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Supporting Information: Assessing the photovoltaic technology landscape: efficiency and energy return on investment

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Abstract This study builds on previous meta-analyses of photovoltaic (PV) systems to assess the tradeoff between efficiency and energy inputs (i.e. cumulative energy demand, CED) in the energetic performance (as measured by EROI) of PV technologies under both high-cost and low-cost balance of system scenarios. This study focus on three existing technologies groups (wafer, thin film and organic). We find that earlier projections of third-generation (high-efficiency, low-cost), thin-film technologies have not yet emerged, since "third-generation" technologies currently have low-cost but also low-efficiency. We further find the best advances in energetic performance to date come from thin film technology.

1. Introduction

1.1. Factors affecting PV system performance

A number of factors can affect PV system performance, which include panel efficiency [%], system lifetime [yrs], solar irradiance [$kWh/m^2/yr$], performance ratio [%], capacity factor [$kWh_{el}/W_p/yr$], and electricity conversion factor [kWh_{el}/kWh_{PE}]. Each of these factors will be explained in detail in the following sections.

Panel Efficiency. Panel efficiency is very important factor affecting PV system performance. Under the same irradiance, a higher efficiency means higher electricity output. In fact, efficiency depends on semiconductor material, different energy input. In this report, we want to find relation between efficiency and different solar technologies. Single-crystalline (sc-si) silicon panel usually has slightly higher efficiency than multi-crystalline silicon (mc-si) [1].

Lifetime. Panel lifetime affects system performance as longer-lived PV panel can generate more electricity under the same condition. PV panel usually has a 25-year warranty for crystalline silicon and thin film solar cells, which means that the output energy should be guaranteed at least 80% of the original rated output. For most PV technologies, lifetime is usually 25 years [2]. We compare with each data by using 25-year lifetime.

Solar Irradiance. Solar irradiance is a key factor affecting the solar cell performance. Solar panels could generate more electricity by absorbing more solar irradiation. From the Figure, we see that the equator has greater solar irradiation. Area near the arctic pole has the lowest amount of solar irradiation. Compared to other continent, Africa has the greatest irradiation, suggesting it is a good place to install solar panels.

Performance Ratio. Performance ratio (PR) is the ratio of alternating current yield and theoretical solar system DC output. Many factors influence PR, including the temperature of the PV panel, solar irradiation angle, shading and contamination of PV panel, and efficiency of inverter [3]. Usually, the lower temperature results in the higher PR because the efficiency is reduced as the panel heats up. The normal degradation of PV panel and shading will negatively influence the electricity output. If the PV system has higher efficient inverters, it means that it could reduce the energy loss in inverting the DC to AC.

Capacity Factor. Capacity factor is the ratio of actual system output to the electricity generation if the system operated at peak output for the entire year. The higher value of capacity factor means that the actual system energy is closer to theoretical energy output. So good PV performance has a higher capacity factor value.

Electricity Conversion Factor. Electricity conversion is used for converting unit between kWh to MJ. Since the electricity is generated from burning fossil fuel. People use MJ to calculate the energy in burning fossil fuel. However, when using fossil fuel to generate electricity, most of energy are heat waste. So we need use electricity conversion factor to calculate how much electricity is generated from total energy of fossil fuels. Some studies used electrical energy in units of kWh to compare the energy inputs for PV system, while others use primary energy in MJ. Units of MJ need to be multiplied by an electricity conversion factor to convert into kWh. If studies use the unit of MJ to measure CED of PV system, electricity conversion factor would not have influence on PV performance. If studies use unit of KWh and convert it into the unit of MJ, larger electricity

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conversion factor means less energy demand cost based on unit of MJ.

1.2. Crystalline Silicon Solar Cells

Silicon is the second most abundant element in the Earth's crust [4]. The first solar cell made of crystalline silicon was invented in the Bell Lab in 1954 [5]. First generation crystalline silicon solar cells, include two wafer types which are single-crystal silicon(Sc-Si) and multi-crystalline silicon (Mc-Si).

Sc-Si has a homogeneous crystal structure throughout the material, which means that orientation, lattice parameter, and electronic properties are constant [6]. The Sc-Si is developed using the Czochralski process that uses highly purified poly-silicon as an input material. In this process, poly-silicon is melted in crucible at 1425-degree Celsius. Impurities are added to dope the silicon, which changes the silicon into p-type or n-type. In a pure semiconductor, each nucleus uses its four valence electrons to form four covalent bonds with its neighbours. When adding the dopants (Group 3 elements) to the semiconductor, there will only be three electrons around each Si nucleus, leaving one hole to accept free electrons. So we called it acceptor and p stands for "positive". N type stands for negative. P/N crystalline silicon junctions increase free electron carriers and current flows. The ingot is pulled from the molten silicon by controlling the temperature and speed of the rotation [7]. This is the crystal growth process. Due to single crystalline unified distribution of atom, sc-Si solar cell has a higher efficiency of conversion of radiation into electricity than mc-Si.

Mc-Si is composed of many smaller crystals with varied orientation. Multi crystalline silicon is made by melting purified silicon and re-solidifying it to orient crystals in a fixed direction to get a rectangular ingot, which is sliced into thin wafers [8]. Multi c-Si solar cells have a lower cost than mono c-Si solar cells, however the efficiency is lower because its structure is not uniformly distributed, therefore it has less electrical conductivity. However, multi crystalline cause less metal contamination in production process than mono crystalline silicon module [9].

1.3. Thin Film Solar Cells

Thin film solar cells are termed 'second generation' PV technology [10]. They are produced by depositing a thin layer of photovoltaic material on a substrate. The thickness of film varies from tens of nanometers (nm, 10^{-9} m) to a few micrometers (µm, 10^{-6} m), while the thickness of crystalline silicon can be up to 200 µm [11][12]. Thin film solar cells include cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (a-Si).

Amorphous silicon (a-Si) is another popular material for thin-film solar cells. Compared to CdTe and CIGS, the material of a-Si is abundant and less toxic. Amorphous is a non-crystalline form of silicon with random distribution, however, it has 40 times higher light absorption rate than mono crystalline silicon and high 1.7 eV band gap [13]. Bandgap is an energy range where no electron states can exist, which determines the electrical conductivity of a solid. The higher bandgap means the lower electrical conductivity. Due to low material complexity and easy manufacturing, the cost for a-Si is cheaper than the other two thin-film solar cells however, a-Si doesn't have a large market share because of its lower efficiency than crystalline silicon. Amorphous silicon solar cell is produced using a mixture of silicone and hydrogen to form thin layer of silicon on a substrate that is then coated with a transparent conducting layer. In 2013, the share of a-Si in total PV production was 2% [14].

CdTe was chosen to produce thin-film solar cells because it has high light absorption coefficient and high 1.5 eV bandgap [15]. CdTe makes up more than 50% of the thin film market with 5% of total worldwide PV production [16].

CIGS solar cell has a similar structure to CdTe solar cell however, CIGS has higher efficiency. Whole structure includes front contact, buffer layer, CIGS layer, back contact and glass substrate. Glass is used as substrate, because sodium in glass can increase the open-circuit voltage [17]. A molybdenum (Mo) metal layer on the top of the glass serves as back contact and reflect light to CIGS layer. CIGS makes up more than 20% of thin-film mark with 2% share of worldwide solar energy production [18].

1.4. Organic Solar Cells

Organic solar cell is a "third generation" of photovoltaic technology, driven by the need for low cost and high efficiency module [19]. Organic PV is an emerging technology, first study has been developed in 1950s [20]. Organic solar cells use polymer material between the two electrodes. The top electrode is usually indium tin oxide because of its optical transparency and electrical conductivity [21]. Although organic solar cells have just 4-5% efficiency, their low cost makes them competitive. Combining different technology layers, the efficiency of organic solar panel could be more than 33%, the Shockley-Queisser limit [22]. Such tandem or multi-junction solar cells are becoming more and more popular.

2. Methodology

The methodology comprises a number of steps: (A) literature search, (B) literature screening, (C) Harmonization of study boundary and data, (D) PV formula. Each of these steps will be explained in the following sections.

2.1. Literature Search

Thorough literature search was conducted using Google Scholar. The search keywords combined with "PV" were: "embodied energy", "cumulative energy demand", "life cycle assessment", "life cycle inventory", "energy payback time", "net energy ratio" (NER), "energy yield ratio" (EYR), "energy return on investment" (EROI).

After reviewing each paper's abstract, articles that have discussed the solar PV energy, energy payback time, sustainability, life cycle assessment or energy return on investment should be obtained. The initial search returned close to 500 results.

2.2. Literature Screening

Our study covered most types of commercial solar technologies, including crystalline PV, thin-film PV, OPV, CIGS, and concentrating PV. This report ignored any data, harmonization and discussion of concentrating system and multi-cells system. Also, while the balance of system (BOS) data about the PV systems installed on rooftops was omitted, the CED data of the solar panel themselves was included. Several criteria were used to determine which article should pass the literature screening process. The overall criteria were used for literature screening: Study should be in English. The study should be original research or should reference data used. The study should include original numeric data on the energy metric, for example, if a study only reports energy payback time or energy return on investment with no supporting data, it failed the screening. All studies should discuss the solar technologies (crystalline silicon, thin-film, CIGS, OPV, dye-sensitized solar cell) we discussed before. A whole PV system consists of the PV module and balance of system (BOS). The article must at least have the embodied energy data for the PV module. The life cycle phases for a PV system consists of raw material acquisition (cradle), manufacturing of the panel (gate), operation and decommission (grave). Articles that don't have the cradle-to-gate LCA were eliminated. Because the data could be really variable in the distribution, operation, maintenance, and the end of management processes for PV system. A cradle-to-gate system boundary was chosen. In fact, studies show that the transportation distance and end of life management do not have an important influence on the cumulative energy demand of PV system [23][24]. Currently, few studies have the data for the BOS. BOS, performance ratio and degradation ratio are not used as screening criterion. The studies without the other parameters were eliminated.

Each paper has its own scenarios, which indicates that there are many analysis methods to calculate EPBT and EROI. In order harmonize all original data, we calculate these two metrics by harmonizing parameters as discussed in the following section.

2.3. Harmonization of System Boundary and Data

The International Energy Agency (IEA) Photovoltaic Power Systems (PVPS) program recommends that some parameters need to be reported in the PV LCA studies, which are location and sunlight irradiation, module efficiency, time frame of data, system lifetime, system degradation ratio, system boundaries, and balance of system and cumulative energy demand [25]. In our study, we use the standard irradiation as 1000 w/m^2. The location and sunlight irradiation would not be a factor that influences the performance of PV system. The performance is the ratio of actual output and theoretical output of PV system. System output will continuously decrease in the whole lifetime operation. The degradation ratio is the ratio of decreased output and total output of each year. We assume that it is equal to 0, which means that we don't consider that factor.

Capacity Factor. Capacity factor is the ratio of actual electricity output to the electricity that could be generated if the energy system operated at continuous full power during the same time period [26]. The capacity factor is a key driver to measure the productivity of energy generating assets [27]. For solar energy, it depends on many factors, cloud cover, latitude, different seasons and location. In order to use the same scenario for screened studies, we download the data from IEA to calculate the capacity factor.

Conversion factor. Conversion factor is the ratio of generated electricity to primary energy. Primary energy is the energy form found in nature that has not been converted or transformed. Fossil fuels are the main form of primary energy used in the energy industry. Due to the energy efficiency and heat loss, the primary energy cannot totally be transformed into electricity. We convert between primary energy (which will always be given in units of megajoules with a 'p' subscript, MJp) and electricity equivalents (with units kWhe) by using the conversion factor. We will use the conversion factor given in the studies. If there is no conversion factor mentioned, a standard conversion factor of 30% was used in our study.

Standard Irradiation. Usually, the solar panel efficiency is measured under the standard conditions (STC). STC corresponds to an air mass 1.5 (AM1.5) spectrum and an irradiance of 1000 W/m2 at a temperature of 25 ºC. STC specifies a clear day with sunlight incident upon a sun-facing 37º tilted surface with the sun at an angle of 41.81º above the horizon [28]. This represents solar noon intensity in the continental United States with solar cell facing directly at the sun when the subsolar point is on the equator. For example, under STC a solar cell of 20% efficiency with a surface area of 1 m2 would produce 20 W.

Lifetime. Currently, many solar panels (c-Si, thin-film) have an operation lifetime of more than 25 years. Since the majority of manufacturers offer the 25-year standard solar panel warranty and power output is no less than 80% of rated power after 25 years, we assume that crystalline silicon and thin-film solar cell will have 25-year lifetime. For the OPV, we assume that solar cell will have 5 years.

Unit Conversion. There are usually 4 type of units to describe the embodied energy for solar cells, which are MJp/m2, kWhe/m2, MJp/Wp, and kWhe/Wp. Wp is the peak output of solar panel under the STC, also called the nameplate capacity. To convert one unit to the other, we need multiply it by some factors. Conversion CED with MJ/m2 (or kWh/m2) to MJ/Wp (or kWh/Wp) is given by:

$$CED\left(\frac{\mathrm{MJ}}{\mathrm{m}^2}\right)\times\frac{Efficiency}{Standard\ irradiation\left(\frac{1000W}{\mathrm{m}^2}\right)}=CED\left(\frac{\mathrm{MJ}}{W_P}\right)$$

Conversion CED with MJ_p/m^2 (MJ_p/W_p) to kWh_e/m^2 (kWh_e/W_p) is given by:

$$CED\left(\frac{\mathrm{MJ}}{\mathrm{m}^2}\right)\times\frac{\text{Conversion factor}}{3.6\left(\frac{MJ}{kWh}\right)}=CED\left(\frac{kWh}{m^2}\right)$$

2.4. PV System Formula

The lifetime output, E_{out}, for 1 W_p of PV capacity is defined as:

$$E_{OUT}\left(\frac{kWh}{W_p}\right) = P \times T \times \delta \times \frac{365 \times 24\ h/yr}{1000\ W/k}$$

Where , P is the power capacity (1 W), δ is the capacity factor, and T is the lifetime of system.

The energy return on investment (EROI) is defined as:

$$EROI = \frac{E_{OUT}}{E_{IN}}$$

Where E_{OUT} is the total net energy output over the product's lifetime, E_{IN} is the cumulative energy demand for the solar system, which contains CED for module and BOS.

The energy input E_{IN} is defined as:

$$E_{IN} = E_{Mod} + E_{BOS}$$

Where E_{MOD} is the total energy demand for the PV module, E_{BOS} is the total energy demand for the PV balance of system.

The energy payback time (EPBT) is defined as:

$$EPBT = \frac{T}{EROI}$$

Where T is the lifetime of system, EROI is the energy return on investment.

To make the data comparable, we need harmonize the electricity conversion factor. The harmonized energy demand is defined as:

$$E_{HAR} = \frac{E_{IN}}{\alpha_1} \times \alpha_2$$

Where $\alpha_1$is the electricity conversion factor that study used, $\alpha_2$is the conversion factor we use in this study, which is 30%.

Decreasing rate (DR) is defined as:

$$E_{IN} = kC^{-DR}$$

Where C is the installed capacity of that year. k is coefficient.

CED Learning rate (β) when installed capacity doubles is defined as:

$$\beta = 1 - 2^{-DR}$$

3. Results

After literature screening, 40 studies have passed. All the studies and data could be found in the Appendix A in Zikai Research [32]. Some studies do not have the vintage of PV system. If so, we will use the study year instead. When using the study year, it would influence the outcome of section A, B, C, D. Because the vintage of PV system is ahead of the study year. The curves would be delayed if using study year.

The discussion is made of several sections: (A) efficiency relation with year, (B) cumulative energy demand relation with year, (C) cumulative energy demand relation with efficiency, (D) learning rate, (E) balance of system, (F) comparison and selection with different axis, (G) comparison with different generation of PV technologies. Each of steps will be explained in detail in the following sections. This discussion will discuss and compare with 7 main different materials for 3 generation of PV system, which are single crystalline silicon, multi crystalline silicon, amorphous silicon, ribbon silicon, cadmium telluride, copper indium gallium selenide and polymer (OPV).

3.1. Efficiency Relation with Year

For single crystalline silicon (SC-SI), the efficiency has a range between 12.2% and 20.1% in Fig 1. 93% of them has a range between 12.2% and 15.5%. Sunpower company has produce high performance solar module installed in Philippines, which has 20.1% efficiency [29]. The best research-cell efficiency of Sc-si is 27.6%, which means that efficiency on that year could not be higher than best research-cell. Compared to other material, single crystalline has the highest efficiency because of the united atom arrangement. As the Fig 1 shows, the efficiency of single crystalline has slightly increased as the time goes by. However, it is not obviously increasing. And the highest efficiency study came up in 2011.

Multi crystalline has the largest amount of the studies. For multi crystalline silicon (MC-Si), the efficiency has a range between 10% and 16%. 92% of them locate at a range between 12% and 14.1%. However, the best research-cell efficiency of multi crystalline silicon module is 20.4%. The highest efficiency study came up in the 2008. Usually, multi crystalline silicon has lower efficiency than single crystalline silicon module. Efficiency of multi crystalline silicon increases slightly with time, however it is not obvious.

Amorphous silicon (A-SI) module belongs to thin film technology. Because of the relatively low price of amorphous silicon and plenty of silicon, market share of amorphous silicon becomes more and more popular. For amorphous silicon, the efficiency has a range between 5% and 10%, while 70% of them locates in a range between 6% and 8%. However, the best research-cell efficiency of amorphous silicon module is 13.4%. The highest efficiency studies came up in 1998 and 2013. Random atom arrangement make amorphous silicon have an even lower efficiency than the first generation solar panel. Amorphous silicon does not have an obviously trend with time.

Ribbon silicon (R-SI) module belongs to thin film technology. Only four study on ribbon silicon are found in Google Scholar and Engineering Village. For ribbon silicon, the efficiency has a range between 11% and 13.2%. Due to not enough data, it is hard to tell the trend for ribbon silicon module with year. The highest efficiency study came up in 2009, which is 13.2%.

For cadmium telluride (CdTe), the efficiency has a range between 7.1% and 13%. 80% of them locates in the range between 9% and 12%. However, the highest efficiency study came up in year 2000. The best research-cell efficiency of CdTe is 18.7%. Efficiency of CdTe PV module does not have an increasing or decreasing trend with studies year.

For copper indium gallium selenide (CIGS), efficiency has a range between 10.5% and 11.7%. The highest efficiency study came up in year 2011. The best research-cell efficiency of CIGS is 20.4%. Due to insufficient data, plot could not show any relation between efficiency and year.

For organic PV (OPV), efficiency has a range between 2% and 10%. The highest efficiency came up in year 2010. Since OPV is such new technologies, studies that have detail data on OPV start at year 2010. The best research-cell efficiency of OPV is 11.1%. Also, Plot could not show any trend between efficiency and study year, because all studies happens between 2010 and 2013.

For the first PV generation, efficiency is between 10% and 20.1%, which has the highest efficiency compared to the others generation technologies. Efficiency of two types of PV modules would slightly increase as study time goes. For the second PV generation, efficiency is between 7.1% and 13.2%, which is higher than the OPV. Relation between study year and module efficiency does not shown in the second PV generation. OPV has the lowest efficiency, which is between 2% and 10%. Also there is no relation between study year and PV efficiency.

3.2. Cumulative energy demand relation with year

In Fig 2 and Fig 3, two figures show relation between CED and year. Efficiency of PV module does not have obvious relation with year, this section will analysis the relation between cumulative energy demand (kWh_e/m^2) for PV module with study year.

The reason why we use unit of kWh_e/m^2 instead of kWh_e/W_p is because latter one will also contain the factor of efficiency. Some studies used different electricity conversion factor to convert MJ_p to kWh_e. To make data comparable, we harmonize all the data by using the same electricity conversion factor, which is 30%. This report will compare original data from the previous with harmonized data, which means that all the data was calculated by the same electricity conversion factor.

Original data for CED of Sc-Si has a range between 233 and 1845 kWh/m^2. Average of them is 700 kWh/m^2. While harmonized data has a range between 240 and 1600, Average of them is 645 kWh/m^2. This result is because most previous studies use electricity conversion lower than 30%. This figure shows that CED has obviously decreased over time. CED of Sc-Si has decreased 90% during 20 years. Energy cost for 1 m^2 Sc-Si in 2009 could be as low as 200 kWh.

Original CED of Mc-Si silicon has a range between 150 and 1167 kWh/m^2. Average of them is 436 kWh/m^2. While harmonized data has a range between 150 and 1000 kWh/m^2, Average of them is 387 kWh/m^2. Mc-Si module also have obviously decreasing trend during the time. Several energy cost manufacturing processes will be included in production of Sc-Si. CED of Mc-Si range is much lower than CED range of single Sc-Si.

Original CED of A-Si has a range between 70 and 200 kWh/m^2, average of them is 127 $kWh/m^{2,}$ while harmonized data has a range between 70 and 150 kWh/m^2, average of them is 111 kWh/m^2. CED of A-Si is much lower than first PV generation because of low energy cost manufacture for amorphous silicon. CED of A-Si has decreased 60% during 20 years, but it is not as fast as first generation technology.

Original CED of R-Si module has a range between 125 and 350 kWh/m^2, average of them is 216 kWh/m^2, while harmonized data has a range between 125 and 300 kWh/m^2, average of them is 203 kWh/m^2. CED of R-Si does not have a decreased trend from the plot. The reason is because studies on R-Si are not enough to find a trend. Only four studies on R-Si were collected.

Original CED of CdTe has a range between 50 and 200 kWh/m^2, average of them is 93 kWh/m^2, while harmonized data has a range between 50 and 150 kWh/m^2, average of them is 84 kWh/m^2. CED of CdTe has an obvious decreasing trend with time. The coefficient of determination is more than 0.9, which means it has a strong relation with time. CED for CdTe is as low as 50 kWh_e/m^2.

Original CED of CIGS has a range between 100 and 400 kWh/m^2, average of them is 163 kWh/m^2, while harmonized data has a range between 100 and 350 kWh/m^2, average of them is 150 kWh/m^2. CED of CIGS has no trend with time, since not enough studies data were collected about CIGS technology and the first CIGS study in very detail came up in year 2007.

Original CED of OPV module has a range between 3 and 270 kWh/m^2, average of them is 32 kWh/m^2, while harmonized data has a range between 3 and 50 kWh/m^2, average of them is 28 kWh/m^2. OPV makes up less than 1% of solar energy market. Most studies are based on the research solar-cell. One study has a really high energy cost and efficiency, the efficiency and CED are 10% and 270 kWh/m^2 [30]. CED of OPV does not have obvious trend with time, since OPV came up recent years and does not have enough data on it.

3.3. EROI relation with year

As discussed in the methodology, factors that could influence the EROI are module lifetime, efficiency and CED when PV system are installed in the same place. The two sections above have shown efficiency and CED related with study year. Fig 4 will show the result of relation between EROI and study year, and which of efficiency and CED have larger influence on EROI. EROI represents the energetic performance of PV system, higher EROI means better performance.

EROI of Sc-Si obviously increased with study year. EROI has a range between 2 and 21. In recent years, EROI increased very fast, since the material production cost decreased very fast. Module efficiency just slightly increased during the time period.

EROI of Mc-Si also obviously increased with study year. EROI has a range between 2 and 30. EROI largely increased after year 2005. Again, CED is the main factor that influenced the increase in EROI, since module efficiency did not significantly change.

EROI of A-Si apparently increased with study time. EROI has a range between 5 and 35. Module efficiency does not have obvious trend during more than 20 years.

EROI of R-Si does not have obviously trend with study time. Because not enough studies data were collected. EROI has a range between 11 and 22.

EROI of CdTe obviously increased with study time. EROI has a large range between 11 and 60.

EROI of CIGS obviously increased with study time. EROI has a range between 8 and 37.

EROI of OPV does not have an obvious trend with study time. EROI has a range between 4 and 135. CED has larger impact on the EROI. Although efficiency is 10% in 2009 and 3% in 2012, the EROI in year 2012 is much more than EROI in year 2009.

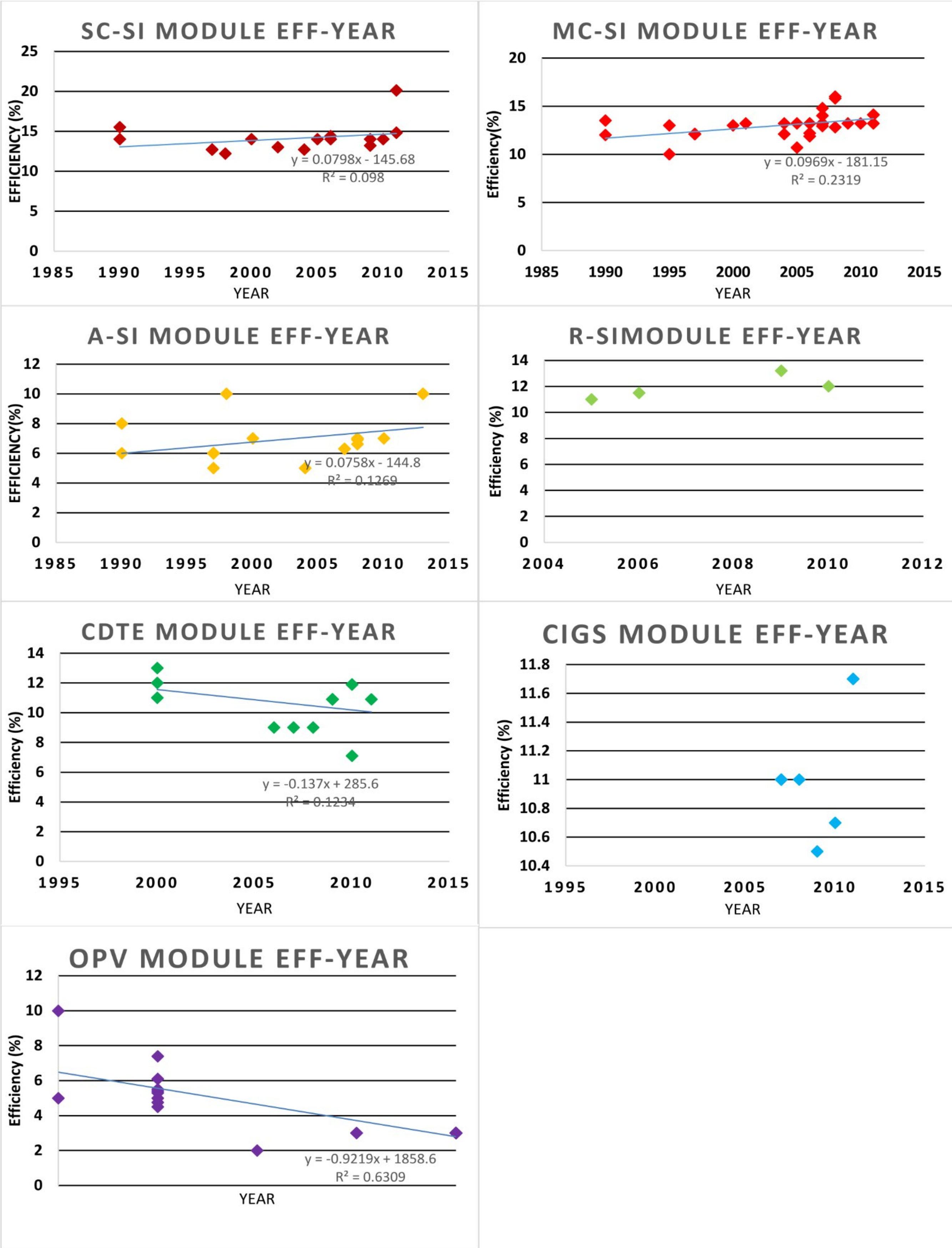

Fig 1 Each Technology Relation curve of efficiency and study year. The trend lines indicate degree between efficiency and study year.

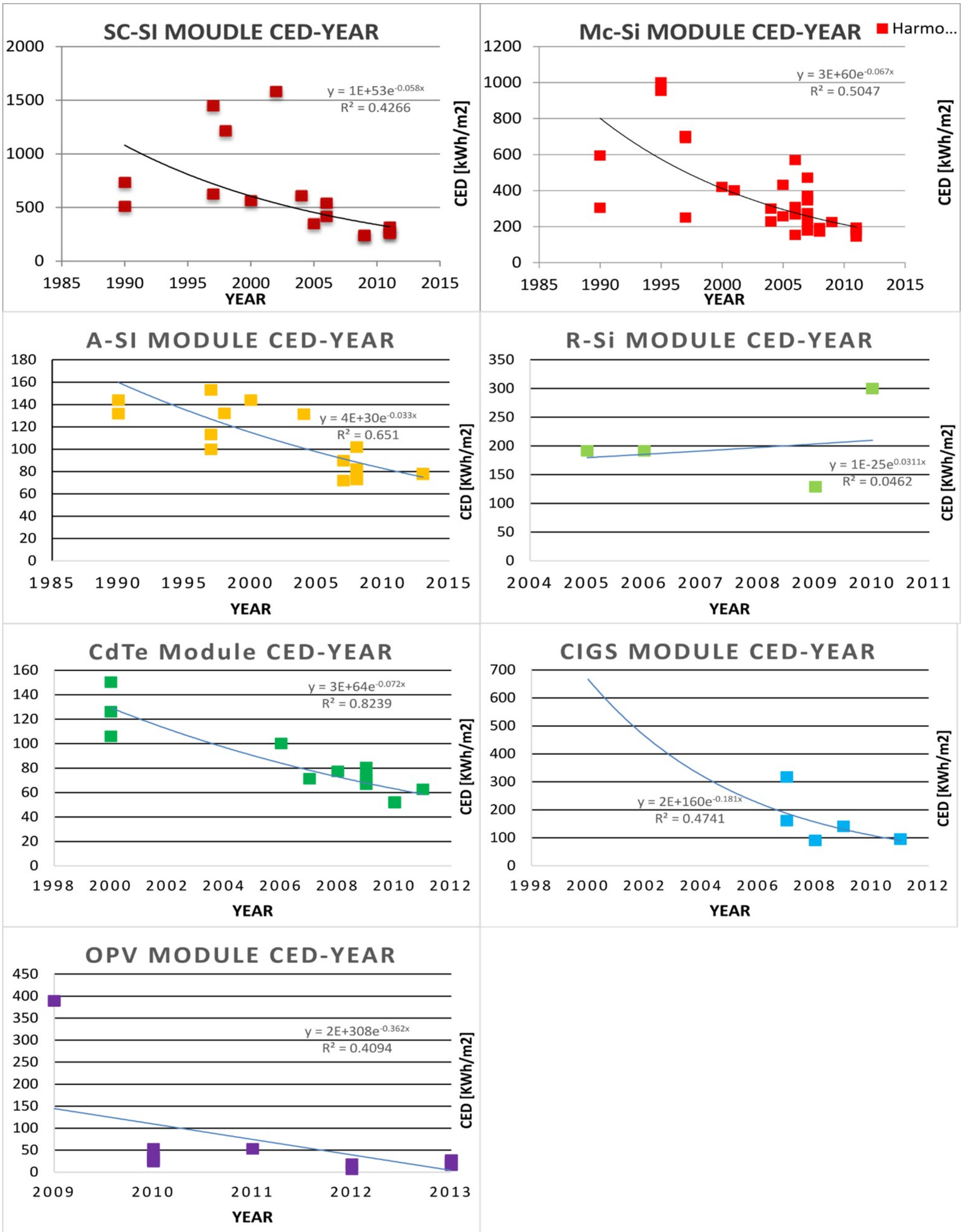

Fig 2 Each technology relation curve of CED and study year by using the harmonized data

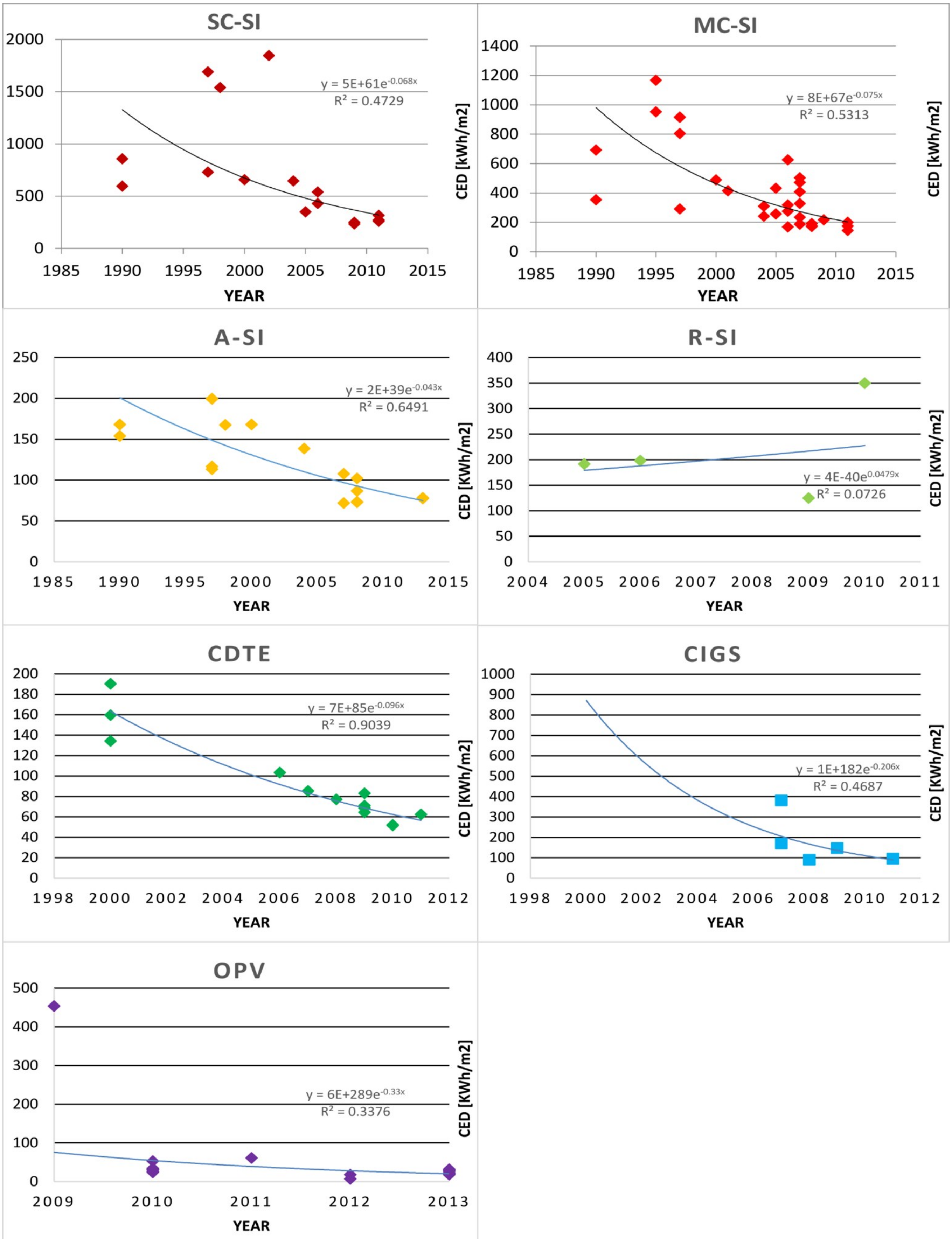

Fig 3 Each technology of relation curve of CED and study year by using original data

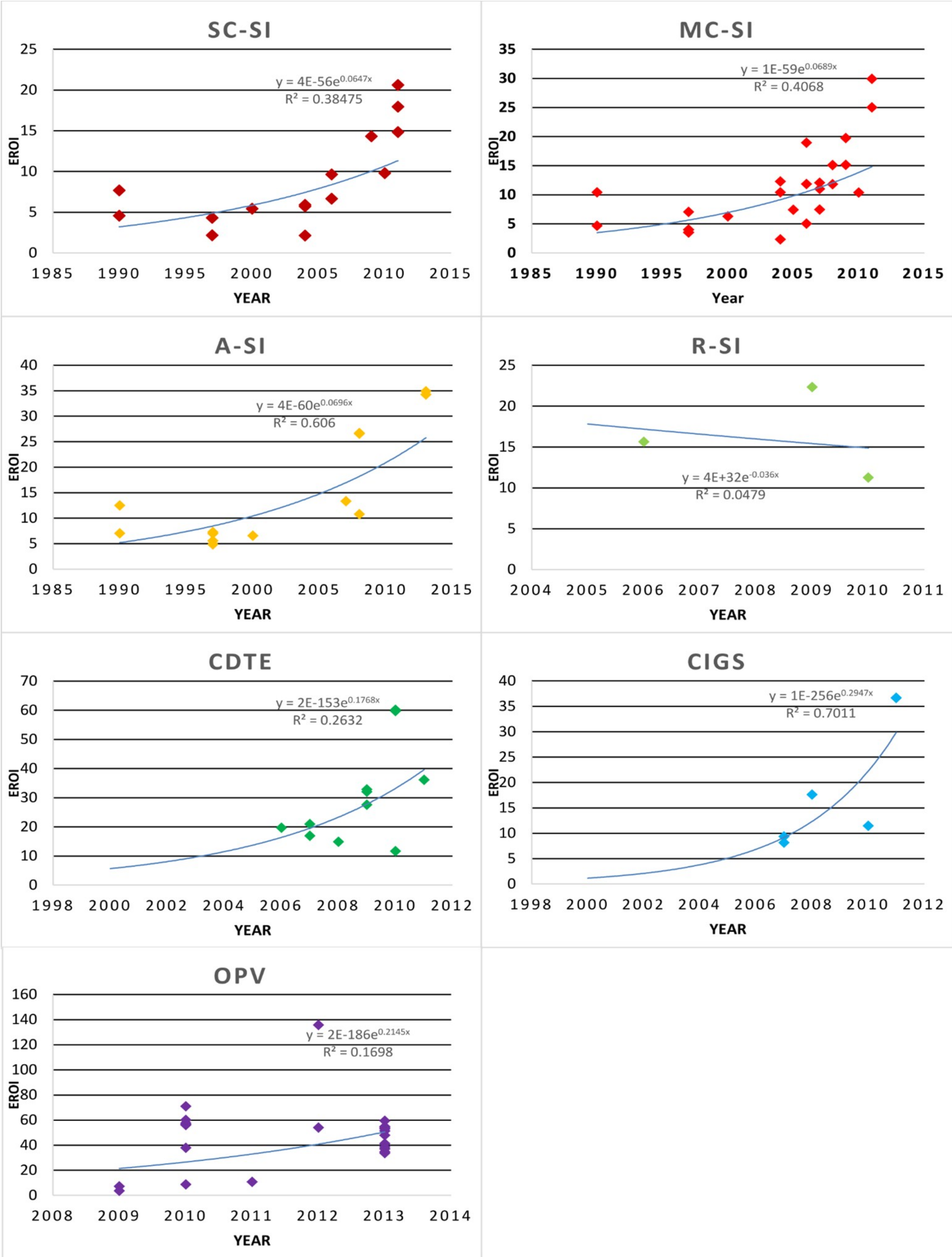

Fig 4 Each technology relation of EROI and study year

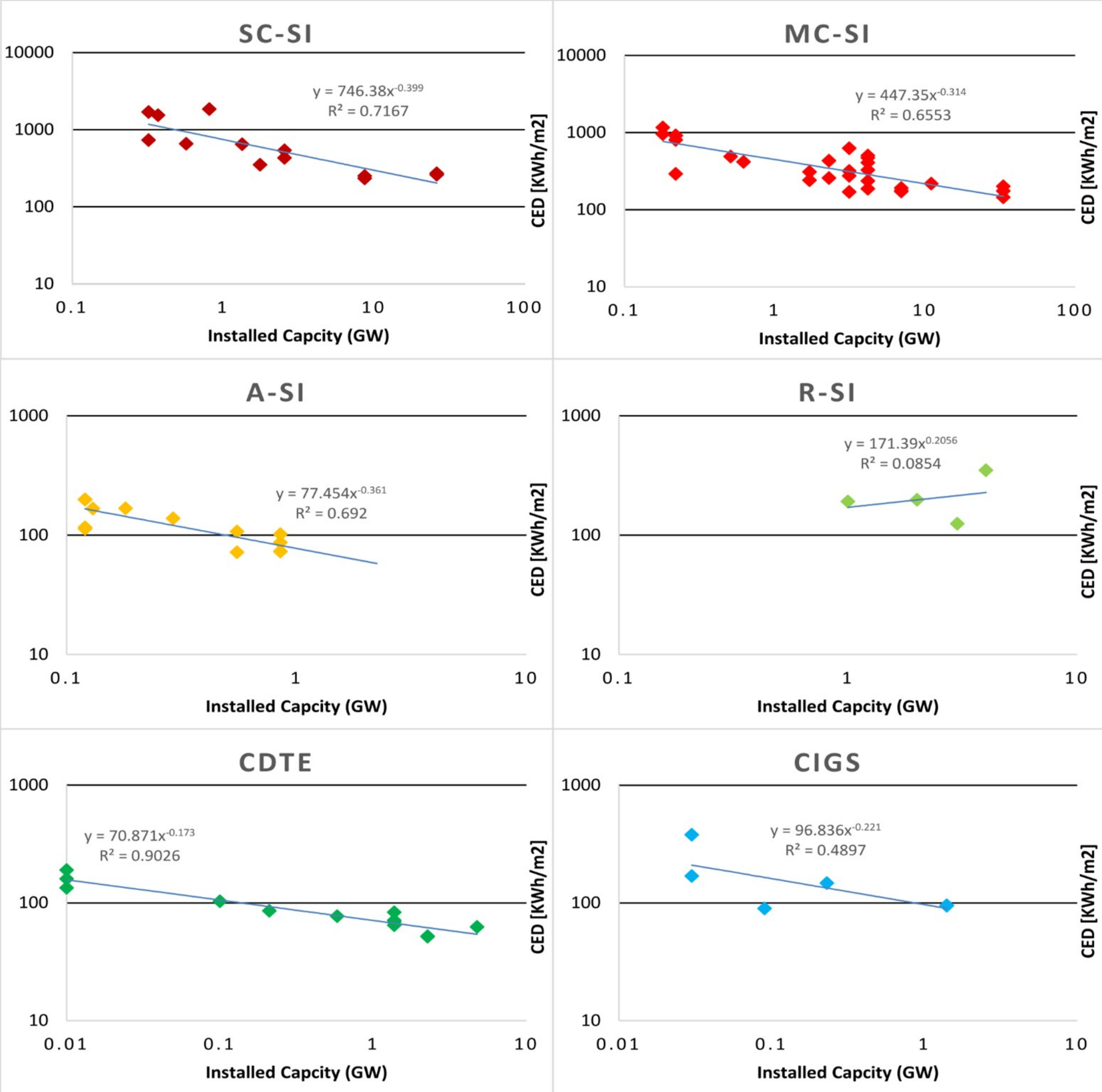

Fig 5 Each technology learning rate curve. OPV is not plotted because it is new technology and earlies study is from 2009

In conclusion, module efficiency does not change a lot as the time goes, while the CED decreased obviously through time. Also the EROI decreased obviously during time. We could conclude that CED has a larger impact on the EROI, which means CED more largely influenced the system performance than module efficiency.

3.4. Learning rate

This section will discuss the learning rate of each kind of material module. However, OPV does not have learning rate curve since the OPV is pretty new technology and lack of installed capacity for each year. From the learning rate, CED decreasing rate could be calculated.

From the Fig 5, decreasing rate of Sc-Si is 0.399 Decreasing rate of Mc-Si is 0.314. A-Si has a decreasing rate of 0.361. However, R-Si has a decreasing rate of -0.2056 and the coefficient of determination for R-Si is only 0.0854. When decreasing rate is minus, it means that CED will increase as installed capacity goes up, which is unreasonable. We could not determine the learning rate since only four data were collected for R-Si module. CdTe has a decreasing rate of 0.173. CIGS has a decreasing rate of 0.221.

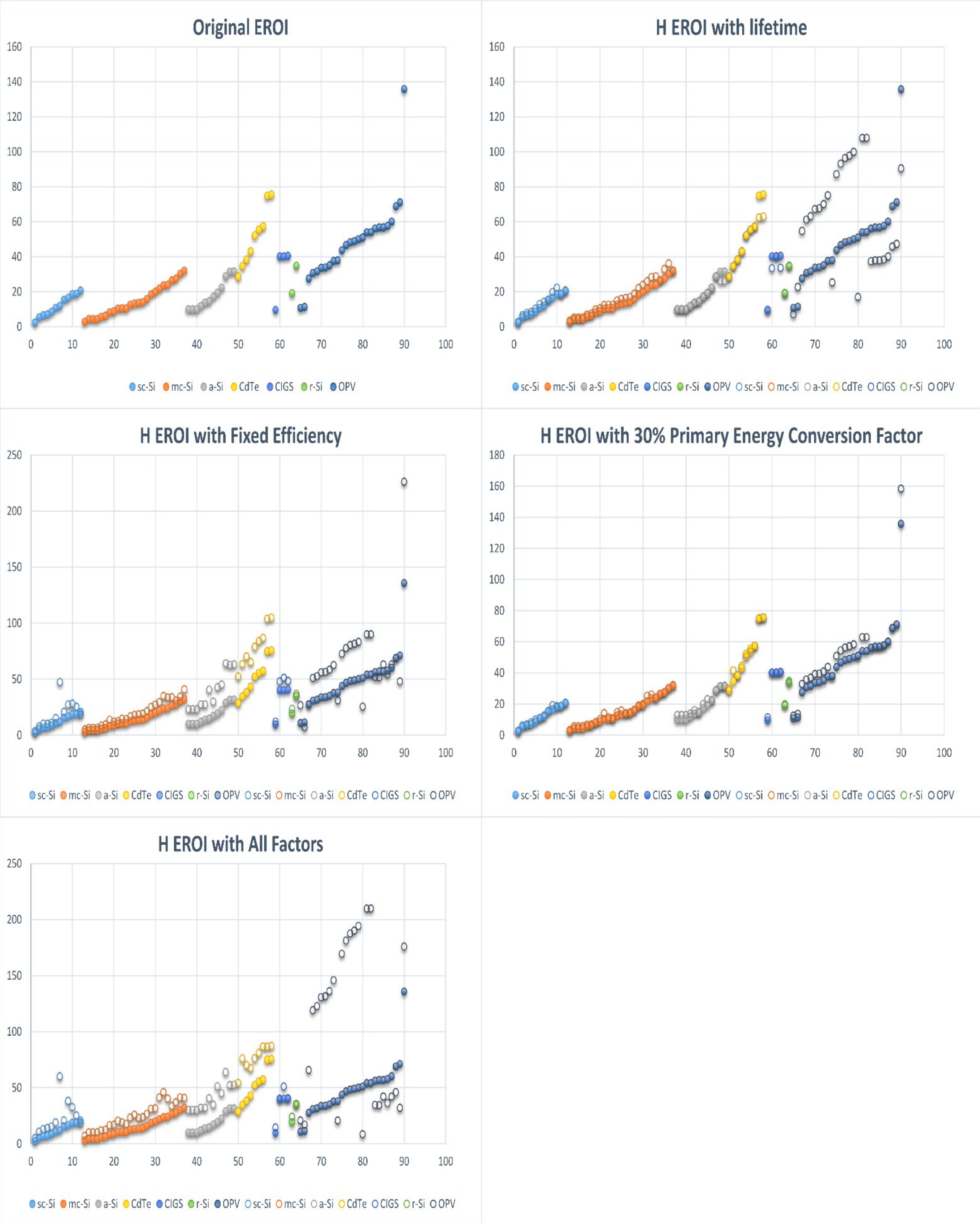

Fig 6 EROI Harmonization of each technology. Hollow points stand for harmonized data. Harmonized EROI with fixed lifetime, different module efficiency of each technology, primary energy conversion factor and all the factor together.

After knowing the decreasing rate, learning rate could be calculated. Sc-Si has a learning rate of 24.2% when installed capacity doubled. Mc-Si has a learning rate of 19.6%. A-Si has a learning rate of 22.1%. CdTe has a learning rate of 11.3%. CIGS has a learning rate of 14.2%.

Sc-Si has the largest learning rate, while CdTe has the smallest learning rate. In general, the first PV generation has larger learning rate than the second PV generation. Although the CED of the second PV generation is much smaller than the first generation in 1990s, then, due to high learning rate, the CED Sc-Si and Mc-Si are getting closer and closer to thin-film technology.

3.5. Harmonization of the data

In this section, we plot the EROI with fixed lifetime, harmonized efficiency, and primary energy conversion factor. Crystalline silicon PV is expected to have 30 yrs lifetime, Thin film PV is expected to have 25 yrs lifetime, and Organic PV is expected to have 10 yrs lifetime. Different technologies are also applied to different harmonized efficiency (Sc-Si 20%; Mc-Si 18%; A-Si 14%; CdTe 16.5%; CIGS 14%; Ribbon-Si 14%; OPV 5%), which is based on their current commercial operating efficiency. In Fig 6,unfortunately, this did not work as well as hoped, since sometime harmonizing the parameters increased the variation in the EROI.

3.6. Balance of system

BOS has a learning rate of 0.3% [31]. CED for BOS only decreases 0.3% when installed capacity of solar energy doubled. We assume that BOS does not change with installed capacity. To know the CED of all the technologies, we draw boxplot to show the min and max of the BOS. Fig 7 is the boxplot for the BOS of all the technologies. From the Fig 6,the min CED_{BOS} is 36.58 kWh_e/m^2, while max CED_{BOS} is 206.36 kWh_e/m^2. In the following section, we will compare all data with high and low fraction of BOS to see the impact on the PV system.

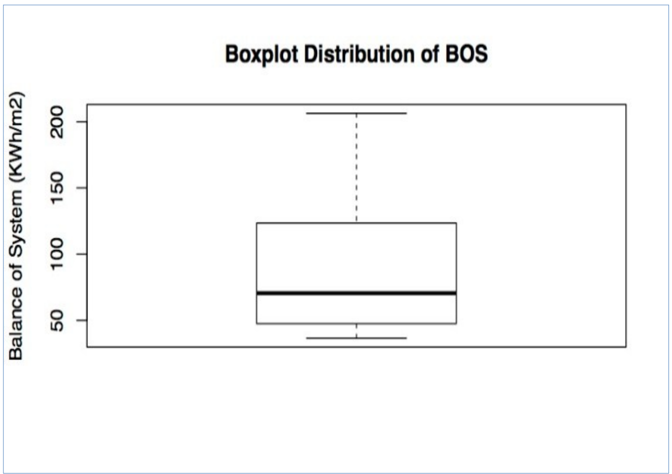

Fig 7 Boxplot Distribution of BOS for all technologies

3.7. Multi-dimensional comparison of PV technologies

In this section, we combine all the PV technology together to compare on the basis of efficiency, CED for the system (CED_{SYS} = CED_{MOD} + CED_{BOS}), and EROI, where EROI contours are plotted using the Equation in Methodology section. EROI, efficiency and CED trend is showed on the plot. Also, Cost/Efficiency of solar system is plotted. To make all the data comparable, we assume a lifetime of 25-year and a 15% capacity factor. Because the world average capacity factor is 15%, and previous studies also usually use 15%. However, the lifetime of OPV usually is 5 years. To adjust for this, the CED_{SYS} for OPV was multiplied by 5 to assume it could be replaced every 5 years to run 25-year scale with other technologies.

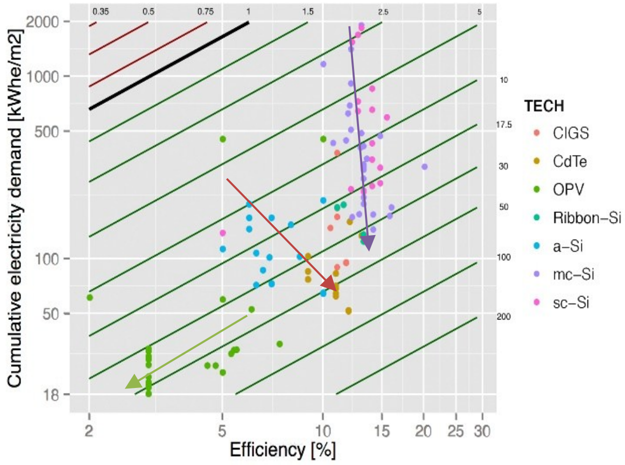

Fig 8 Relation among efficiency, CED and EROI. EROI is the contour. Arrows represents for trend of year. Purple one is the time trend of crystalline silicon module. Orange is the time trend of thin film module. Green one is the time trend of OPV module. Red contour stands for energy sink, while green stands for net energy. Black contour means energy input is equal to energy output. We have assumed a 25-year lifetime and 15% capacity factor which is global average level.

In Fig 8, we plot PV system energy performance for each of seven technologies: single crystal silicon (Sc-Si), multi crystalline silicon (Mc-Si), amorphous silicon (A-Si), ribbon silicon (R-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and polymer (OPV). X-axis is module efficiency (%). Y-Axis is cumulative energy demand for the system, CED_{SYS} (kWh/m^2). Contour (Z-axis) is energy return on investment (kWh_e/kWh_e). Contour of EROI was calculated by the CED and efficiency. Module lifetime and capacity factor were assumed respectively 25 years and 15%. Arrows stands for the time trend of the different generation of solar energy. Red contour means energy output is less than energy input. Green contour means energy output is larger than energy input. Black contour means energy output is equal to energy input. High EROI correlates with low energy payback time. In the plot, multi crystalline has the highest efficiency (20.1%), however it does not have the highest EROI. Although one OPV has the lowest efficiency (2%), its EROI range is between 10 and 17.5, which is a high range. Most of the crystalline silicon data are in up and left side. Crystalline silicon usually has the largest energy cost. Crystalline have the largest energy cost range because of the fastest learning rates. From the arrow, we could tell efficiency of crystalline silicon did not change a lot, energy cost decreased

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very fast. Compared to crystalline, thin film technology did not have very large energy cost range and efficiency is usually lower than crystalline silicon. However, EROI is much higher than crystalline silicon. Because CED of thin film is much lower than crystalline silicon. We could think thin film technology has a better system performance. CED learning rate is slower than crystalline silicon module. Efficiency of thin film is slightly increasing with time. For OPV, it has a larger CED range than thin film. Some OPV module have a very high efficiency (10%), however energy cost is also really high. So EROI of high efficiency OPV was not very higher than low efficiency OPV module. OPV module has the largest EROI, which is between 3 and 70. Most EROI of OPV locates at range between 30 and 70, which is highest among 3 generation technologies. CED obviously decreased with time, however, the efficiency also decreased with time. We could see the trend for solar system among three generations technology, which is that efficiency falls down due to different material, However, CED decreased much stronger than efficiency through the time.

In Fig 9, we show the energy cost (CED_{SYS}) with kWh_e/W_p unit. The higher value means lower EROI. Crystalline silicon has a range between 1 kWh_e/W_p and 16 kWh_e/W_p, while crystalline silicon cost is between 1 kWh_e/W_p and 2 kWh_e/W_p after year 2009. Due to large amounts of silicon storage in the world and low energy cost, crystalline silicon is more competitive in the PV industry. Thin-film technology has a range between 0.4 kWh_e/W_p and 4 kWh_e/W_p, although it has a lower efficiency. OPV has a range between 0.3 kWh_e/W_p and 10 kWh_e/W_p. But most of them are between 0.3 kWh_e/W_p and 2 kWh_e/W_p. Polymer material does not have the problem of scarcity. It is also very good choice of PV material. Because most of OPV are only on research scale and performance is not stable, it does not have a large market share. In the future, OPV might be more competitive.

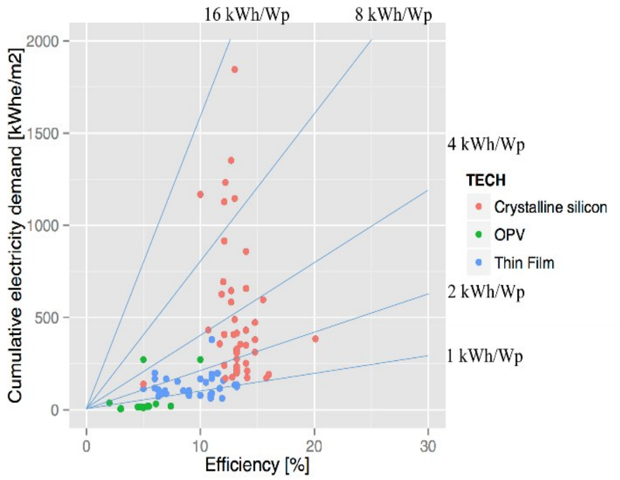

Fig 9 Cost/Efficiency of Photovoltaic Technology in lifetime of 25 years. This plot is not log-log plot. We could intuitively look energy cost based on kWh/m2 scale. OPV was plot by assuming a lifetime of 25 years.

In Fig 9, we plot the data by using their own lifetime. Compared to Fig 8, the module that has lifetime shorter than 25 years had lower CED performance than the module in Fig 8, this is because we did not convert it into 25-year scale. OPV system has larger impact than the other technologies, because lifetime for OPV solar system is usually shorter than 25 years. For OPV, the lowest CED per unit area is 3.6 kWh/m², while the lowest CED per unit capacity could be 0.1 kWh_e/W_p. The highest CED is 272 kWh/m², while the highest CED is 454 kWh/m² in Fig 10.

The original data for CED of Sc-Si has a range between 233 and 1845 kWh/m². Average of them is 700 kWh/m². While harmonized data has a range between 240 and 1600, Average of them is 645 kWh/m². This result is because most previous studies use electricity conversion lower than 30%. This figure shows that CED has obviously decreased over time. CED of Sc-Si has decreased 90% during 20 years. Energy cost for 1 m² Sc-Si in 2009 could be as low as 200 kWh.

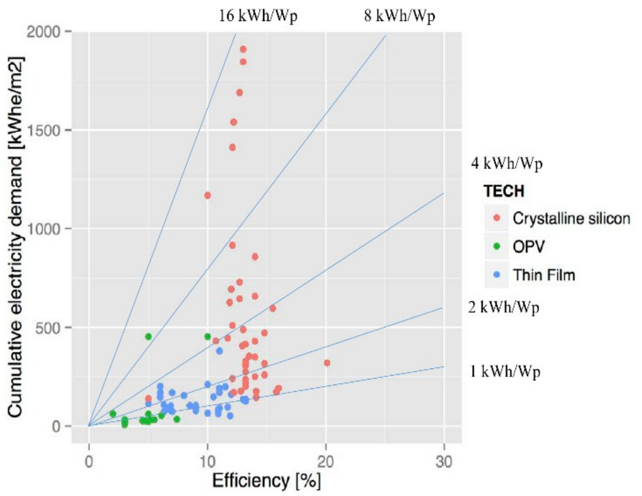

Fig 10 Cost/Efficiency of Photovoltaic Technology in their own original lifetime.

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