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Meta-Analysis of Life Cycle Assessment Studies on Solar Photovoltaic Systems

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META-ANALYSIS OF LIFE CYCLE ASSESSMENT STUDIES ON SOLAR PHOTOVOLTAIC SYSTEMS

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ABSTRACT

Nowadays, greenhouse gas emission problem is becoming more and more severe. At the same time, world energy demand increases a lot every year. All the countries focus on using renewable energy and take it as the solution of future energy demand problem. Although the solar energy only makes up 1% market share of the total renewable energy, it grows rapidly recent years. Because the energy coming from sun is tens of time more than energy coming from the fossil fuel. There are three main type of the photovoltaic technologies, which are crystalline silicon solar cell, thin-film solar cell and polymer solar cell. Crystalline silicon solar cell is the first generation technology, which make up 90% market share of the solar energy industry. Thin-film solar cell is the second generation technology, which makes up 10% market share of the solar energy. The goal of this thesis are 1) to evaluate the efficiency of each technologies of solar energy; 2) to compare the cumulative energy demand (CED) of solar module of each technology; 3) to compare the energy return on investment (EROI) of each technologies; 4) to know energy demand of balance of system of all technologies; 5) to show the trend of different generation of solar energy through time by showing relation between efficiency, cumulative energy demand and energy return on investment. To accomplish these goals, we use a meta-analysis method in thesis. We collect all the studies on solar energy which has passed the criteria we set. After getting all the data, we evaluate the CED and EROI by using our own method to harmonized each data.

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SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
A-Si	Amorphous Silicon
BOS	Balance of System
CdTe	Cadmium Telluride
CED	Cumulative Energy Demand
CIGS	Copper Indium Gallium Selenide
DC	Direct Current
DR	Decreasing Rate
EPBT	Energy Payback Time
EROI	Energy Return on Investment
GaAs	Gallium Arsenide
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
LR	Learning Rate
Mc-Si	Multi Crystalline Silicon
OPV	Organic Photovoltaic
PR	Performance Ratio
PV	Photovoltaic
R-Si	Ribbon Silicon
Sc-Si	Single Crystal Silicon

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I. Introduction

A. Motivation

As energy demand has grown rapidly all over the world, solar energy has become more and more popular in recent years. Global greenhouse gas (GHG) emissions result from burning fossil fuels. The problem of global warming is becoming more and more severe. All countries are trying to increase their share of renewable energy to face the global warming problem. However, solar energy currently only makes up 1% of world total primary energy supply. There are three main types of solar photovoltaic (PV) technologies: crystalline silicon, thin-film technology, and organic polymer. Few studies have been done to compare all the three type of solar PV technologies, especially organic PV. Our objective of this study is to compare system performance of all the three types of solar technologies and find trends in efficiency, cumulative energy demand and energy return on investment for the solar PV industry. Thereby, we can analyse the benefits and weakness of each technology and project the development of each technology. In order to do this, we will use meta-analysis to collect all the studies by using google scholar and engineering village. Then, we will calculate and harmonize the data in the way that we want to compare solar photovoltaic system's efficiency, CED and EROI of different types of solar technologies.

B. Report structure

This report has five main parts, which are introduction, background, methodology, results and conclusion.

The background will introduce basic information on the current world energy system, the different types of solar PV technology, and life cycle assessment (LCA) of PV. The section on the current energy system (Current Energy System) includes information on current total primary energy supply, the environmental problems caused by burning fossil fuel (climate change from GHG emissions and air pollution), and the advantages of solar PV. The section on the different types of PV technology (Section PV technology) include a description of the components of a solar PV system (module and balance of system), factors affecting PV system performance, and different material of solar cells. The section on life cycle assessment (LCA, Section Life Cycle Assessment) include commonly used metrics from LCA, evaluation method of solar cells, and summaries of previous meta-analyses.

The methodology (Part Methodology (Meta-analysis)) presents the literature search, literature screening, commensuration of study boundary and data, and PV formula sections.

The results and discussion (Part Results) introduces data on panel efficiency as a function of time, cumulative energy demand (CED) as a function of time, energy return on investment (EROI) as a function of time, learning rate of different PV technologies, cumulative energy demand of the balance of system (BOS), comparison and selection with different axis, comparison with different generation of photovoltaics (PV) technology.

The conclusion (Part Conclusion) discusses limitations of the project and some directions for future research.

II. Background

A. Current Energy System

1. Current structure

As society has developed, energy demands has grown rapidly. Total primary energy supply (TPES) increased by 119% between 1973 and 2012 to a value of 559.8 EJ/yr (155,500 TWh) [1]. The US uses 25% of the world's TPES with a share of the world population at 4.59%, while China uses just 19.1% of the world's TPES with 19.6% of the world population [2]. US and China together use 45% of the world's TPES in total.

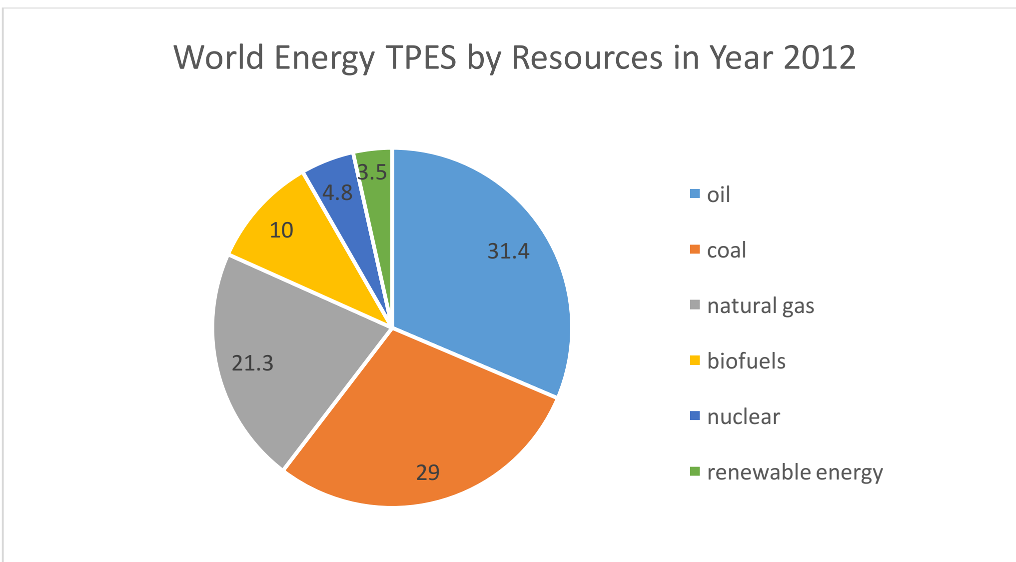


Figure II.1World Energy TPES by Resources in Year 2012. Data comes from Schaeffer's study [3].

As the Figure II.1 shows, in 2012,, world energy TPES by resource was: oil 31.4%, coal 29.0%, natural gas 21.3%, biofuels and waste 10.0%, nuclear 4.8%, and renewable energy 3.5% with solar energy only making up 1% of the world primary energy [3]. Fossil fuel (oil, coal, natural gas) makes up more than 82% of total energy supply. Since experiencing two oil crises in 19 century, many industrialized countries began increasing energy supply from gas, coal and nuclear, as well as increasing energy efficiency and investing in "new energy" development, such as solar, wind and geothermal energy [4]. However, fossil fuels are not renewable resource and could peak within a few decades [5]. Researchers have begun to focus more and more on renewable energy technologies, especially solar power. Solar power has a greater potential than wind, hydro and other renewable resources [6], [7]. The International Energy Agency (IEA) has predicted that solar energy could make up a third of the final energy demand beyond 2060 with lower CO_2 emissions [8].

2. Environmental problems with fossil fuels (GHG, Pollution)

Global warming emissions result from burning fossil fuel [9]. As the Figure II.2 shows, fossil fuel has really higher GHG emission than the renewable energy. Carbon dioxide (CO_2) is an important trace gas in Earth's atmosphere, growing from 280 ppm to 400 ppm since the Industrial Revolution [10]. CO_2 is a potent greenhouse gas and has large impact on Earth's surface temperature through greenhouse effect [11]. Atmospheric concentration of CO_2 is currently rising at a rate of approximately 2 ppm per year [12]. Increasing concentration of CO_2 in the atmosphere leads to climate change.

An estimated 30-40% of the CO_2 released by humans into the atmosphere dissolves into oceans, rivers and lakes, which contributes to ocean acidification [13], [14]. Greenhouse gases are not the only emissions associated with energy extraction and use. Large amounts of pollutants such as sulfur dioxide, nitrous oxides, and particulate matter are produced from the combustion of fossil fuels and biomass [15]. The World Health Organization estimates that 7 million premature deaths are caused each year by air pollution (WHO, 2014).

Faced with the climate change and air pollution, a number of nations have signed the Paris Agreement to avoid dangerous climate change by limiting global warming to well below 2 ºC [17] and are implementing policies to increase their share of renewable electricity. The advantages of renewable energy resources is that they do not emit GHGs, especially wind and solar energy, because they are abundant and much larger than TPES, [18]. Hydroelectricity made up 16.3% of total world electricity generation in 2014, while other renewable resources contributed 3.5%. Consequently, there is a big development space for wind and solar energy.

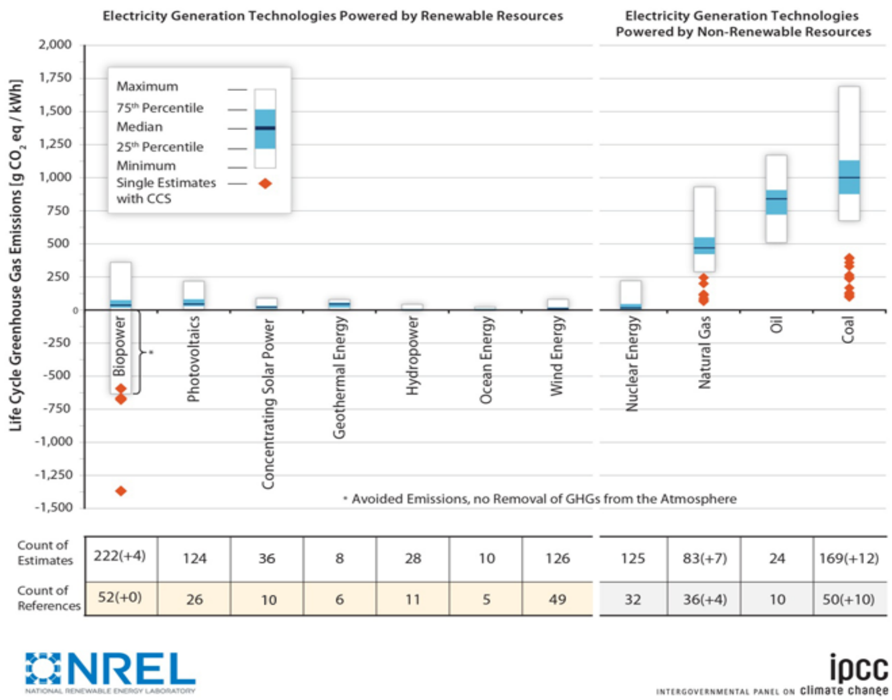


Figure II.2 Electricity Generation Technologies Powered by Renewable Resources. Picture is from www.nrel.gov.

3. Advantages of PV

Solar energy is important, because it is abundant enough for world energy demands and is distributed across the globe. Solar energy is one of the cleanest energy resources with fewer GHG emission than fossil fuels [19]. The United Nations Development Programme, in its 2000 World Energy Assessment found that the annual absolute potential of solar energy was between 1,575 and 49,387 EJ/yr, many times larger than the total world energy demand [20].

B. PV technology

Solar modules absorb photons from sunlight to generate electricity through the photovoltaic effect wherein photons excite electrons into a higher state of energy, allowing them to form electric current [21]. Semiconductors have an electrical conductivity between conductor and insulator and are sensitive to light and heat, making them ideal for use in solar cells [22].

1. PV systems: modules and balance of system (BOS)

A PV system comprises module and balance of system. The module consists of solar cells on the surface that generate the solar energy. The BOS components encompass all other supporting infrastructure, including wiring, switches (to connect to the electrical grid) and inverters (to convert the direct current to alternating current).

a. PV module

Usually, the PV module contains four main parts as the Figure II.3 shows. The first layer is the antireflection coating, which is on the glass, which have a support and antireflection function. Solar module will have two metal contacts layers, which can conduct the electrons, the top contact is made of transparent metal layer, normally indium-tin oxide (ITO). Between the two metal contacts layer, is the semiconductor layer. Semiconductor materials that have been given much attention are crystalline silicon, amorphous silicon, cadmium telluride (CdTe), copper indium gallium (di)selenide (CIGS), organic polymer, and gallium arsenide (GaAs) [23].

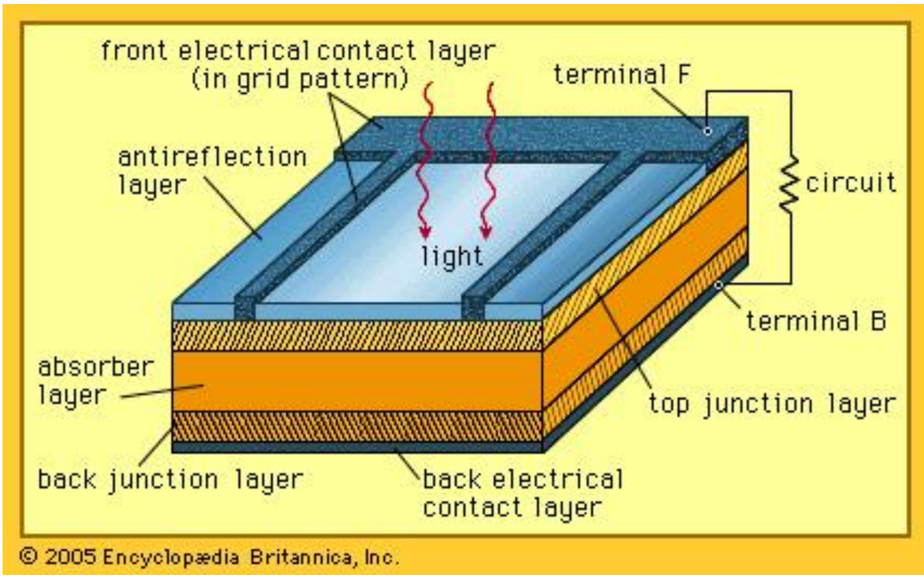


Figure II.3 Common structure of solar panels. Retrieved from: www.britannica.com

b. PV balance of system (BOS)

The balance of system (BOS) comprises all the other components of the PV system including cables, switches, mounting system, inverters and storage devices [24]. BOS has a learning rate of 0.3% [25]. So CED of BOS does not change a lot during the time.

In the PV system, cables interconnect the solar panel and the other electrical components. Because the cables need to be installed outdoors and be exposed to high temperatures and UV radiation, they should be UV and weather-resistant. Usually, A single core cable has a maximum voltage of 1.8 kV and can be used in a temperature range of –40 °C to +90 °C. Switches are used for connecting and disconnecting to protect and control the whole DC system circuits in the photovoltaic system. The mounting system has the function of supporting the solar panel and has two main types;

roof mounting and ground mounting. The inverter converts the direct current (DC) produced by the PV panels into alternating current (AC), which can be added into the local grid. Battery storage may also be included (especially in residential or commercial systems) in order to make electricity available when the sun is not shining.

2. 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.

a. 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) [26].

b. 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 [27]. We compare with each data by using 25-year lifetime.

c. 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 II.4, 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.

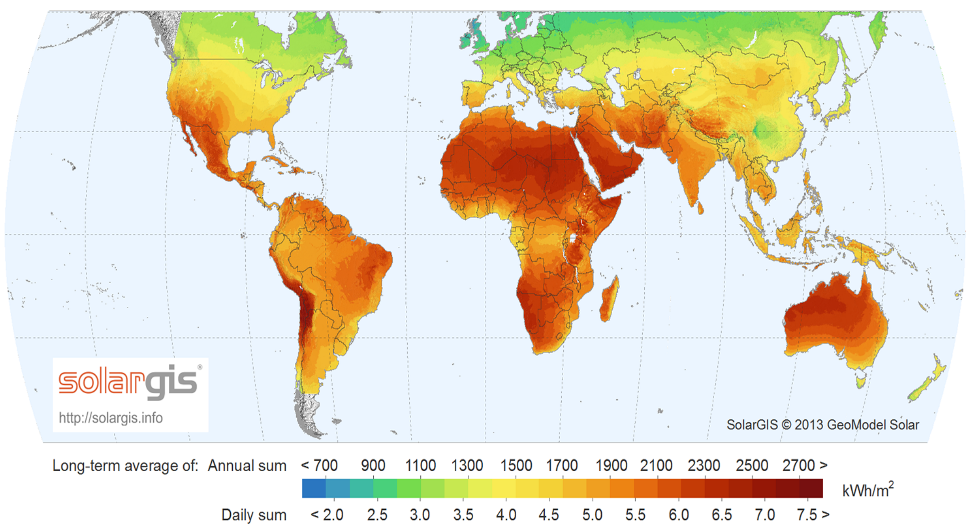


Figure II.4 Annul and daily sun irradiation of the whole world. Picture retrieved from: www.solarcoin.org.

d. 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 [28]. 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.

e. 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. Table II-1is the actual capacity factor for each area.

Area	**Capacity Factor**
Africa	0.188896319
Asia & Oceania	0.287638468
Central & South America	0.404507432
Europe	0.130491211
North America	0.154501619
world	0.162760013

Table II-1 Capacity factor in different area and whole world

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

3. Crystalline silicon solar cells

Silicon is the second most abundant element in the Earth's crust [29]. The first solar cell made of crystalline silicon was invented in the Bell Lab in 1954 [30]. 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 [31]. 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 neighbors. 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 [32]. 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 [33]. 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 [34].

4. Thin film solar cells

Thin film solar cells are termed 'second generation' PV technology [35]. 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) [36], [37], while the thickness of crystalline silicon can be up to 200 μm. Thin film solar cells include cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (a-Si) (Fthenakis, 2009).

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 [39]. 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 are 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% [40].

CdTe was chosen to produce thin-film solar cells because it has high light absorption coefficient and high 1.5 eV bandgap [41]. CdTe makes up more than 50% of the thin film market with 5% of total worldwide PV production [42].

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 [43]. 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 [44].

5. GaAs

This kind of solar cell uses gallium arsenide as the absorption layer. The thickness of GaAs solar cell is between crystalline silicon (200 μm) and thin-film solar cell (20 μm). The highest efficiency of single layer GaAs solar cells is 28.8% in the research lab

[45]. As such it is often used for multi-junction devices and concentrator PV module [46]. However, the cost of GaAs solar cell is very high [47].

6. Organic PV

Organic solar cell is a “third generation" of photovoltaic technology, driven by the need for low cost and high efficiency module [48]. Organic PV is an emerging technology, first study has been developed in 1950s [49]. 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 [50]. 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 [51]. Such tandem or multi-junction solar cells are becoming more and more popular.

7. Future prospect of PV

Inorganic-organic perovskite solar cell have recently attracted great interest [52]. The efficiency of perovskite solar cells currently exceeds 20.1% with cheap solution process, which make it commercially viable in the future PV [53]. The term “perovskite” is characterized by the general form ABX_3: A being the organic cation, e.g. CH_3NH_3; B is the metal cation, e.g. Pb, Ca; and X is the halide anion, e.g. Cl, Br, I. However, the stability of perovskite limits the development of this technology. Moisture, UV light and temperature have a large impact, degrading the perovskite layer.

C. Life Cycle Assessment

1. General LCA

Life cycle assessment (LCA) is a tool to assess environmental impacts of products and services by evaluating all the phases of production from cradle to grave [54]. The interest in LCA grew rapidly during the 1990s, when the first scientific publications with term "LCA" came out [55]. An LCA study includes four main stages: goal and scope, life cycle inventory analysis, life cycle impact assessment, and interpretation [56]. The goal and scope gives the broad context of focus and environmental impacts in terms of functional unit and system boundaries [57]. Life cycle inventory (LCI) analysis involves compilation and quantification of inputs and outputs from and to the natural environment for a given product system [58]. Life cycle impact assessment evaluates the environmental impact of the LCI flows. The environmental impacts could include different aspects like global warming, ozone depletion and eutrophication [59]. The interpretation evaluates results from the previous stages in order to reach the conclusions and recommendations [60].

2. Metrics of LCA

This report utilizes three important metrics from LCA: cumulative energy demand, energy payback time, and energy return on investment.

a. Cumulative energy demand

The cumulative energy demand (CED) is the sum of all primary energy that must flow from the environment in support of the lifecycle of a given product or service [61]. Calculating energy and material inputs is part of inventory analysis in LCA [62]. Studies on CED have become more and more popular. Seven European countries have conducted CED of the first generation PV technology research [63]. CED has also been criticized because it only takes care of the energy [64]. Nowadays, energy payback time and energy return on investment are becoming increasingly important in the research.

b. Energy payback time

Energy payback time (EPBT) is the time required for an energy system to generate an equivalent amount of energy equal to the cumulative energy demand [65]. EPBT indicates the energetic sustainability of the energy system [66]. The EPBT is also related to the CO_2 mitigation potential, which means that a short EPBT indicates high substitution of CO_2 emissions for solar energy [67]. For renewable energy system, EPBT varies between months and years. For example, the EPBT of a grid-connected multi crystalline silicon PV rooftop system is about 3 years by comparison of primary inputs with electricity output [68], whereas wind turbines need only a few months to amortize energetically [69].

c. Energy return on investment

Energy return on investment (EROI) is the ratio of the amount of useful energy delivered from a specific energy resource to the amount of energy required to obtain the energy resource [70]. It is a critical parameter to understand and rank different energy sources in the LCA studies. The term EROI has shown up since 1970s, but gained little attention until ten years ago [71]. When the EROI is less than 1, a resource is an "energy sink" since more energy must be expended than is delivered. It cannot be used as energy resource. EROI is one measure of energy surplus or energy balance within net energy analysis [72]. Since interest in peak oil and alternative energy technologies has increased, many studies on EROI have been published, especially on renewable energy. Bhandari's study shows that mean harmonized EROI for PV could be between 8.7 and 34.2 [73]. Pickard reports the EROI for mono-crystalline silicon photovoltaic has the range of 2.2 to 8.8 [74]. Furthermore, Fthenakis estimates that the EROI of thin-film PV technology could be as high as 60 [75]. The other popular renewable energy technology is wind. The EROI of wind energy is between 20 and 50 [76]. The fossil fuel usually have the EROI value between 10 and 80 [77]. Although the fossil fuels have higher EROI, but they also cause more pollution and CO_2 emission.

3. Evaluation of PV

Evaluation of different PV technologies requires identifying several key factors: module conversion efficiency, expected lifetime, energy and fuel consumption, balance of system (BOS), and EROI. Pacca et al. studied the LCA of crystalline silicon solar cell and thin film solar cell. Although the efficiency of thin film technology is lower, Energy return on investment (EROI) that is ratio of the amounts of the energy required to release the useable to amount of useable energy which are energy that could be used by people is higher than the crystalline solar cell [78]. The expected lifetime for crystalline silicon and thin film solar cells could be 30 years [79]. Espinosa has studied LCA of different technologies. The EPBT for crystalline, thin film and OPV solar cells are 1.65-4.62, 0.73-2.26 and 0.2-4 years, respectively [80]. Lifetime of OPV was assumed 1 year. The total energy consumption for the crystalline silicon solar cells is 2.3 times the process energy consumed for the thin-film solar cells, because processing of silicon crystal is an energy intensive process [81]. The crystalline silicon solar cells have the highest energy conversion efficiency and highest energy cost. However, EROI of OPV and thin film solar cells are higher. Thin film has the better EROI performance, however its development is limited by the material resources [82]. The material of OPV is cheap and easy to get. However, the stability of and lifetime of OPV have limit its market share. Nowadays, the market share of crystalline silicon is more than 90%. As the technology develops, the latter will increase rapidly.

4. Meta-analysis

Meta-analysis is a statistical technique to gain the weighted average of results or conclusion by combining the outcomes of numbers of individual studies [83], [84]. The reason why meta-analysis is becoming more and more popular is because there is always common truth and certain error within the individual studies [85]. The aim of meta-analysis is to use statistical methods to find the truth and minimize the error. Meta-analysis has many advantages. The results could be applied to larger population. The inconsistent outcomes could be quantified and analyzed. The key benefit is that the precision of results will be improved by using more data. However, this method also has its own problem. A meta-analysis of several small studies cannot replicate the result of a single large study [86]. A badly designed study will cause inaccurate outcome of statistic. To avoid these problems, this report will collect enough data and make sure all data will be recalculated in the same condition.

a. Meta-analysis in LCA

i) Previous meta-analyses of LCA for electricity generation technologies

Heath and Mann used meta-analysis of GHG emission from different electricity generation technologies, including coal, solar power, wind, and nuclear energy. They had a comprehensive search of published literature to ensure no bias by publication type. Then, all the articles were reviewed by using predefined screening criteria. To interpret the multiple different LCAs, a deep understanding must be developed of their methods and assumptions [87]. Barnhart and Benson evaluated cradle-to-gate energy demand of energy costs of storage technologies by using the LCA data coming from the various reports and software databases [88]. Lenzen and Munksgarrd have reviewed 72 life cycle analyses on the energy and greenhouse gas intensity of wind turbines by using the data that are lifetime, load factor, power rating and country of manufacture [89]. Kubiszewski and Cleveland calculated the EROI of 119 wind turbines by using harmonization method to review 50 studies, ranging in publication date from 1977 to 2007 [90]. Dale reviewed studies on electricity generation technologies (solar PV, concentrating solar power and wind) from a number of publication types (peer-reviewed journals, industry report, reports by national agencies, and unpublished paper like conference paper and doctoral theses), and used selected terms (e.g. CED, NER and EROI) to search studies in google scholar [91]. Price and Kendall reviewed 39 studies and got original 18 life cycle assessment data for wind turbines in the 1 to 5 MW range, and evaluated the greenhouse gas emission intensity for wind turbines [92]. Nugent and Sovacool evaluated the wind and solar GHG intensity from data of 41 most relative studies by reviewing 153 life cycle studies, and concluded that wind energy emit 0.4g CO_2 eq/kWh to 364.8g, while solar energy emit 1g CO_2 eq/kWh to 218g [93]. Schreiber and Zapp evaluated GHG reduction of three different CCS technologies from 15 LCA studies, including different regions and different time horizon and different electricity generation [94].

ii) Previous meta-analyses of CED of PV technologies

There are many studies that have conducted meta-analysis for the PV technologies. Bhandari and Collier reviewed 232 solar energy studies of which 11 and 23 respectively passed the criteria for EPBT/EROI and embodied energy demand. They evaluated five PV technologies of the selected studies in the EROI and energy demand [73]. Dale and Benson conducted a meta-analysis collecting original data from other PV studies to evaluate different PV technologies to analyze if the global PV industry is a net electricity provider [95].

Methodology of this study is similar to the methods in the mentioned studies. The methodology will be discussed in the next section.

III. Methodology (Meta-analysis)

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

A. 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.

B. 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 [96], [97].

. 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.

C. Commensuration of Study Boundaries 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 (Fthenakis, Frischknecht, & Raugei, 2011). 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

1. 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 [99]. The capacity factor is a key driver to measure the productivity of energy generating assets [100]. 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.

2. 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, MJ_p) and electricity equivalents (with units kWh_e) 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.

3. 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/m^2 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 [101]. 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 m^2 would produce 20 W.

4. 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.

5. Unit Conversion

There are usually 4 type of units to describe the embodied energy for solar cells, which are MJ_p/m^2, kWh_e/m^2, MJ_p/W_p, and kWh_e/W_p. W_p 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:

1) Convert CED with MJ/m^2 (or kWh/m^2) to MJ/W_p (or kWh/W_p)

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

2) Convert CED with MJ_p/m^2 (MJ_p/W_p) to kWh_e/m^2 (kWh_e/W_p)

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

D. PV System Formula

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

$$E_{\text{OUT}}\left(\frac{kWh}{W_p}\right)=P\times T\times\delta\times\frac{365\times24\ h/yr}{1000\ W/k}$$

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:

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

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:

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

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:

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

IV. Results

After literature screening, 40 studies have passed. All the studies and data could be found be found in the Appendix A (

Appendix A Table for Data Resources). 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).

A. Efficiency relation with year

For single crystalline silicon, the efficiency has a range between 12.2% and 20.1% in Figure IV.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 [102]. 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 figure 4.1.1 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. In Figure IV.2, for multi crystalline silicon, 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 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. In Figure IV.3, 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 module belongs to thin film technology. Only four study on ribbon silicon are found in Google Scholar and Engineering Village. In Figure IV.4, 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%.

In Figure IV.5, 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.

In Figure IV.6, 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.

In Figure IV.7, 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.

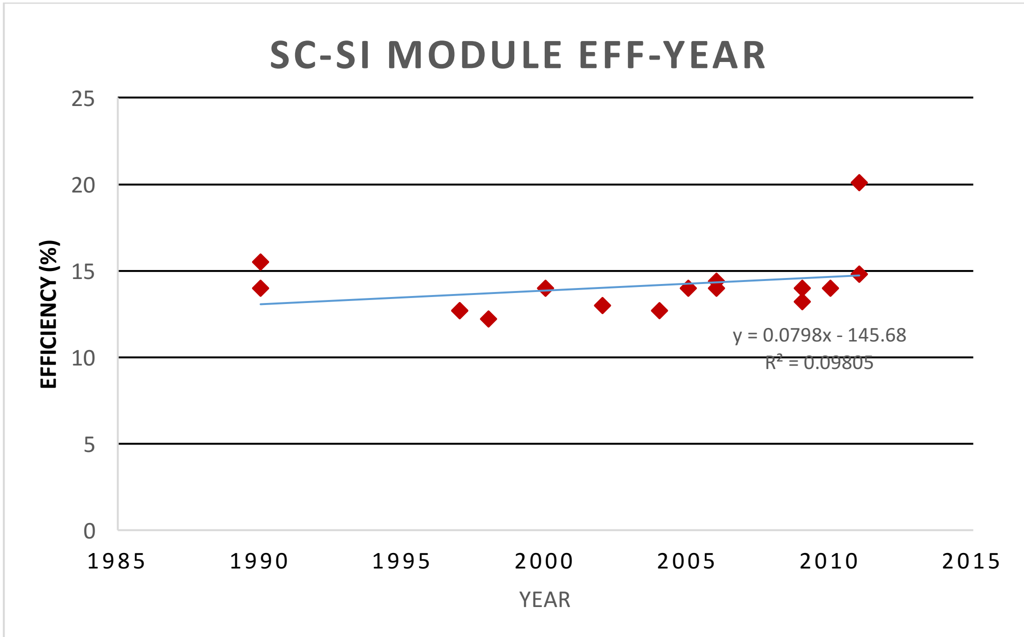


Figure IV.1 Sc-Si Relation curve of efficiency and study year from 1990 to 2011

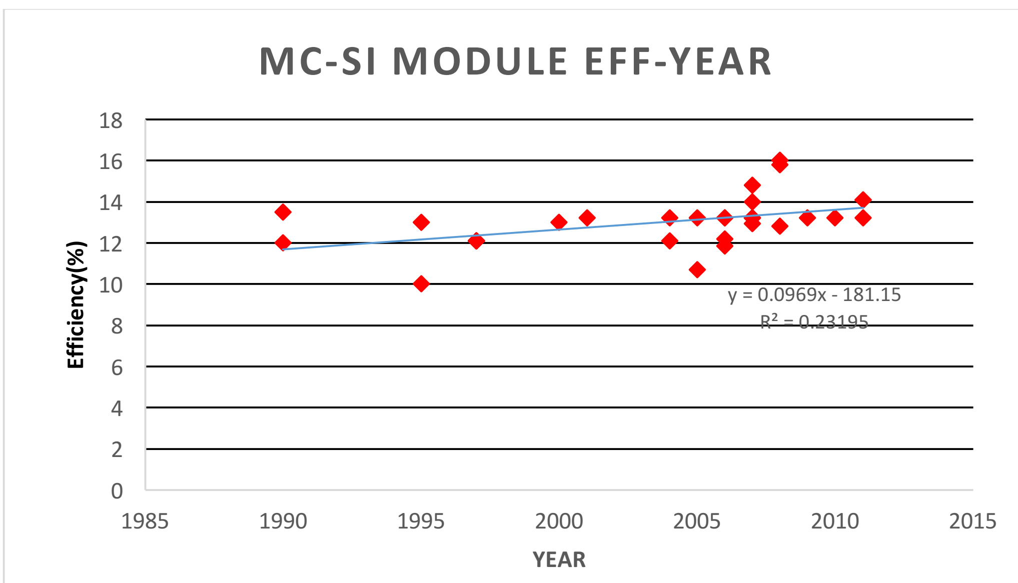


Figure IV.2 Mc-Si Relation curve of efficiency and study year from 1990 and 2011

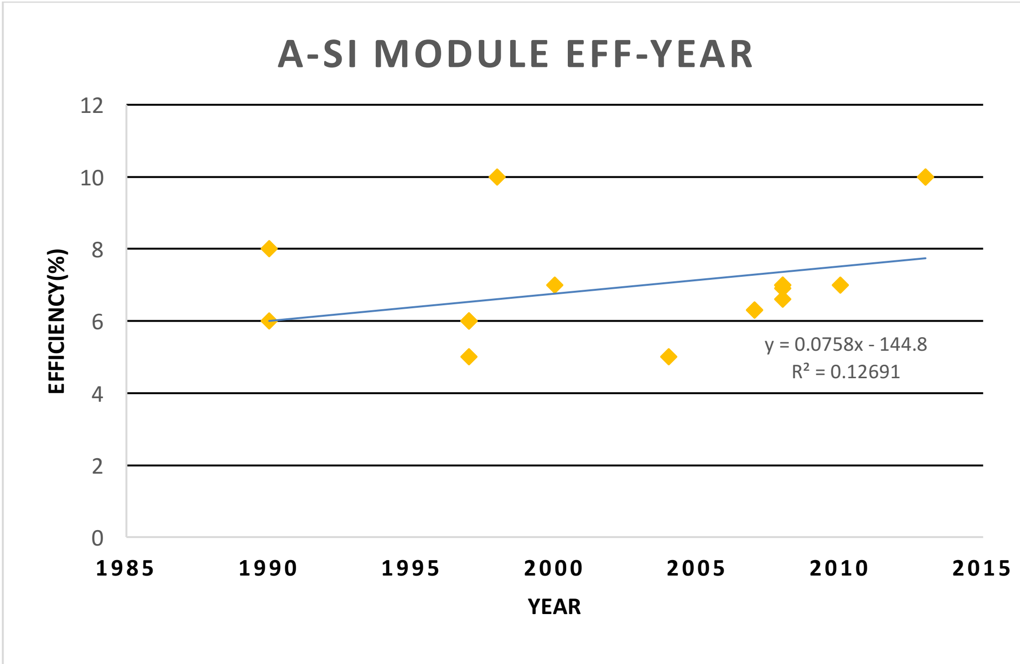


Figure IV.3 A-Si Relation curve of efficiency and study year from 1990 and 2013

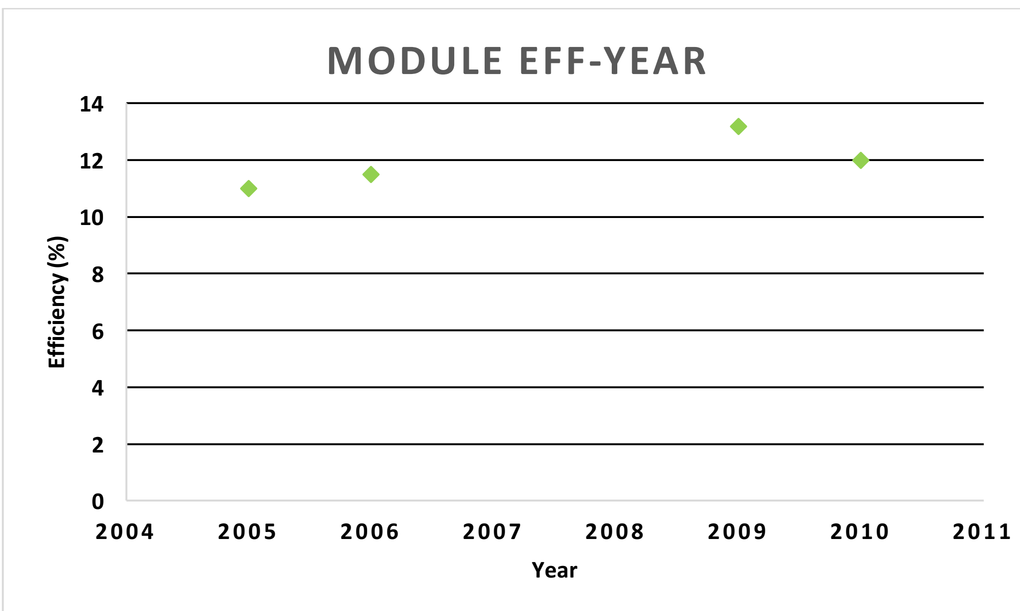


Figure IV.4 R-Si Relation curve of efficiency and study year from 2005 and 2010. Only 4 studies were collected, so could not tell relation between efficiency and study time.

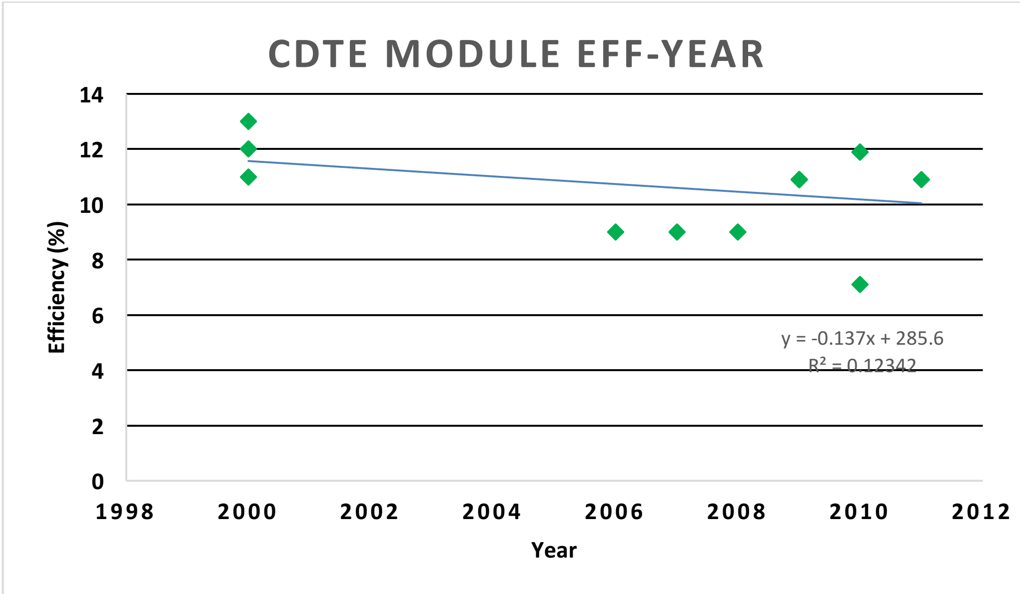


Figure IV.5 CdTe Relation curve of efficiency and study year from 2000 and 2011

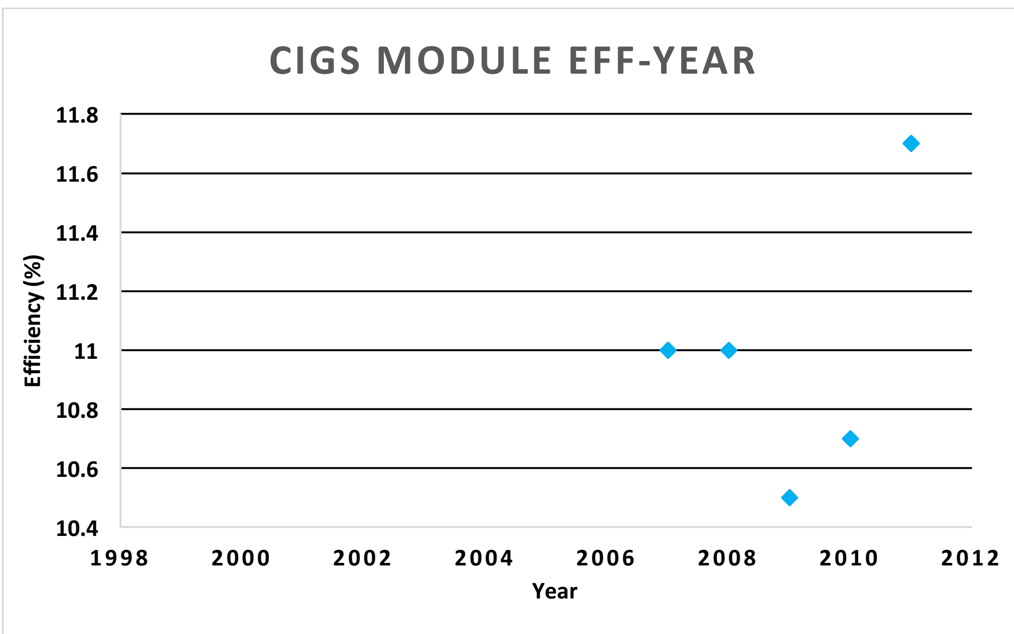


Figure IV.6 CIGS Relation curve of efficiency and study year from 2007 and 2011. Only five studies were collected, no trend could be shown over the five years.

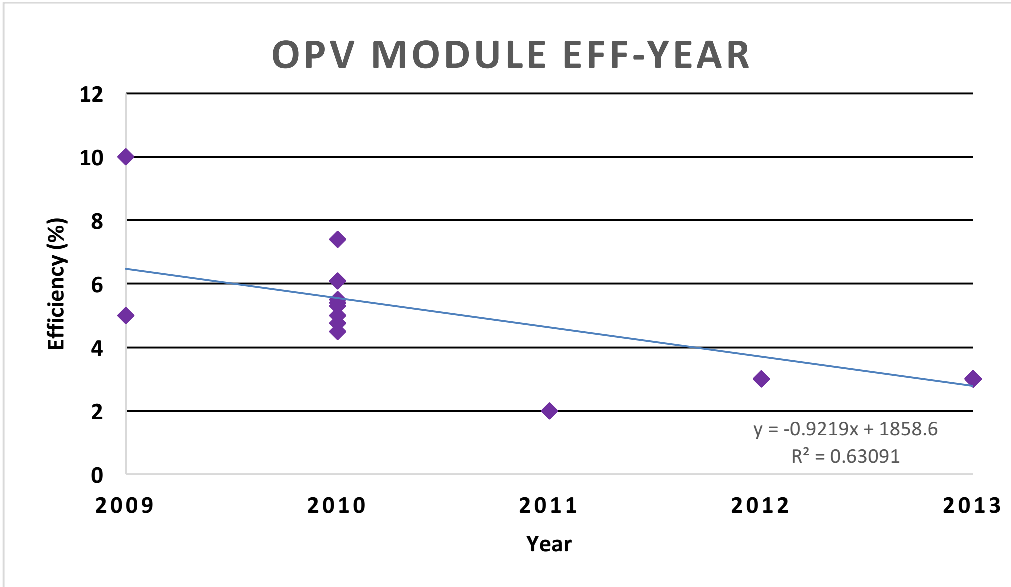


Figure IV.7 OPV Relation curve of efficiency and study year from 2009 and 2013.

B. Cumulative energy demand for module relation with 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.

As shown in Figure IV.8, the 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.

Figure IV.9, 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.

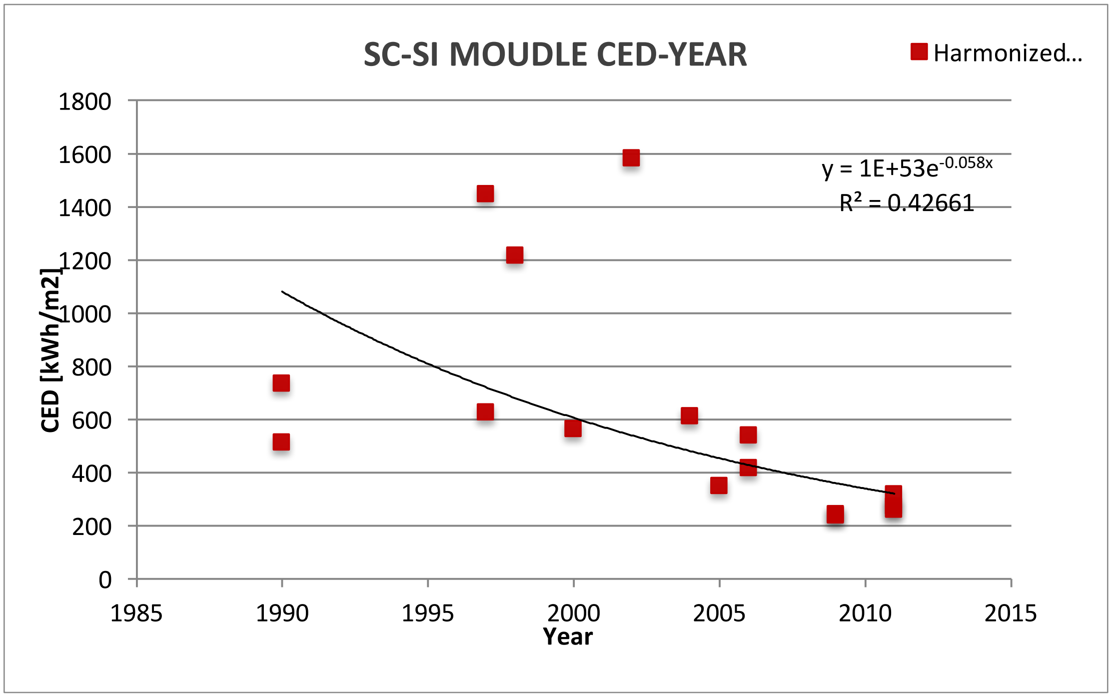
Figure IV.10, original CED of A-Si has a range between 70 and 200 kWh/m^2, average of them is 127 $kWh/m^{2,}$ while harmonized data has a range between 70 and 150 kWh/m^2, average of them is 111 kWh/m^2. CED of A-Si is much lower than first PV generation because of low energy cost manufacture for amorphous silicon. CED of A-Si has decreased 60% during 20 years, but it is not as fast as first generation technology.

Figure IV.11, 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.

Figure IV.12, 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.

Figure IV.13, 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. CIGS is relatively new compared with other thin film technologies, since the first CIGS study in very detail came up in year 2007.

Figure IV.14, 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 [103]. CED of OPV does not have obvious trend with time, since OPV came up recent years and does not have enough data on it.



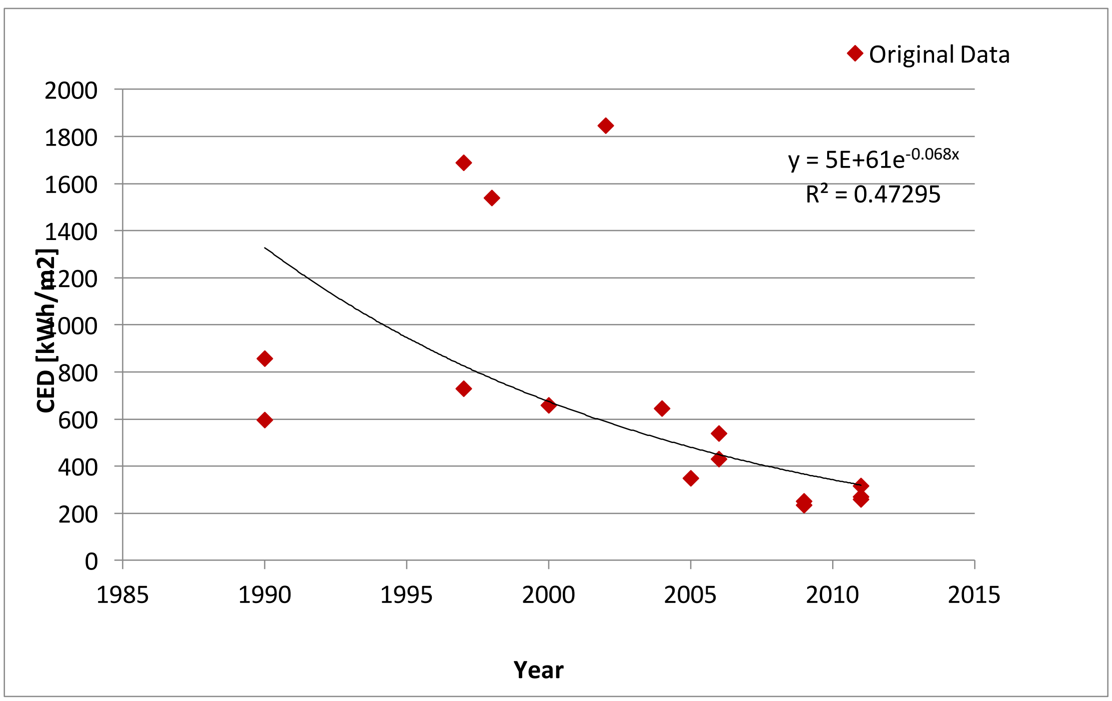
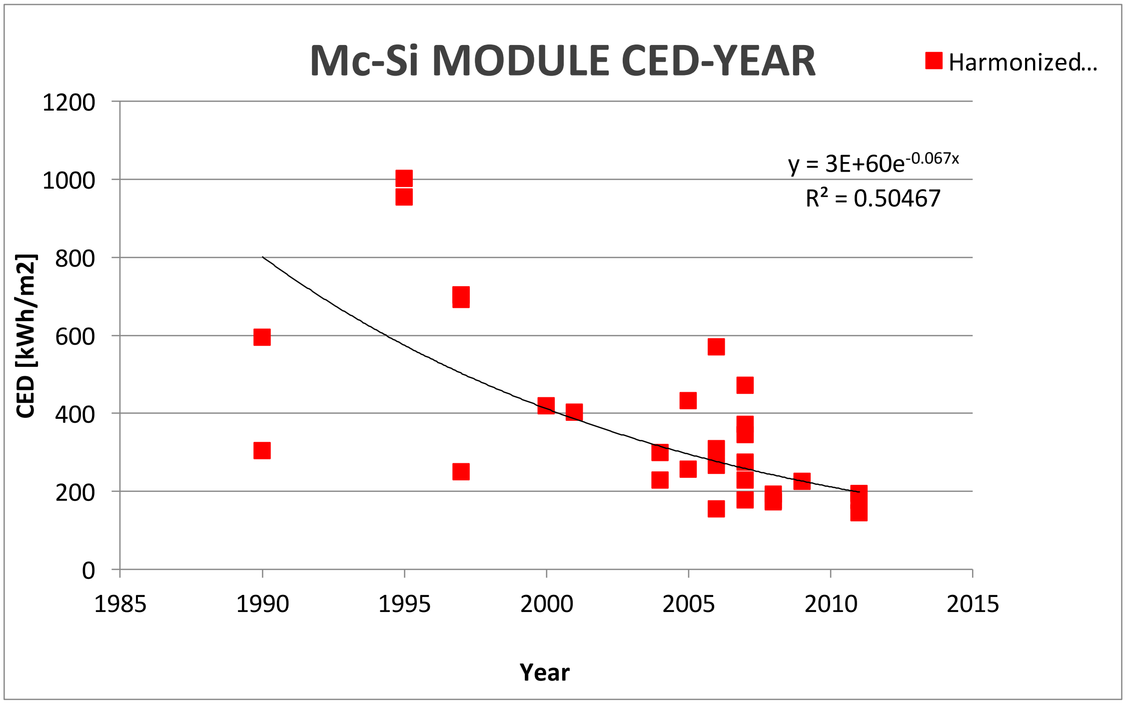


Figure IV.8 Sc-Si Relation curve of CED and study year from 1990 to 2011



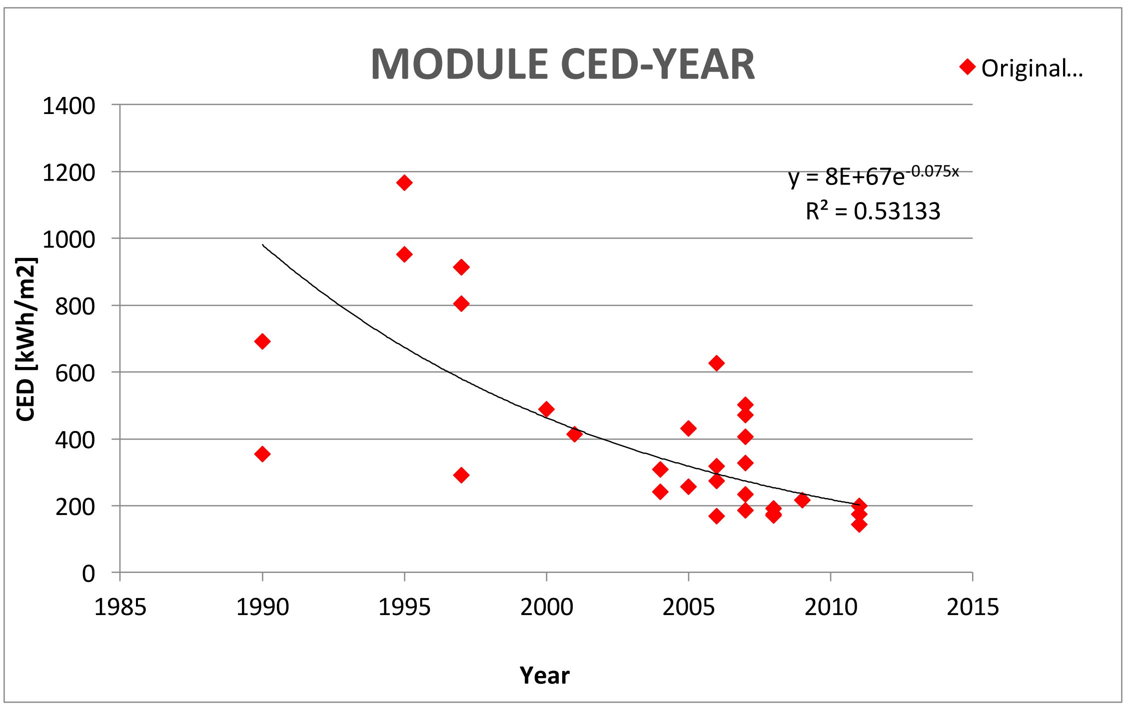
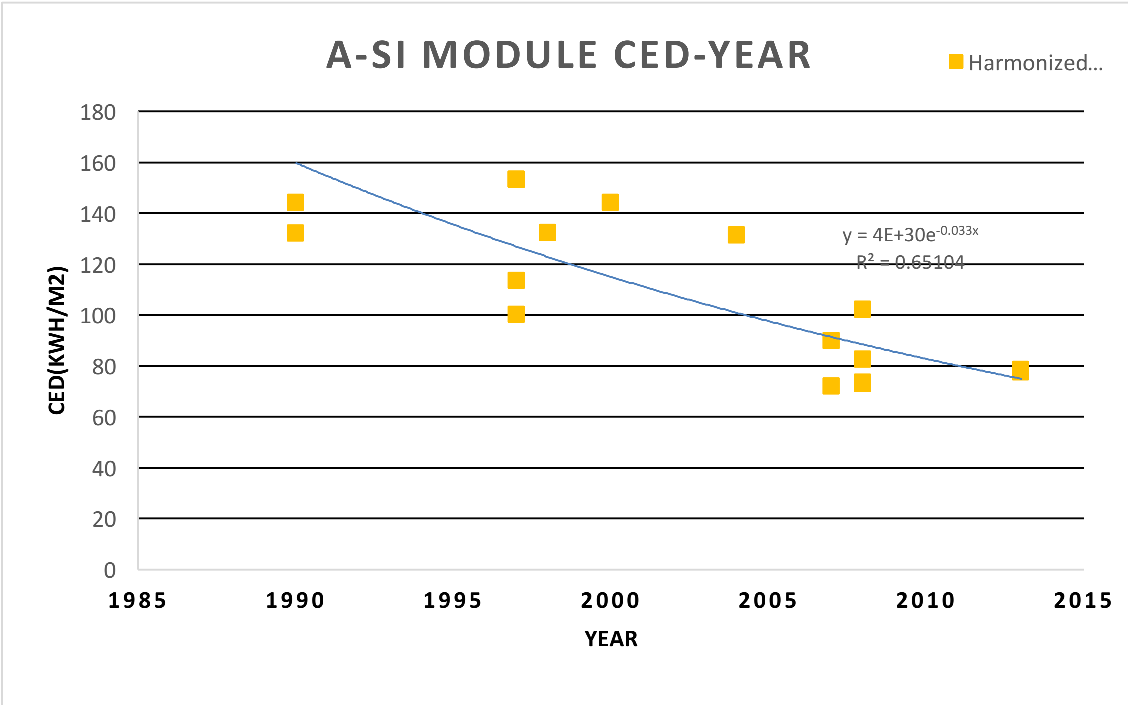


Figure IV.9 Mc-Si Relation curve of efficiency and study year from 1990 to 2011



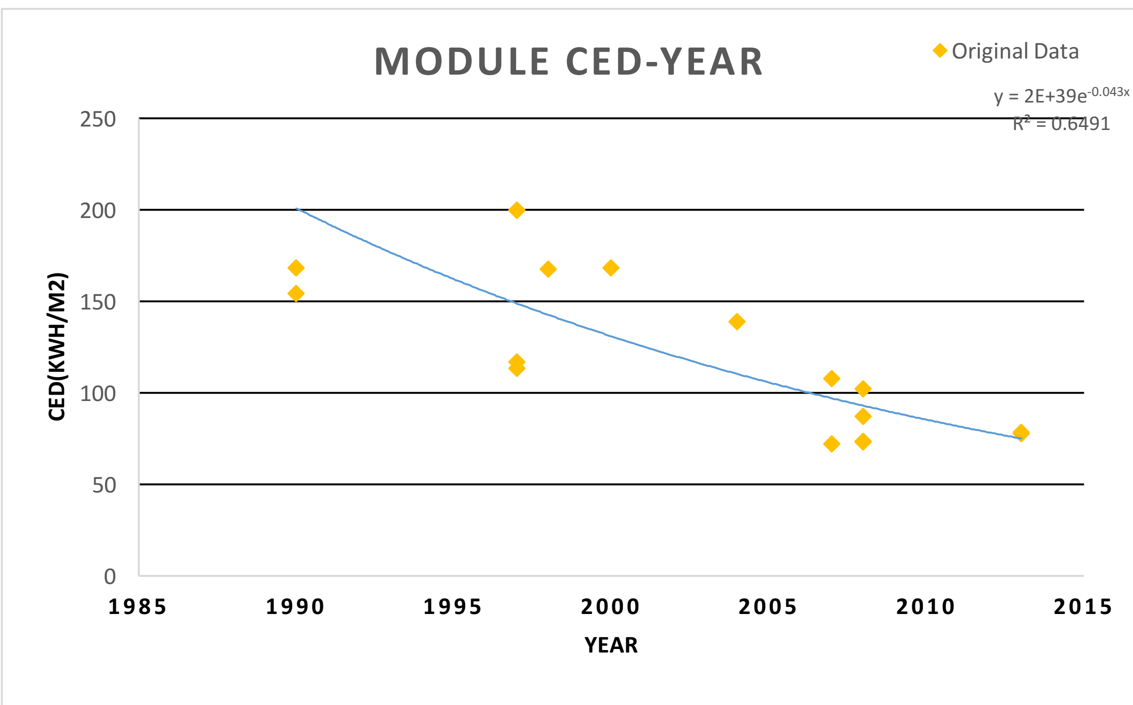
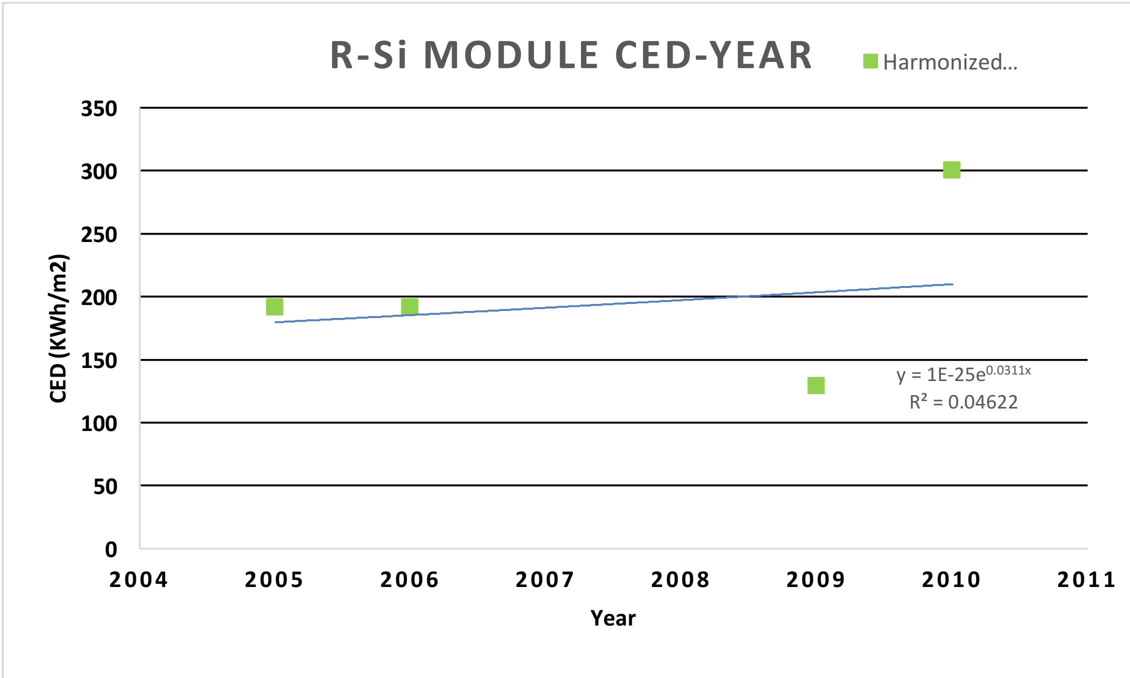


Figure IV.10 A-Si Relation curve of CED and study year from 1990 to 2013



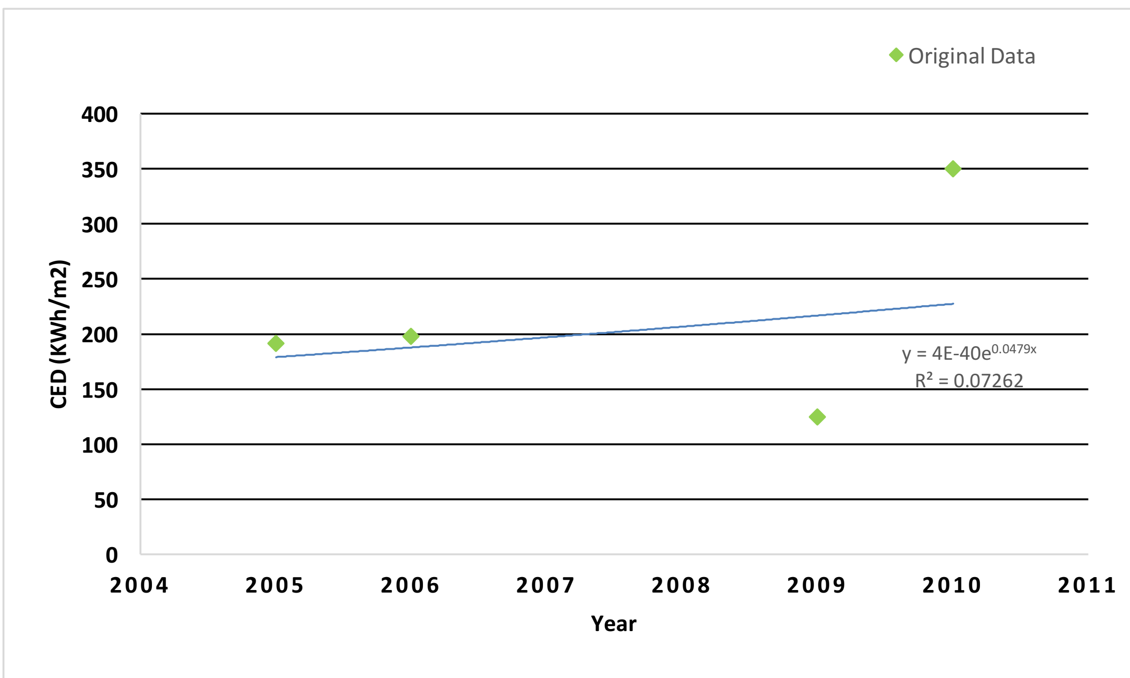
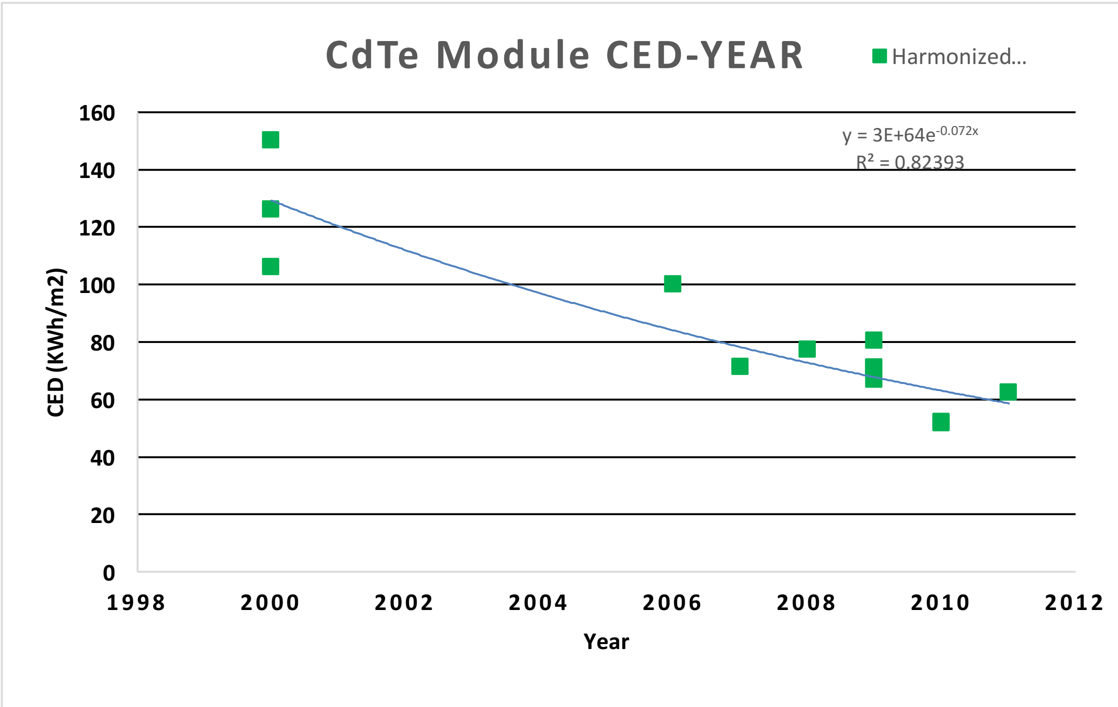


Figure IV.11 R-Si Relation curve of CED and study year from 2005 and 2010. Only 4 studies were collected, so no trend could not be told relation between CED and study time.



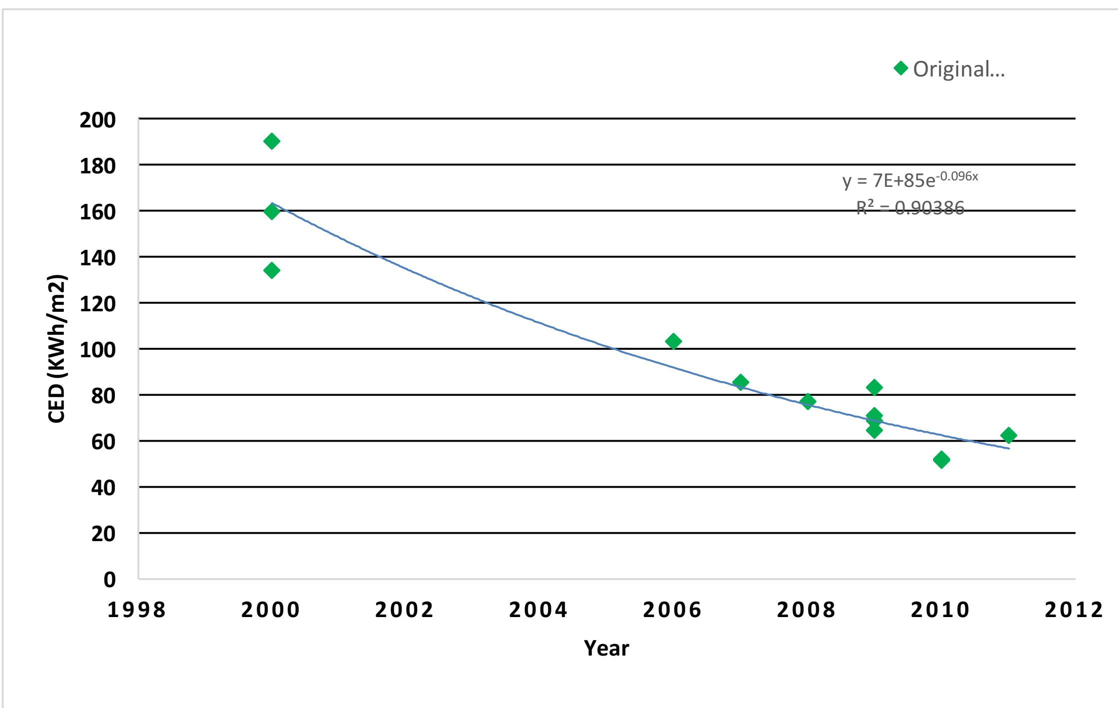
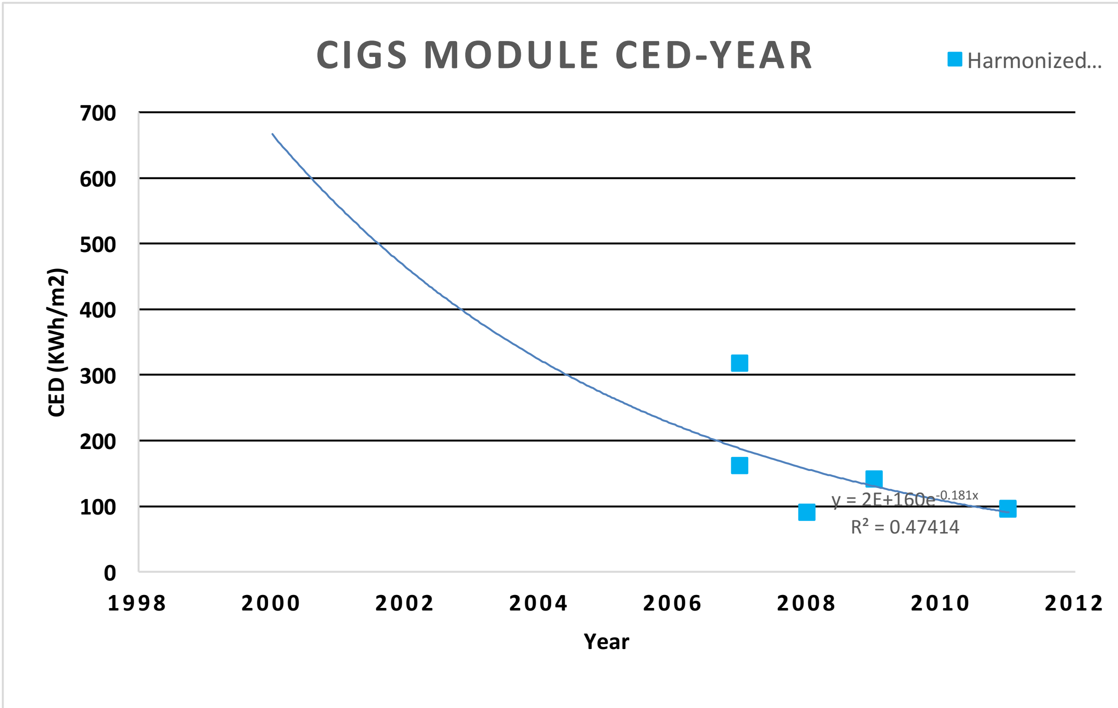


Figure IV.12 CdTe Relation curve of CED and study year from 2000 and 2011



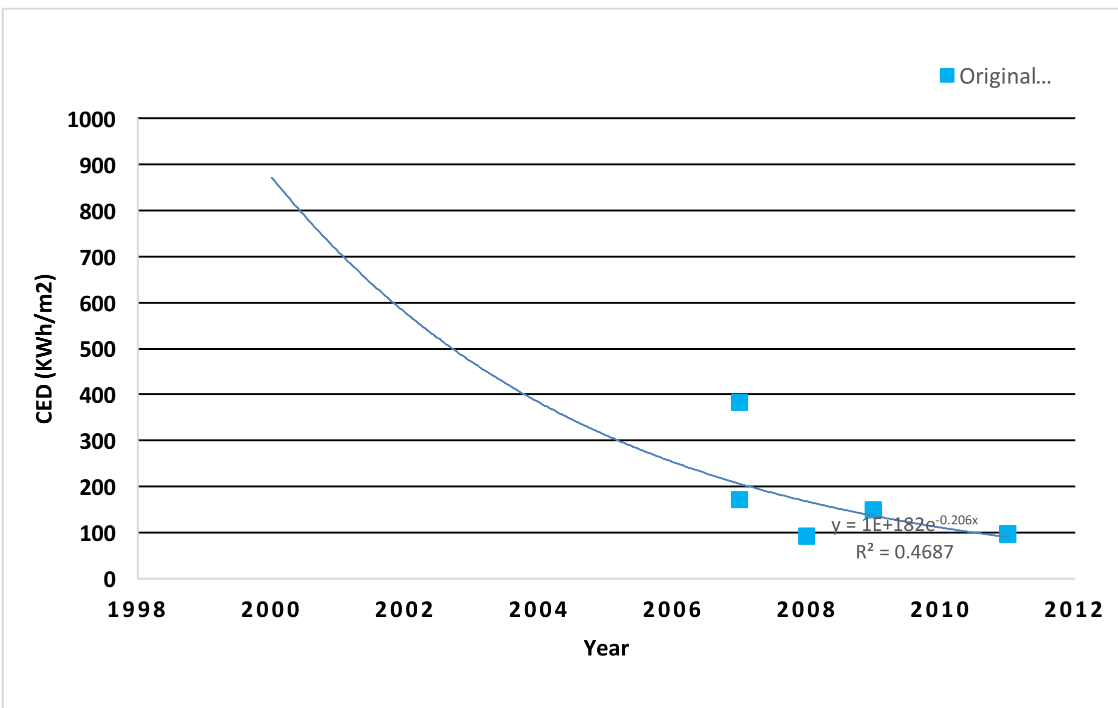


Figure IV.13 CIGS Relation curve of CED and study year from 2007 and 2011.

Only five studies were collected, no trend could be showed in five years.

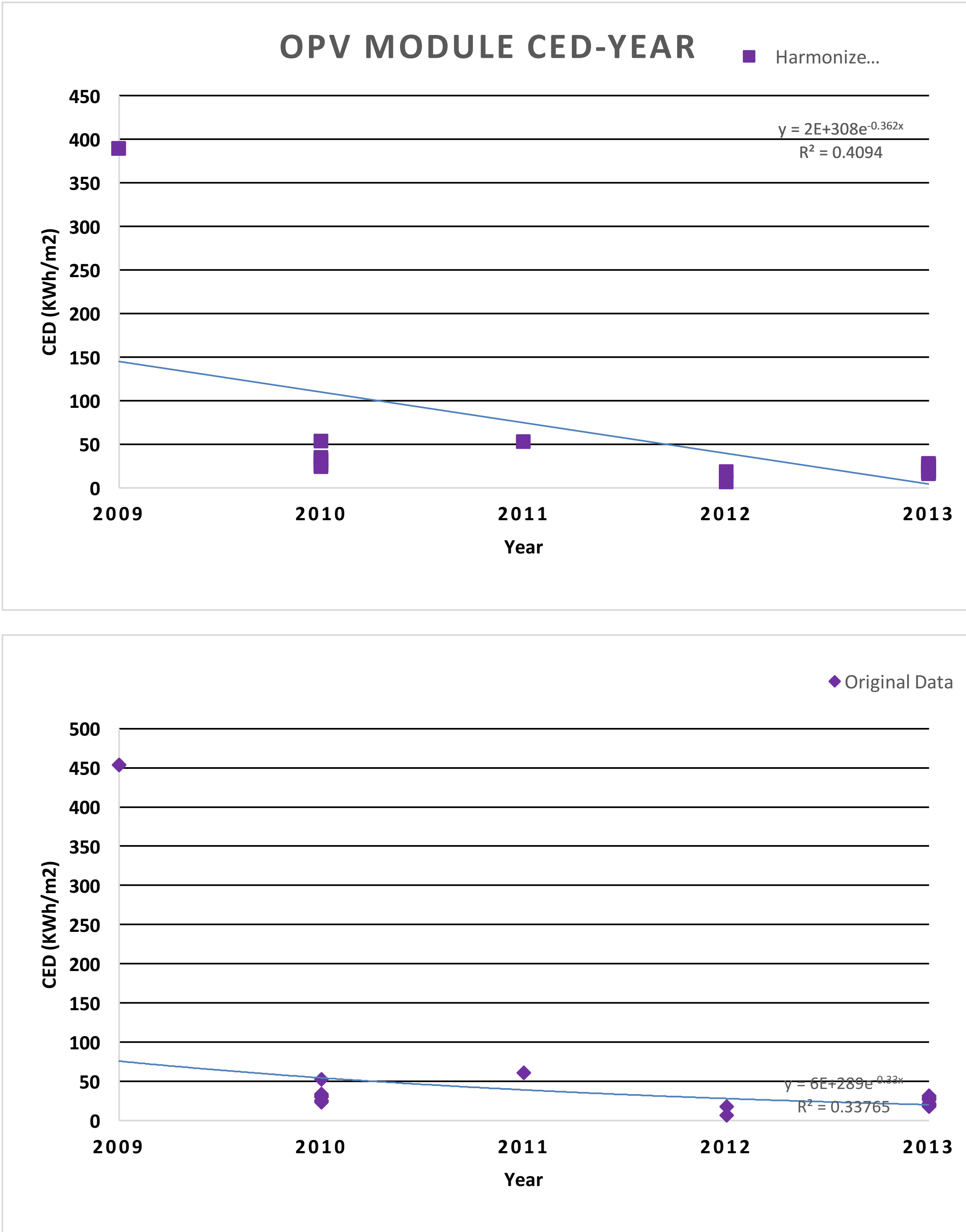


Figure IV.14 OPV Relation curve of CED and study year from 2009 and 2013.

C. Energy return on investment (EROI) relation with year

As discussed in the methodology section (Section [INSERT CROSS-REF]), 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. This section 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.

Figure IV.15, 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.

Figure IV.16, 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.

Figure IV.17, 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.

Figure IV.18, 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.

Figure IV.19, EROI of CdTe obviously increased with study time. EROI has a large range between 11 and 60.

Figure IV.20, EROI of CIGS obviously increased with study time. EROI has a range between 8 and 37.

Figure IV.21, 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.

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.

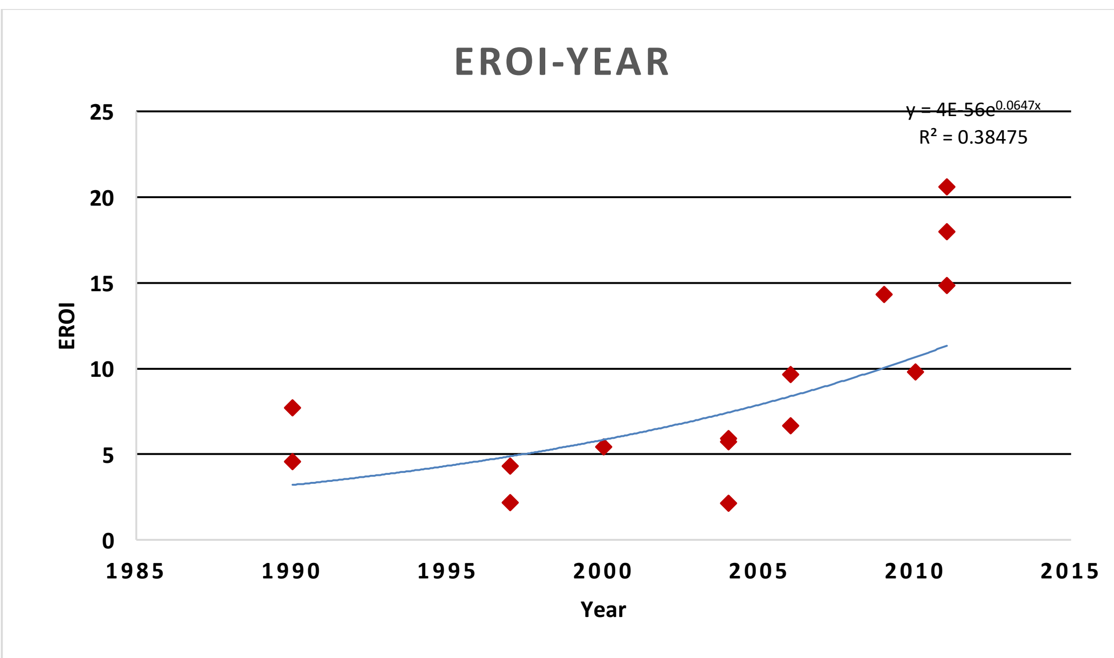


Figure IV.15 Sc-Si Relation curve of EROI and study year from 1990 and 2012

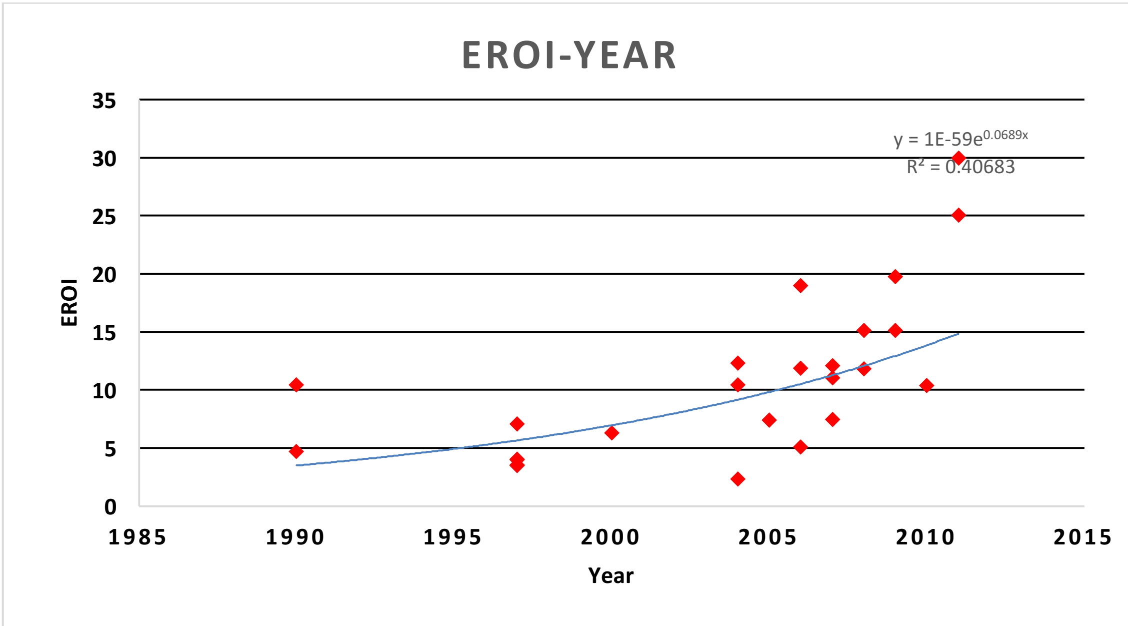


Figure IV.16 Mc-Si Relation curve of efficiency and study year from 1990 to 2011.

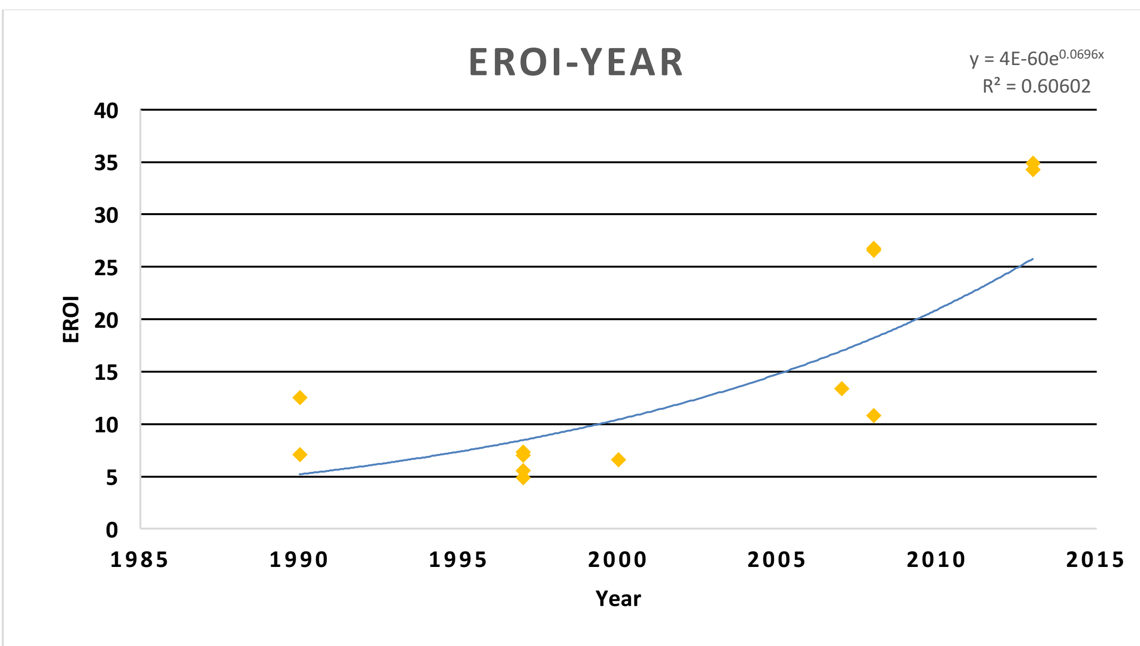


Figure IV.17 A-Si Relation curve of EROI and study year from 1990 to 2013.

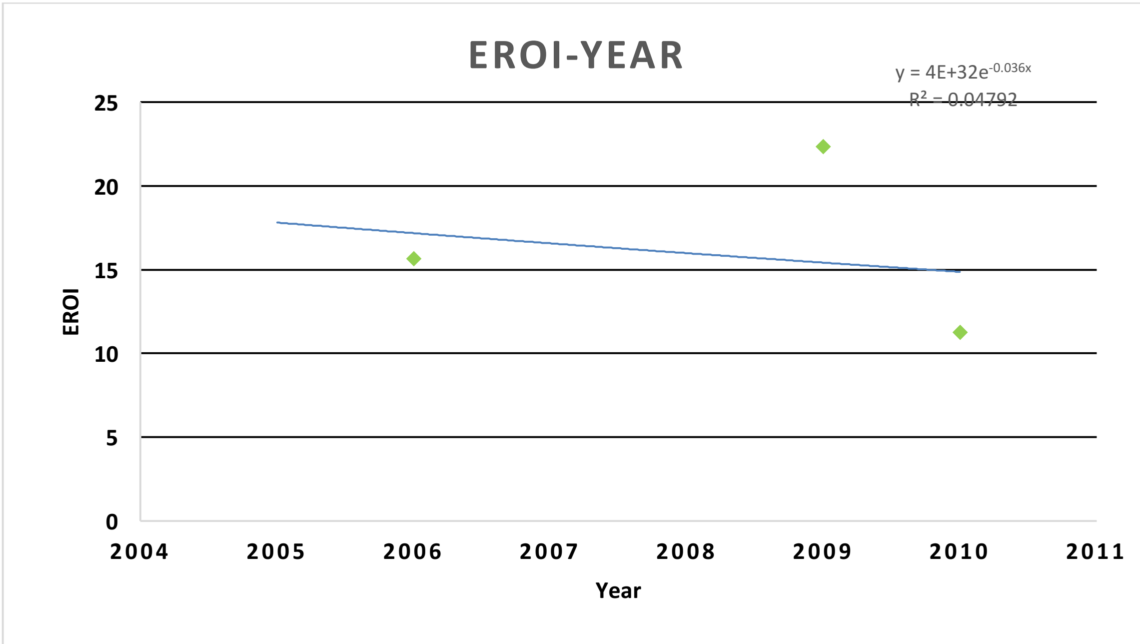


Figure IV.18 R-Si Relation curve of EROI and study year from 2006 and 2010.

Only 3 studies were collected, so no trend could not be told relation between EROI and study time.

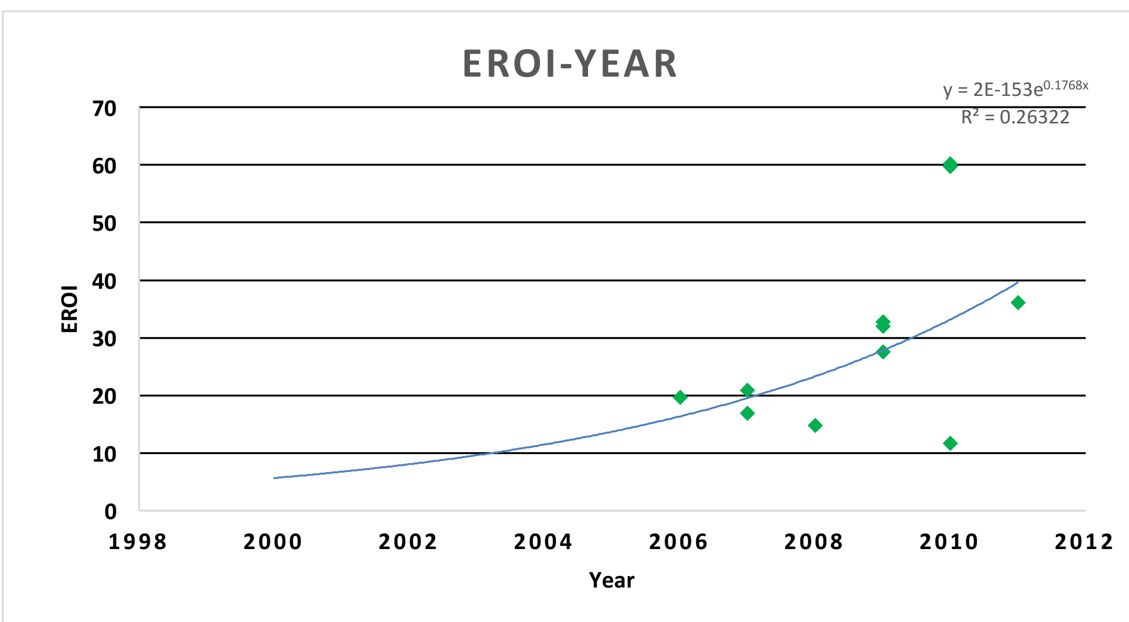


Figure IV.19 CdTe Relation curve of CED and study year from 2000 and 2011

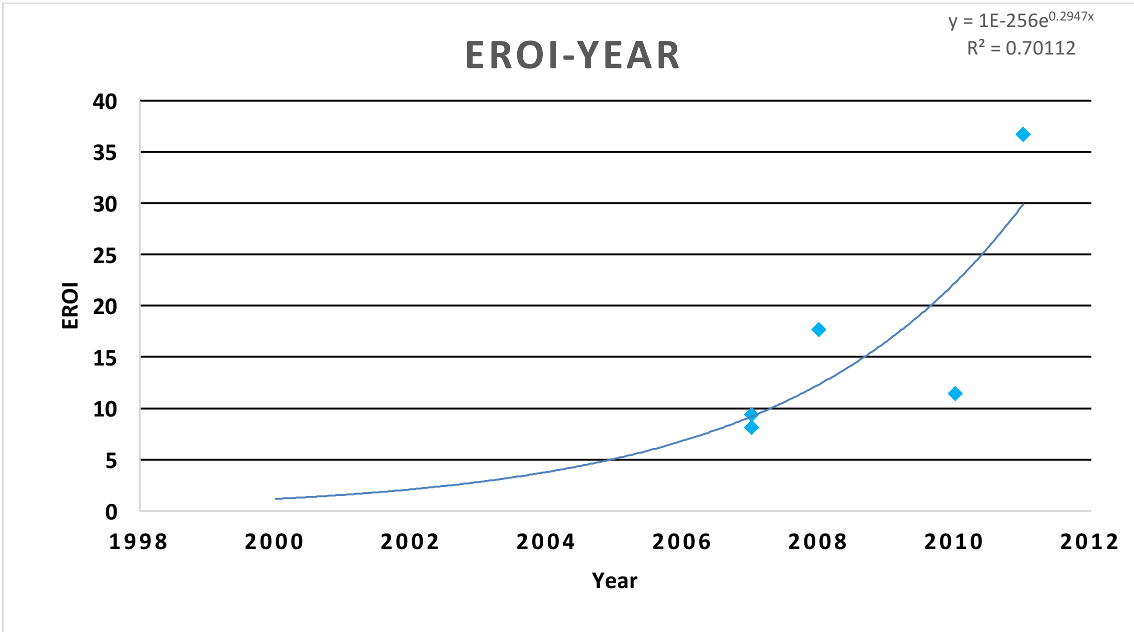


Figure IV.20 CIGS Relation curve of EROI and study year from 2007 and 2011.

Only five studies were collected, no trend could be showed in five years.

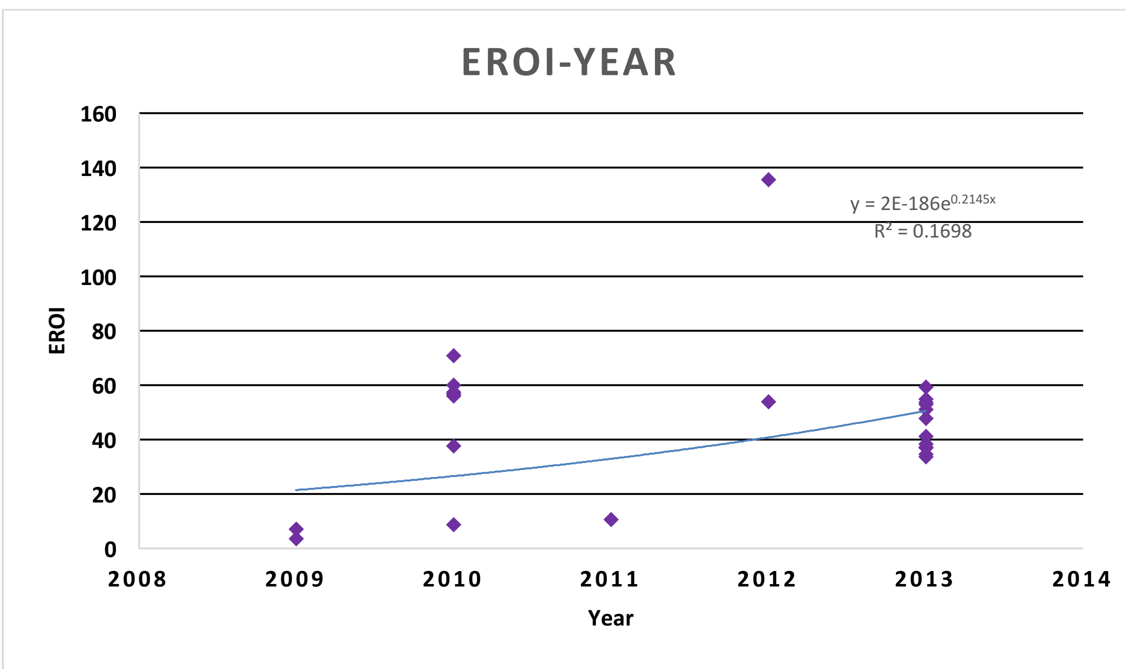


Figure IV.21 OPV Relation curve of EROI and study year from 2009 and 2013.

D. 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 figures, 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.

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.

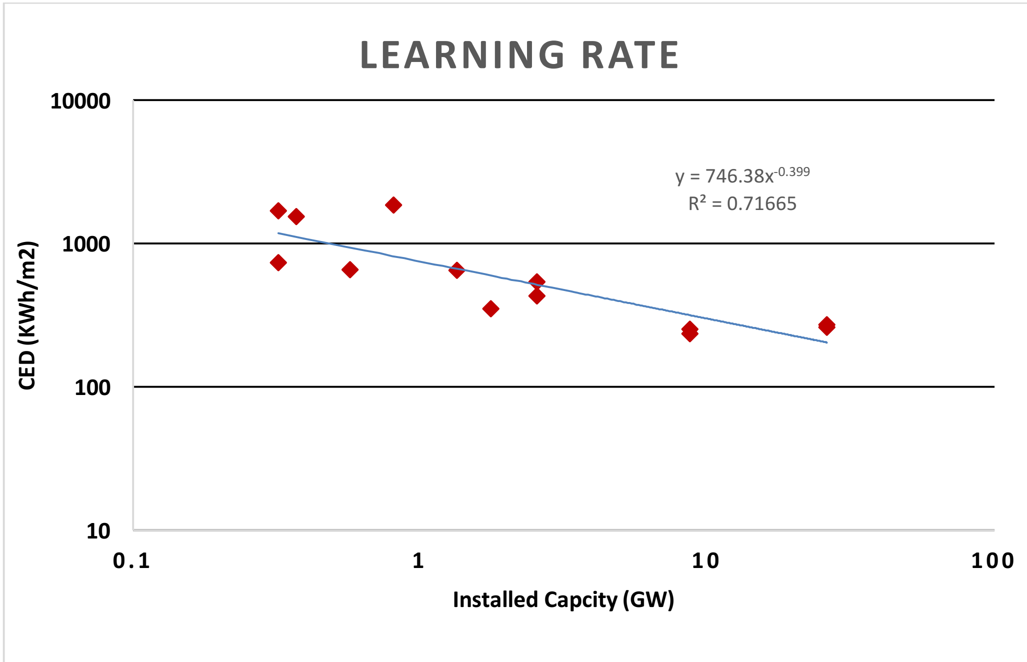


Figure IV.22 Learning curve of Sc-Si module.

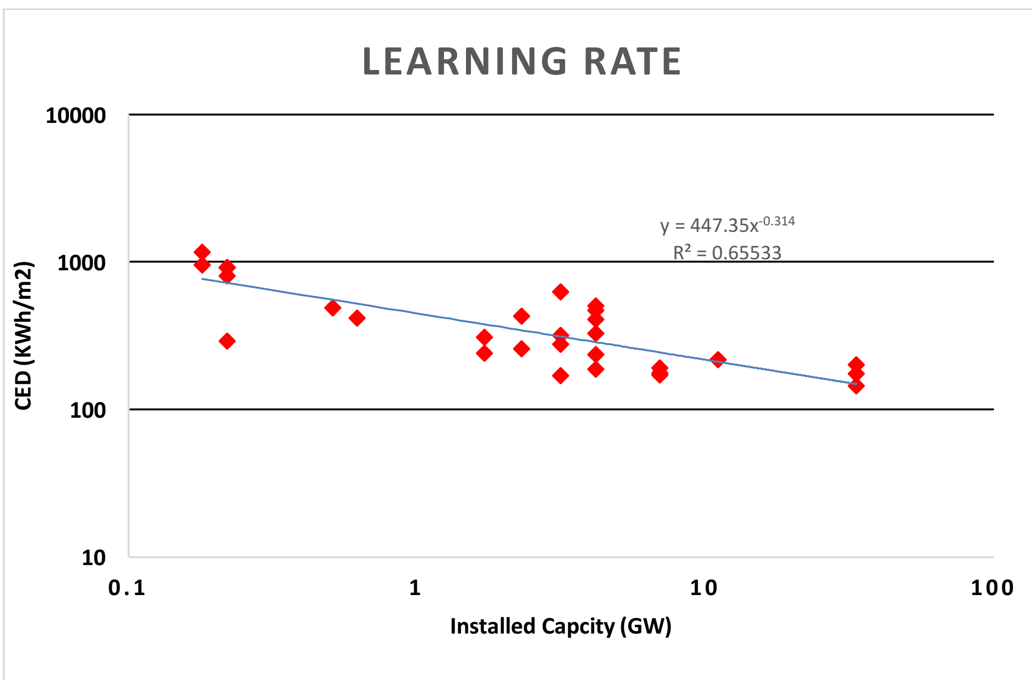


Figure IV.23 Learning curve of Mc-Si module.

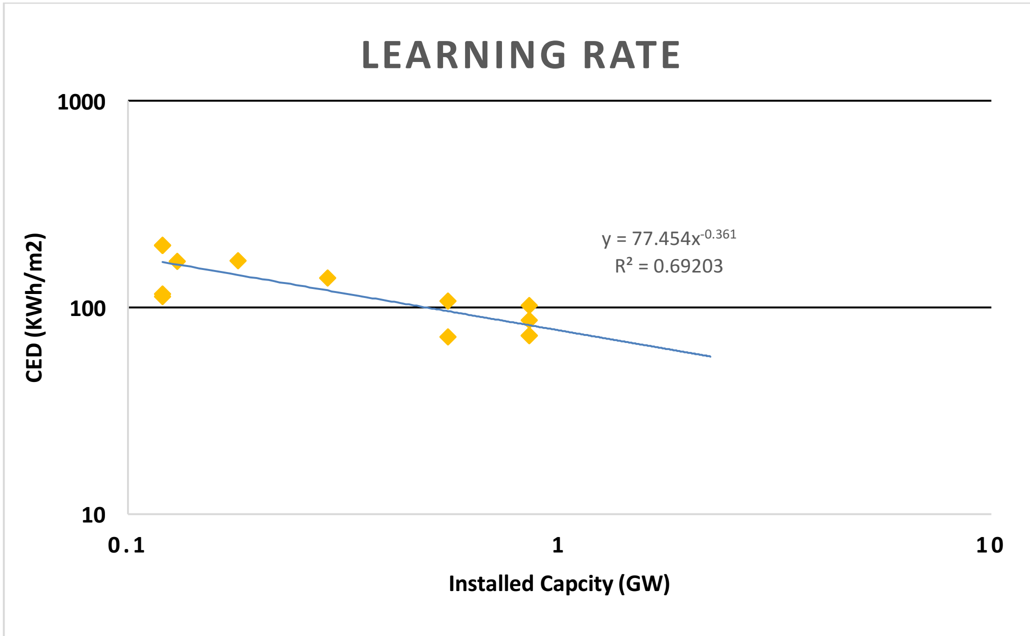


Figure IV.24 Learning curve of A-Si module.

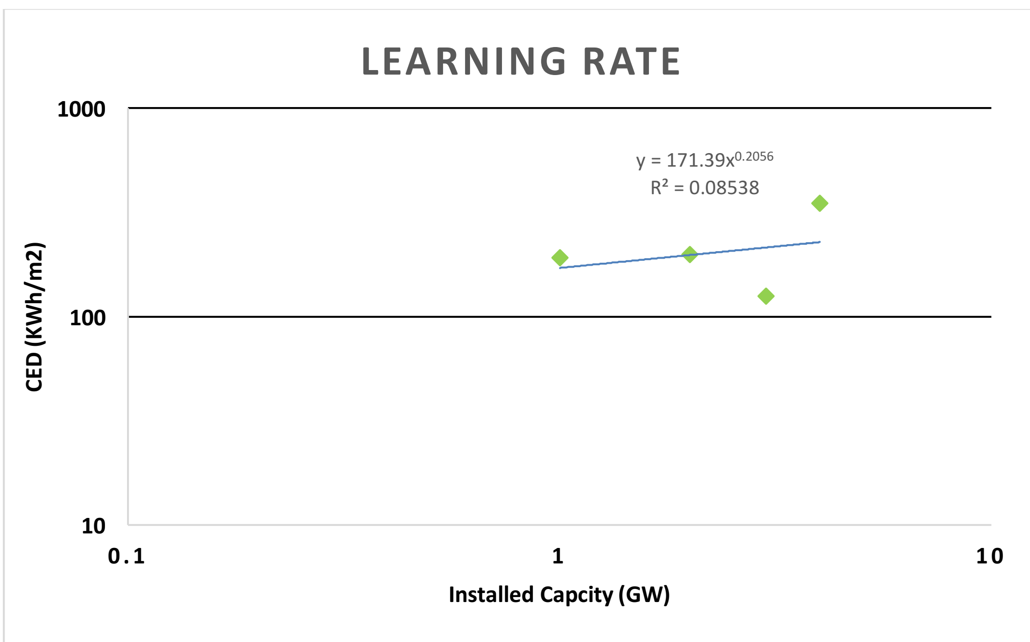


Figure IV.25 Learning curve of R-Si module. R-Si has a negative learning rate which is unreasonable. Also, only four data were collected.

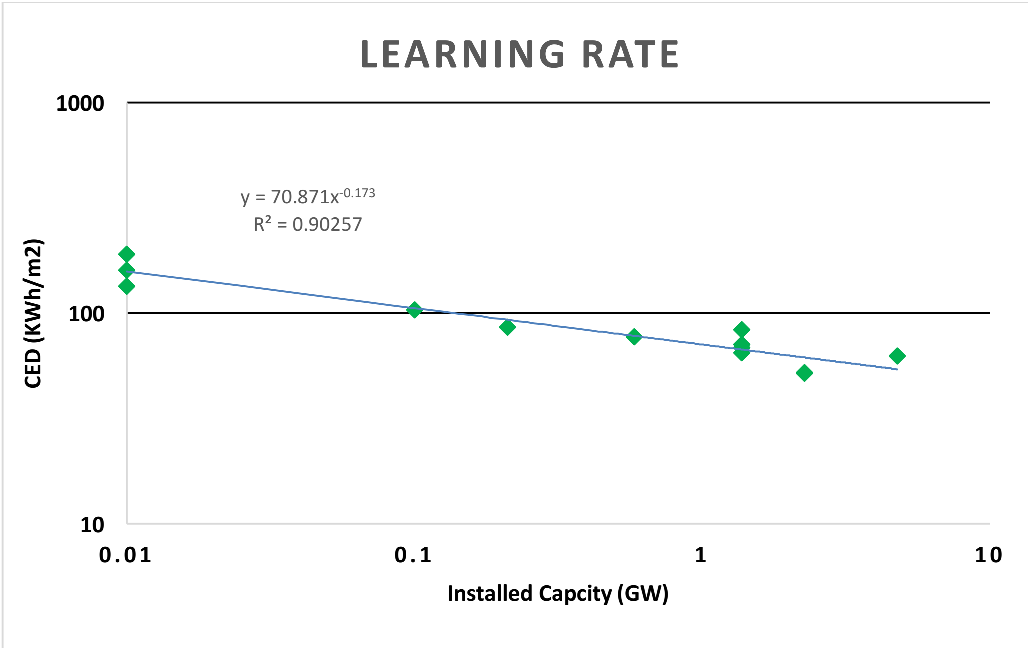


Figure IV.26 Learning curve of CdTe module.

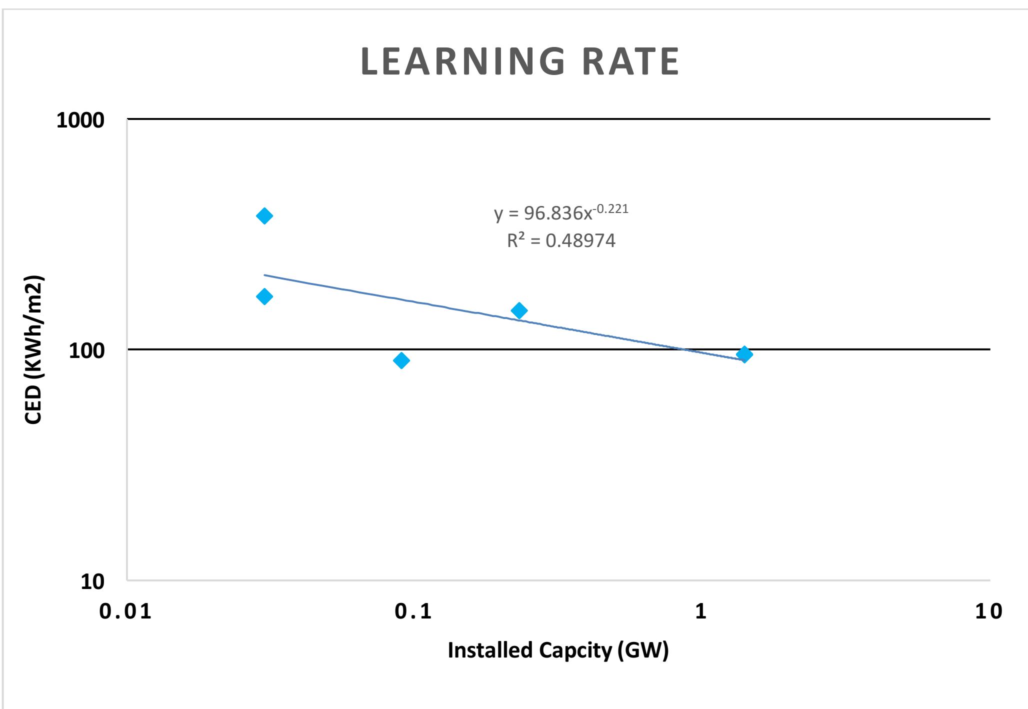


Figure IV.27 Learning curve of CIGS module.

E. Balance of system

BOS has a learning rate of 0.3% [25]. 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. Figure IV.28 is the boxplot for the BOS of all the techonologies. From the Table IV-1,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.

Table IV-1 Quartile of Balance of System in all the different material studies.

Quartile	**BOS**
Min	36.5833333
Q1	47.52
Median	70.5972222
Q3	123.555667
Max	206.36111

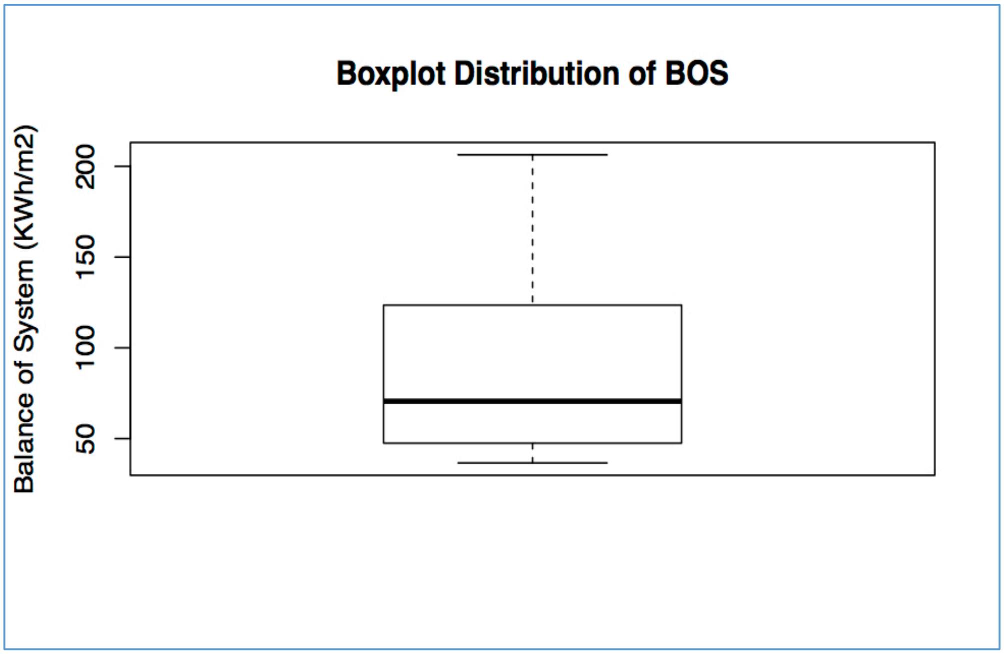


Figure IV.28 Boxplot of CED for BOS of all technologies.

F. Comparison and selection with different axis

In this section, we draw the plots with different axis. From the equation in the methodology section, EROI can be calculated by knowing efficiency and CED. EROI could be draw as contour. All three kinds of data could be displayed. We draw EROI, efficiency and CED as contour separately to find which way is better to show the relation between them directly and easily.

In Figure IV.29, efficiency is X-axis, CED is Y-axis, while EROI is the contour (Z-axis). The red line where EROI is less than 1 means energy sink, because energy output is less than energy input. Since efficiency and CED are known in previous studies on solar system, making EROI as contour is reasonable. At the same time, we could make use of all the plot area.

In Figure IV.30, efficiency is X-axis, EROI is Y-axis, while CED is the contour. Since all the CED of PV locate in the range between 18 and 2000. Contours that are larger than 2000 or smaller than 18 were not draw. From this plot, only part of the area has the contours, which is not useful to compare different technology. It is also hard for us to use CED and efficiency to locate the value of EROI.

In Figure IV.31, CED is X-axis, EROI is Y-axis, while efficiency is the contour. Since all the efficiency of PV locate in the range between 2 and 30. Contours that are larger than 30 or smaller than 2 were not draw. From this plot, all the contours were very closed to each other, which means only small part of the area could be plot the sample points. It is hard to find any trend and relation in this plot.

After compare different contours, we chose the first one to add previous studies sample, because we could clearly locate the points and find the trend of each technology.

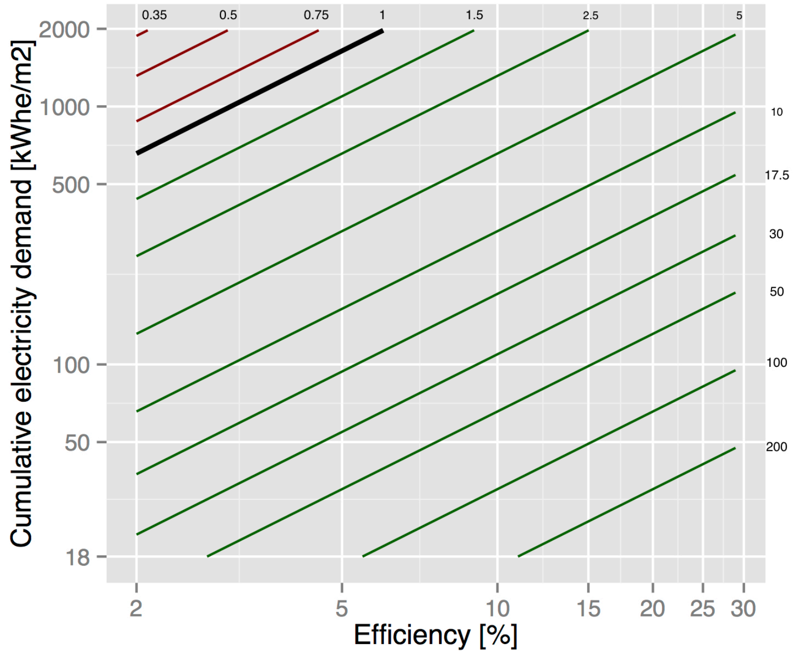


Figure IV.29 EROI as contour to draw the coordinate plot

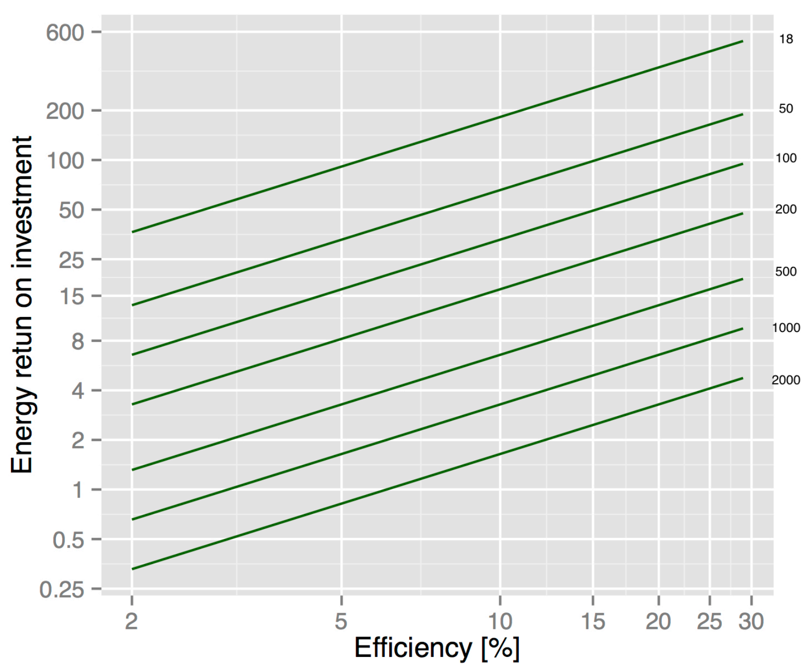


Figure IV.30 CED as contour to draw the coordinate plot

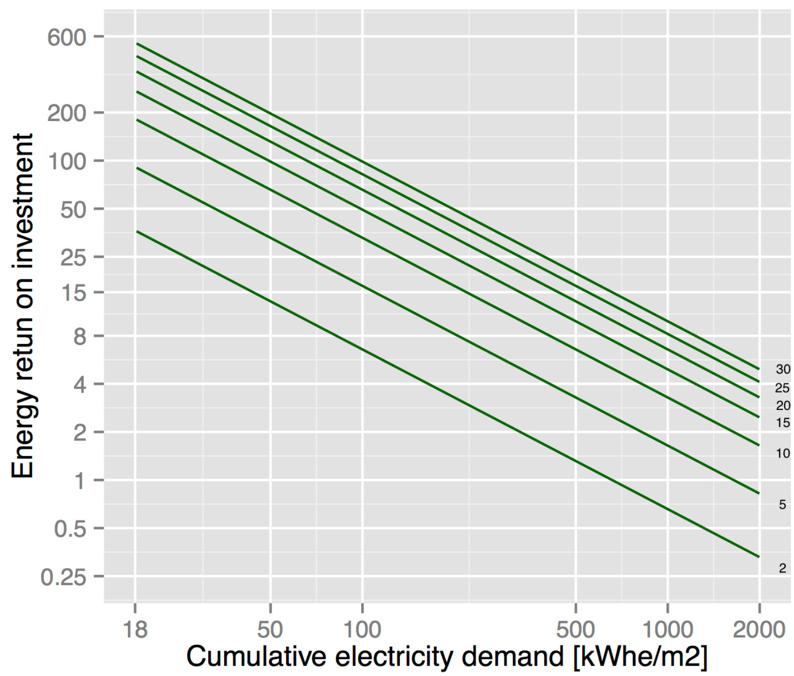


Figure IV.31 Efficiency as contour to draw the coordinate plot.

G. 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.

In Figure IV.32, 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 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 Figure IV.33, 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.

In Figure IV.34, we plot the data by using their own lifetime. Compared to figure 4.7.2, the module that has lifetime lower than 25 years had lower CED than figure 4.7.2, since we did not convert it into 25-year scale. OPV has larger impact than the other technologies, because lifetime for OPV is usually shorter than 25 years. For OPV, the lowest CED per unit area is 3.6 kWh/m^2, while the lowest CED per unit capacity could be 0.1 kWh$_e$/W$_p$. The highest CED is 272 kWh/m^2, while the highest CED is 454 kWh/m^2 in figure 4.7.2.

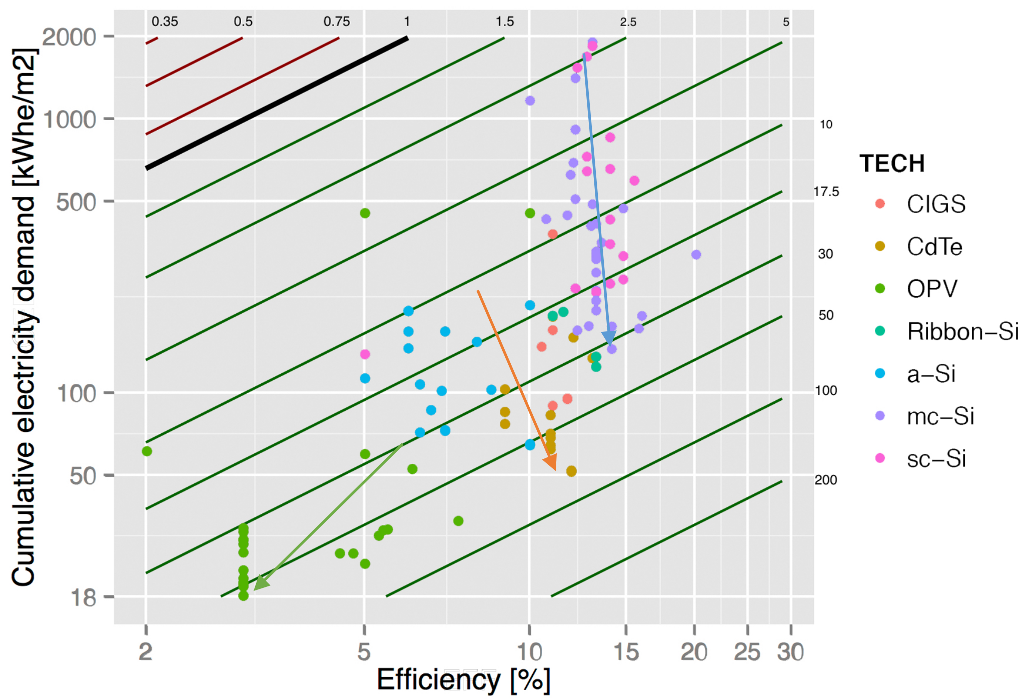


Figure IV.32 Relation among efficiency, CED and EROI. EROI is the contour. Arrows represents for trend of year. Blue one is the time trend of crystalline silicon module. Orange one is the time trend of thin film module. Green one is the time trend of OPV module. Red contour stands for energy sink, while 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.

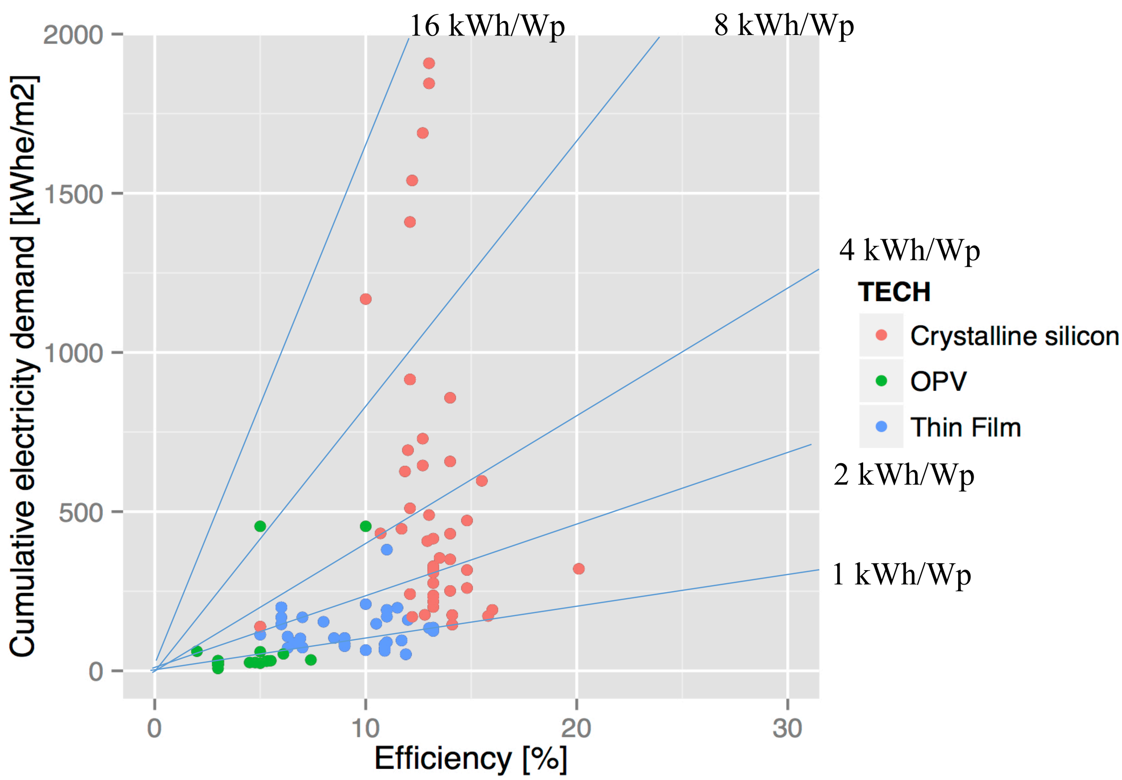


Figure IV.33 Cost/Efficiency of Photovoltaic Technology in lifetime of 25 years. This plot is not log-log plot. We could intuitively look energy cost based on kWh/m2 scale. OPV was plot by assuming a lifetime of 25 years.

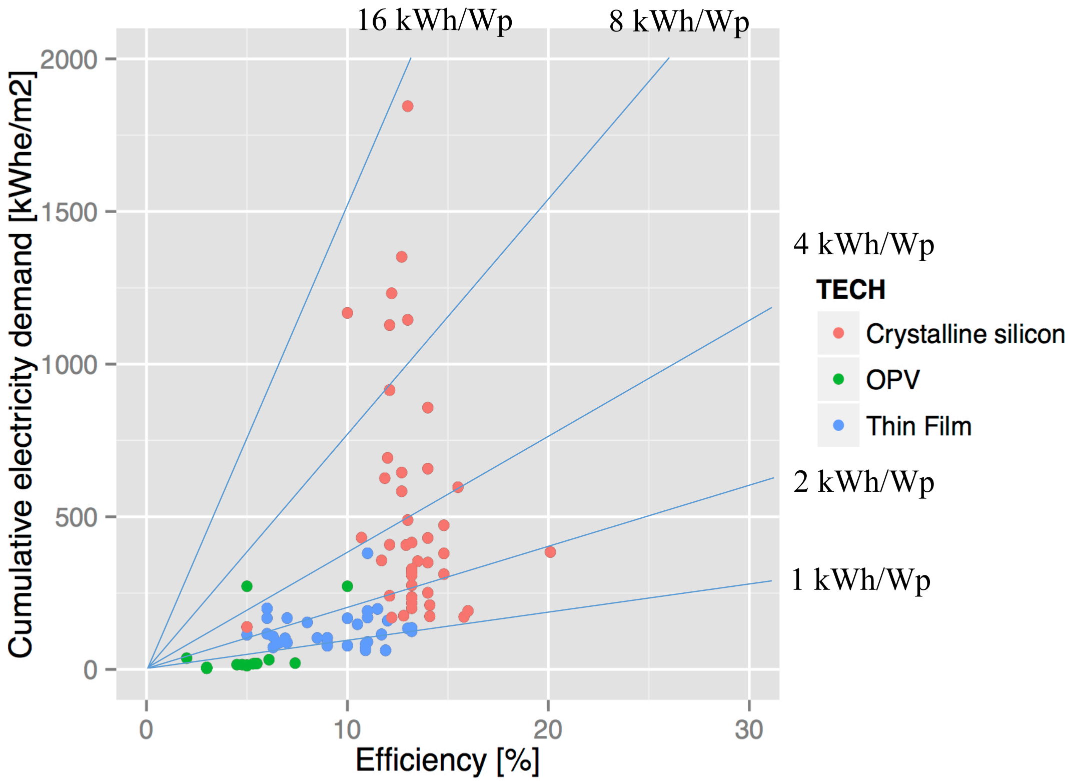


Figure IV.34 Cost/Efficiency of Photovoltaic Technology in their own original lifetime.

V. Conclusion

1.For crystalline silicon module, efficiency increases slightly during the time. It has the highest efficiency among 3 types of solar system, especially for single crystal silicon module. Efficiency of crystalline silicon has a range between 10% and 20.1%. For thin-film module, efficiency increase slightly during the time except for R-Si, which is also not very obvious. It has the second highest efficiency among 3 types of solar system. Efficiency of thin-film module has a range between 5% and 13.2%. For OPV module, all the previous studies were between year 2009 and 2013. We could not tell the time trend from four years. Usually, it has the lowest efficiency. Efficiency of OPV has a range between 2% and 10%.

2. For crystalline silicon, CED decreases obviously during the time. It has the highest CED among 3 types of solar system. CED of crystalline has a range between 150 kWh/m^2 and 1845 kWh/m^2. For thin-film technology, CED decreases obvious during the time. It has the second highest CED. CED of thin-film module has a range between 50 kWh/m^2 and 400 kWh/m^2. For OPV, CED also decreases obvious during the time. It has the lowest CED among 3 types of solar system. CED of OPV has a range between 3 kWh/m^2 and 272 kWh/m^2.

3. For crystalline silicon, EROI increases obvious during the time because of decreasing CED. EROI of crystalline silicon has a range between 2 and 30. It has the lowest EROI range. For thin-film technology, EROI increases obvious during the time because of decreasing CED. It has the second largest EROI among 3 types of solar system. EROI of thin-film has a range between 5 and 35. For OPV, EROI increases

obvious during the time because of decreasing CED. It has the largest EROI, which is between 4 and 135.

4. For crystalline silicon module, it has the larger learning rate than thin-film technology, which means CED decreases faster than CED of thin-film. Although, CED of thin film is much less than CED of crystalline silicon module, CED is getting closer and closer to thin-film due to higher learning rate. Because of lack of capacity factor and only four years range, we did not draw the learning rate for OPV.

5. To know how much is cost for all the technologies, we draw boxplot for BOS of all the material. Then, we choose the minimum and maximum BOS as the low BOS scenario and high BOS scenario. Minimum BOS is 36.6 kWh/m^2, while the maximum BOS is 206.4 kWh/m^2.

6. From all the different contour plots, we chose to use the EROI as contour. Because we could look the efficiency and CED more intuitively and have more area to use. Also, EROI is calculated by CED and efficiency. It is reasonable to use the EROI as contour plot.

7. Combining all 3 types of solar system, we concluded that high efficiency did not means high EROI. Crystalline has the highest efficiency and lowest EROI. The trend for the 3 generation technology is that efficiency goes down, CED decreases strongly and EROI goes up with time.

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Appendix A: Table for Data Resources

Table A-1 In this table, all the studies data come from by different technologies.

Technologies	Studies Sources
Sc-Si	[63], [68], [79], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113], [114], [115], [116]
Mc-Si	[63], [78], [79], [96], [104], [107], [108], [109], [111], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127], [128]
A-Si	[63], [68], [78], [104], [107], [108], [109], [114], [115], [125], [126], [129], [130]
R-Si	[79], [114], [116], [128]
CdTe	[79], [97], [115], [116], [124], [125], [131], [132]
CIGS	[105], [114], [115], [124], [125], [126]
OPV	[103], [133], [134], [135], [136], [137]