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Review of life cycle analyses and embodied energy requirements of single-crystalline and multi-crystalline silicon photovoltaic systems

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ABSTRACT

While photovoltaic (PV) technology is considered a renewable energy source, it nonetheless has a degree of environmental impact. In order to completely capture the net environmental gain of a PV system, its necessary to conduct a life cycle analysis (LCA). This paper attempts to summarise the latest developments of two prominent crystalline, i.e. single crystalline (sc-) and multi crystalline (mc-) silicon PV systems with regards to their environmental performance and sustainability. The PV life cycle is assumed to begin at pre-production, after which PV module production, operation, installation geography, and finally recycling/disposal are also included. The embodied energy requirement, energy payback time (EPBT), and greenhouse gas (GHG) emission for crystalline silicon PV technologies were reviewed, summarised and evaluated. All environmental impact results were further discussed to highlight existing constraints in previous LCA studies. Both sc-Si and mc-Si share Siemens process during manufacturing, however sc-Si requires the additional Czochralski process which results in higher embodied energy requirement and EPBT for sc-Si technology. Therefore while sc-Si retains a higher conversion efficiency, this increased electrical energy output for a given surface area is still not enough to lower sc-Si's EPBT to levels comparable to ms-Si. Higher conversion efficiency however means that sc-Si panels outperform mc-Si on space efficiency. A set of recommendations for further work form the concluding parts of this work, in particular full examination of LCA of hybrid c-Si given that it combines the best features of sc- and mc-Si PVs, and currently, there is very little data available on hybrid c-Si.

Contents

1. Introduction

Present rates of energy production and utilisation have been increasing to meet energy demand because of the increase in human population and infrastructure expansion. Exploitation of

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Nomenclature

Sc-Si	Single Crystalline Silicon
MG-Si	Metallurgical Grade Silicon
kWh	kiloWatt Hour
LCA	Life Cycle Analysis
GWP	Global Warming Potential
EPBT	Energy Payback Time
FFC	Fossil Fuel Consumption
PR	Performance Ratio
Mc-Si	Multi Crystalline Silicon
PPM	Parts per Million
kWp	KiloWatt Peak
BOS	Balance of System
STC	Standard Test Condition
GHG	Greenhouse Gas
PV	Photovoltaic

non-renewable energy sources such as fossil fuels is the major reason for air pollution, climate change and the ensuing global warming [1]. The need to exploit renewable resources to reduce environmental degradation is becoming very important. Solar energy is one of these renewable sources that is abundant but under-utilised.

Photovoltaic (PV) technologies are growing in popularity as a readily accessible and familiar technology with a comparatively easy installation process. The abundant nature of solar energy has been a key factor in its adoption to meet the world's growing electricity energy demand. Life Cycle Analysis (LCA) is acknowledged as an invaluable approach to evaluate the energy and environmental profile of a PV product system [2].

To have a thorough understanding of the LCAs of PVs, it is first important to understand their developments over the past few decades and the main contributors to the embodied energy. Lower embodied energy requirement indicates improved manufacturing processes and best practices to achieve the lowest possible environmental footprint for PVs. This article conducts review of previous LCA studies of the two dominant types of photovoltaic systems, i.e. single (sc-) and multi-crystalline (mc-) silicon.

2. Life cycle analysis (LCA)

Life cycle analysis (LCA) for photovoltaic system refers to a standardised framework series of ISO 14040 international standards which allows the application of a similar sequence of procedures [3]. LCA is primarily performed as a foundation approach to evaluate the relationship between any products, services or systems, and their environmental impacts throughout the whole life cycle or expressed differently, to enable a structured and comprehensive 'cradle to grave' analytical approach [4,5]. LCA should cover the following:

1. Goal and scope definition: To formulate assumptions, set the system boundaries and define the type of environmental impact. Fig. 1 elucidates the system boundary of PV life cycle.
2. Inventory analysis: To identify all types of material flow;
3. Impact analysis: To convert all types of energy requirement into primary energy consumption;
4. Interpretation: To identify, analyse and suggest recommendations for future environmental development by taking into account the uncertainties and assumptions made prior.

3. Crystalline PV and its production

Crystalline PV modules have been the most desirable choice for years and dominate approximately 85–90% of the global PV market at domestic level [6]. Conversion efficiency provided by manufacturers are usually expressed under STC (irradiance of 1000 W/m^2, global AM 1.5 spectrum, 25 °C). C-Si PV modules naturally operate inversely proportional to temperature ($\sim$0.4% efficiency gain or penalty per each degree C). The conversion efficiency of PV is affected by the following factors [7]: (i) the operating orientation and temperature greatly influence the module efficiency; (ii) an increase in working temperature would decrease the conversion efficiency of PV modules, and (iii) efficiency losses occur at inverters and electrical transfer wiring.

Dones and Frischknecht [8] stated that majority of GHG emission associated with PV system is generated by overall module production process. The electrical energy consumed during production is drawn from non-renewable plants (e.g., fossil fuel plant). GHG emission linked to present PV systems for sc-Si and mc-Si is mostly derived from electricity demand in production phase which is between 80% and 90% of total energy requirement. Mc-Si has a higher GHG emission due to additional material needed for larger surface area in order to yield equal power output. The authors claimed that if all electricity supplies for PV productions were generated entirely from fossil fuel plants, the GHG emission and other combustion products would roughly double [8]. In contrast, if the electricity consumed for PV production was generated by a combination of fossil fuel and renewable energy power plants, the GHG emission would be reduced [8].

The overall process of silicon manufacturing to final assemblies of PV module is described under the system boundaries (refer to Fig. 1). All known process information is noted which includes carbothermic/quartz reduction (removing oxygen from silica), metallurgical grade silicon (MG-Si) purification, solar grade (SOG) or electronic grade (EG) silicon construction, silicon ingot crystallisation, wafer slicing, PV module assembly and concludes with module and laminate construction [9]. A simplified PV system process is shown in Fig. 2 to provide a better understanding.

Firstly, the silica (also known as silicon dioxide, SiO_2) is collected, placed into an arc furnace and undergo carbothermic reduction process (using carbon electrodes with wood, charcoal and coal). This process draws a huge amount of energy whilst a considerable amount of output product gas, CO_2 is emitted into the atmospheres.

Silica is reduced into metallurgical grade silicon (MG-Si, at least 98% purity) but needs to be further refined and purified due to the presence of impurities. Purification process produces an output of either electronic grade silicon (EG-SI, 9N purity or 99.9999999%) or solar grade silicon (SoG-Si, 6N purity or 99.9999%). Silicon purification is described by various methods such as Siemens process, modified Siemens process, Czochralski process or Schumacher process depending on the purity of silicon required for certain PV application.

Siemens process plays a large role in determining the silicon's grade and purity levels. Efficiency is crucial in PV application, therefore silicon is required to be in a high grade of purity. The process uses Hydrogen (H_2) and trichlorosilane ($SiHCl_3$) to produce high purity poly silicon and silicon tetrachloride ($SiCl_4$). It has to

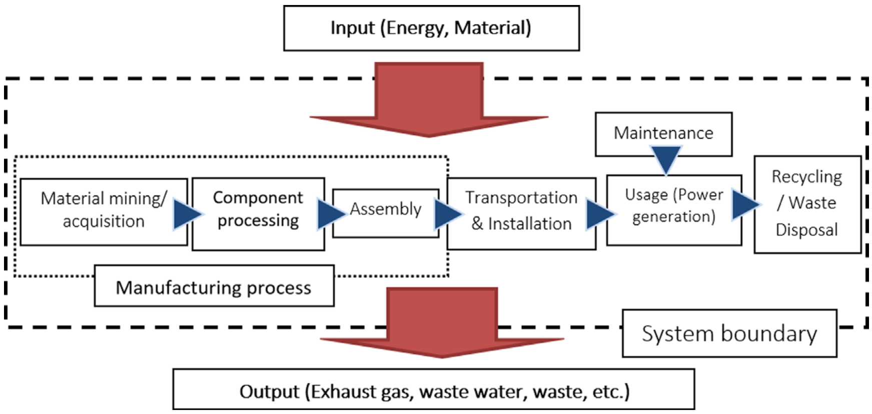

Fig. 1. System boundary of hybrid c-Si PV system.

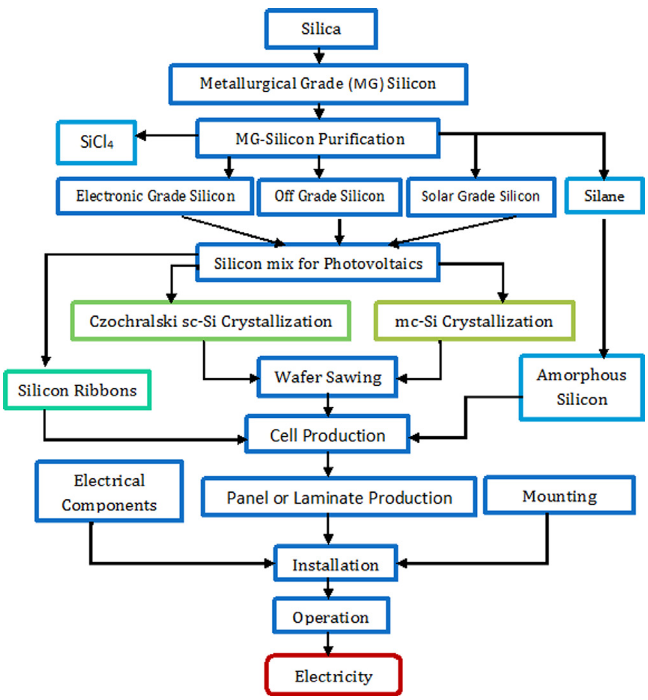

Fig. 2. Manufacturingprocessofsiliconbasedphotovoltaicmodules.

operate at a high working temperature condition (typically 1100–1200 °C) for an optimum reaction to occur [10].

The main drawback of Siemens process is that it consumes a huge amount of energy due to its high working temperature in the reaction chamber. Lately, various solar modules were produced using modified Siemens process because it requires less energy. The process temperature is approximately 800 °C therefore energy usage would be lower [11,12] and this affects the overall performance of the PV system life cycle. Apart from the traditional methods, a number of novel processes are currently being developed (e.g., fluidised bed reactor process). Fluidised bed reactors can reduce energy usage by 570 MJ primary energy for producing 1 kg of mc-Si relative to Siemens process [13].

The PV industry has been producing a larger silicon wafer area over the growing years. During earlier silicon generation, the typical size of silicon wafers was $100 \times 100\ \text{mm}^2$ which later increased to $125 \times 125\ \text{mm}^2$. Recent solar cells are currently $156 \times 156\ \text{mm}^2$ with a common thickness of 180–270 μm. Silicon ingots are usually mechanically sawed into columns with a cross section which is governed by the final wafer size [14]. For mc-Si, the wafer's thickness is commonly 180–240 μm [15–17].

3.1. Embodied energy requirement

Embodied energy requirement or life cycle energy requirement is an overall energy consumed during the three phase cycle (production, operation and maintenance, recycle/disposal) of any goods, services or technology. This evaluation is imperative to analyse and determine the efficiency of the PV system because energy inputs are commonly related to GHG emission. Hence, it is crucial to understand whether a technology either contributes or mitigates global warming. Researchers began investigating the embodied energy requirement of crystalline silicon (c-Si) PV system to determine its feasibility and durability to replace non-renewable energy resources.

Hunt [18] estimated an energy requirement value of 3588 kWh per kilogram to produce silicon solar cells from raw silica material. The Energy Payback Time (EPBT) was 12 years for terrestrial cells due to excessive input energy. The author noted that there were various inaccuracies incorporated under analysis section because limited information was available and the article primarily focused upon embodied energy content of silicon per kilogram. Thus, the article ignores other input data such as secondary cell manufacturing process and sub-materials involved.

Brown [19] conducted a LCA study on a 300 kW sc-PV plant in Austin and stated that the total embodied energy requirement was 16.5 GWh, or 6300 kWh/m^2 (total surface of 2620 m^2). The energy value includes PV modules, BOS components and indirect energy utilisation for installation/site preparation. Phylipsen and Alsema [20] conducted a LCA based on mc-Si PV modules and concluded the embodied energy content was 1145 kWh/m^2. The PV cells accounts for 970 kWh/m^2 of total embodied energy content while the frame module accounts for the remaining 175 kWh/m^2.

Wilson and Young [21] reported another embodied energy requirement value of 2496 kWh/m^2 based upon past study conducted by Hagedorn [22]. The latter figure was taken because each stage of silicon wafer and module materials were closely related and corresponded to the proposed (BP Solar) modules specification [23]. Therefore, the embodied energy content was concluded to be the most reliable at the moment. Hagedorn's figure proposed a worst case scenario of 450 μm wafer thickness manufactured under a single shift facility.

Dones and Frischknecht [8] reviewed on present and future grid connected PV embodied energy requirement based on sc-Si and mc-Si cell technologies under Switzerland's irradiation conditions. The direct energy requirement for 3 kW$_p$ sc-Si and mc-Si per unit were 11,060 kWh/ kW$_p$ unit $^{-1}$ and 18,770 kWh/kW$_p$ unit $^{-1}$. The authors assumed that the energy requirement considers all processes from MG-Si production to module fabrication and also incorporating all indirect contributions (BOS components and transportation needs).

Kato et al. [24] explored the embodied energy requirement for sc-Si PV production modules with three system boundary conditions for silicon wafer production. The energy allocations in wafer silicon production were between 4159 MJ/m^2 and 15,524 MJ/m^2. MG-Si production through Czochralski process and wafer production were the main contributors to high energy allocation requirement because these processes were conducted at very high temperature and had bad yield (15,524 MJ/m^2). The proposed option was to consider silicon tetrachloride as a secondary product made from the manufacturing process of silicon. The authors concluded the best method to examine the total energy requirement was based on mass distribution (approximately 11,670 MJ/m^2).

Alsema [25] conducted numerous PV studies for both sc-Si and mc-Si embodied energy requirements. The author had determined the most accurate and practical estimate conditions for assessing embodied energy requirement based upon previous studies. The only main uncertainty was the supply of silicon materials, thus producing a range of estimates. Since the late 1990 s, the input of EG-Si production in their LCA studies had been excluded [25]. This is due to the decreased demand and was undesirable by many PV manufacturers owing to high energy consumption and cost in production process. Since then, the market share of EG-Si had decreased to a small significant percentage (5%) in 2005. Another justification was that this simplifies the allocation issue on life cycle inventory data between "full spec" and "off spec" silicon thus allowing data to be more easily gathered and computed.

Assumptions in LCA studies such as silicon purification and crystallisation processes were the major influences for crystalline silicon modules. The values vary between 5300 MJ/m^2 and 16,500 MJ/m^2 for sc-Si technology and between 2400 MJ/m^2 and 7600 MJ/m^2 for mc-Si technology. Other assumptions could be explained by further minor factors such as wafer thickness and wafer silicon losses by two different c-Si technologies. Table 1 summarises the constituents of total embodied energy requirements for c-Si systems.

Alsema [25] estimated embodied energy requirement for sc-Si and mc-Si modules were given as 5700 MJ/m^2 and 4200 MJ/m^2 (Table 1). Sc-Si crystallisation and contouring process requires a much higher energy requirement in contrast to mc-Si process. This is a major apparent drawback for sc-Si production even though it has higher conversion efficiency but require much higher energy intensity during production.

Kannan et al. [7] studied a 2.7 kW$_p$ solar PV system in Singapore and reported the total energy utilisation throughout the whole lifecycle to be 2.94 MJ/kWh (primary energy consumption over electrical energy production). The embodied energy requirement considers all secondary inputs such as aluminium (9.7%), concrete (0.1%), metal recycling (7.5%), inverters (0.9%), and transportation (0.5%). The PV module manufacturing was responsible for the majority life cycle energy consumption (81%).

Table 1
Breakdown of energy requirement for both mc-Si and sc-Si module production [25].

Process	mc-Si	sc – Si
MG-Siproduction (MJ/m^2)	450	450
Siliconpurification (MJ/m^2)	1800	1800
Crystallisation& contouring (MJ/m^2)	750	2300
Wafering (MJ/m^2)	250	250
Cellprocessing (MJ/m^2)	600	550
Moduleassembly (MJ/m^2)	350	350
Totalmodule(frameless)(MJ/m^2)	4200	5700

Nawaz and Tiwari [26] observed embodied energy for both PV modules and BOS components in manufacturing phase and estimated a value for open field and roof-top PV system to be 6156 MJ/m^2 and 1380 MJ/m^2. Fthenakis et al. [27] carried out an embodied energy requirement study on a sc-Si PV module in various locations and regions. The energy demand in different countries differed, i.e. from 3942 MJ/m^2 for Norway to 5096 MJ/m^2 for Korea. The largest proportion of the total energy requirements came from poly silicon purification process followed by sc-Si crystallisation process.

Kim et al. [28] reported 518.4 MJ of energy was needed to produce 1 kg of sc-Si ingots. On the other hand, 123.1 MJ energy was consumed during the production of mc-Si silicon ingots. The primary source of differences in embodied energy content consumed during manufacturing process was identical to previous LCA studies conducted by Kato et al. [24] and Alsema [25]. Sc-Si ingots go through a high temperature process of approximately 1500 °C whereas mc-Si ingots are allowed to cool and crystallised at room temperature (25 °C).

Based on evaluations from past to present studies (refer to Tables 2 and 3), there has been a gradual decrease in embodied energy requirement for both PV technologies from higher than 10,000 MJ/m^2 in the early 1990s to around 3000 in 2014. Technology in manufacturing process had grown rapidly in the PV industry and continuous improvements are predicted in the future. Tables 2 and 3 present the results of past embodied energy requirement for sc-Si and mc-Si PV module. The various reasons behind the reduction of embodied energy requirement are listed below:

(1) Increase in silicon material process efficiency. This includes decreasing the PV wafer depth thus reducing the amount of silicon material needed for production process.
(2) Lower energy consumption and silicon purity is achieved by substituting electronic grade silicon purification process with devoted silicon process.
(3) Improved crystallisation process such as modified Siemens process and float zone process which decrease the energy needed for producing sc-Si.
(4) Reduction, reuse and recycling of silicon materials.

3.2. Development of single crystalline photovoltaic module

Brown [19] constructed a LCA for 300 kW PV power plant in the United States. The analysis contained all stages from construction, operation and maintenance, and the net power output. Results were compared with the power output and CO_2 production from a 747-MW$_e$ coal burning power plant analysed by past authors [29,30]. The PV module conversion efficiency and lifecycle was 8.5% and 30 years. The PV plants generated a GHG emission of 280 g CO_2-eq./kWh whilst the coal burning plant generated a much higher CO_2 production, close to 1000 g CO_2-eq./kWh. The majority of CO_2 production took place during the construction phase of PV power plant. On the other hand, the coal burning plant produced 97% of the CO_2 primarily during its operation phase from fossil fuel combustion. The author concluded that PV power plant emitted much less CO_2 over a 30 years lifecycle than coal burning plant.

A study had been conducted between two buildings in United Kingdom in 1996 on sc-Si PV system with conversion efficiency of 12%. The EPBTs for two PV systems were between 7.4 and 12.1 years [21]. Various circumstances such as theoretical optimal location, constant positive irradiation circumstances and the incorporation of battery bank were used to indicate the EPBT. Different module orientations on two building causing dissimilar solar irradiation were the parameters that cause different EPBTs between the studied buildings [21]. At that period of time, it seemed that PVs appeared to be highly undesirable due to long EPBT and their high cost was a major issue. The authors concluded that more research and studies had to be conducted to improve the PV efficiency whilst reducing the energy required and cost of raw materials (mainly silicon) in PV module production.

Kato et al. [24] conducted a LCA on sc-Si PV system in Japan and the modules were manufactured using present production technology. In the case of including off-grade silicon to the PV cell production and taking into consideration the energy required for all production process from MG-Si process, Siemens process and Czochralski process, the EPBT was 11.8 years and CO_2 produced was 61 g CO_2-eq./kWh. The LCA was performed under irradiation of 1427 kWh/m^2/yr. On the contrary, disregarding off-grade silicon and treating it as a waste product from total silicon production process will considerably decrease the EPBT to 3.3 years but authors felt it was too optimistic to assume otherwise. Nonetheless, expanding PV production magnitude from 10 to 100 MW/year would reduce one third of the total embodied energy requirement and CO_2 emission. Apart from increasing PV production, another solution was to design frameless PV modules which reduce the amount of aluminium and glass material needed in the future.

Dones and Erischknecht [8] summarised that the sc-Si PV system required huge amounts of raw materials consumption and was an energy intensive process. However, the total GHG emission was much lower than the conventional non-renewable system in the long run. In forthcoming years, the GHG emission would reduce with less material utilisation and lower energy demand during the manufacturing stage.

An LCA study [7] was conducted in Singapore for a 2.7 kW$_p$ sc-Si PV system. Two metrics were used to illustrate the findings which were EPBT and GHG emission with good energy yield. The findings illustrated that EPBT and GHG emission were 6.74 years and 217 *g* CO_2-eq./kWh. The results were based upon assumed conversion efficiency of 11.86%, irradiation of 1635 kWh/m^2/yr and lifecycle of 25 years. Besides investigating the proposed PV system, various solutions were suggested by Kannan et al. [7] to reduce the embodied energy requirement. Firstly, mass production will decrease the rate of energy usage. If production was multiplied by a factor of two, the energy usage would drop by 50%. As a result, the EPBT and GHG emission would be 3.5 years and 129 g CO_2-eq./kWh. An alternative would be to replace (or reduce) aluminium utilisation in module production for supporting structure. By replacing the amount of aluminium used in the manufacturing process, total energy requirement was reduced since the energy usage and cost for aluminium were eliminated. Another approach would be integrating solar modules within the building as a single assembly hence eliminating the additional support structure function.

From 2000 to 2006, various studies were conducted and updated by Alsema in collaboration with different researchers based on actual production data obtained from PV manufacturers for PV technology [15,25,31,32]. The studies were conducted in various EU locations and under the assumed irradiation of 1700 kWh/m^2/yr. There was a decrease in both EPBT and GHG emission for sc-Si PV system over the years. In 2000, the EPBT was 2.5 to 3 years and GHG emission was 50 to 60 gCO_2-eq./kWh. Alsema [31] predicted that there was a definite possibility of further reduction in both EPBT and GHG emission for future PV systems. In a follow up study, the EPBT decreased from 2.7 in 2004 to

Table 2
Energy requirement for manufacturing single crystalline silicon photovoltaic module.

Authors	Year	Si Feedstock (MJ/m^2)	MG-Si (MJ/m^2)	CZ Process (MJ/m^2)	Wafer Process (MJ/m^2)	Cell Production (MJ/m^2)	Module Assembly (MJ/m^2)	Frame(MJ/m^2)	Total (MJ/m^2)
Yueetal. [35]	2014	1231.6	–	1436.8	307	308.8	615.8	–	3900
Fthenakisetal. [27]	2012	–	446	1841	581	643	772	Frame(379)	4662
Lalemanetal.[34]	2011	–	2397	432	–	–	684	–	3513
LuandYang [33]	2010	–	162	1119	432	–	684	Frame	2397
DeWild – Scholten [32]	2009	–	728	1266	–	389	477	Frameless	2860
Jungbluthetal. [14]	2009	888	141	1208	562	595	466	Frame	3860
Alsema and De Wild-Scholten [30]	2005	–	1759	2391	–	473	394	Frame(236)	5253
Knapp and Jester [31]	2001	–	3950	4100	–	–	–	–	8050
Alsema [30]	2000	1800	450	2300	250	550	350	*Frameless*	5700
Alsema et al. [29]	1998	1900	500	2400	250	600	350	*Frameless*	6000
Kato et al. [24]	1998	797	298	9808	–	261	509	–	11,673

Table 3
Energy requirement for manufacturing multi crystalline silicon photovoltaic module.

Authors	Year	SI Feedstock (MJ/m^2)	Wafer Process (MJ/m^2)	Cell Production (MJ/m^2)	Module Assembly (MJ/m^2)	Frame(MJ/m^2)	Others (MJ/m^2)	Total (MJ/m^2)
Yue et al. [35]	2014	1222.8	658.4	339	790	-	-	3010
Zhai and William [40]	2010	1260	420	550	350	150	–	2730
Jungbluthetal. [14]	2009	1030	968	544	523	Frame	–	3065
DeWild – Scholten [32]	2009	1110	744	378	467	Frameless	–	2699
Alsema and De Wild-Scholten [39]	2007	1400	550	400	500	Frame(270)	–	3120
Paccaetal. [38]	2007	–	3247	–	–	–	–	4322
Alsema and De Wild-Scholten [37]	2005	1759	1078	473	276	Frame (236)	118	3940
Battisti and Corrado [36]	2005	3904	535.6	113.3	556.2	–	36	5150
Alsema and Nieuwlaar [25]	2000	2200	1000	300	200	Frame (400)	500	4600
Alsema et al. [29]	1998	2250	1000	600	350	Frameless	–	4200
Kato et al. [24]	1998	1562	717	353	709	–	39	3380

2.6 years in 2005. Similarly, GHG emission reduced from 45 g CO_2-eq./kWh to 41 g CO_2-eq./kWh [32].

Over the years, various methods had been devised to produce thinner PV wafers in order to reduce the input materials and energy usage while implementing more efficient techniques that produce higher cell quality and lower kerf loss. Kerf loss is associated with any type of cutting and sectioning of materials that determine edge quality and surface finish aspects. Jungbluth et al. [33] stated that approximately half the silicon ingots were lost due to kerf losses. The sawing dust is mixed with the abrasive sawing slurry. The used sawing slurry can be recycled (thus lowering the embodied energy of PV) but currently, there is no commercial known process able to recycle the sawing dust.

Many PV systems have preference to utilise sc-Si PV modules in recent years. They are considered a mature technology (1st generation), providing much higher efficiency, reliability, and durability for converting sunlight to electrical energy. Sc-Si SunPower module E20 series (efficiency, η=20.1%) currently possesses the highest conversion efficiency amongst other modules in the market. According to the manufacturer's data, E20 Series has the capability to deliver large amounts of energy per peak power due to its excellent low light feature combined with its anti-reflective glass panels [34,35].

Fthenakis et al. [27] conducted a comparative study between SunPower sc-Si PV module and other sc-Si PV modules. Modern cell design and materials were used in the SunPower PV modules that produce significantly higher conversion efficiency. Moreover, the energy inventories invested in the module manufacturing was considered to be distinctive from the traditional crystalline silicon module processes. The study established that an increase in conversion efficiency would result in lower environmental impacts. This was because higher efficiency PV system would require smaller amount of land area on a kilowatt basis. The EPBTandGHG emission for SunPower sc-Si PV system were 1.4 years and 642 g CO_2/W. The NEPV (Net Energy Present Value) being generated after EPBT (1.4 years) would be higher compared to other sc-Si PV system (approximately 1.7 years). Findings were based on average U.S irradiation (1800 kWh/m^2/year). There is a possibility to achieve higher conversion efficiency, i.e. as high as 29% (theoretical limit). However, in an actual silicon PV cell, this is not achievable and researchers foresee that efficiency would be limited to 26% conversion efficiency.

Table 4 presents the results and summary of sc-Si PV systems from 1990 to 2014. The EPBT varied from 1.4 to 12.1 years. There were variations in many studies due to several factors such as PV module conversion efficiency, irradiations levels (low, medium, high), manufacturing process technology (silicon feedstock preparation), different assumptions and types of installation (residential, commercial buildings, or large power plant system). The GHG emission were between 30 and 280 g CO_2-eq./kWh.

3.3. Development of multi crystalline photovoltaic module

Multi-crystalline photovoltaic modules are made up from silicon off-cuts. They consist of bits and small pieces of pure crystals to create a cell. As the individual crystals are not perfectly aligned together, mc-Si PV modules are not as efficient as sc-Si PV modules. Losses at the joints between crystals contribute to lower efficiency. Main advantage of mc-Si is that they require a smaller amount of embodied energy requirement. Thus, mc-Si PV system is expected to provide shorter EPBT and lower GHG emission compared to sc-Si PV system.

Phylipsen and Alsema [20] conducted a LCA study based in Southern Europe (irradiation of 1700 kWh/m²/yr). The conversion efficiency of the mc-Si modules was given as 13% (worst case scenario). The performance ratio for the mc-Si module was 0.75 and the EPBT was 2.7 years. The author estimated approximately half the embodied energy required than the former value specified by Hagedorn [22], and Hagedorn and Hellriegel [36]. It was due to the assumption of thinner silicon wafers (300 μm versus 450 μm) and dedicated production route for higher purity silicon causing higher process yield leading to an overall lower energy demand.

Table 4
LCA results review of single crystalline silicon PV systems.

Authors	Year	Location	Mounting type	Irradiation (kWh/m^2/yr)	PR	Module efficiency (%)	Lifecycle (Year)	EPBT (Year)	GHG emission (g CO_2-eq./kWh)
Kim et al. [28]	2014	South Korea	Ground Mounted	1301.35	0.80	15.96	30	4.65	41.8
Fthenakis et al. [27]	2012	United States	Ground Mounted	1800	0.80	20.1	30	1.4	64.2
Ito et al. [51]	2010	China	Ground Mounted	1702	0.78	N/A	30	2.5	50
Lu and Yang [33]	2010	Hong Kong	Roof Mounted	1600	N/A	13.3	20-30	7.3	671
De Wild-Scholten [32]	2009	Europe	Roof Mounted	1700	0.75	14	30	1.75	29
Fthenakis et al. [12]	2008	Europe	Ground Mounted	1700	0.80	14	30	2.7	36
Jungbluth et al. [50]	2007	Switzerland	Roof Mounted	1117	0.75	14	30	3.3	N/A
Kannan et al. [7]	2006	Singapore	Roof Mounted	1635	N/A	11.86	25	5.87	217
Muneer et al. [49]	2006	United Kingdom	N/A	800	N/A	11.5	30	8	44
Alsema et al. [15]	2006	Europe	Roof Mounted	1700	0.75	14	30	2.1	35
Alsema and de Wild-Scholten [37]	2005	Europe	Roof Mounted	1700	0.75	13.7	30	2.6	41
Jungbluth [9]	2005	Switzerland	Roof Mounted	1117	N/A	16.5	30	3.0–6.0	79
Mathur et al. [48]	2002	India	N/A	1800	N/A	13	20	3.2	60
Knapp and Jester [31]	2001	United States	N/A	1700	0.80	N/A	30	4.1	N/A
Alsema [30]	2000	Europe	Roof Mounted	1700	0.75	14	30	2.5–3	50–60
Kato et al. [24]	1998	Japan	Roof Mounted	1427	0.81	12.2	20	8.9	61
Dones and Frischknecht [8]	1998	Switzerland	Roof Mounted	1117	N/A	16.5	30	N/A	114
Frankl et al. [47]	1998	Italy	Ground Mounted	1700	0.85	11.2	25	9	200
Kato et al. [46]	1997	Japan	Roof Mounted	1427	0.81	N/A	20	15.5	91
Wilson and Young [21]	1996	United Kingdom	Roof Mounted	573–1253	0.80	12	20	7.4–12.1	N/A
Brown [19]	1990	United States	Ground Mounted	N/A	N/A	8.5	30	N/A	280

Furthermore, the data for energy requirement was more accurate and recent in contrast to Hagedorn's data.

Kato et al. [24] carried out LCA in Japan based upon mc-Si conversion efficiency of 12.8%, performance ratio of 0.81, lifecycle of 20 years and irradiation of 1427 kWh/m²/yr. The findings concluded that the EPBT and GHG emission were 2.4 years and 20 g CO_2-eq./kWh. Alsema et al. [37] conducted another study in 1998 for mc-Si ground mounted and roof mounted PV system. The EPBT was estimated to be from 3 to 8 years (irradiation of 1700 kWh/m²/yr) and was presumed to decrease further in the forthcoming years to 1.2–2.4 years.

In the following years, the EPBT of mc-Si (conversion efficiency, 13%) was approximately 2.5–3 years for a roof mounted system and 3 to 5 years for a large ground mounted system [31]. The performance ratio was rated as 0.75 and lifecycle of 30 years. The GHG emission was between 50 and 60 g CO_2-eq./kWh.

Alsema and Nieuwlaar [25] conducted similar LCA study in Western Europe (assumed irradiation of 1700 kWh/m²/yr) comparing two different mc-Si conversion efficiencies which were 15% and 17%, respectively. It was observed that with similar approach to manufacturing process and production, the estimated EPBT for 15% and 17% mc-Si modules were 2.1 and 1.9 years respectively. The GHG emissions for 15% and 17% mc-Si modules were 30 g CO_2-eq/kWh and 20 g CO_2-eq./kWh.

Obtaining more revised figures on PV technology in 2004 to early 2005, the EPBT of mc-Si PV system ranged from 1.5 to 2 years and GHGemission was 36 g CO_2-eq./kWh. All estimation parameters remained constant from previous studies except for an increase in conversion efficiency, 13.2% [38]. These values were once more updated by the author with an actual measured data given by PV manufacturers for mc-Si modules. The authors presented an EPBT and GHG emission of 1.9 years and 36 g CO_2-eq./kWh, with similar conversion efficiency, 13.2% [15].

Ito et al. [39] examined the sustainability of a very large scale PV system in Gobi desert, China. The purpose of this study was to conduct an analysis from an economic and environmental point of view to determine whether the PV scheme was feasible and profitable. The EPBT and GHG emission were 1.7 years and 12 g CO_2-eq./kWh, respectively. These results were exceptionally low and the author speculated that PV plants were indeed a promising alternative energy resource in terms of energy and environment benefits for Gobi district in years to come.

Stoppato [40] conducted a LCA in Italy and found the EPBT and GHGemission to be 3.7 years and 569 g CO_2-eq./kWh, respectively, under irradiation of 1552 kWh/m²/yr. The PV systems were mc-Si grid connected and installed at an angle of 30°. The author estimated an EPBT of 6.5 years for a worst scenario where PV module lifecycle was assumed to be 28 year, operating under a low irradiation level of only 890 kWh/m²/ yr. The author agreed with the previous findings reported by Alsema [31] and concluded that the EPBT of PV system was correlated to the improvements in module production and reduction in wafer thickness. In the future, the author predicted a reduction in wafer thickness from 300 µm to 200 µm (in 2010) and ultimately 150 µm (in 2020). Apart from that, new silicon process technology to produce silicon wafers would possibly decrease the silicon rejection during cutting phase. In an optimistic future condition, the EPBT of 2 years had been estimated by the author with a constant conversion efficiency increment of 17% in 2010 and 18% in 2020. The EPBT for three various geographic locations were summarised in Fig. 3.

Müller et al. [41] analysed the environmental impacts using recycling process for mc-Si PV modules. The authors stated that the recycling route has a much lower environmental impact compared to other methods of managing PV waste products. High energy usage is required to produce new wafers and by recycling silicon wafers, 70% of cumulative energy is being recovered and

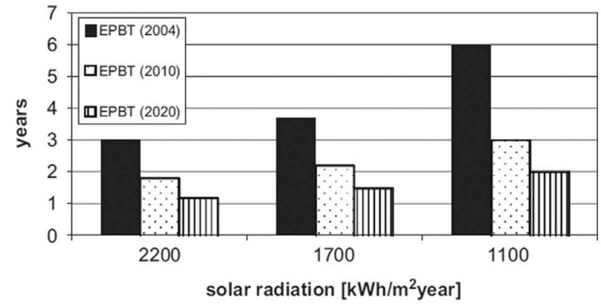

Fig. 3. : EPBT evolution for different solar irradiation values.

Table 5
Energy consumption of module with new wafers and module with recycled wafers [56].

	NewModule	RecycledModule
Waferproduction	355	-
Recyclingprocess	-	92
Cellprocessing	66	66
Moduleassembly	38	38
Total	**459**	**196**

the corresponding EPBT of PV module decreased from 3.3 years to 1.6 years (EPBT of new module assumed to be 3.3 years). Table 5 shows energy consumption of both new and recycled modules in kWh per module. Another key benefit from recycling PV modules was the recycled PV modules would attain higher conversion efficiency of approximately 14%. This was due to newer technology and processing method implemented in the recycled cell manufacturing production.

A modern technique was developed by Elkem Solar Silicon (ESS) to manufacture solar grade silicon whilst serving as an improved alternative method to traditional Siemens process. There was a 66% reduction in energy consumption by employing ESS technology in solar grade silicon production relative to traditional Siemens process. Glockner et al. [42] employed the ESS technology in the LCA study on mc-Si roof mounted system and concluded that the EPBT was as little as 1.1 years and GHG emission was estimated to be 23 g CO_2-eq./kWh. Through conventional Siemens process, the EPBT would be 1.6 years assuming an irradiation concentration of 1700 kWh/m²/yr.

Ito et al. [43] performed another LCA of very large scale photovoltaic systems (VLS-PV) located at Gobi desert district. The VLS-PV systems were assumed to have an irradiation of 1702 kWh/m²/yr and performance ratio of 0.78. The EPBT and GHG emission for mc-Si PV system were 2 years and 43 g CO_2-eq./kWh, respectively.

Sumper et al. [44] conducted a LCA on a 200 kW roof mounted PV system in Spain. From the re-evaluation of previous work and literatures, they discovered that there were considerable variations and inconsistency in the EPBTs and GHG emissions. The EPBTs varied from 1.7 to 9 years and the GHG emission varied from 22 to 180 g CO_2-eq./kWh. The authors expressed that fluctuation in values might be caused by various boundary setups for each study, different grid mix generation used for module production, and different production technologies. In the revised mc-Si LCA study, effects of solar irradiation on EPBT were included and the authors conducted a sensitivity analysis to determine a more accurate EPBT estimation. By increasing the solar irradiation from 1408 kWh/m²/ yr to 1930 kWh/m²/yr, theEPBT was reduced from 4.94 to 3.67 years.

Yue et al. [45] stated that despite the fact that the largest demands were in Europe, most PV modules were outsourced and manufactured in non-OECD countries (e.g., China), which have a substantially diverse degree of industrialisation and environmental law restriction. Embodied energy requirement in the overseas manufacturing scenario was evaluated to be 30% higher and the carbon footprint was roughly double the amount of a domestic manufacturing scenario (Domestic = 31.8 g CO_2-eq./kWh, Overseas = 69.2 g CO_2-eq./kWh). Analysis and results were based on Southern European conditions with mc-Si conversion efficiency of 13.2% and a performance ratio of 0.75. The EPBT and GHG emission for mc-Si PV modules manufactured in Europe were 1.6 years and 31.8 g CO_2-eq./kWh. In contrast, PV modules manufactured abroad illustrated a higher EPBT and GHG emission of 2.3 years and 69.2 g CO_2-eq./kWh. Overseas manufacturing production uses a large portion of coal for electricity generation which is the least climate friendly fossil fuel because of its high carbon intensity. Yue et al. [45] concluded that even though lower cost of silicon PV modules could be achieved in the overseas manufacturing scenario, contribution to the risk of global warming was actually twice as much.

Kim et al. [28] employed LCA methodology to evaluate the EPBT and GHG emission of mc-Si PV system in Korea. If present electricity grid mix in Korea was partly incorporated with the mc-Si PV system, the EPBT and GHG emission would be 3.68 years and 31.5 g CO_2-eq./kWh. Mc-Si PV system were able to reduce more environmental impact than sc-Si PV system because of lower energy consumption from ingot crystallisation process. Hence, mc-Si PV system was considered a better choice of alternative energy source than sc-Si PV system.

Table 6 lists the results and summaries of mc-Si systems from 1995 to 2014. The reviewed results for EPBT showed figures from 1.4 to 5.7 years and GHG emissions were from 12 to 569 g CO_2-eq./kWh. Differences in various studies were influenced by several parameters such as conversion efficiency, irradiations level, and types of installation (roof mounted or ground mounted systems).

3.4. Differences between sc-Si and mc-Si

Sc-Si modules consist of a single cylindrical cut of silicon crystal, resulting in a region of uncovered modules located at every edge [46] while mc-Si does not [47]. Sc-Si PV modules can easily be distinguished by their black or iridescent blue appearance. Sc-Si PV modules are generally considered space efficient modules since they yield higher conversion efficiency than mc-Si. Mc-Si PV modules generally require larger surface to produce the same power output when compared to sc-Si. Ito et al. [43] found out that mc-Si VLS-PV systems produced the least GHG emission.

The main unfavourable factors of sc-Si are higher embodied energy requirement to produce PV modules, longer EPBT and high cost when compared to mc-Si. It was found that the silicon wafer production step was the major contributor in electrical energy consumption (56% for single and 52% for multi silicon) [8]. Mc-Si total energy requirement process requires less than two thirds of sc-Si and usually presents a shorter EPBT. The higher energy requirement for sc-Si is due to the additional silicon purifying (Czochralski process) to produce a continuous sc-Si structure, leading to an increase in cost and environmental impacts [41]. Czochralski process is essential as it increases the wafer's resistance to thermal stress that are induced internally and offers a high oxygen concentration (gettering agent) to remove any metal impurities from the active region surfaces in order to achieve a high and reliable device performance (also known as Internal Gettering) [48].

Mc-Si modules have lower conversion efficiency than sc-Si modules because mc-Si cells are grown in multiple orientations which form random crystal boundaries. The benefit of mc-Si is that the silicon crystals are grown and cut out in square wafers rather than the rounder shape of sc-Si crystalline cells, therefore mc-Si can achieve more solar module area and less waste of space. Resistance is represented in the formation of heat and because mc-Si is heavier and has lower purity. The internal resistance increases as surrounding temperature increases. Sc-Si has a lower level of internal resistance due to Czochralski manufacturing processes that produce higher purity to lower density ratio compared to mc-Si. This reduces the internal resistance of sc-Si, thus exhibiting higher conversion efficiency. This resistance loss effect is more pronounced in mc-Si.

Table 6
LCA results review of multi crystalline silicon PV systems

Authors	Year	Location	MountingType	Irradiation ($kWh/m^2/yr$)	PR	ModuleEfficiency (%)	Lifecycle(Year)	EPBT (Year)	GHGemission (g CO_2-eq./kWh)
Yue et al. [35]	2014	South Europe	Roof Mounted	1700	0.75	13.2	30	1.6	31.8
Kim et al. [28]	2014	Korea	Ground Mounted	1310	0.8	14.9	30	3.68	31.5
Desideri et al. [63]	2012	Italy	Ground Mounted	1552	0.8	14.4	25	4.17	88.7
Nishimura et al. [62]	2010	China	Ground Mounted	1701	0.8	15.8	20	1.73	N/A
Ito et al. [51]	2010	Japan	Ground Mounted	1725	0.78	N/A	30	2	43
Zhai and William [40]	2010	South Europe	Roof Mounted	1700	0.75	13.2	30	1.4	24
De Wild-Scholten [32]	2009	Europe	Roof Mounted	1700	0.75	13.2	30	1.75	28
Stoppato [55]	2008	Italy	Roof Mounted	1552	N/A	16	28	3.7	569
Stoppato [55]	2008	Italy	Roof Mounted	1251	N/A	16	28	4.8	569
Ito et al. [61]	2008	China	Ground Mounted	1702	0.78	12.8	30	1.9	12.1
Pacca et al. [38]	2007	United States	N/A	1359	N/A	12.9	20	5.7	72.4
Raugei et al. [60]	2007	South Europe	Roof Mounted	1700	0.75	14	20	2.4	72
Jungbluth et al. [50]	2007	Switzerland	Roof Mounted	1117	0.75	13.2	30	2.9	N/A
Fthenakis and Alsema [53]	2006	Europe	Roof Mounted	1700	0.75	13.2	30	1.5–2	36
Alsema and De Wild-Scholten [15]	2006	Europe	Roof Mounted	1700	0.75	13.2	30	1.9	32
Battisti and Corrado [36]	2005	Italy	Roof Mounted	1530	0.8	10.7	30	3.3	N/A
Hondo [59]	2005	Japan	Roof Mounted	1314	0.77	10	30	N/A	53.4
Ito et al. [54]	2003	China	Ground Mounted	1675	0.78	12.8	30	1.7	12
Alsema and Nieuwlaar [25]	2000	West Europe	Roof Mounted	1700	0.75	13	30	3.2	60
Alsema and Nieuwlaar [25]	2000	West Europe	Roof Mounted	1700	0.75	15	30	1.7	30
Alsema [30]	2000	Europe	Ground Mounted	1700	0.75	13.2	30	3.2	60
Kato et al. [24]	1998	Japan	Roof Mounted	1427	0.81	12.8	20	2.4	20
Dones and Frischknecht [8]	1998	Switzerland	Ground Mounted	1117	N/A	14	30	N/A	189
Phylipsen and Alsema [20]	1995	Europe	Roof Mounted	1700	0.75	13	25	2.7	N/A

Sopori et al. [49] studied the presence of a degradation phenomenon in crystalline modules termed light induced degradation (LID). LID is a loss of PV module performance upon exposure to light energy (from 1% to 3% loss in conversion efficiency). This effect primarily depends on the composition and quality of the silicon being used in wafer manufacturing. LID mainly affects traditional p-type boron-doped wafers using Czochralski process (most typical sc-Si PV modules are manufactured in this way). However, the sc-Si PV module E series are not affected by LID due to a distinctive process using n-type doped wafers [50].

Kim et al. [28] conducted a LCA study on PV system in Korea. They found that mc-Si PV system obtained a lower GWP and fossil fuel consumption values for existing conversion efficiency. The EPBT for sc-Si and mc-Si PV system would be reimbursed in 3.11 and 2.97 years. In addition, the GWP for sc-Si and mc-Si PV system would be compensated in 1.66 and 1.53 years.

Table 7
Summary of differences between cc-Si and mc-Si PVs.

Attributes	Sc-Si	Mc-Si
Efficiency[a]	15.84%	14.11%
EPBT (years)[a]	3.52	2.33
Processes	Siemens and Czochralski	Siemens
Si wafer production's electrical energy consumption relative to the total embodied energy requirement	56	52
Embodied energy requirement[a]	3532 MJ/m^2	2876 MJ/m^2
GHG emission (g CO_2-eq./kWh)[a]	171.2	41.2
Silicon wafer thickness (μm)	155	200
Shape of wafer	Rounder thus inducing more waste space	Square thus inducing less waste space

[a] Average values from more recent years (2009–2014).

4. Discussion

This study shows a small difference between sc-Si and mc-Si EPBT values. Despite sc-Si PV technology demanding more energy to produce the PV module, its conversion efficiency is greater than mc-Si. The differences in early studies for all silicon based PV systems largely originated from uncertainties and absence of actual energy requirement data for types of silicon feedstock, silicon purification and crystallisation process. Both sc-Si and mc-Si show a reduction in embodied energy requirement over the years. However, regardless of newer technologies such as incorporating modified Siemens process and dedicated silicon feedstock route in PV process, currently manufacturing high purity sc-Si PV module still require greater energy input than mc-Si PV technologies.

A different approach had been proposed to manufacture a type of crystalline silicon PV that is able to closely exhibit the best features of sc-Si high conversion efficiency and combines the cost and low energy requirement of mc-Si. A hybrid c-Si (a combination of single and multi-crystalline) manufacturing is derived from a concept of utilising the benefits of mc-Si low energy intensive process with additional seeded directional solidification technique of sc-Si [51]. This creates a higher cell quality and performance than mc-Si whilst closer to present sc-Si conversion efficiency when made by Czochralski process. Hybrid c-Si falls between two aforementioned PV modules with a higher efficiency rating than mc-Si PVs while having a lower manufacturing energy process and cost compared to sc-Si PVs. Another key characteristic of hybrid c-Si manufacturing process was a reduction in waste from silicon wafer sawing process and better scrap utilisation. Present crystalline silicon PV techniques result in a significant amount of waste, particularly sc-Si process (generally found after silicon ingot sawing).

Aside from increasing the conversion efficiency over the years, efforts have been made to reduce the thickness of silicon wafer used in PV modules to preserve expensive high grade silicon materials; wafer thickness reduced from 300 to 200 μm with modern methods such as edge-defined film-fed growth to produce wafers. The current thickness of hybrid, sc-Si and multi c-Si were reported to be 130, 155, and 200 μm. Silicon wafer thickness has a significant effect on the PV module efficiency; a thicker wafer will absorb a comparatively larger amount of sunlight than a thinner wafer. However, this effect can be mitigated by the use of reflective back-coatings which increase chances of photon capture while decreasing the thickness.

Table 7 succinctly summarises the major differences between mc-Si and sc-Si.

5. Future work

The major process of converting silicon feedstock to solar grade silicon involves a large amount of electricity consumption. The possibility of incorporating reused and recycled PV modules back into the production processes of PV modules could eliminate a significant portion of embedded energy of new MG-Si and reduce the EPBT of c-Si PV technologies.

Various types of energy loss would occur in the actual PV module operation. Energy loss in PV is taken into consideration when defining the Performance Ratio (PR). The PR is the ratio of actual energy output over theoretical energy output of a PV system. The factors governing the PRs of both sc- and mc-Si are similar, i.e. module temperature, dirt and dust coverage of the array, mismatch and wiring losses, and DC to AC conversion losses. Over the last 20 years, the average PR has improved from 0.66 to 0.84 (see Woyte et al. [52] for a concise coverage of ways to increase PR). The PR however does not take into account thermal degradation for which mc-Si is much more susceptible. Most LCA researchers assume a life cycle of 30 years for both types of Silicon systems (refer to Tables 4 and 6). Thermal degradation and subsequently shorter life cycle of mc-Si should hence be incorporated into future LCA research.

In the future, smaller surface area and reduction in wafer thickness suggest that less raw material and primary energy will be required in PV production leading to an improvement in EPBT. Due to higher conversion efficiency, a nominated power output can be met by smaller surface area. Electricity mix for the production of PV affects GHG emissions of PVs, whereby for example, if electricity is derived from a fossil fuel plant, the GHG emission of PV will increase. Utilising renewable energy such as PV energy for PV production could considerably reduce the environmental impact of module manufacturing.

An actual analytical energy model is recommended in future LCA study which includes real world operational losses calibrated against field data. Such a model can capture actual PV operating cell temperature, influence of PV module orientation and hourly irradiation and weather data to provide greater insight into sc-, mc- and hybrid crystalline silicon systems. Apart from LCA, conducting a lifecycle cost analysis is also a possible extension of this research. Unlike mc-Si and sc-Si, life cycle inventory database for hybrid crystalline Si is still missing, hence the lack of LCA studies on hybrid c-Si. The majority of hybrid c-Si are under experimental and development stages and no information currently exist on their installed volumes [53,54], therefore future work should include updating life cycle inventory database of hybrid-Si. Since hybrid c-Si is incorporating part of a single cast technology, there might be a probability that hybrid c-Si PV modules are also affected by LID (light induced degradation). This needs to be further investigated.

Grid efficiency should take into account: (i) conversion efficiency of various types of primary energy sources being converted to electricity, (ii) transmission efficiency of electricity, and (iii) grid efficiencies of leading PV manufacturers (i.e. China, Japan, Germany, Taiwan, Malaysia, USA, Korea, Spain, India, Mexico (de Wild-Scholten, 2013) [45]). Future research could therefore shed light on the extent to which embodied energy requirement (or primary energy requirement) of PV production in these countries differs. It is worth noting that, grid efficiency around the world can be estimated from energy mix data made available by the latest IEA PVPS Task 12 report [55], Garrain et al. [56] and Itten et al. [57]. The conversion factors (primary energy sources to electrical energy) are published in report by IINAS [58].

6. Conclusion

Within publications that were examined in this work, significant variations existed on operational and manufacturing GHG emission of sc-Si and mc-Si PV modules. These were fundamentally due to the range of input parameters that included quality and amount of silicon consumed, PV module efficiency, assumed PV lifecycle, and location irradiation profiles. Differences in installation, such as building integrated vs. free-standing systems, as well as PV modules orientation, direction and performance of the BOS also have notable effects on the GHG emission results.

Improvements in conversion efficiency decrease the PV module GHG emissions, since larger lifetime electricity output is guaranteed with equivalent manufacturing efforts and similar solar energy availability. At lower conversion efficiencies PV module requires additional arrays (collection of PV modules) and BOS components thus more materials, energy demand and pollutant emission. Therefore, improvement in conversion efficiency is key to improve the environmental profile of c-Si PV systems.

Despite a degree of variations, the this review work's main conclusion found the embodied energy requirement and the EPBT of sc-Si to be reported higher than mc-Si because the former has an additional Czochralski process which requires a significantly high energy input. While higher manufacturing energy results in greater conversion efficiency for sc-Si, it is insufficient to lower sc-Si's EPBT to levels comparable to ms-Si. Sc-Si modules however out-perform mc-Si not only on conversion efficiency, but smaller space requirement too.

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