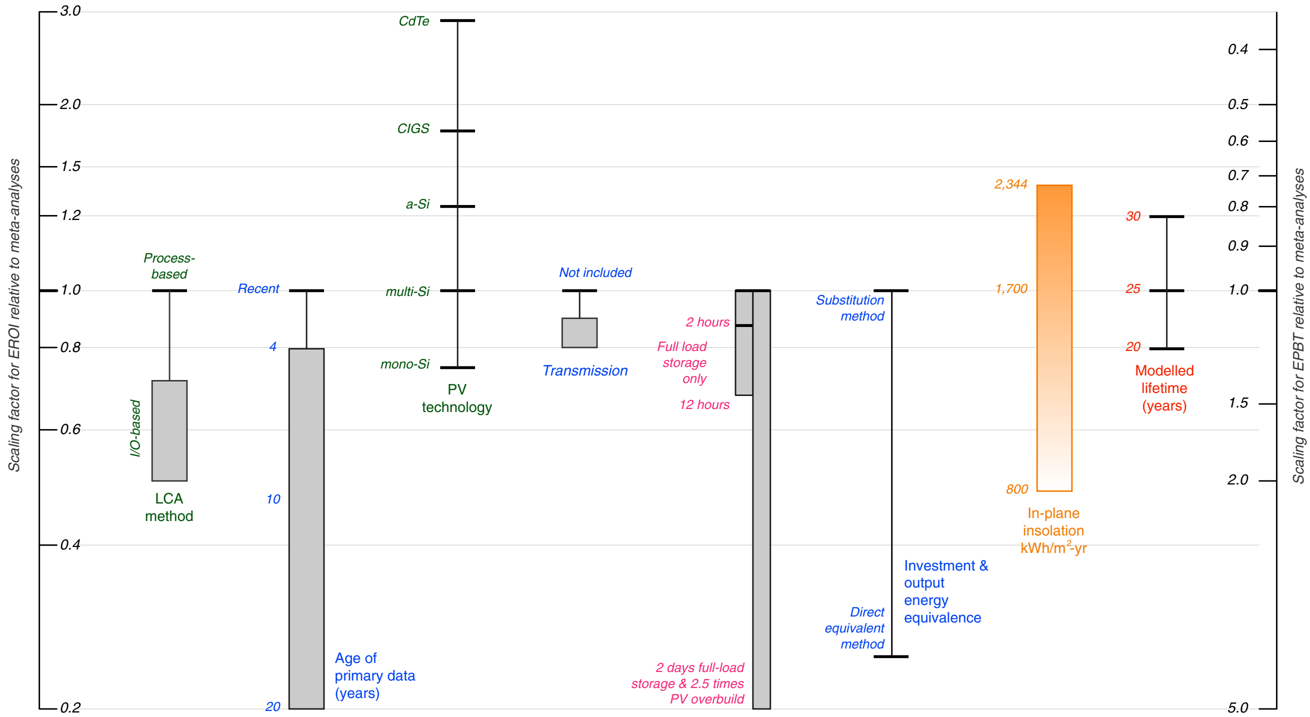

Fig. 6 Stylised depiction of the scaling impact of methodological factors from Table 4. Left scale gives approximate scaling factors for EROI for different assumptions relative to meta-analyses considered in this study. Right scale expressed in relation to EPBT. Length of columns depicts sensitivity of aggregate result to respective factors. Factors can be compounded. For example, studies that applied an insolation of 2200 kWh/m^2 year have an EROI around 1.2 times (20 %) higher, but studies using data that are 10 years old calculate an EROI around 0.5 times lower (50 % lower). The meta-analyses considered in this study adopted a 25- or 30-year lifetime. PV technology shown scaled relative to multi-Si. Hybrid LCA method shown with 30 to 50 % of CED falling outside process-based boundaries. Storage and overbuild estimated from Palmer (2017, Table 2) using Li-ion with 70 % depth-of-discharge

and output energy form equivalence involves a straightforward scaling of either the investments or output, but results in a threefold difference in reported values for EROI. Both methods can be legitimate in any given situation, though one may be preferred over the other depending on study purpose.

Importantly, the meta-analyses discussed in this study harmonise only for parameters related to factors 2, 3, 6a and 6b, leaving a significant gap in relation to factors 1, 4a, 4b and 5. Findings from studies that have adopted different methodologies, boundaries or investment-output energy form equivalence adjustments are therefore not directly comparable unless appropriate adjustments are first made for these methodological factors.

Conclusions

NEA is a tool that has been widely applied to energy supply technologies to explore their present and potential future physical economic roles. However, apparent wide divergence in findings for solar PV has cast doubt on NEA's relevance to energy transition feasibility assessment. We have shown that most of the apparent divergence between studies can be attributed to six factors—life-cycle assessment methodology, age of the primary data, PV cell technology, treatment of intermittency, equivalence of investment and output energy forms, and assumptions about real-world performance. The apparent divergence in findings between studies due to these factors can often be traced back to different goal definitions. NEA's contribution to understanding PV performance, especially in the context of a large-scale renewable energy transition, will be improved if study purposes and goals are clearly and fully stated.

Similarly, there is a role for *interpreters* of NEA findings to take into account the many contextual factors that underlie NEA studies. We believe the findings of this study support the view that NEA is an essential tool for making sense of economic situations in biophysical terms. In turn, this is essential for coming to grips with questions about sustainability of current forms of social organisation, viability of alternatives and feasibility of transition pathways between them. We hope that this study might support increased awareness of contextual issues affecting PV NEA findings, and in doing so contribute to more widespread appreciation for the role that NEA can play in investigating energy transition questions.

Acknowledgements The authors would like to acknowledge the contribution of correspondence with Charlie Hall, Rembrandt Koppelaar, Pedro Prieto, Marco Raugei and Gail Tverberg, and others at the BPE Workshop: Society in Transition; and separately with Vasilis Fthenakis. Thanks also to anonymous reviewers for valuable comments and feedback.

Funding This research was not funded by any specific grants from agencies in the public, commercial or not-for-profit sectors.

Compliance with Ethical Standards

Conflict of interest The authors declare no conflicts of interest.

References

Aghahosseini A, Bogdanov D, Breyer C (2016) 100 % Renewable energy in North America and the role of solar photovoltaics. In: EU-PVSEC conference, June 20–24, 7DV.4.8

Alsema E (2000) Energy payback time and CO_2 emissions of PV systems. Prog Photovolt 8:17–25

Bhandari KP, Collier JM, Ellingson RJ, Apul DS (2015) Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: a systematic review and meta-analysis. Renew Sustain Energy Rev 47:133–141

Billinton R, Allan RN (1996) Reliability evaluation of power systems, 2nd edn. Springer, New York

Breyer C, Schmid J (2010) Population density and area weighted solar irradiation: global overview on solar resource conditions for fixed tilted, 1-axis and 2-axes pv systems. In: 25th European photovoltaic solar energy conference and exhibition/5th World conference on photovoltaic energy conversion, 6–10 September 2010, Valencia, Spain, pp 6–10

Budischak C, Sewell D, Thomson H, Mach L, Veron DE, Kempton W (2012) Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9 % of the time. J Power Sources 225:60–74

Carbajales-Dale M, Raugei M, Fthenakis V, Barnhart C (2015) Energy return on investment (EROI) of solar PV: an attempt at reconciliation. Proc IEEE 103:995–999

Commission European (2017) Commission implementing regulation EU 2017/367 of 1 March 2017. Report, European Commission, Brussels

Crawford R (2011) Life cycle assessment in the built environment. Spon Press, Oxfordshire

Crawford R, Treloar GJ, Fuller R, Bazilian M (2006) Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit. Renew Sustain Energy Rev 10:559–575

Dale M, Benson SM (2013) Energy balance of the global photovoltaic (PV) industry—is the PV industry a net electricity producer? Environ Sci Technol 47:3482–3489

de Wild-Scholten MM (2013) Energy payback time and carbon footprint of commercial photovoltaic systems. Sol Energy Mater Sol Cells 119:296–305

Ferroni F, Hopkirk RJ (2016) Energy return on energy invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation. Energy Policy 94:336–344

Finkel A, Moses K, Munro C, Effeney T, OKane M (2017) Independent review into the future security of the National Electricity Market. Commonwealth of Australia, Canberra

Frischknecht R, Althaus HJ, Dones R, Hischier R, Jungbluth N, Nemecek T, Primas A, Wernet G (2007a) Renewable energy assessment within the cumulative energy demand concept: challenges and solutions. In: Proceedings from SETAC Europe 14th LCA case study symposium: energy in LCA-LCA of Energy, 3–4 Dec 2007

Frischknecht R, Jungbluth N, Althaus HJ, Bauer C, Doka G, Dones R, Hischier R, Hellweg S, Humbert S, Köllner T, Loerincik Y, Margni M, Nemecek T (2007b) Implementation of life cycle impact assessment methods, Data v2.0, ecoinvent Report No. 3. Ecoinvent

Frischknecht R, Itten R, Sinha M, de Wild-Scholten M, Zhang V, Fthenakis V, Kim H, Raugei M, Stucki M (2015a) Life cycle inventories and life cycle assessment of photovoltaic systems report T12-04:2015

Frischknecht R, Wyss F, Knöpfel SB, Lützkendorf T, Balouktsi M (2015b) Cumulative energy demand in LCA: the energy harvested approach. Int J Life Cycle Assess 20:957–969

Frischknecht R, Heath G, Raugei M, Sinha M, de Wild-Scholten M, Fthenakis V, Kim H, Alsema E, Held M (2016) Methodology guidelines on life cycle assessment of photovoltaic electricity, 3rd edn. IEA PVPS Task 12 Report IEA-PVPS T12-08:2016

Fthenakis V, Kim HC (2011) Photovoltaics: life-cycle analyses. Solar Energy 85:1609–1628

Fu Y, Liu X, Yuan Z (2015) Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China. J Clean Prod 86:180–190

Glöckner R, de Wild-Scholten M (2012) Energy payback time and carbon footprint of Elkem Solar Silicon. In: 27th EUPVSEC, Frankfurt, Germany, 24–28 Sept 2012

Gross R, Heptonstall P, Anderson D, Green T, Leach M, Skea J (2006) The costs and impacts of intermittency: an assessment of the evidence on the costs and impacts of intermittent generation on the British Electricity Network. UK Energy Research Centre, London

Grubler A, Johansson TB, Muncada L, Nakicenovic N, Pachauri S, Riahi K, Rogner HH, Strupeit L (2012) Energy primer. In: Global energy assessment: toward a sustainable future. Cambridge University Press, Cambridge

Heptonstall P, Gross R, Steiner F (2017) The costs and impacts of intermittency 2016 update. UK Energy Research Centre, London

Huva R, Dargaville R, Rayner P (2016) Optimising the deployment of renewable resources for the Australian NEM (National Electricity Market) and the effect of atmospheric length scales. Energy 96:468–473

IEA (2016a) Energy technology perspectives: data visualisation. https://www.iea.org/etp/explore/. Accessed 10 May 2016

IEA (2016b) IEA-PVPS trends in photovoltaic applications: survey report of selected IEA countries between 1992 and 2015. Report, IEA Photovoltaic Power Systems Programme, Paris, France

IEA (2017) Commentary: understanding and using the energy balance. http://www.iea.org/newsroom/news/2017/september/commentary-understanding-and-using-the-energy-balance.html. Accessed 11 Sept 2017

ISO (1998) ISO 14041: environmental management life cycle assessment goal and scope definition and inventory analysis. Report, International Organization for Standardization

ISO (2006) ISO 14040: environmental management-life cycle assessment-Principles and framework. Report, International Organization for Standardization

Ito M, Kato K, Sugihara H, Kichimi T, Song J, Kurokawa K (2003) A preliminary study on potential for very large-scale photovoltaic power generation (VLS-PV) system in the Gobi desert from economic and environmental viewpoints. Sol Energy Mater Sol Cells 75:507–517

Ito M, Kato K, Komoto K, Kichimi T, Kurokawa K (2005) Analysis of transmission losses of very large-scale photovoltaic power generation systems (VLS-PV) in world desert. In: Photovoltaic specialists conference, 2005. Conference record of the thirty-first IEEE, IEEE, pp 1706–1709

Ito M, Kato K, Komoto K, Kichimi T, Kurokawa K (2008) A comparative study on cost and lifecycle analysis for 100 MW very largescale PV (VLSPV) systems in deserts using mSi, aSi, CdTe, and CIS modules. Prog Photovolt 16:17–30
Ito M, Lespinats S, Merten J, Malbranche P, Kurokawa K (2016) Life cycle assessment and cost analysis of very largescale PV systems and suitable locations in the world. Prog Photovolt 24:159–174
Johnston W (2017) How long will your solar panels last, and how well will they perform? ReNewEconomy, London
Jones C, Gilbert P, Raugei M, Mander S, Leccisi E (2016) An approach to prospective consequential life cycle assessment and net energy analysis of distributed electricity generation. Energy Policy 100:350–358
Jordan DC, Kurtz SR, VanSant K, Newmiller J (2016) Compendium of photovoltaic degradation rates. Prog Photovolt 24:978–989
Kannan R, Leong K, Osman R, Ho H, Tso C (2006) Life cycle assessment study of solar PV systems: an example of a 2.7 kW p distributed solar PV system in Singapore. Solar Energy 80:555–563
Kirby B, Milligan M, Makarov Y, Hawkins D, Jackson K, Shiu H (2003) California renewables Portfolio standard renewable generation integration cost analysis. The California Energy Commission and The California Public Utilities Commission, San Francisco
Koppelaar R (2016) Solar-PV energy payback and net energy: meta-assessment of study quality, reproducibility, and results harmonization. Renew Sustain Energy Rev 72:1241–1255
Kubiszewski I, Cleveland CJ, Endres PK (2010) Meta-analysis of net energy return for wind power systems. Renew Energy 35:218–225
Kummu M, Varis O (2011) The world by latitudes: a global analysis of human population, development level and environment across the north-south axis over the past half century. Appl Geogr 31:495–507
Leccisi E, Raugei M, Fthenakis V (2016) The energy and environmental performance of ground-mounted photovoltaic systems: a timely update. Energies 9:622
Lenzen M (2000) Errors in conventional and input output based life cycle inventories. J Ind Ecol 4:127–148
Lenzen M, McBain B, Trainer T, Jtte S, Rey-Lescure O, Huang J (2016) Simulating low-carbon electricity supply for Australia. Appl Energy 179:553–564
Lightfoot HD (2007) Understand the three different scales for measuring primary energy and avoid errors. Energy 32:1478–1483
Louwen A, van Sark WG, Faaij AP, Schropp RE (2016) Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development. Nat Commun 7:13728
Meydbray J, Dross F (2016) PV module reliability scorecard report 2016. DNV-GL
Moeller D, Murphy D (2016) Net energy analysis of gas production from the Marcellus Shale. BioPhys Econ Resour Qual 1:1–13
Murphy DJ, Hall CA (2010) Year in review: EROI or energy return on (energy) invested. Ann N Y Acad Sci 1185:102–118
Murphy DJ, Hall CA, Dale M, Cleveland C (2011) Order from chaos: a preliminary protocol for determining the EROI of fuels. Sustainability 3:1888–1907
Nakicenovic N, Grubler A, Ishitani H, Johansson T, Marland G, Moreira J, Rogner HH (1996) Energy primer. Climate change 1995, impacts, adaptations and mitigation of climate change: scientific-technical analyses. Cambridge University Press, Cambridge
NASA (2017) NASA surface meteorology and solar energy: global data sets. https://eosweb.larc.nasa.gov/cgi-bin/sse/global.cgi. Accessed 6 May 2017
NERC (2011) Planning resource adequacy analysis, assessment and documentation, BAL-502-RFC-02. http://www.nerc.com/files/BAL-502-RFC-02.pdf. Accessed 26 March 2017
Nugent D, Sovacool BK (2014) Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: a critical meta-survey. Energy Policy 65:229–244
OFGEM (2013) Electricity capacity assessment report 2013. Report, OFGEM, London
Palmer G (2013) Household solar photovoltaics: supplier of marginal abatement, or primary source of low-emission power? Sustainability 5:1406–1442
Palmer G (2017) A framework for incorporating EROI into electrical storage. BioPhys Econ Resour Qual 2:6
Palzer A, Henning HM (2014) A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies—Part II: results. Renew Sustain Energy Rev 30:1019–1034
Phylipsen GJM, Alsema EA (1995) Environmental life-cycle assessment of multicrystalline silicon solar cell modules. Department of Science, Technology and Society, Utrecht University, Utrecht
Preston G (2015a) 100% solar and wind power simulation for ERCOT. http://egpreston.com/100percentrenewables.pdf. Accessed 9 May 2016
Preston G (2015b) A simple calculation procedure for LOLE, LOLH, and EUE, calculation of probabilistic transmission line flows, and study results for extreme renewables in ERCOT. http://egpreston.com/Presentation3.pdf. Accessed 5 Nov 2016
Prieto P, Hall C (2013) Spain's photovoltaic revolution: the energy return on investment. Springer, New York
Pulsford S (2016) PV module quality: challenges for the Australian market. Clean Energy Council, Melbourne
PV Education (2016) Average solar radiation. http://www.pveducation.org/pvcdrom/average-solar-radiation. Accessed 2 Oct 2016
Raugei M (2013) Comments on "Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants": making clear of quite some confusion. Energy 781:1088–1091
Raugei M, Fullana-i Palmer P, Fthenakis V (2012) The energy return on energy investment (EROI) of photovoltaics: methodology and comparisons with fossil fuel life cycles. Energy Policy 45:576–582
Raugei M, Carbajales-Dale M, Barnhart CJ, Fthenakis V (2015) Rebuttal: comments on "Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants": making clear of quite some confusion. Energy 82:1088–1091
Raugei M, Frischknecht R, Olson C, Sinha P, Heath G (2016) Methodological guidelines on net energy analysis of photovoltaic electricity, IEA-PVPS Task 12, Report T12- 07:2016. IEA-PVPS
Sayeef S, Heslop S, Cornforth D, Moore T, Percy S, Ward JK, Berry A, Rowe D (2012) Solar intermittency: Australia's clean energy challenge: characterising the effect of high penetration solar intermittency on Australian electricity networks. CSIRO, Canberra
Sims R, Mercado P, Krewitt W, Bhuyan G, Flynn D, Holttinen H, Jannuzzi G, Khennas S, Liu Y, Nilsson LJ (2011) Integration of renewable energy into present and future energy systems In: IPCC special report on renewable energy sources and climate change mitigation
Sims R, Schaeffer R, Creutzig F, Cruz-Nunez X, DAgosto M, Dimitriu D, Figueroa Meza M, Fulton L, Kobayashi S, Lah O, McKinnon A, Newman P, Ouyang M, Schauer J, Sperling D, Tiwari G (2014) Transport. In: Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change
Sonnemann G, Vigon B, Rack M, Valdivia S (2013) Global guidance principles for life cycle assessment databases: development of training material and other implementation activities on the publication. Int J Life Cycle Assess 18:1169–1172

Suh S, Huppes G (2002) Missing inventory estimation tool using extended input-output analysis. Int J Life Cycle Assess 7:134–140
Suh S, Huppes G (2005) Methods for life cycle inventory of a product. J Clean Prod 13:687–697
Tillman AM (2000) Significance of decision-making for LCA methodology. Environ Impact Assess Rev 20:113–123
UNEP/SETAC (2011) Global guidance principles for life cycle assessment databases: a basis for greener processes and products. UNEP/SETAC Life Cycle Initiative, Paris, United Nations Environment Programme
Weißbach D, Ruprecht G, Huke A, Czerski K, Gottlieb S, Hussein A (2013) Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants. Energy 52:210–221. https://doi.org/10.1016/j.energy.2013.01.029. Accessed 23 Sep 2016
Weißbach D, Ruprecht G, Huke A, Czerski K, Gottlieb S, Hussein A (2014) Reply on 'Comments on "Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants" Making clear of quite some confusion'. Energy 68:1004–1006
White SW, Kulcinski GL (2000) Birth to death analysis of the energy payback ratio and CO_2 gas emission rates from coal, fission, wind, and DT-fusion electrical power plants. Fusion Eng Des 48:473–481
Wu X, Xia X, Chen G, Wu X, Chen B (2016) Embodied energy analysis for coal-based power generation system-highlighting the role of indirect energy cost. Appl Energy 184:936–950
Yang CJ, Jackson RB (2011) Opportunities and barriers to pumped-hydro energy storage in the United States. Renew Sustain Energy Rev 15:839–844
Yao Y, Chang Y, Masanet E (2014) A hybrid life-cycle inventory for multi-crystalline silicon PV module manufacturing in China. Environ Res Lett 9:114001
Zhai P, Williams ED (2010) Dynamic hybrid life cycle assessment of energy and carbon of multicrystalline silicon photovoltaic systems. Environ Sci Technol 44:7950–7955