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Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis

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ABSTRACT

There is a fast growing interest in better understanding the energy performance of PV technologies as evidenced by a large number of recent studies published on this topic. The goal of this study was to do a systematic review and a meta-analysis of the embedded energy, energy payback time (EPBT), and energy return on energy invested (EROI) metrics for the crystalline Si and thin film PV technologies published in 2000–2013. A total of 232 references were collected of which 11 and 23 passed our screening for EPBT/EROI and embedded energy analysis, respectively. Several parameters were harmonized to the following values: Performance ratio (0.75), system lifetime (30 years), insolation (1700 kWh m^{-2} yr^{-1}), module efficiency (13.0% mono-Si; 12.3% poly-Si; 6.3% a:Si; 10.9% CdTe; 11.5% CIGS). The embedded energy had a more than 10-fold variation due to the variation in BOS embedded energy, geographical location and LCA data sources. The harmonization narrowed the range of the published EPBT values. The mean harmonized EPBT varied from 1.0 to 4.1 years; from lowest to highest, the module types ranked in the following order: cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), amorphous silicon (a:Si), poly-crystalline silicon (poly-Si), and mono-crystalline silicon (mono-Si). The mean harmonized EROI varied from 8.7 to 34.2. Across different types of PV, the variation in embedded energy was greater than the variation in efficiency and performance ratio suggesting that the relative ranking of the EPBT of different PV technology today and in the future depends primarily on their embedded energy and not their efficiency.

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1. Introduction

Photovoltaic technology (PV) offers some unique benefits that are not realized by other renewable energy technologies. It is a silent energy source requiring no moving parts. It has a long system lifetime with low maintenance costs and has experienced substantial reduction in upfront cost over the past two decades. Being a decentralized technology, PV systems can also increase the resilience of the energy infrastructure.

Globally, the solar generated electricity is expected to make up only 0.38% of the global electric energy generation (consisting of 87 TW h of the total 22,700 TW h) in 2015 [1]. However, depending on the political drive, the annually installed PV power capacity is expected to grow from 31 GW_p in 2012 to the range of 48–84 GW_p in 2017, representing an annualized growth rate 11–34% respectively [2]. The highest growth rates are expected in China and in the U.S. [2]. Historically, annual PV production has grown at an average rate of nearly 43% from 2000–2012 [2]. Future growth will depend on the policies that are adopted in response to PV's evolving economics and role in addressing an increasingly apparent anthropomorphic influence on global climate.

As the PV market grows, it is becoming increasingly important to understand the energy performance of PV technologies. Energy payback time (EBPT) and energy return on energy invested (EROI) are the two most common metrics used to represent the energy performance of different technologies. The length of time a PV system must operate before it recovers the energy invested throughout its life time is ascertained by EPBT. So, if the EPBT of a PV system is 3 years, we get energy free of cost for 27 years assuming that the life time of the system is 30 years. For understanding the energy source's long term viability, EROI is a better term to consider than EPBT. EROI tells us about how much energy is obtained from a system of an energy source compared to how much of that energy is required to create and implement the system. Hence, EROI is a unitless ratio of the energy returned to the society to the energy required to make that energy (i.e. embedded energy). If the EROI is less than 1:1, the energy source is not considered viable. The minimum EROI required to maintain current rich-world industrial societies is set as 3:1 [3]. This ratio was determined specifically for oil and corn-based ethanol but applicable for other energy sources as well.

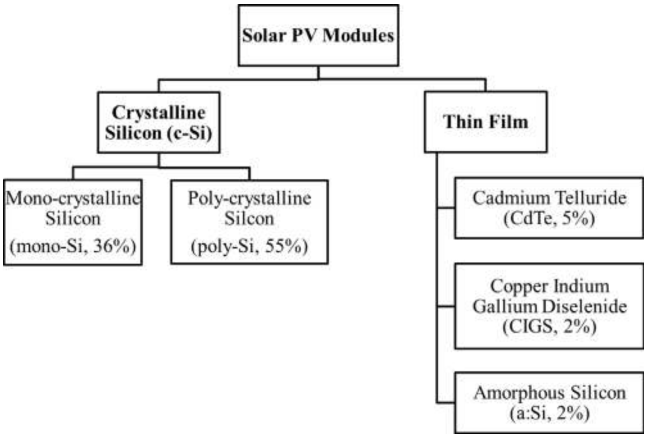

Fig. 1. Technologies included in this study and their estimated percentage of market share. These market share percentages were calculated in 2013 [19].

A few early studies on the EROI of PV systems led people to believe that PV technologies compare poorly with other energy sources, such as coal and natural gas, and are not a viable energy option [4]. The data used by these early studies, however, is now outdated due to the increases in efficiency of PV modules and the processes used in manufacturing them [5]. There is a renewed interest in understanding the embedded energy, EPBT, and EROI from PV systems and several authors compiled data on these three metrics [6–8]. However, these recent studies have either presented a limited dataset or they did not follow a systematic approach to compiling and analyzing previously published data. As data on these metrics continue to grow, it is now timely to do a systematic review and meta-analysis of the data. A systematic review aims to provide an exhaustive summary of current literature based on set criteria for which studies to include. Meta-analysis is the statistical analysis of the data collected using systematic reviews. Systematic reviews and meta-analysis are often found in health sciences and clinical research [9,10] but are gradually entering into the life cycle assessment (LCA) literature as well [11–14].

We have conducted a meta-analysis of the literature data on embedded energy, EPBT and EROI of PV systems to produce more accurate evaluations and comparisons of the energy performance of different types of PV technologies established in 2000–2013. To achieve this goal, a thorough literature review was conducted. EPBT and EROI data collected from the literature were harmonized for the specific parameters (module efficiency, solar insolation, and system lifetime) that affect the life cycle performance of the PV system [15]. Our study follows the approach of Hsu et al. and Kim et al. who harmonized the greenhouse gas emissions from silicon and thin film based PV systems, respectively [16,17]. We expand on prior work by focusing on the harmonization of the EPBT and EROI metrics, by analyzing both thin film and crystalline silicon based systems, and by providing a comprehensive analysis of the embedded energy metric.

We also present our work in the context of a more recent (2013) study by Dale and Benson [18] who discussed the net electricity consumption vs. production of the full PV industry, in order to answer the question, "Is the global PV industry a net electricity producer?". In their study, the authors analyzed data from 2005 to 2008, including a global capacity factor for PV systems, meta-analysis of the cumulative energy demand (CED), and trends toward reduction of energy cost of PV systems. Using these data, they introduced a model which forecasts electrical energy requirement to scale up the PV industry and determine the electricity balance of the global PV industry to 2020. With respect to these authors, our study remains relevant for the following reasons: Dale and Benson [18] dealt with the global PV industry but did not harmonize EPBT for individual PV technologies; their systematic review and meta-analysis is limited to CED, and omits harmonization of electricity production by technology.

2. Methods

2.1. Collection of literature

A thorough literature review was conducted using Google Scholar and Web of Knowledge. The keywords used were "energy payback time", "mono-crystalline silicon", "poly-crystalline silicon", "amorphous silicon", "CdTe", "CIGS", and "photovoltaics".

Our study focused on the most relevant commercial technologies, falling into the categories of mono-crystalline silicon (mono-Si), poly-crystalline silicon (poly-Si), amorphous silicon (a:Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS) (including some results from CIS which is closely related to CIGS). The market shares of these five technologies are provided in Fig. 1 and, as of 2013, thin film technologies represent about 9% of the total terrestrial PV market [19]. We omitted any data, harmonization, and discussion of ribbon crystalline silicon, organic solar cells, dye-sensitized solar cells, solar concentrator systems, and quantum dot based cells because these technologies do not play a significant role in the commercial market at present.

After reviewing each article's abstract, it was determined to obtain the full article if the abstract discussed energy, payback times, sustainability, or environmental issues or impacts of photovoltaic systems. Additional articles were also obtained using the ancestry approach and the citation index. We collected a total of 232 references (Table S1 in Supporting information). From this total, 7 (11) papers on mono-Si, 6 (11) on poly-Si, 3 (7) on a:Si, 6 (11) on CdTe, and 5 (8) on CIGS passed our screening for EPBT (embedded energy) (Tables S2–S12 in Supporting information). It is common in systematic reviews to discard over 90% of the studies from the initial list [20].

2.2. *Criteria for inclusion*

Several criteria were used in determining which studies to include in the analysis. All studies that did not discuss one of the five PV system types (mono-Si, poly-Si, a:Si, CdTe, CIGS) that dominate today's commercial market were eliminated. A PV system consists of the PV module and the balance of system (BOS) components. The module encompasses the surface that harnesses the solar energy. The BOS components encompass all other supporting infrastructure and can include the wiring, switches (for connecting to the existing electric grid), support racks, and inverter (to convert direct current to alternating current). The life cycle stages of a PV system include raw material acquisition and processing, manufacturing of the module, operation, and end of life management. All papers that did not explicitly report the cradle to gate energy (raw material through manufacturing stages) from both the module and the BOS were eliminated. To be included in the analysis, the paper also had to report original data for both the BOS and the module. Some papers reported original data for the module but not the BOS. These studies were eliminated.

A cradle to gate system boundary was selected for the analysis because there is limited and widely varying data available for the distribution, operation, maintenance, and end of life management of PV systems. Transportation distances are often not modeled or explicitly reported in PV LCA studies and it would not have been possible to harmonize the data for different types of waste management such as disposal in landfill versus recycling. Some existing data for transportation and end of life management show that these stages do not contribute significantly to the life cycle energy demand [21–25].

The International Energy Agency (IEA) Photovoltaic Power Systems (PVPS) program recommends the following parameters to be reported in PV LCA studies: irradiation level and location, module efficiency, performance ratio, time-frame of data, type of system (e.g., roof-top, ground mount fixed tilt or tracker), expected system lifetime, degradation ratio of PV and BOS, system's boundaries, production location, and goal of the study [26]. Reporting of these parameters is deemed important for methodological transparency and for adequately following existing ISO LCA standards. The degradation ratio of PV and BOS, was reported only by one recent study [27] and was therefore not used as a screening criterion. However, papers that did not explicitly report the other parameters were eliminated from the study.

Once papers were screened, the next step was to screen the scenarios used within papers. The word ‘scenario’ here refers to the different analyses some papers did where they varied some of the parameters such as efficiency, performance ratio, insolation, and embedded energy to see its effect on EPBT. If the same embedded energy value was used while varying other parameters, the harmonized EPBT calculated in our study would be the same for the different scenarios. In these cases we recorded data for each embedded energy value provided by a study and not for each scenario. Similarly, if a study varied the embedded energy to predict future changes, these projected scenarios were excluded from the dataset we used for harmonizing the studies.

For the EPBT data set, we verified the EPBT data reported by the studies by independently calculating the EPBT values using the IEA recommended parameters reported by the study. If our calculated EPBT value differed by more than about 10% from the EPBT value reported in the study, that particular scenario or study was excluded. The reason for the mismatch between our independent calculations and the EPBT values reported by the studies might be possible typing errors in the papers or our misinterpretation of the reported data. By using this approach, we were able to verify the EPBT values of most of the studies (see Supporting information Tables S8B–S12B); only two data points were excluded when we could not match the EPBT value reported in the study.

Finally, we aimed to define an objective criterion for screening the papers that would be using outdated technology based on the information provided by the studies such as the thickness of absorbing semiconductor layer, efficiency, module manufacturing processes and design. However, some studies that passed our screening from other criteria did not provide comprehensive information on these parameters. Therefore, we determined ‘modernity’ of technology and used this as a final screening criterion based on the year the study was published. Several papers that passed our other screening criteria were eliminated because they were published prior to 2000. Ultimately, our screening resulted in 11 papers (38 scenarios) to be included in the EPBT harmonization dataset [27–37] and 23 papers to be included in the embedded energy dataset (all cited in supporting information). All of these papers were published in between 2000 and 2013. Studies that passed all screening criteria are reported in Tables S8–S12 of the Supporting information.

2.3. *Calculation of energy payback time and energy returned on energy invested*

EPBT and EROI were calculated using the following equations respectively:

$$\text{EPBT (year)} = \frac{\text{Embedded (primary) energy (MJ m}^{-2})}{\text{Annual (primary) energy generated by the system (MJ m}^{-2}\,\text{yr}^{-1})} = \frac{W_1(\text{MJ m}^{-2})}{W_2(\text{MJ m}^{-2}\,\text{yr}^{-1})} = \frac{W_1}{(I \times \eta \times \text{PR}/\varepsilon)} \quad (1)$$

$$\text{EROI} = \text{lifetime energy output/Embedded energy} = \frac{W_3\ (\text{MJ m}^{-2})}{W_1\ (\text{MJ m}^{-2})} = \frac{W_2\ (\text{MJ m}^{-2}) \times \text{LT (year)}}{W_2\ (\text{MJ m}^{-2}\,\text{yr}^{-1}) \times \text{EPBT (year)}} = \frac{\text{LT (year)}}{\text{EPBT (year)}} \quad (2)$$

where

W_1 = embedded (primary) energy (MJ m^{-2});
W_2 = annual energy generated by the system expressed as primary energy (MJ m^{-2} yr^{-1});
W_3 = total energy generated by the system over its lifetime expressed as primary energy (MJ m^{-2});

ε=electrical to primary energy conversion factor;
I=total solar insolation incident on the unit-surface, per year (MJ m^{-2} yr^{-1});
η=average module efficiency (%);
PR=system performance ratio (%);
LT=lifetime of the system (year)

In Eq. (1), product $I \times \eta \times \mathrm{PR}$ is the annual electrical energy generated from the system, which is converted to primary energy equivalent using the electrical to primary energy conversion efficiency factor (ε). This conversion factor depends on a country's electricity mix. Some studies either reported the energy values in primary energy units or they specified the conversion efficiency factor from electrical to primary. For other studies, we assumed a conversion factor of 0.35 for primary to electrical energy [32,33,38,39].

Embedded energy (W_1), also known as the embodied energy, is the total primary energy required to extract and process the raw materials and manufacture the modules and BOS for the PV system being analyzed. This energy encompasses the cradle to gate system boundary in our analysis. Full life cycle energy would have been more accurate but is not currently feasible to include in this systematic review due to lack and discrepancy of data regarding transportation, operation, and waste management life cycle stages (see Section 2.2).

Recent studies typically report the embedded energy data in MJ m^{-2}, while earlier studies sometimes reported it in kW h kW_p^{-1}. All embedded energy values were converted to MJ m^{-2} based on the power rating definition given in Eq. (3) (see Supporting information for more details):

$$\text{Power Rating } (W_p) = (1000 \text{ W m}^{-2}) \times \text{module efficiency } (\%) \times \text{module area } (m^2) \tag{3}$$

where standard test conditions (STC: incident sunlight with a spectral distribution defined by AM1.5G and an integrated intensity of 1000 W m^{-2}, and module temperature equal to 25 °C (77 °F)) are applied, and efficiency is expressed as a fraction (i.e. 15% efficiency is written as 0.15). In this way, a 15% module efficiency yields an areal power output (at STC) of 150 W_p m^{-2}. To convert a module's efficiency to an areal rated power density (W_p m^{-2}), one needs only to multiply the fractional efficiency by 1000 W_p m^{-2}. An example calculation for this conversion is provided in the Supporting information.

We evaluated Eq. (1) with the values reported by each reference in order to verify the reported EPBT. If there was a small discrepancy (less than10 %) between our calculated EPBT and the reported EPBT, we used the reported EPBT as our unharmonized value. Since none of the papers calculated EROI, we used Eq. (2) to calculate the unharmonized EROI based on the reported lifetime and EPBT. Once the unharmonized EPBT and EROI values were determined, we then used the harmonization parameter values of module efficiency, performance ratio, insolation, and lifetime to calculate the harmonized EPBT and EROI. The embedded energy value was not changed for the harmonization calculation. This parameter was considered to be already harmonized since only studies that considered the same stages (only raw material acquisition through manufacturing) were included in our analysis. The harmonized results only apply to the conditions we set with our parameters, but they may easily be changed since all of the factors are linear. Example calculations using higher module efficiency and performance ratio values are presented in supporting information.

Table 1
Module efficiencies used for harmonization.

Module type	mono-Si	poly-Si	a:Si	CdTe	CIGS
Average lifetime efficiency (%)	13.0	12.3	6.3	10.9	11.5

2.4. Harmonized parameters

2.4.1. Module efficiency

Solar cell efficiency (photo-conversion efficiency, PCE or η%) is the ratio of the electrical energy output of a solar cell to the light energy incident on the solar cell. Efficiency is calculated by dividing the output power of a cell at its maximum power point ($P_{\mathrm{mpp}} = I_{\mathrm{mpp}} \times V_{\mathrm{mpp}}$) in Watts by the product of the incident radiation (in W m^{-2}) and the surface area of the solar cell (A in m^2). A module is the package of large number of cells (for example, 60 cells is common in present-day crystalline Si modules). There can be a large difference between solar cell efficiency and fully packaged module efficiency. In general, three types of losses can be seen in a module: loss due to the physical layout of the module including framing and gaps between cells, optical loss from reflection and absorption associated with encapsulation, and electrical loss due to series resistance developed from cell interconnections.

The module efficiency reported by manufacturers represents the initial efficiency of the module under STC. Environmental influences such as moisture penetration, temperature fluctuation, and weathering of the encapsulation layers result in module efficiency degradation over its lifetime [40,41]. However, this degradation does not have a large effect on the EPBT calculation. For example, a module with initial 15.0% efficiency exhibiting performance degradation at a rate of 0.5% annually would result after 30 years in only a 2.0% reduction to 13.0% efficiency, and an average life time efficiency of 14.0%. In our harmonization, we adopted the average life time efficiency values that were used by Hsu, et al. [16] and Kim, et al. [17] to harmonize the greenhouse gas emission from PV systems (Table 1). These values were calculated based on a 0.5% per year degradation over a 30 year life time.

2.4.2. Performance ratio

The performance ratio (PR) is the ratio of the actual to theoretical energy output of a PV module, in which the theoretical output energy is calculated based simply on the product of the total insolation (e.g., W m^{-2}) and the module specified efficiency (e.g. 0.15 for a 15% efficient module). It reveals how well a system behaves under actual conditions. The PR consists of all inefficiencies in actual energy output, including the effects of variations in insolation, reduced efficiency associated with elevated module temperature, shading, soiling or snow-cover, and inverter inefficiency. PR measures a location-independent quality of a PV. PR is expressed as a percentage such that a PR of 75% means that approximately 25% of the theoretical energy generation is lost due to such factors as snow or other environmental factors, or reduced conversion efficiency associated with elevated module temperature, or system down time [42].

When calculating the EPBT for scenarios from studies that did not state the PR of the system, we assumed a PR of 75% for roof top and 80% for ground mount installations [26]. For harmonization, a value of 75% was chosen for consistency. In today's practice, PR values can reach as high as 90% [43].

2.4.3. Solar insolation

EPBT depends on the incident solar radiation as shown in Eq. (1). As annual insolation (solar radiation incident per unit area per year) increases, EPBT decreases. The “universal” insolation value we used for harmonization was 1700 kW h m^{-2} yr^{-1} which

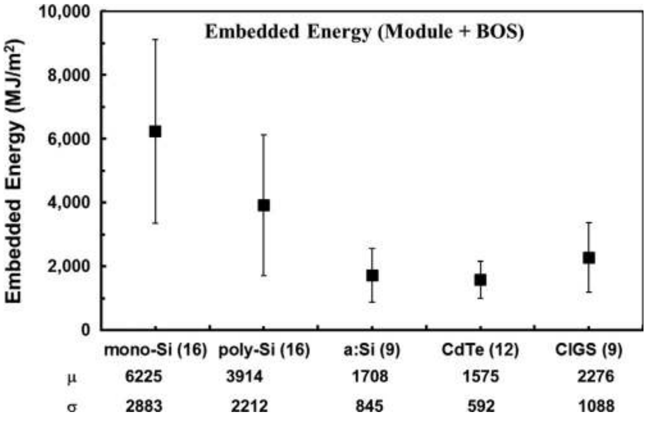

Fig. 2. Module and BOS mean (μ) and standard deviation (σ) of embedded primary energy with error bars representing one standard deviation. The number of values for each module type is indicated in parentheses. (Raw data is presented in Tables S2–S6 in Supporting information.)

is representative of the average global insolation [44] and has also been used for the insolation of Southern Europe [45]. The results for the irradiation values of four other places (Los Angeles, California; Trenton Mercer County, New Jersey; Las Vegas, Nevada; and average US) are reported in the supporting information to help give readers an idea of the effect it has on EPBT.

2.5. Statistical analysis

The mean embedded energy, EPBT, and EROI from each PV type were compared for statistical significance using analysis of variance (ANOVA) and Tukey's test. Since technology becomes more efficient with time, one would expect the embedded energy and efficiency of PV to be lower in more recent years. The effect of time on compiled data was analyzed using correlation analysis. All statistical analyses were performed using JMP software.

3. Results and discussion

3.1. Embedded energy

The embedded energy data had a more than ten-fold variation with highest (13,428 MJ/m^2) and lowest (894 MJ/m^2) values reported for mono-Si and CdTe, respectively. Our observation of the large variation in embedded energy parallels the large variation in life cycle GHG emissions reported by Kim et al. [17] and Hsu et al. [16]. In our data set, there was a larger variation in the embedded energy of crystalline Si than of thin film (Fig. 2). In general, we would expect part of this variation to be due to improvements in PV technology that would reduce the embedded energy from improvements in existing processes, introduction of new processes and use of less material to make solar cells. This time based improvement was evident in the statistically significant correlation ($p < 0.05$) between the embedded energy and publication date of the poly-Si dataset (Supporting information Figs. S2–S6). Contrary to our expectations, other PV types did not have a significant correlation between time and embedded energy. We note that our dataset is not large and the statistical correlation (or lack thereof) should be interpreted within this context. In addition, we note that our choice of units MJ/m^2 includes the efficiency of the module in the value reported for embedded energy since efficiency is used in converting MJ/kW$_p$ to MJ/m^2 (see Supporting information example calculation). This would have strengthened the correlation between embedded energy and time if the efficiencies were increasing with time. We also note that contrary to our observation from a larger dataset, Fthenakis et al. [36] used a smaller dataset (and use MJ/kW$_p$) but noted, a drop in CdTe in embedded energy by more than 20% between 2005 and 2008.

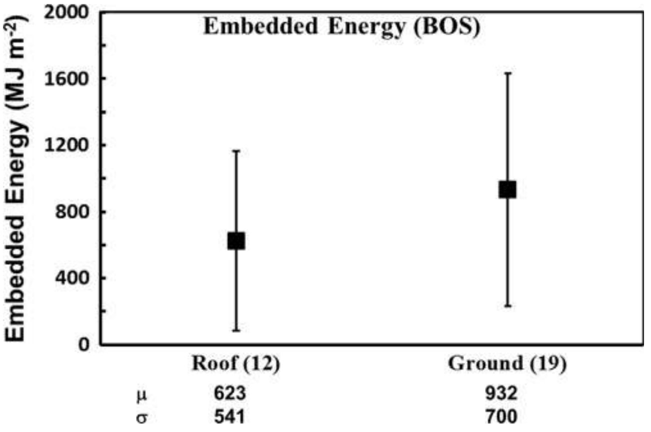

Fig. 3. Mean embedded energy values reported by the collected references with error bars representing one standard deviation for the manufacturing of BOS. (Raw data is presented in Table S7 in Supporting information.) The number of scenarios included is shown in parentheses after the installation type. The BOS data were only grouped by installation type and not module type because some references stated different values for different module types while others reported the same value for every module type.

In the mono-Si dataset, the large variation of the embedded energy is mainly due to the high values reported by Bizzari and Morini [30] (11,153 MJ/m^2) and Garcia-Velverde et al. [32] (13,428 MJ/m^2) and the low value (1708 MJ/m^2) reported by Ito et al. [46]. The same two references [30] (9101 MJ/m^2) and Ito et al. [46] (1008–1322 MJ/m^2) also caused the large variation in the poly-Si dataset. Excluding these three references reduces the variation in embedded energy to about two fold difference for mono-Si and three fold difference for poly-Si (to about 4000–8000 MJ/m^2 for mono-Si and 2200–6600 MJ/m^2 for poly-Si dataset). In general, we would expect the large variation reported by different studies to not be due to manufacturing energy differences among manufacturers since the competitive nature of the PV industry promotes a ‘race to the bottom’, which causes costs to be minimized. Since energy demand would correlate with costs of the PV module, there is indirectly a ‘race to the bottom’ on embedded energy as well. Irrespective of differences in different companies, there can still be some difference in embedded energy of a module manufactured by the same company but in different locations. For example, Fthenakis et al. [36] reported that the embedded energy of a module manufactured in Frankfurt, Germany was about 10% lower than the same unit manufactured in Perrysburg, USA.

The inclusion of BOS in the analysis could explain some of the variation in the embedded energy shown in Fig. 2 since BOS can contribute to a large portion of the total embedded energy [47]. The mean and standard deviations of the ground and roof BOS embedded energy are shown in Fig. 3. The BOS embedded energy varied almost by 50 times with lowest value (44 MJ/m^2) reported by Meijer and Kulchinski [48] for an unframed roof installation and highest value (2300 MJ/m^2) reported by Alsema [34] for a framed ground installation. Ground BOS requires more materials for mounting and its embedded energy was significantly higher than that of roof BOS only when data prior to year 2000 was included (t-test, $p < 0.05$). The BOS itself is often not well described in studies. For example, PV modules may or may not have a solar tracker, power functioning unit, power optimizer (smart module) all of which would have affected the BOS embedded energy. These and other module specific (e.g. thickness

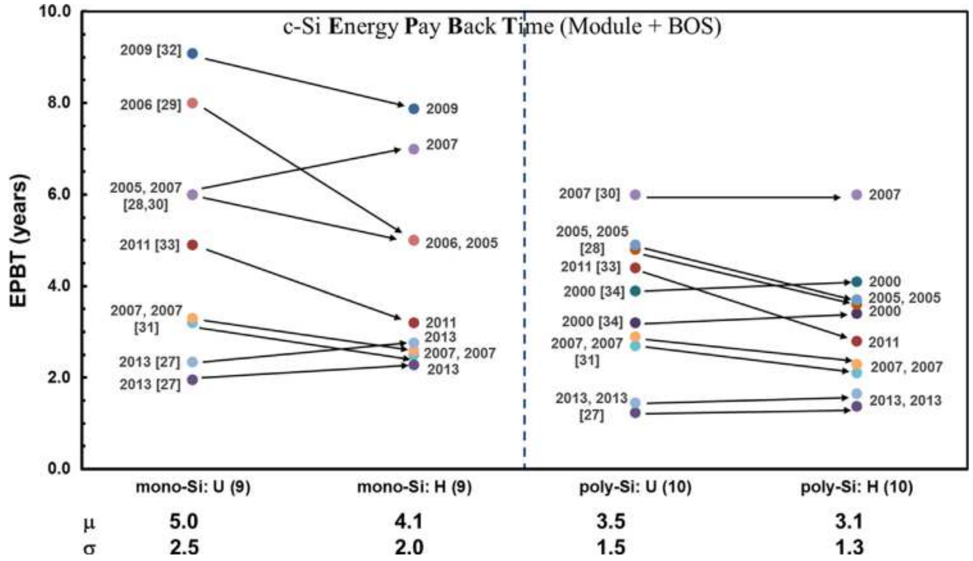

Fig. 4. Unharmonized (*U*) and harmonized (*H*) EPBT for crystalline silicon solar cells. The number of scenarios included is shown in parentheses after the technology name. Mean (μ) and standard deviation(σ) are shown on the bottom of graph. Numbers in brackets next to the data points indicate the reference for which this data comes from.

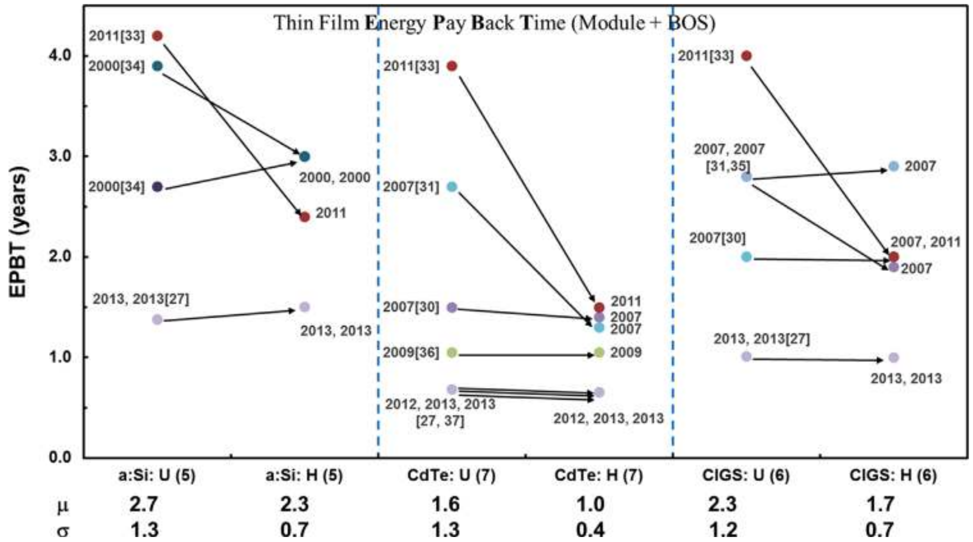

Fig. 5. Unharmonized (*U*) and harmonized (*H*) EPBT for thin film solar cells. The number of scenarios included is shown in parentheses after the technology name. Mean (μ) and standard deviation(σ) are shown on the bottom. Numbers in brackets next to the data points indicate the reference for which this data comes from.

or specific manufacturing process) technology details should be provided in future studies to better understand the variability of embedded energy across published data.

While choice of units (per m^2 versus per kW_p), geographical differences, inclusion of BOS contributed to the variation of the embedded energy reported across studies, the primary reason that caused the observed variation in our dataset is the lack of transparency and the choice of data sources used by the different authors. The detailed life cycle inventories were not reported in many of the studies included in our dataset. By nature, LCA models often use a mix of original data, published data, and calculations/interpretations derived from both. This can hold true even if a primary dataset for LCA is collected directly from the manufacturing facility. This aspect of LCA modeling applied to the PV LCA papers we reviewed as well, which is likely the primary cause of the variation in the dataset.

The means of the embedded energy from the five different PV types were statistically different (ANOVA test, $p < 0.05$). We anticipated the embedded energy of mono-Si and poly-Si to be significantly higher than those of thin film due to the high energy requirements for producing solar-grade silicon [35] as well as the larger material requirements (>100 μm absorbent layer for crystalline silicon versus <5 μm for thin film). However, post-hoc Tukey's test ($\alpha = 0.05$) confirmed this hypothesis only when studies published prior to year 2000 were included in the analysis. When only data published after 2000 is included the embedded energy of poly-Si, a:Si, and CIGS were not significantly different from one another but were significantly higher than that of CdTe (Tukey's test, $\alpha = 0.05$).

3.2. Energy payback time

Figs. 4 and 5 demonstrate EPBT with respect to the PV module type and publication date from 2000 to 2013. The EPBT dataset had fewer scenarios than the embedded energy dataset since it only included the studies that reported an EPBT value that was verified by us within 10% error (see Tables S8–S12 in Supporting information). Across all technologies, the mean harmonized EPBT ranged from 1.0 to 4.1 years. From lowest to highest EPBT, the module types ranked in the following order: CdTe, CIGS, a:Si, poly-Si, and mono-Si. This was the same order as the most recent data reported by De Wild-Scholten [27] whose data were also included in this study. The ranking of the PV types was also similar to the order observed for embedded energy with one exception. In EPBT, a:Si was higher than CIGS; in embedded energy CIGS was higher than a:Si. The reason can be explained by analyzing the parameters used in calculating the EPBT. The only parameters that varied in the harmonized EPBT calculation were the embedded energy and the efficiency since performance ratio and insolation values were the same across different PV types. The efficiency of a:Si was only 55% of that of CIGS which caused the change in ranking of the EPBT.

As a result of the harmonization, the ranges of EPBT for each technology narrowed and the mean shifted down. This shift was caused primarily by the change in the insolation value between the unharmonized and harmonized calculations. Table 2 provides the mean values of the unharmonized and harmonized parameters. Depending on the technology, the harmonized PR (0.75) was about 2.6% lower than the unharmonized PR values used in the studies. Such a small difference between the harmonized and unharmonized PR value does not have a large impact on the EPBT. Also, the change in the module efficiency ranged between a decrease of 8.7% and an increase of 9%. This would not account for the consistent decrease in EPBT as a lower module efficiency for harmonization would increase the EPBTs while a higher efficiency would decrease them. On the contrary, the insolation consistently increased, between 10% and 28%. The changes observed here are larger than those among the PR values and they would always contribute to lowering the EPBT, unlike the efficiency. In some cases, such as for CdTe, the change in module efficiency and the change in insolation worked together to decrease the EPBT while in others, such as mono-Si, they worked against each other (see Table 2). However, the insolation generally had the greater impact and is the primary reason for the reduction in the mean EPBT. This result is similar to the findings of Hsu et al. [16] who attributed the reduction in the median of the harmonized life cycle emissions to insolation and module lifetime.

Future EPBT values will depend on the improvements in embedded energy, efficiency and performance ratio. Performance ratio is already 75 to 85%. There is room for improvement for only ~10% more. The embedded energy data did not show significant correlations with time except for poly-Si PV. However, the

Table 2
Mean unharmonized (*U*) and harmonized (*H*) parameters for each photovoltaic technology with the percentage difference.

Parameter	**Module efficiency (%)**		**Performance ratio**		**Insolation (kW h/m^2/yr)**		**Lifetime (years)**	
Module type	***U* (*H*)**	**% Diff**	***U* (*H*)**	**% Diff**	***U* (*H*)**	**% Diff**	***U* (*H*)**	**% Diff**
mono-Si	14.2 (13)	−8.4%	0.75 (0.75)	0%	1328 (1700)	28%	28.9 (30)	3.8%
poly-Si	13.3 (12.3)	−7.5%	0.77 (0.75)	−2.6%	1372 (1700)	24%	29.5 (30)	1.7%
a:Si	6.9 (6.3)	−8.7%	0.76 (0.75)	−1.3%	1550 (1700)	10%	30 (30)	0%
CdTe	10.0 (10.9)	9.0%	0.77 (0.75)	−2.6%	1525 (1700)	11%	28.3 (30)	6.0%
CIGS	11 (11.5)	4.5%	0.77 (0.75)	−2.6%	1450 (1700)	17%	26.7 (30)	12.4%

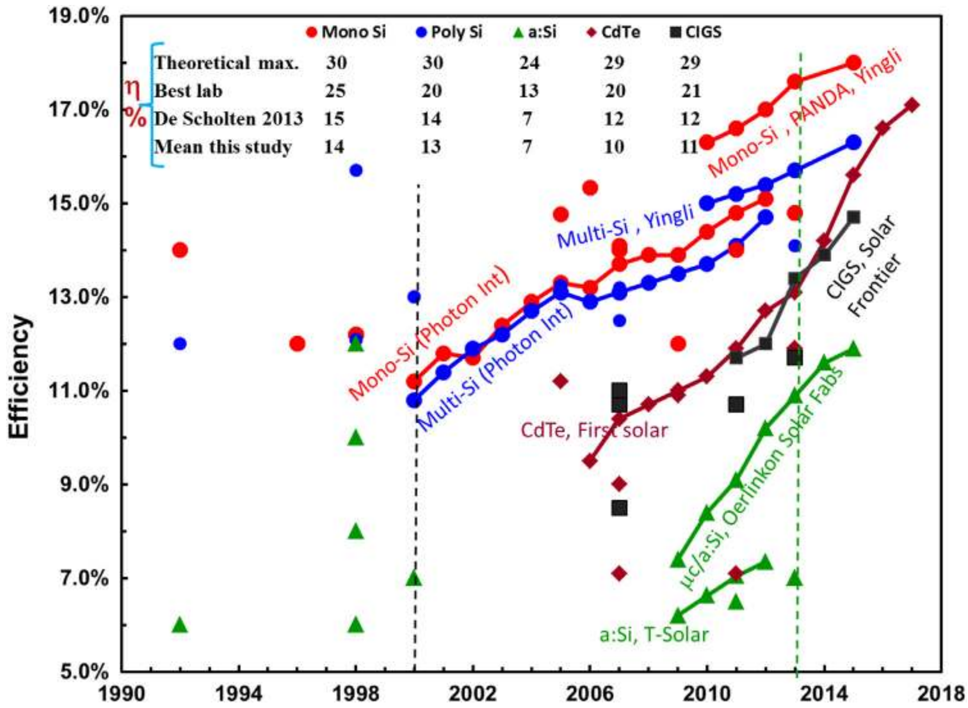

Fig. 6. Efficiency values from the studies that passed all screening as well as the ones that did not pass the year 2000 cutoff criteria (for modernity criterion). A vertical line (black) placed in year 2000 is used to indicate that data to the right of this line is considered 'modern' and passed our screening. Most recent data published by de Wild Scholten is shown as solid lines [27]. The vertical line (green) at 2013 separates the actual and expected efficiencies from existing plants [27]. Best lab efficiencies were obtained from NREL [50]. Graph shows theoretical max. efficiencies [51] and mean efficiencies from this study (also shown in Table 2) are calculated from the EPBT dataset (years 2000–2013).

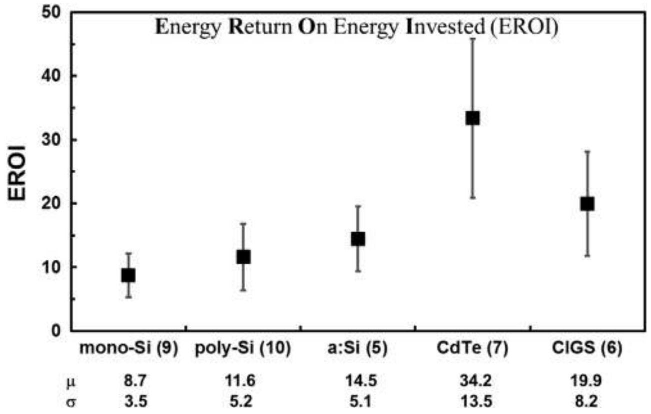

Fig. 7. Mean harmonized EROI with error bars representing one standard deviation. The number of values for each module type is included in parentheses. Mean (μ) and standard deviation (σ) are shown at the bottom of the graph.

embedded energy of the most recent data from de Wild- Scholten [27] were much lower than the mean embedded energy of the other studies resulting in the 2013 harmonized EPBT data to be 1.5 to 3 times lower (1.8 for mono-Si, 2.9 for poly-Si, 1.5 for a:Si, 1.5 for CdTe, 1.7 for CIGS) than the mean harmonized EPBT of the entire EPBT dataset. A theoretical embedded energy for PV has not yet been established. However, the global learning curve for PV suggests a 22% price reduction for each doubling of cumulative volume since 1979 [49]. Since price and embedded energy would be expected to be correlated, the future reductions in embedded energy would depend on the PV installation volume.

An analysis of the efficiency data is presented in Fig. 6. There was a large amount of scatter among published efficiency values. The efficiency data among the screened studies show a significant correlation ($p < 0.05$) with publication date for mono-Si and poly-Si only when studies before 2000 are included. Actual and expected efficiencies reported by de Wild-Scholten are also plotted in Fig. 6. These show a clear increasing trend. The mean efficiencies from this study and from De Wild-Scholten [27] were 1.4–1.9 times lower than the current best lab efficiencies [50] and 2.2 to 3.4 times lower than the theoretical maximum efficiencies [51]. There is therefore about 1.5 to 3.5 times more room for efficiency improvement, which would further lower the EPBT of PV technology.

Embedded energy and efficiency will determine which PV technology may have the best EPBT in the future. Across different types of PV, the variation in embedded energy is greater than the variation in efficiency. Among the screened studies, the embedded energy varied over more than a factor of 10. In the latest data from de Wild-Scholten [27], the embedded energy varied more than a factor of four among different types of technologies (See Supporting information Tables S2–S6). In contrast, the mean efficiencies varied by a factor of two across different types of PV and the theoretical max efficiencies for all five PV types are similar. Among different types of technologies, the differences in embedded energy are greater than the differences in efficiency (and theoretical max efficiency). The implication of this finding is that, until the differences in embedded energy among different types of PV are significantly reduced, any increases in module efficiency will not play a dominant role in determining EPBT. The relative ranking of the EPBT of different PV technologies depends primarily on their embedded energy and not their efficiency.

3.3. *Energy returned on energy invested*

The mean harmonized EROI varied from 8.7 to 34.2 and the EROI of the different technologies ranked in the reverse order as was observed for EPBT (Fig. 7). This is due to EROI being calculated by dividing the lifetime with the embedded energy. As embedded and corresponding EPBT increases, the EROI decreases.

Raugeti et al. [6] discussed the intricacies in comparing PV EROI to the EROI from fossil fuel sources and noted that the meaningful comparison would be to compare the PV EROI calculated from Eq. (2) to the EROI of fuel which is calculated as the ratio of energy in a given amount of the extracted and delivered fuel to the total primary energy used in the supply chain including the construction of the power plants. Based on this calculation, Raugei estimated the EROI of mono Si and Poly Si PV as about 20 and of CdTe as about 40. The mean values estimated in this study were lower than Raugei's estimate. Similarly, Raugei estimated the maximum oil and coal EROI as 30 and 80, respectively. Based on the efficiency and embedded energy improvement potentials discussed in this paper, it is likely for PV technology to catch up to the maximum EROI from coal in the future.

4. Conclusions

We conducted a systematic review and meta-analysis of embedded energy, energy payback time and energy return on energy invested for the crystalline silicon and thin film photovoltaic systems. Out of 232 references collected, 7 (11) papers on mono-Si, 6 (11) on poly-Si, 3 (7) on a:Si, 6 (11) on CdTe, and 5 (8) on CIGS passed our screening for EPBT (embedded energy). Photovoltaic module parameters such as performance ratio, system lifetime, module efficiency and insolation were harmonized to calculate the less disturbed EPBT/EROI values and these values were compared with values before harmonization. Our study showed that the embedded energy reported in the literature varies greatly with a minimum of 894 MJ/m^2 for thin film to 13,428 MJ/m^2 for mono-crystalline silicon. We expected newer studies to report lower embedded energy. However, statistical correlation between publication time and embedded energy was found only for the poly-Si dataset. Other PV technologies did not have a significant correlation likely because of the small sample population of the dataset and the variations in geographical location, BOS energy, and LCA data sources across included studies. We selected MJ/m^2 as our choice of units for the embedded energy analysis since this set of units has been more commonly used in more recent papers. We noted that for comparing different studies, kW_p based units instead of m^2 based units (e.g. MJ/kW_p instead of MJ/m^2) would be more appropriate since efficiency is incorporated into the embedded energy in the area based (MJ/m^2) unit.

The harmonization narrowed the range of the published EPBT values. The mean harmonized EPBT varied from 1.0 to 4.1 years; from lowest to highest, the module types ranked in the following order: cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), amorphous silicon (a:Si), poly-crystalline silicon (poly-Si), and mono-crystalline silicon (mono-Si). The mean harmonized EROI varied from 8.7 to 34.2. Among different types of PV, the variation in embedded energy was greater than the variation in efficiency and performance ratio suggesting that the relative ranking of the EPBT of different PV technology today and in the future depends primarily on their embedded energy and not their efficiency.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2015.02.057.

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