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Life cycle assessment of perovskite solar cell based on rapid convective deposition at electron transport layer

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Abstract

Photovoltaic (PV) devices made of perovskite materials have much potential to become an excellent source of energy with high-power conversion efficiency (PCE) as well as being environment-friendly. Perovskite solar cells (PSCs) will be a rising star in the PV market share due to their efficiency that has increased substantially over the past few years. PSCs have additional advantages of being environment-friendly, having high PCE, and are low cost. This paper reports on a life cycle assessment (LCA) of PSCs with an electron transport layer produced by a rapid convective deposition method instead of the conventional spin coating technique used in other reports. The advantage of using the rapid convective deposition technique is that it offers low material consumption compared to the conventional spin coating technique. LCA can assess the environmental consequences and energy consumption of a product over its whole life cycle according to ISO 14040:2006 and ISO 14044:2006. In the LCA process, the greenhouse gas (GHG) emissions and the energy payback time (EPBT) of PSCs were compared to those of crystalline silicon (c-Si) solar cells, both mono-Si solar cells and multi-Si solar cells. The LCA results showed that PSCs had the shortest EPBT compared to other solar PV technologies. Future research developments should improve the PCE, increase the lifetime, and reduce the materials and energy consumption of PSCs to further reduce GHG emissions and EPBT.

Keywords: Perovskite solar cells, Rapid Convective Deposition, Crystalline silicon solar cells, Life cycle assessment, Photovoltaic technologies, Environmental analysis, Greenhouse gas emission, Energy payback time

1. Introduction

Solar energy is a renewable energy source that refers to the exploitation of direct solar radiation [1]. Solar radiation can be harnessed by using a photovoltaic (PV) cell to produce electricity through a PV effect process [2,3]. In the next 15 years, solar energy is predicted to replace fossil fuel energy that releases greenhouse gas (GHG). Solar energy has better electric conversion efficiency and a lower environmental impact than fossil fuels [4]. Carbon dioxide emission from electricity generation using fossil fuel is the largest source of GHG emissions that creates heat in the atmosphere, causing various subsequent climate changes.

PV devices based on crystalline silicon (c-Si), which account for approximately 90% of the global market share, are the most important photovoltaic technology, with a power conversion efficiency (PCE) range of 13-16% [5,6]. Silicon solar cells offer the advantage of having a photoactive absorber material that is stable, abundant, and well known compared to other PV technologies. However, silicon wafer production lines involve high-energy consumption and high toxicity. On the other hand, Perovskite solar cells (PSCs) are excellent prospects for future

solar cells because they are less complicated in manufacturing, have a potentially higher PCE, and involve more flexible panel fabrication than silicon solar cells [7]. The developmental progress of PSCs has been the fastest in terms of PCE, increasing from 3.8% in 2009 to 25.2% in 2020 [8].

Life cycle assessment (LCA) assesses the environmental consequences and energy consumption of a product over its whole life cycle according to ISO 14040:2006 and ISO 14044:2006 [9,10]. Many PV technologies have had their environmental consequences assessed using LCA. Aside from the life cycle effect indicators used in traditional LCA studies, one of the most commonly used sustainability metrics to compare PVs is the energy payback time (EPBT), which assesses how long it takes a PV device to generate the same amount of energy as was used to manufacture the device.

Although solar cells have advantages as a source of renewable energy with less GHG emissions than conventional fossil fuel energy sources, there may be concerns about GHG emissions and other environmental impacts in other phases in the life cycle, such as production, waste management, and recycling.

In this work, a cradle-to-gate LCA of PSCs was investigated using the rapid convective deposition method to create an electron transport layer to evaluate the environmental impacts of PSCs. Compared to the spin-coating method, the rapid convective deposition method uses less raw material consumption for laboratory-scale solar cells and is suitable for scale-up to commercial-scale solar cells, offers thickness adjustability, and has better solar cell performance [11,12]. The vapor deposition method generates 70% material loss while the spin coating method loses 90% during production process [13]. EPBT and GHG emissions were also calculated and compared to those from mono-Si solar cells and multi-Si solar cells to gain better understanding of the PSCs in the context of other well-established crystalline silicon technologies. Furthermore, sensitivity analysis was undertaken of EPBT and GHG emissions concerning the uncertainties of lifetime and PCE to guide the development of PSCs for environmental sustainability.

2. Materials and methods

The work was divided into 2 parts: 1) preparation of the perovskite solar cell (PSC) and 2) collecting data for an environmental impact assessment using LCA.

2.1 Preparation of perovskite solar cell

The structure of a PSC consists of an anode layer, an electron transport layer (ETL), a perovskite layer, a hole transport layer (HTL), and a cathode layer, as listed in Table 1 that shows the specific types of materials used in each layer. The preparation of PSC layers is shown in a process flow diagram in Figure 1.

Table 1 Structure of perovskite solar cell with rapid convective deposition at electron transport layer.

Layer	Component
Anode layer	Fluorine-doped tin oxide (FTO) coated glass
Electron transport layer	TiO_2
Perovskite layer	$CH_3NH_3PbI_3$
Hole transport layer	$C_{81}H_{68}N_4O_8$(Spiro-OMeTAD)
Cathode layer	Gold

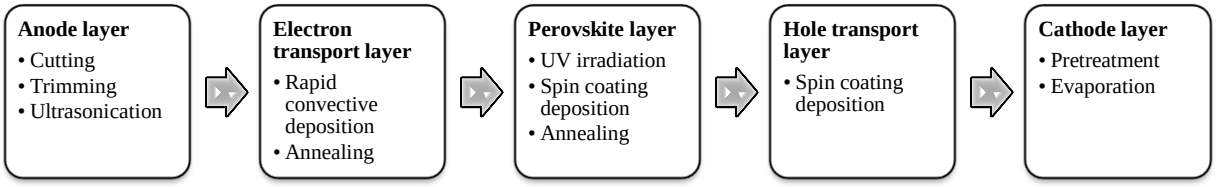

Figure 1 Process flow diagram of perovskite solar cell.

The first anode layer is made of transparent conductive oxide (TCO) glass, which is either fluorine-doped tin oxide (FTO) or indium tin oxide (ITO). FTO coated glass (Luminescence Technology Corporation; Taipei, Taiwan; 25 × 25 mm, 5 Ω/sq.) was chosen because it is less expensive and is commonly used in the photovoltaic market [14]. The FTO-coated substrates were first cleaned in an ultrasonic bath with Alconox® detergent solution, rinsed with deionized water and then with isopropyl alcohol.

For the ETL, TiO_2 solution was prepared from a mixture of titanium solgel in ethanol solution [15]. During the synthesis, 2.7 mL titanium (IV) butoxide (97%; Sigma Aldrich; MO, USA), 0.57 mL ethyl acetoacetate (99%; Sigma Aldrich; MO, USA), 57 µL 2,4-pentanedione (99%; Sigma Aldrich; MO, USA) and 57 µL 2,3-butanedione (97%; Sigma Aldrich; MO, USA) were mixed and stirred at room temperature overnight. TiO_2 was coated on the FTO coated glass using the rapid convective deposition method, as shown in Figure 2 [11,16] with a deposition speed of 3,000 µm/s for two layers [17] and annealed at 500°C for 1 hour to improve the electron migration efficiency because annealing can be a high-energy cost [18]. The rapid convective deposition method is a process to prepare thin film on a nanometer scale. A schematic diagram of the rapid convective deposition method, shown in Figure 2, consists of a deposition blade and a controllable translation stage. The deposition procedure was: (1) using only 40 µL TiO_2 solgel to deposit a thin film per 6.4516 square centimeters in area between the deposition blade and the substrate; (2) dragging the substrate away horizontally at a speed of 3,000 µm/s to generate a thin-film; (3) completely evaporating the TiO_2 solgel, leaving a thin coating on the substrate.

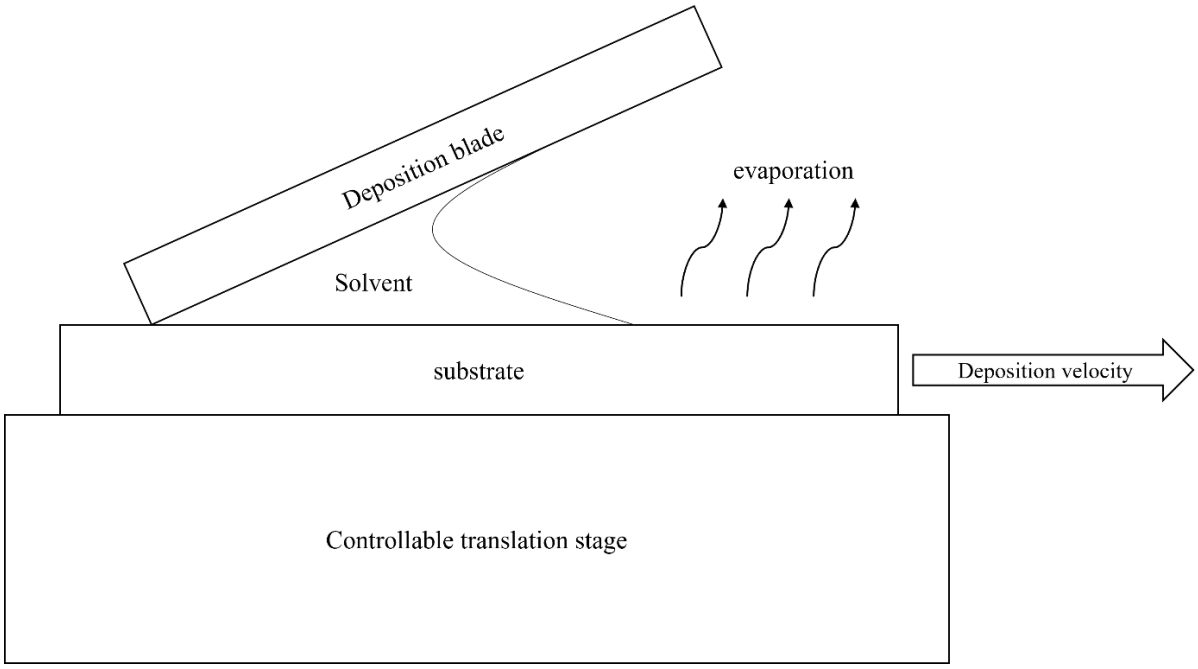

Figure 2 Schematic representation of rapid convective deposition method to produce an electron transport layer.

For the perovskite layer, the cell was treated with an ultraviolet (UV) irradiation device to increase the PCE [19]. After that, perovskite solution in 1:4 (v/v) Dimethylformamide (DMF): Dimethyl sulfoxide (DMSO) was spin coated onto the ETL layer at 1,000 rpm for 10 sec, followed by 30 sec of spin coating with chlorobenzene solution at 3,500 rpm to generate the $(Cs_{0.05}(FA_{0.85}MA_{0.85})_{0.95}Pb(I_{0.85}Br_{0.15})_3$ perovskite absorbing layer. For MAPbIxCl3-x ink formation, 2.4 g of MA iodide (CH_3NH_3I; MAI) (Ossila Ltd.; Sheffield, UK) and 1.4 g PbCl2 (Sigma Aldrich; MO, USA) were mixed and stirred in 5 mL anhydrous dimethylformamide (Sigma Aldrich; MO, USA) at 70°C for 2 hours. Then, the cell with the perovskite layer was annealed at 100°C for 90 min before the next step.

The HTL was created at 4,000 rpm by HTL spiro-OMeTAD solution spin coating onto the perovskite layer. Then, the sample was kept in a vacuum environment overnight.

To deposit the cathode layer, the cell was cleaned with dimethylformamide and acrylonitrile as a pretreatment process. After that, a patterned gold contact was deposited using an evaporation method. However, gold is relatively expensive and unsuitable for mass production. It is only used on a laboratory scale.

After completing the whole process, the PSC was tested with a solar simulator with 100 mW/cm^2 (ABET technology) standard intensity and a source measurement unit (Keithley 2450) to analyze the cell performance and compared with other PV systems.

The energy payback time (EPBT) is the duration of time required for the device to produce the energy used in its manufacture. In this work, all the energy used to produce solar cells was collected throughout the life cycle to calculate the EPBT using Equation (1):

$$EPBT = E_{input} / \left(I \times PCE \times (PR/\varepsilon)\right) \quad (1)$$

E_{input} = the embodied energy (kWh/m^2) which is collected from all processes that consume energy including: ultrasonication of the anode layer (15.515 kWh/m^2), rapid convective deposition of the electron transport layer (0.011 kWh/m^2), annealing of the electron transport layer (17.281 kWh/m^2), UV radiation treatment at the perovskite layer (0.68 kWh/m^2), spin coating of the perovskite layer (68 kWh/m^2), annealing the hole transport layer (0.531 kWh/m^2), and evaporation of the cathode layer (163.26 kWh/m^2). The total embodied energy was 265.278 kWh/m^2.

I = the total solar insolation incident on the unit-surface/year, calculated from average irradiation in Thailand (18.2 MJ/m2/day or 1,845.27 kWh/m^2/year) [20].

PCE = average module efficiency (%)

PR = system performance ratio (%) from [21]

ε = electrical to primary energy conversion factor from [21]

EPBT = the time required for the device to produce the equivalent energy that was used in its manufacture (years)

2.2 Life Cycle Assessment

According to ISO 14040:2006 and ISO 14044:2006, LCA is a commonly used methodological framework for estimating and assessing the environmental consequences associated with a product's life cycle. LCA consists of 4 main steps: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation [9,10].

2.2.1 Goal and Scope Definition

The goal and scope of an LCA define the objectives, the scope of assessment, and the methods, including the functional unit used in the environmental impact assessment. The goal of this study was to evaluate the life cycle and environmental impacts of perovskite solar cells. The system boundary of the study was cradle-to-gate LCA, for which the system boundary is illustrated in Figure 3. There were 4 life cycle stages: (1) raw material acquisition; (2) production; (3). use (electricity generation); and (4) disposal. Installation of a PV system, transportation, and disposal were excluded from the system boundary compared to other PV technologies [22,23]. In addition, in this work, the production was on a laboratory scale, with some deposition methods not being applicable on a commercial scale. The functional unit (FU) of solar cells generates electricity, and our selected functional unit was 1 kWh of electricity generated. The assumption of a lifetime was 10,000 hours, as a reference from another study [24]. The efficiency was calculated from solar irradiation using the average irradiation of Thailand of 18.2 MJ/m^2/day [20].

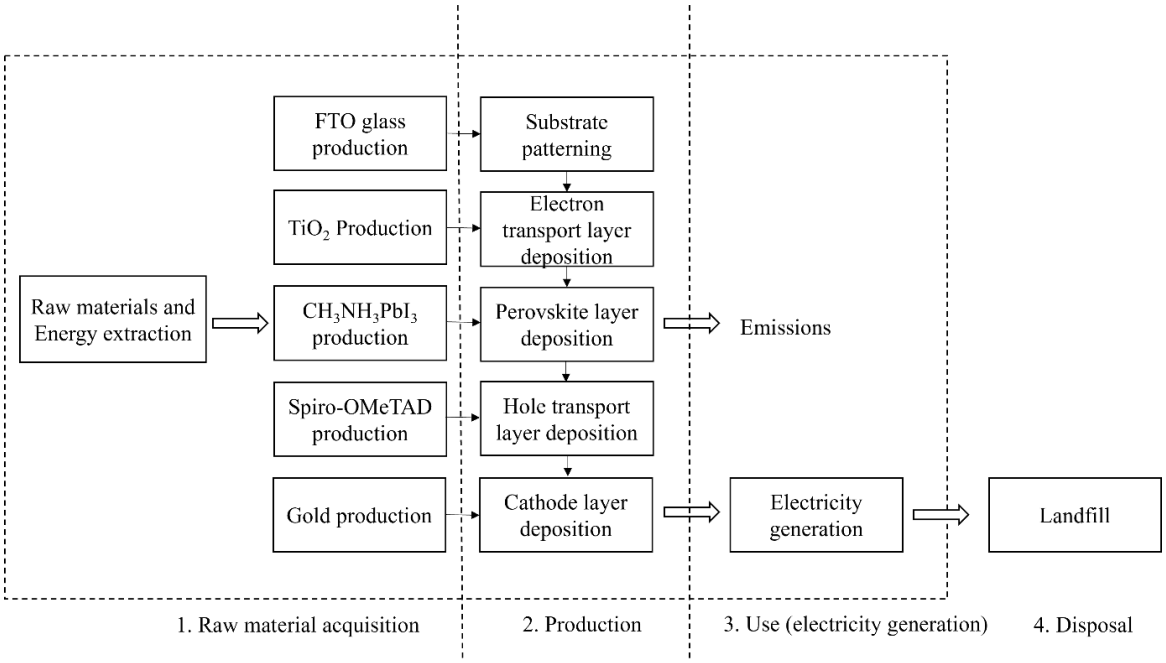

Figure 3 System boundary from cradle-to-gate of a perovskite solar cell with electron transport layer produced using rapid convective deposition.

2.2.2 Life Cycle Inventory Analysis

LCI entails compiling a list of the input and output flows from the process within the system boundary [25]. Data collected was raw materials, energy, and wastes in PSC production as primary data and quantification of each per FU. The inventory analysis calculation used secondary data references for raw material acquisition from the Ecoinvent v3 database [26] and from the Thai National Life Cycle Inventory Database for the electricity used in the production process.

2.2.3 Life Cycle Impact Assessment

LCIA evaluates the environmental impact from the incoming-outgoing substances throughout the life cycle, according to the scope determined from the inventory analysis. In this study, the impact method ILCD 2011 Midpoint+ V.1.10 in the SimaPro V.9.0.0.49 software was used to assess 16 midpoint environmental impact categories: (1) ionizing radiation E (interim); (2) water resource depletion; (3) land use; (4) ozone depletion; (5) marine eutrophication; (6) climate change; (7) particulate matter; (8) ionizing radiation human health (HH); (9) acidification; (10) photochemical ozone formation; (11) terrestrial eutrophication; (12) freshwater eutrophication; (13) human toxicity (cancer effects); (14) freshwater ecotoxicity; (15) mineral, fossil, and renewable resource depletion; and (16) human toxicity (non-cancer effects). The normalization of the international Reference Life Cycle Data System (ILCD) Midpoint+ method was also evaluated to compare the contribution of all impacts from the 16 midpoint environmental impact categories. In addition, GHG emissions (in g CO_2/kWh unit) and the EPBT were compared with those from mono-Si solar cells and multi-Si solar cells from the literature [27].

2.2.4 Life Cycle Interpretation

The final step in the LCA study was life cycle interpretation, a method for analyzing, quantifying, verifying, and evaluating information from the results of the LCI and LCIA, from which appropriate conclusions and recommendations can be drawn. In this study, the impacts throughout the life cycle of the perovskite solar cells were assessed to identify the environmental hotspots.

3. Results and discussion

3.1 Perovskite solar cell test

The prepared PSCs were tested to determine the current density and voltage (J-V) curve (as shown in Figure 4) and compared with other solar cells.

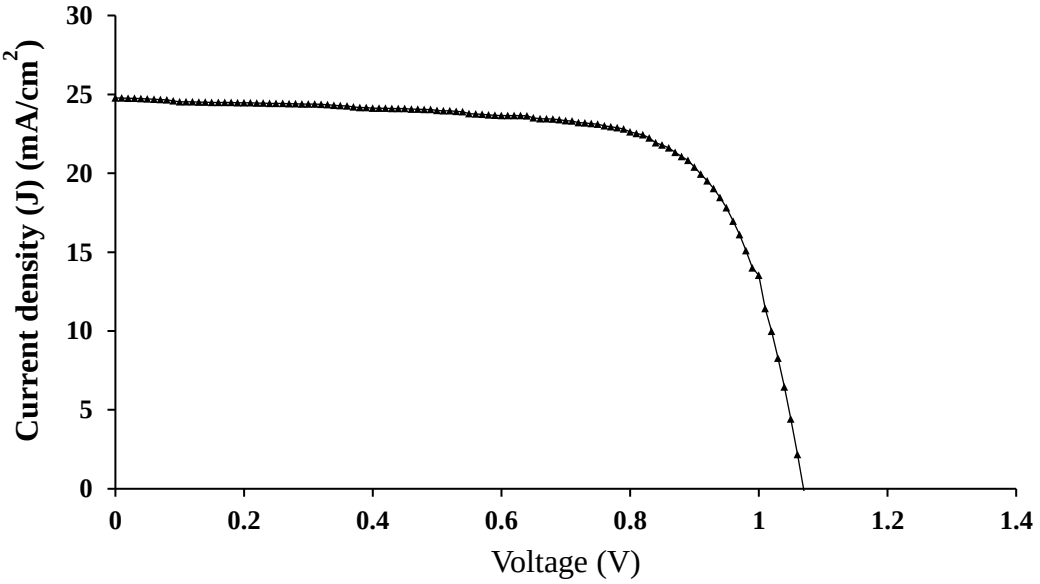

Figure 4 J-V curve of a perovskite solar cell with electron transport layer prepared using rapid convective deposition.

We get the electrical parameters of perovskite solar cell with electron transport layer prepaid using rapid convective deposition: Vov 1.06 V, Jsc 24.86 mA/cm^2, Fill factor 70.49, and PCE 18.52%.

Key performance parameters of the laboratory scale FTO/TiO_2/Perovskite/Spiro-OMeTAD/Au perovskite solar cell had the best performance values from the 28 experiments. There was a slight variation in the averaged open-circuit voltage (Voc) values in the range -0.2 to 1.2 with a maximum of 1.06. The short-circuit current density (Jsc) averaged 24.86 from the devices. The fill factor (FF) symbolizes the charge transport balance between a hole and an electron in a photovoltaic cell. The maximum FF value was 70.49. The ratio of the maximum output power to the simulated input power is represented by the power to current efficiency (PCE%), which was 18.52% in this experiment. The performance of the laboratory scale solar cell with the Cs0.05(FA0.85MA0.85)0.95Pb(I0.85Br0.15) perovskite absorber and TiO_2 electron transporting layer agreed well with other published data. The efficiency could be increased by improving the absorber and electron transport layer.

We get the energy payback time of perovskite solar cell with electron transport layer prepared using rapid convective deposition: E_{input} 265.278 kWh/m^2, I 1,845.27 kWh/m^2/year, PCE 18.52%, PR 0.75%, Ɛ 0.35 and EPBT 0.3727139 years.

The EPBT is determined by the amount of energy consumed in preparing the materials used in the system and the manufacture of its components (embodied energy and the amount of electricity produced per year), calculated from the solar irradiance, PCE, system performance ratio, and electrical input to the primary conversion factor. The EPBT for this study was 0.37 years, which was in the range 0.2-5.4 years reported from other studies [23,28-31].

3.2 Life Cycle Assessment

3.2.1 Life Cycle Inventory Analysis

The number of raw materials and energy used for synthesizing a cell that could generate 1 kWh electricity in the process were calculated as amounts per function unit. Table 2 lists the input primary data of raw materials, energy, and wastes in PSC production and outputs, which were calculated as a quantity per functional unit. In the calculation, the inventory analysis used secondary data reference for raw materials and energy acquisition from the database. The resources that were consumed the most in the perovskite solar cell preparation process were gold and electricity in the evaporation process.

Table 2 Material and energy consumption inventory of investigated perovskite solar cell per functional unit.

Input	Amount per functional unit	Unit
Glass with fluorine doped tin oxide	2.9173	g
Zinc powder	0.8620	g
Hydrochloric acid	86.2015	µL
Deionised water	34.4806	µL
Alcolox	34.4806	ml
Isopropanol	724.0930	ml
Titanium dioxide	17.2403	µL
Acetone	689.6124	µL
Perovskite	86.2015	µL
Chlorobenzene	301.7054	µL
Spiro-MeOTAD	86.2015	µL
Dimethylformamide	689.6124	µL
Gold	0.0098	g
Electricity	0.9799	kWh
Output	**Amount per functional unit**	**unit**
Emission - Hydrochloric acid	86.2015	µL
Emission - Alcolox	34.4806	ml
Emission - Titanium dioxide	15.5162	µL
Emission - Acetone	689.6124	µL
Emission - Isopropanol	689.6124	µL
Emission - Perovskite	77.5813	µL
Emission - Chlorobenzene	271.5348	µL
Emission - Spiro - MeOTAD	77.5813	µL

3.2.2 Life Cycle Impact Assessment

The LCI data were transformed to various indicators in the impact assessment phase, and these served as the foundation for examining the contributions of individual entries in the inventory to various environmental consequences. In this study, 16 midpoint indicators according to the ILCD 2011 Midpoint+ V.1.10 method were

considered to determine the environmental impacts, as listed in Table 3. The climate change impact value of 258.962 gCO_2/kWh was used for comparison with other PV systems.

Table 3 Impact assessment of investigated perovskite solar cell from ILCD 2011 Midpoint+ V.1.10 method.

Impact category	Total	Unit
Climate change	0.258962	kg CO_2 eq
Ozone depletion	2.19E-08	kg CFC-11 eq
Human toxicity, non-cancer effects	4.24E-07	CTUh
Human toxicity, cancer effects	5.91E-09	CTUh
Particulate matter	0.000171	kg PM2.5 eq
Ionizing radiation HH	0.009185	kBq U235 eq
Ionizing radiation E (interim)	7.81E-08	CTUe
Photochemical ozone formation	0.001966	kg NMVOC eq
Acidification	0.002213	molc H+ eq
Terrestrial eutrophication	0.008987	molc N eq
Freshwater eutrophication	0.001945	kg P eq
Marine eutrophication	0.00071	kg N eq
Freshwater ecotoxicity	3.028521	CTUe
Land use	0.734887	kg C deficit
Water resource depletion	-0.00139	m3 water eq
Mineral, fossil, and renewable resource depletion	0.000489	kg Sb eq

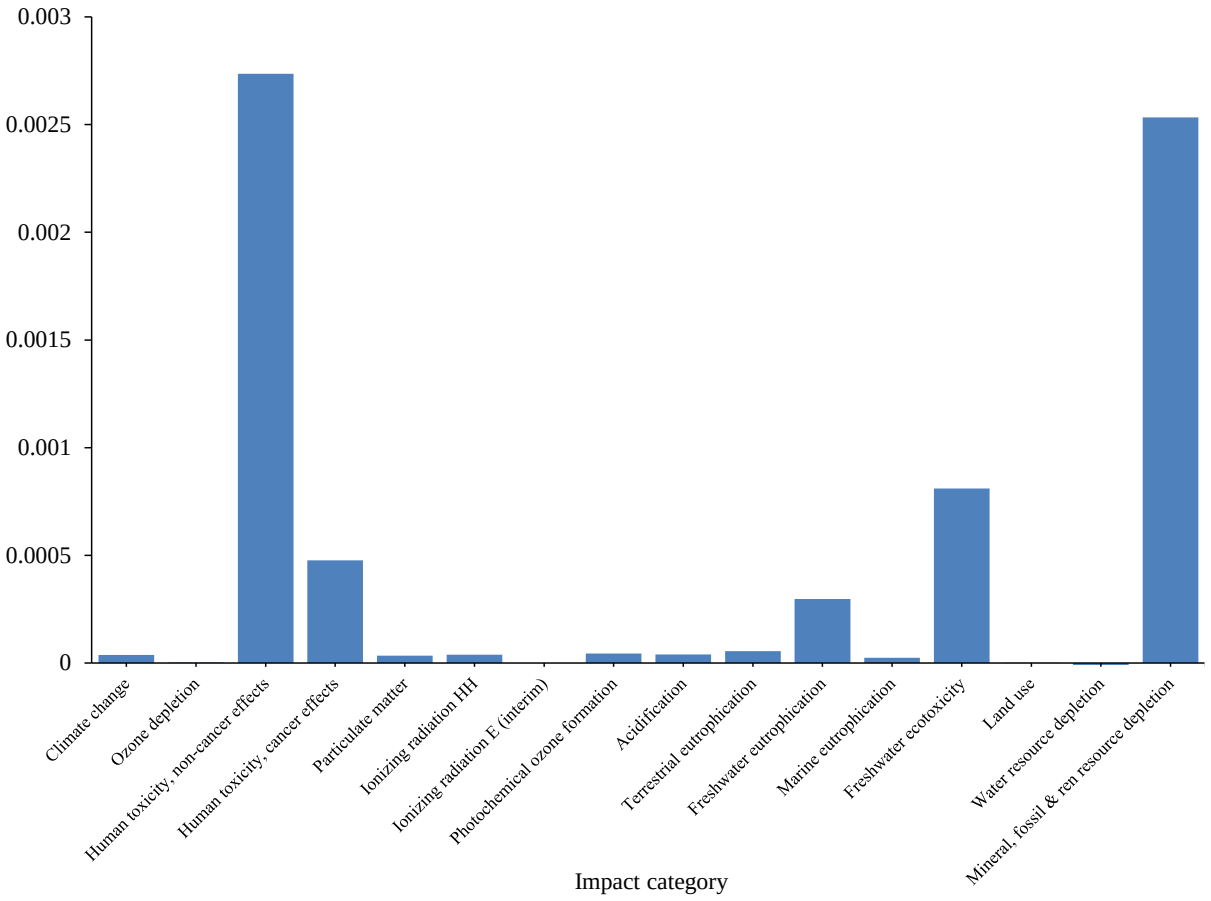

Figure 5 Normalization impact assessment of the perovskite solar cell from ILCD 2011 Midpoint+ V.1.10 method.

Comparison of the results between impact categories was not possible because the units of measure were not the same. Therefore, normalization was performed to bring the impacts to the same unit so the results could be compared. Normalization is the calculation of the magnitude of the category indicator results relative to the reference information. The normalization results of the impact category were calculated by multiplying the indicator results from characterization impacts of the impact category by the normalization factors of the impact category connected to the reference value, as shown in Equation (2):

$$\text{Normalization results} = \text{Characterization results} \times \text{Normalization factors} \quad (2)$$

The reference value may relate to a given community, person, or other systems. Each method had different normalization factors related to the reference value. For example, the characterization factor of the PSC for mineral, fossil, and renewable resource depletion impact category was 0.000489 kg Sb eq and had a fresh ecotoxicity impact category of 3.03 CTUe. Therefore, the results from different impact categories cannot be compared with their different units of measure until the characterization factor of each impact category has been multiplied by the normalization factor of the impact category connected to the reference value, namely 0.0145138 for the mineral, fossil, and renewable resource depletion impact category and 0.00026738 for the fresh ecotoxicity impact category After applying Equation (2), all the results were on the same scale.

Figure 5 shows the impacts from PSC preparation in order from high to low, namely: (1) human toxicity (non-cancer effects); (2) mineral, fossil, and renewable resource depletion; (3) freshwater ecotoxicity; (4) human toxicity (cancer effects); and (50 freshwater eutrophication. The highest impacts from PSC preparation were due to the gold process in the evaporation method used to coat gold on the cathode layer. This effect can be mitigated by choosing an alternative material to replace the use of gold in the cathode layer of PSC. Other materials may reduce energy consumption in the coating process as well. However, it is important to consider whether the efficiency of a PSC that uses a different material is cost-effective compared to using gold.

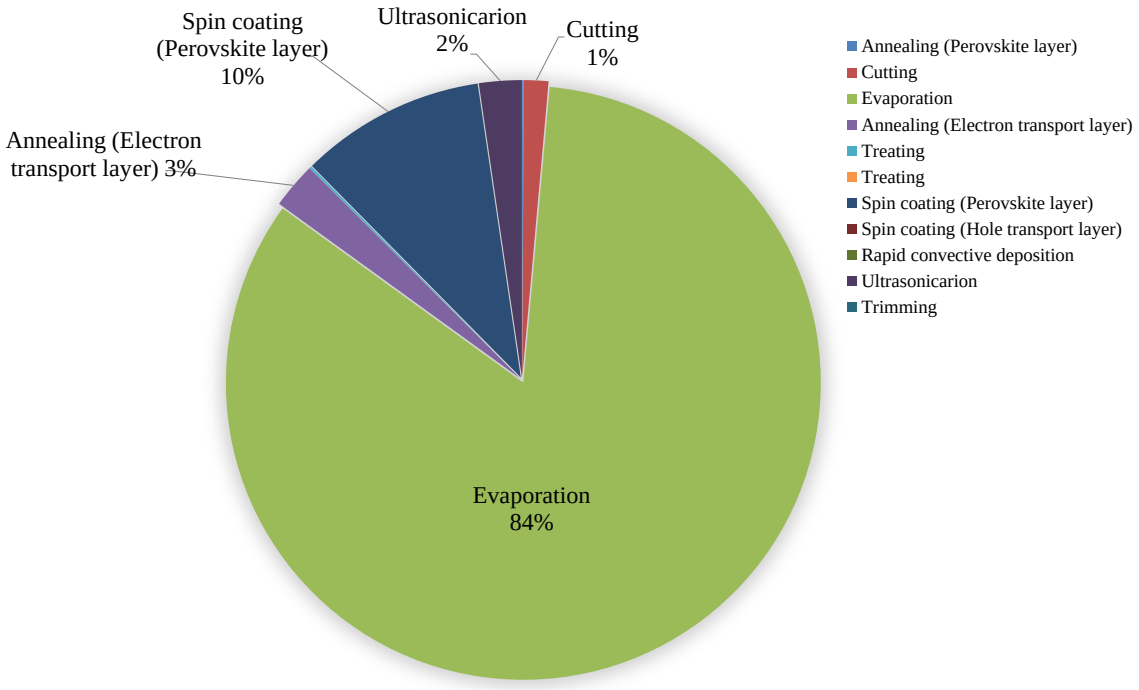

Figure 6 Characterization impact assessment climate change category of perovskite solar cell from ILCD 2011 Midpoint+ V.1.10 method.

Figure 6 shows the climate impact assessment of the PSC as a percentage. The sum of effects throughout the solar cell preparation process was 258.9621 g CO_2/kWh, with the evaporation process having the most impact, followed by spin coating, annealing, ultrasonication, and cutting.

Table 4 Summary of EPBT and GHG emissions of different solar cells.

Type of solar cells	Irradiation (kWh/m^2/yr)	PR	Module efficiency (%)	System lifetime (yr)	EPBT (yr)	GHG emissions (g CO_2/kWh)	Reference
Mono-Si	1,200	0.70	17.0	25	2.3	87.3	[27]
Multi-Si	1,200	0.70	17.5	25	2.1	81	[27]
PSC	1,845.27	0.75	18.0	1*	0.37	258.96	This study

*System lifetime of PSC was assumed as 1 year from reference [32].

Table 4 shows that the EPBT result of PSC was much lower than for the other types of solar cells. However, PSC released higher GHG emissions than the other types of solar cells due to their high embodied energy and the PSC lifetime of 1 year from the reference [32], compared to the others with a longer system lifetime of 25 years. PSC has greater energy consumption due to its shorter lifetime than others. As a result, PSC had higher GHG emissions than the other types of solar cells.

3.2.3 Life Cycle Interpretation

As listed in Table 4, mono-Si solar cells and multi-Si solar cells have 25 years lifetime that is much longer than PSC but less GHG emissions than PSC due to the high embodied energy of PSC and the short 1 year lifetime. If the PSC lifetime were increased to 20 years, using the same amount of embodied energy, the PSC GHG emissions would decrease, as shown in Figure 7.

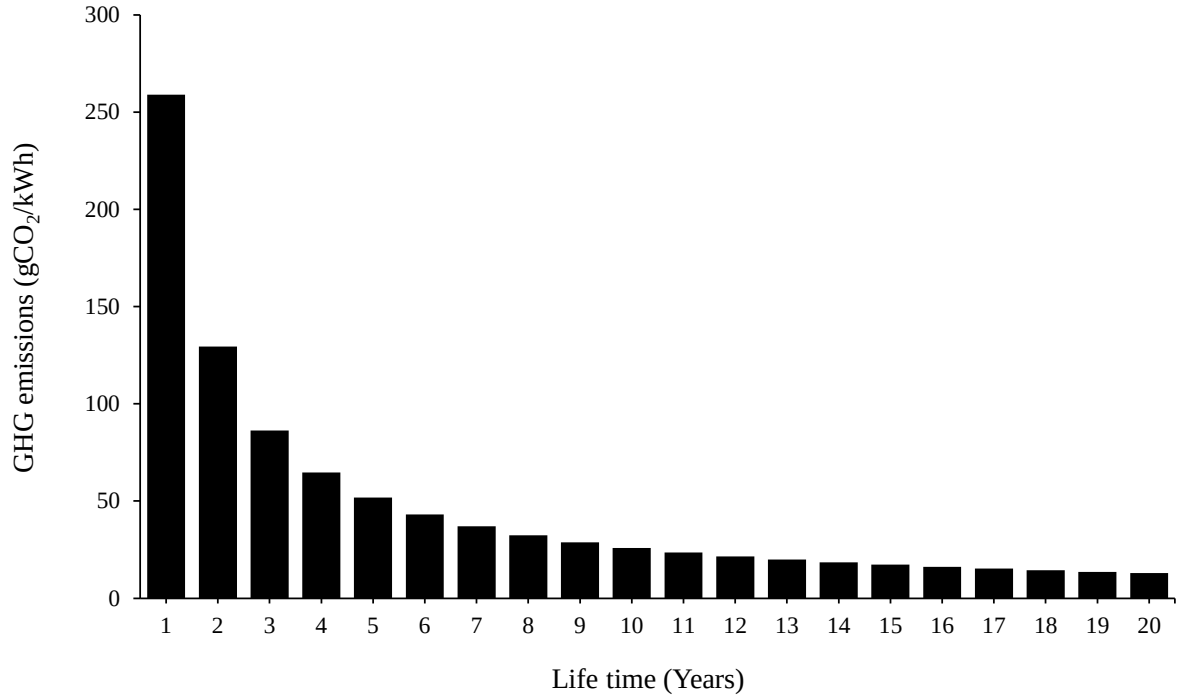

Figure 7 Sensitivity analysis of GHG emissions of perovskite solar cell for extended lifetime across 20 years.

From Table 6, the GHG emission of PSC was 258.96 g CO_2/kWh for a lifetime of 1 year. If the PSC had a longer lifetime with the same power conversion efficiency and same resource consumption, the PSC would produce the same amount of energy with less surface area, while consuming less resources and emitting less GHG over a longer lifetime.

A PSC that produces 1 kWh electricity requires a surface area of 5.56 cm^2 for a lifetime of 1 year. However, if the PSC had a 3 year lifetime, only 1.85 cm^2 of PSC surface area would be required to produce 1 kWh electricity and the GHG emission would be reduced from 258.96 to 86.32 g CO_2/kWh, which is less than for mono-Si solar cells and multi-Si solar cells. As shown in Figure 7, the lifetime impacts on GHG emissions, since a longer lifetime causes less generation of GHG emissions. Therefore, one of the primary drivers that will reduce the PSC environmental impact in the future is increasing the PSC lifetime.

The PCE is also an essential factor affecting the cell area size. As efficiency increases, the need for the cell area to produce the same functional unit decreases. Therefore, the sensitivity analysis of PCE was analyzed to examine the different effects of other cell sizes, as shown in Figure 8.

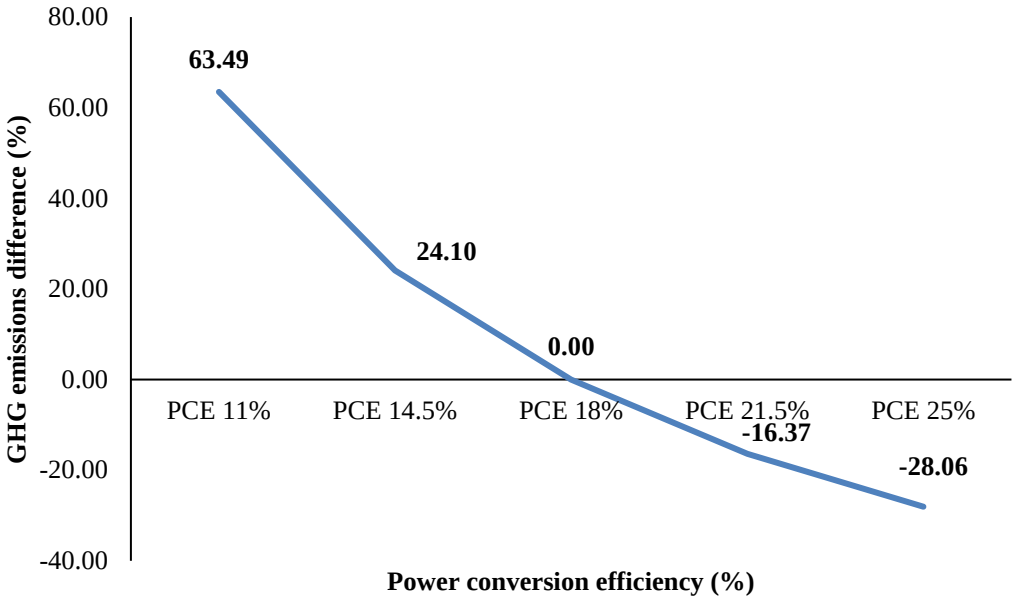

Figure 8 Sensitivity analysis for power conversion efficiency (PCE) of perovskite solar cell.

Table 5 Sensitivity analysis for power conversion efficiency of perovskite solar cell.

Power conversion efficiency (%)	GHG emissions (g CO_2/kWh)	GHG emission difference (%)
11	423.38	63.49
14.5	321.37	24.10
18	258.96	0
21.5	216.58	-16.37
25	186.30	-28.06

If the PSC power conversion efficiency is higher, the surface area of the PSC is smaller, leading to lower GHG emissions because the smaller surface area requires fewer resources and less energy consumption.

Table 5 shows that power conversion efficiency of PSC was 18% with GHG emissions of 258.96 g CO_2/kWh. If the power conversion efficiency of the PSC increased to 21.5%, the GHG emissions of the PSC would be reduced to 216.58 g CO_2/kWh. In addition, the GHG emission difference as a percentage was calculated and this indicated that the use of the 18% PCE with 258.96 g CO_2/kWh GHG emissions was the threshold. When the PCE was 25%, the GHG emissions were reduced by 28.06%. However, when the PCE was 11%, the GHG emissions increased by 63.49% despite the same 7% difference in the PCE (11%, 18%, and 25%). The effect obtained when the PCE was 11% was higher than the reduction in GHG emissions when the PCE was 25%, despite the same range of difference.

4. Conclusions

As the PSC has evolved rapidly in recent years with the unprecedented development of PCE, the PSC has become a major competitor to other PV technologies. However, there are still a few key factors that need to be solved. For example, a better encapsulation technology is required to protect cells from the external environment to improve the PSC lifetime. In brief, before any PSC can be commercialized, the lifetime problems must be solved. Even though the PSC is still in the early stages of development, it has demonstrated excellent environmental sustainability potential. This work investigated a cradle-to-gate LCA of PSC on a laboratory scale. If the LCA of a commercial-scale PSC were to be considered, the results might show less energy consumption per function unit due to different coating methods that could coat a greater cell surface. Furthermore, using other raw materials instead of gold would reduce the environmental impact as well as the cost. The life cycle environmental impact assessment on the climate change impact category used ILCD 2011 Midpoint+ V.1.10 in the SimaPro V.9.0.0.49 software. The results showed that the PSC had the shortest EPBT of 0.37 years compared

to 2.3 years for mono-Si solar cells and 2.1 years for multi-Si solar cells because of the energy consumption in the PSC preparation process was lower than for the mono-Si and multi-Si solar cells. Currently, the EPBT of the PSC was consistent and competitive. However, the life cycle and GHG emissions excluding the disposal and recycling phase of PSC were less stable with GHG emissions of 258.96 g CO_2/kWh, which was the highest value compared to the mono-Si solar cell value of 87.3 g CO_2/kWh and the multi-Si solar cell value of 81 g CO_2/kWh. This was caused by the gold coating on the PSC cathode layer that substantially increased energy consumption in the evaporation and gold production processes. In the future, it will be necessary to find alternative material instead of gold because of its high cost, high environmental impact, and high energy requirement in the evaporation and spin coating processes. The rapid convective deposition method presented in this study is one of the key optimization processes in reducing environmental impacts.

Lastly, through sensitivity analysis, in terms of future development to improve the efficiency and extend the lifetime, the PSC could be the most environment-friendly PV. If the PSC could achieve a lifetime of 3 years, the GHG emissions would be 86.32 g CO_2/kWh, which is better than for mono-Si and multi-Si solar cells. Therefore, future studies should focus on increasing the lifetime of the PSC to reduce EPBT and GHG emissions.

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