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Assessment of the Carbon Footprint, Social Benefit of Carbon Reduction, and Energy Payback Time of a High-Concentration Photovoltaic System

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Abstract: Depleting fossil fuel sources and worsening global warming are two of the most serious world problems. Many renewable energy technologies are continuously being developed to overcome these challenges. Among these technologies, high-concentration photovoltaics (HCPV) is a promising technology that reduces the use of expensive photovoltaic materials to achieve highly efficient energy conversion. This reduction process is achieved by adopting concentrating and tracking technologies. This study intends to understand and assess the carbon footprint and energy payback time (EPBT) of HCPV modules during their entire life cycles. The social benefit of carbon reduction is also evaluated as another indicator to assess the energy alternatives. An HCPV module and a tracker from the Institute of Nuclear Energy Research (INER) were applied, and SimaPro 8.0.2 was used for the assessment. The functional unit used in this study was 1 kWh, which is produced by HCPV, and inventory data was sourced from Ecoinvent 3.0 and the Taiwan carbon footprint calculation database. The carbon footprint, EPBT, and social benefit of carbon reduction were evaluated as 107.69 g CO_2eq/kWh, 2.61 years, and 0.022 USD/kWh, respectively. Direct normal irradiation (DNI), life expectancy, and the degradation rate of HCPV system were subjected to sensitivity analysis. Results show that the influence of lifetime assumption under a low DNI value is greater than those under high DNI values. Degradation rate is also another important factor when assessing the carbon footprint of HCPV under a low DNI value and a long lifetime assumption. The findings of this study can provide several insights for the development of the Taiwanese solar industry.

Keywords: high concentration photovoltaics (HCPV); carbon footprint; life cycle assessment; energy payback time (EPBT); direct normal irradiation (DNI); lifetime assumption; social benefit of carbon reduction

1. Introduction

Energy scarcity and climate change have become critical problems worldwide in the 21st century. Energy demand is estimated to increase in the near future because of economic development. According to the United Nations Sustainable Development Goals, ensuring affordable, reliable, sustainable, and modern energy services and enhancing facilitated access to clean energy research and technology are important global targets for 2030 [1]. Therefore, greenhouse gas (GHG) emissions are expected to exceed the planetary capacity and lead to an unsustainable future if humans continue to rely on traditional fossil fuels [2]. The development of renewable energy has become an optimal solution to achieve a sustainable energy system and address global sustainable development goals [3]. The total renewable energy capacity increased to 147 GW in 2015, and the solar PV capacity increased to 229 GW worldwide in the same year. The annual market was nearly 10 times larger than the world's cumulative solar PV capacity in the last decade [4,5]. Moreover, the total solar PV is expected to increase to 290 GW until 2017 [6]. The capacity of the PV solar system has increased around the world. For example, China is facing an environmental crisis because of coal and other fossil fuels. Coal causes 85% of carbon dioxide, 74% of sulfur dioxide, 60% of hydroxide, and 70% of particles in the environment. Energy demand and environmental pollution have prompted the development of the PV solar-powered system in China [7]. This system has become a strategic energy source in Europe, and its contribution to the cumulative PV installation was equal to 49% in 2014 [3,8]. A large amount of energy is consumed in the manufacture of a solar-powered system, although the operation of this system produces nearly zero GHG emission.

Several studies have evaluated the GHG emissions of various types of PV systems. Kato et al. [9] calculated the total GHG emission of a mono-Si PV system located in Japan, and the results showed roughly 61 g CO_2eq/kWh emission under irradiation of 1427 kWh/m^2/year. Held and Ilg [10] assumed that a cadmium telluride (CdTe) PV system was installed under 1200–1700 kWh/m^2/year and assessed the carbon footprint of the PV system to be in the 19–30 g CO_2eq/kWh range. Kim et al. [11] also applied life cycle assessment to calculate the carbon footprint of a CdTe PV system in Malaysia, and the result showed that the GHG emission was 15.1 g CO_2eq/kWh. Fthenakis and Kim assessed HCPVs installed in different sites to analyze the GHG emissions between 2009 and 2011 [12]. Different PV systems have different carbon footprints, and lifetime assumption and locations can affect the carbon footprint of a PV system. Laleman et al. [13] presented residential PV systems under a low solar irradiation area of 900–1000 kWh/m^2/year; the lifetime of the PV systems were assumed to be 30 and 20 years, and the carbon footprints were calculated at 80 g CO_2eq/kWh and 120–130 g CO_2eq/kWh, respectively.

In addition to the carbon footprint, the social benefit of carbon reduction was introduced in this study. The social benefit of carbon reduction is calculated according to the carbon price. The carbon price in a business strategy is an emerging issue in managing the risk of climate change in corporate sustainability, and 1249 companies disclosed their practice of pricing carbon emissions in 2015 [14]. No study has evaluated the marginal cost of carbon in a PV system. The three common approaches to value carbon prices are the market price of carbon dioxide, the marginal abatement cost (MAC) of carbon, and the social cost of carbon (SCC) [15,16]. The market price of GHGs is the cost of the emissions based on carbon taxes, trading system, and crediting mechanisms. The price of carbon covers approximately 40 national and 20 subnational markets or national policies. The prices between different countries have a significant range, that is, from US $1/ton CO_2 in Mexican tax to US $168/ton CO_2 in Swedish carbon tax. The price in the trading system is estimated to be low because the market price of carbon does not reflect on non-traded carbon cost, fuel taxes, subsidies for fossil fuels removed, and low-carbon technology support [15]. Market price can be affected by economic changes such as the low carbon price in the EU emission trading system since 2008. The MAC is based on the cost of reduction effort for policy discussions, prioritization of investments, and forecasts of carbon allowance prices. The MAC indicated the financial cost to reduce carbon rather than the benefit of GHG reduction to society [16]. The estimate of MAC is influenced by several factors, such as fossil fuel price, adoption of abatement technologies, and policy measures.

The social cost of carbon is determined by evaluating its total marginal cost of carbon for society because of the climate change effect, and SCC allows agencies to incorporate the social benefits of reducing carbon emission into the cost-benefit analyses of regulatory actions [17]. The SCC was suggested to value the marginal cost of GHGs [15,16] because it reflects the full global cost of the climate change effects on economics, environment, and society. The estimate of SCC was calculated and provided by the United States Environmental Protection Agency. The average and high estimates of SCC at an assumed 3% discount rate were 36 and 105, respectively, in 2007 USD per ton of CO_2 [17].

Energy payback time (EPBT) is another widely used environmental indicator to assess the sustainability of an energy system [18]. The EPBT indicator is defined as the years required for a PV system to generate a given amount of energy for the compensation of total energy consumption across the life cycle of a PV system, which includes raw material, transportation, assembly, operation and maintenance, and end of life [12,19]. Jungbluth et al. [20] compared different PV systems that were under the same irradiation (1117 kWh/m^2/year) to assess the EPBT. Their results showed that the EPBT of the mono-Si PV, multi-Si PV, a-Si PV, CdTe PV, and CIS thin film systems were 3.3, 2.9, 3.1, 2.5, and 2.9 years, respectively. Other studies have also recognized EPBT as an important indicator in the comparison of various PV systems [21–25]. Apart from the assumptions of radiation and life cycle, the type of PV modules, conversion efficiency, performance ratio, and electricity generation efficiency are also key factors that affect the energy output results as well as the results of EPBT and GHG emissions [18,26].

Solar power generation has been recognized as an available renewable energy source to fulfill energy demands. A high-concentration photovoltaic (HCPV) power generation system is a type of solar-powered system. The aim of HCPV technology is to lower the cost of energy by reducing the material and replacing it with an optical device that concentrates the sunlight received on a small PV [27]. HCPV has higher conversion efficiency than other traditional solar energy systems because it uses concentrating and tracking technologies. An HCPV system can be divided into two components: photovoltaic (PV) modules and a tracking system (Figure 1). PV modules are categorized into several types, including monocrystalline (mono-Si), multi-crystalline (multi-Si), amorphous silicon (a-Si), II–VI cell (CdTe thin film), III–V cells, and dye-sensitized solar cell (DSSC).

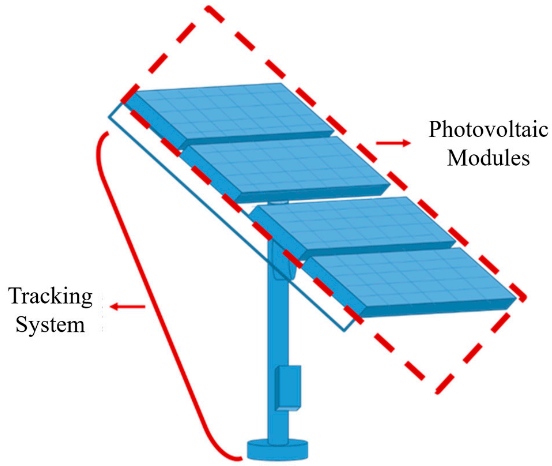

Figure 1. HCPV system (The picture was provided by the INER).

This study applied III–V cells, which have more than 40% solar conversion efficiency, as a core PV module of HCPV [28]. The PV modules were combined with Fresnel lens, III–V cells, and an inner structure. The tracking system comprises a motor, an inverter, a sensor, and a foundation. HCPV can concentrate solar energy through the Fresnel lens into the cells, transform heat and light into electricity, and receive sufficient solar energy through the tracking system. The III–V cells are composed of III–V compounds that include several metals, such as gallium arsenide and gallium antimonite. The III–V compounds manufactured through organometallic chemical vapor deposition are the key materials of the HCPV system used in this study.

However, fewer studies on HCPV system have been conducted than those on PV systems. Nishimura et al. [29] applied life cycle analysis (LCA)-NET to compare two scenarios that involve HCPV. One scenario compared the HCPV systems installed in two different locations. Another scenario compared the HPCV with III–V cells and a multi-crystalline Si (mc-Si) PV system. The result of the first scenario showed that if the recovery process factor is considered, the environmental effect of the HCPV installed in the Gobi Desert will be lower than that of the HCPV installed in Toyohashi City in Japan. The result of the second scenario showed that the environmental effect of mc-Si PV was lower than that of HCPV because the manufacturing process of the tracking system was the main GHG emission source of HCPV. EBPT was also evaluated in the same study. The results showed that the EPBT of the HCPV located in the Gobi Desert was two years in the first scenario, whereas that of the mc-Si PV in the second scenario was 1.73. Fthenakis and Kim [12] assessed the HCPV using Amonix 7700. Their findings indicated that the carbon footprint of HCPV was in the range of 26–27 g CO_2eq/kWh (under an assumed life cycle of 30 years) and 16 g CO_2eq/kWh (under an assumed life cycle of 50 years). The assessed EPBT in the study was 0.9 year.

In addition to DNI and lifetime assumption, degradation rate can be used to assess the PV solar system [30,31]. Tomosk et al. [32] and Fthenakis et al. [33] suggested that degradation rates can be assumed at 0.5% and 0.7%, which are suitable assumptions in assessing PV systems.

The present study applied LCA to evaluate the carbon footprint of a 7.5 kW HCPV, which was developed by INER [34] to understand GHG emission and EPBT through the manufacture, transport, and installation of HCPV and to compare various renewable energy sources. This study also compared several scenarios to analyze the change of carbon footprint under low DNI value, different life expectancy, and different degradation rate of HCPV to provide insights into the development of solar power generation in Taiwan. Moreover, the concept of social benefit for carbon reduction because of the HCPV replacement of the existing grid in Taiwan was introduced in this study.

2. Materials and Methods

In this study, the carbon footprint of HCPV systems, lifetime assumptions of, degradation rate, and the EPBT of HCPV were based on the guidelines on the LCA of PV systems published by IEA [33].

2.1. System Boundaries and Scope

The system boundary of this study in terms of the life cycle of a building includes the material input, manufacturing, transportation and installation, operation and maintenance, and disposal stages. The process map of 1 kWh power generated by the HCPV system was classified into five stages. All the related input–output of the materials and energy for the HCPV were used in all the stages. Figure 2 shows the details of the HCPV system boundary and scope. Simapro 8.0.2 software (PRé Consultants bv, Amersfoort, The Netherlands) was used in this study.

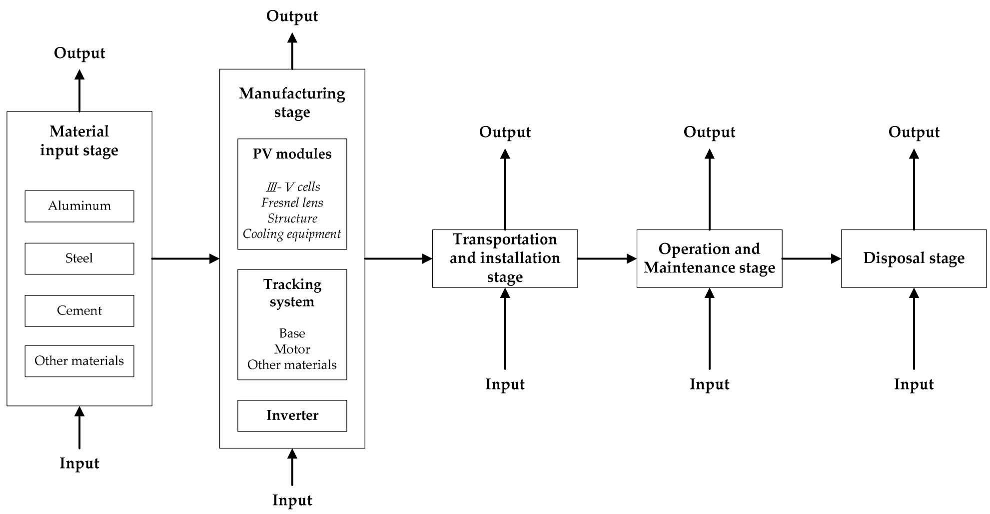

Figure 2. HCPV system boundary and scope in this study.

2.2. Functional Unit

The functional unit of the present study was defined as "1 kWh produced by HCPV". The current study also assessed the EPBT of HCPV in the comparison with other HCPV carbon footprints.

2.3. Data Collection and Assumptions

A 7.5 kW HCPV system comprises 60 PV modules and 1 tracking system, and 40 III–V cells constitute 1 PV module. A 30% HCPV conversion efficiency was assumed by INER. Energy consumption data and the list of materials for the manufacturing stage were provided by INER. Most of the carbon footprint coefficient values of similar materials were obtained from the carbon footprint calculation platform (CFCP) [35], which is a Taiwanese local database, and other data, which were not provided by the Taiwanese database, were obtained from the Ecoinvent 3.0 database [36] and the literature review. The PV module comprises several materials, which includes aluminum, steel, Fresnel lens, and the cooling equipment. The total weight of one PV module was 18.92 kg, and the irradiation area was 34.56 m^2. The tracking system was constructed using aluminum, steel, cement, and motor. The energy generated by HCPV without considering the degradation of efficiency was calculated using the following formula [12].

$$E_{output} = DNI \times A \times R \times 365 \times n \times (1 - G_L) \quad (1)$$

The degradation rate of HCPV efficiency was considered, and the degradation rate could be regarded as linear [11,33]. The formula was transformed as follows.

$$E'_{output} = \left\{ \sum_{y=1}^{n} [DNI \times A \times \{R \times (1 - Nd)\} \times 365] \right\} \times (1 - G_L) \quad (2)$$

where E_{output} is the energy generated by HCPV without considering the degradation rate of HCPV, and E'_{output} is the energy generated by HCPV considering the degradation rate of HCPV. DNI is the direct normal irradiation (kWh/m^2/year). A is the area of the PV module (m^2) in this study and is a constant equal to 34.56 m^2. R is the conversion efficiency rate of the HCPV system. N is the lifetime of HCPV, and d is the degradation rate per year of HCPV. G_L is the grid transmission loss in Taiwan.

2.4. Basic Scenario and Assumptions

Several assumptions were made as the basic scenario to evaluate the EPBT and carbon footprint of HCPV in this study. The assumptions are as follows.

1. All the HCPV elements, except for the cells, were manufactured in Taiwan. The tracking system was manufactured in the same region (Tainan, Taiwan) and transported to the same destination (Taoyuan, Taiwan). The tracking system was manufactured in Taoyuan. All components were transported by the same type of truck, and the total distance was provided by Google Map.
2. The GHG emissions of the transportation of the cells from the USA to Taiwan were considered negligible because the cells made by the Spectrolab in the United States were very light.
3. The carbon footprint of III–V cells were quoted by the literature review, and the result of each III–V cells was 0.0177 kg CO_2eq per cell [37].
4. The conversion efficiency rate of the HCPV system is recommended by INER as 30%, which was the conversion rate of the module and system performance ratio, and the degradation rate was not considered in the basic scenario.
5. For the operation and maintenance stage, the life cycle of the PV module and the tracking system was assumed to be 30 years, and the assumption of inverter life expectancy was 15 years [33].

6. The grid transmission loss would reduce the real electricity generation compared with the ideal electricity generation. The grid transmission loss according to the Taiwan power company (Taipei City, Taiwan) in 2015 was 3.72% [38].
7. The power input for operation and maintenance was 41.79 kWh/year by INER.
8. The HCPV system contained a large amounts of electronic and hazardous wastes. The disposal of waste in Taiwan follows the regulations (e.g., aluminum should be recycled according to the regulated recyclable wastes of electronics).

In the installation stage, electricity was consumed as components of HCPV, and the average electricity used was 2.71 kWh per one set of HCPV. The overall inventory data from the material input and manufacturing stages to the operation and maintenance stage are shown in Table 1.

Table 1. Inventory data of HCPV.

Stages	Categories	Items	Inventory Data	Data Sources
Material input and manufacturing stage	PV modules	Structure (aluminum)	7.49 kg	CFCP
		Inner structure (aluminum)	2.10 kg	CFCP
		Steel	0.412 kg	CFCP
		Fresnel lens (PMMA)	3.35 kg	Ecoinvent
		Heat sink (aluminum)	5.57 kg	CFCP
		III–V cells	40 cells	[12]
		PCB	0.0012	Ecoinvent
		Bypass diodes	0.0024	Ecoinvent
		Power connector (copper)	0.018	[12]
	Tracking system	Aluminum	324.21 kg	CFCP
		Steel	1994.22 kg	CFCP
		Motor	6.3 kg	CFCP
		Base (cement)	5200 kg	CFCP
	Inverter	Inverter (2.5 kW × 3)	50 kg per 2.5 kW inverter	Ecoinvent
Transportation stage	Road transportation	Truck (for tracking system)	195.64 tkm	CFCP
		Truck (for other material)	354.22 tkm	CFCP
Installation stage	Power consumption	Electricity	2.71 kWh	INER
	Other materials	Paste	0.20 kg	CFCP
		Silicon product for installation	0.10 kg	CFCP
Operation and maintenance stage	Energy input	Electricity consumption per year	41.97 kWh	INER
Disposal stage	**Disposal method**	**Waste**	**Disposal of weight**	
	Recycle	Aluminum	339.37 kg	CFCP
		Steel	1998.34 kg	
		Glass (Fresnel lens)	3.35 kg	
		Motor	6.3 kg	
	Hazardous waste treatment	III–V cells (2400 cells)	0.234 g per cell	
		Inverter	150 kg	
	Cleaning to landfill	Base (cement)	5200 kg	

The DNI value was obtained from the Solar and Wind Energy Resource Assessment, which was developed by NREL and powered by OpenEI [39]; the average value of DNI in south Taiwan is higher than in north Taiwan, the value of DNI in a high altitude region is higher than that in a low altitude region, and the value of DNI is higher in summer than in winter.

2.5. Evaluating EPBT

EPBT is a very important factor to consider in energy system assessment. It aims to evaluate the "net gain" from an energy system. Many studies have applied EPBT to solar power systems; thus, the EPBT formula are varied [40,41]. In the present study, the EPBT formula used is as follows.

$$\text{EPBT} = \frac{(\text{CED}_{\text{total}})}{[(\text{E}_{\text{output}} - \text{E}_{\text{input}}) \times \text{R}]} \tag{3}$$

where the cumulative energy demand (CED) is defined as the direct and indirect energy uses, which include the energy consumed during the extraction, manufacturing, and disposal of raw and auxiliary materials [42]. The $\text{CED}_{\text{total}}$ in this study was calculated through the CED 1.08 method, which was established in Simapro 8.0.2. E_{output} is the power generated by an HCPV in its lifetime, and E_{input} is the total energy consumption during the operation of HCPV in its lifetime. R is the factor required to transform electricity into primary energy and is calculated using equivalent caloricity in Taiwan. In this study, R = 8788 kJ/kWh.

2.6. Evaluating the Social Benefit of Carbon Reduction

The social benefit of carbon reduction is evaluated using the target product. The social benefit of carbon reduction by HCPV was designed as follows.

$$\text{Social benefit of carbon reduction} = \left(\text{CF}_{\text{original electricity}} - \text{CF}_{\text{HCPV}}\right) \times \text{SCC} \tag{4}$$

$\text{CF}_{\text{original electricity}}$ is the carbon footprint of the grid in Taiwan, which is equal to 0.66 kg CO_2eq/kWh in the CFCP database. CF_{HCPV} is the carbon footprint of the HCPV in this study in the basic scenario.

2.7. Sensitivity Analysis

Except for the basic scenario, several factors were analyzed under different assumptions, which include the HCPV system installed location change in Taiwan, DNI value, degradation rate assumptions, and life expectancy. The different factors were described as follows.

2.7.1. HCPV System Installed Location Change in Taiwan and High DNI Cities

The NREL database mentions that 42 various DNI values exist in different regions in Taiwan [39], and 42 locations were selected, including the locations of basic scenario (No. 5), and Nos. 1 to 41 were established by setting different DNI values (Table 2). The DNI analysis could be a useful source of information for Taiwanese policy makers for location selection.

Table 2. Different DNI values in 42 Taiwan regions (42 scenarios total).

Taiwan Region				Oversea with High DNI	
Location No.	**DNI (kWh/m^2/year)**	**Location No.**	**DNI (kWh/m^2/year)**	**Location No.**	**DNI (kWh/m^2/year)**
1	660.29	22	934.04	Phoenix (H1)	2482.00
2	557.72	23	1018.72	Seville (H2)	2278.00
3	593.86	24	788.04	Tabuk (H3)	2668.00
4	640.94	25	769.42	Haixi (H4)	2409.00
5	908.85	26	1007.40	Las Vegas (H5)	2600.00
6	675.98	27	1195.01	Calama (H6)	3322.00
7	622.33	28	738.03		
8	673.06	29	770.88		
9	934.04	30	946.08		

Table 2. *Cont.*

Taiwan Region				Oversea with High DNI	
Location No.	DNI ($kWh/m^2/year$)	Location No.	DNI ($kWh/m^2/year$)	Location No.	DNI ($kWh/m^2/year$)
10	960.32	31	1200.12		
11	534.36	32	1003.02		
12	862.50	33	685.47		
13	1108.51	34	711.75		
14	777.09	35	891.33		
15	521.59	36	1003.75		
16	1055.22	37	1011.05		
17	1015.43	38	842.06		
18	1109.24	39	1011.05		
19	586.56	40	1086.24		
20	994.26	41	953.02		
21	1018.35	42	988.42		

The HCPV system was suggested to be installed in a high DNI location [43], and the DNI values in Taiwan are significantly lesser than those in many places around the world. Thus, the locations with high DNI values were selected from other studies [12,43], and six cities were selected in the following sections: H1 (Phoenix, 2482 $kWh/m^2/year$), H2 (Seville, $kWh/m^2/year$), H3 (Tabuk, 2668 $kWh/m^2/year$), H4 (Haixi, 2409 $kWh/m^2/year$), H5 (Las Vegas, 2600 $kWh/m^2/year$), and H6 (Calama, 3322 $kWh/m^2/year$).

2.7.2. Factors of Life Expectancy and Degradation Rate

Equation (2) shows that degradation rate and life expectancy are significantly related with total energy generation during the PV system lifetime. High degradation rate and long life expectancy were assumed. The energy generation would change more than the low degradation rate and short life expectancy assumptions.

The life expectancy of the HCPV system was assumed to be 30 years in the basic scenario. However, the real life expectancy of a PV system and the contract of the feed-in tariff in Taiwan were estimated to be at least 20 years [44]. Life expectancy could also be extended to 50 years by replacing the cells in the field; the inverter could be replaced every 15 years, and other structures could be replaced every 50 years [12]. Degradation rate is a very important factor for energy generation estimation (up to 10% of the energy generation estimate under degradation rate was considered in the 0.7% per year) when the life expectancy of the PV system was assumed to be 30 years [11]. The three degradation rates were considered as 0.5%, 0.6%, and 0.7% per year.

2.7.3. Scenario Portfolio

The scenario portfolio was developed by the factors in Sections 2.7.1 and 2.7.2, which included DNI, life expectancy, and degradation rate. The overall of scenario portfolio and factors are shown in Table 3. Scenario L (scenario locations) was based on different locations with different DNI values, without considering the degradation rate and different life expectancies. The sensitivity analysis of scenario LE (scenario life expectancy) was established in three DNI types (i.e., low, middle, and high) in different life expectancies with 0% degradation rate. Scenario degradation rate (scenario DR) analyzed the sensitivity of the degradation rate in different life expectancies under the same DNI value. The scenario portfolios are shown in Table 3. Scenario L was calculated in the carbon footprint and EPBT of the HCPV system and compared with the basic scenario for sensitivity analysis.

Table 3. Scenario portfolio for sensitive analysis in this study.

Scenario Portfolio	Basic Scenario	Scenario L	Scenario LE	Scenario DR
DNI ($kWh/m^2/year$)	909	shown in Table 2	909	909
Degradation rate of the PV system (%)	0	0	0	0.5, 0.6, and 0.7 per year
Life expectancy (years)	30	30	20–50 years	20–50 years
Analyzed aspects	Carbon footprint and EPBT	Carbon footprint and EPBT	Carbon footprint	Carbon footprint

3. Results and Discussion

3.1. Carbon Footprint of HCPV in the Basic Scenario

After calculating the carbon emission of one set of HCPV without considering the degradation rate of the system, the results showed (Table 4) that the total carbon emission was approximately 29,572.53 kg CO_2eq during its life cycle of 30 years. This study installed an HCPV system in Taoyuan City, where the average DNI is 909 $kWh/m^2/year$. The total energy output, which was calculated using Equation (1) during its life cycle of 30 years, was 282,688.7 kWh, and the carbon footprint for 30 years was 104.61 g CO_2eq/kWh.

Table 4. GHG emission of 7.5 kW HCPV in the basic scenario.

Stages	Categories	Items	GHG Emission (kg CO2eq)
Material input and manufacturing stage	60 PV modules	Structure (aluminum)	5909.61
		Inner structure (aluminum)	1582.56
		Steel	29.91
		Fresnel lens	1378.86
		Cooling aluminum	3375.42
		III–V cells	42.48
		PCB	4.02
		Bypass diodes	45.36
		Power connector (copper)	4.74
	Tracking system	Aluminum	3193.47
		Steel	4826.01
		Motor	340.83
		Base (cement)	4940
	Inverter	Inverter (7.5 kW)	612
Transportation stage	Road transportation	Truck (for tracking system)	45.98
		Truck (for other material)	83.24
Installation stage	Power consumption	Electricity	1.78
	Other materials	Paste	1.57
		Silicon product for installation	0.21
Carbon emission of HCPV before operation			27,487.95
Operation and maintenance stage (30 years)		Inverter replace	612
		Energy input	829.18
Disposal stage		-	372.44
Total HCPV carbon emission for 30-year life expectancy (kg CO_2eq)			29,303.49
Total energy output in life cycle under 3.74% of grid transmission rate (kWh)			272,116.1
Carbon footprint of HCPV (g CO_2eq/kWh)			107.69

Figure 3 shows that the highest HCPV carbon emission among all the HCPV stages was produced by the material input and manufacturing stages (93.35%), which was followed by the operation and maintenance stage (4.92%), disposal stage (1.27%), transportation stage (0.44%), and installation stage (0.01%).

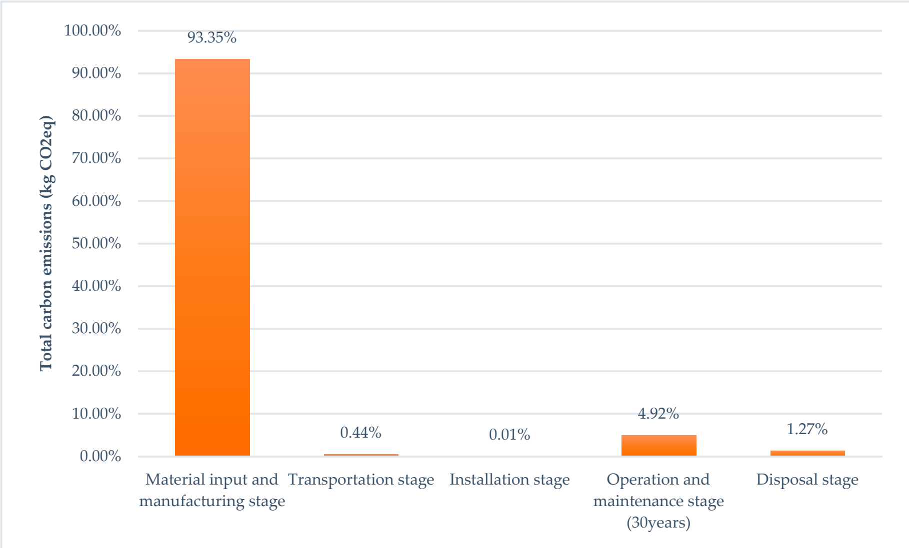

Figure 3. Carbon emission of HCPV in each stage in percentage (life expectancy = 30 years).

The carbon emission percentages of the PV modules, tracking system, and inverter for the material input and manufacturing stage were 45.76%, 52.02%, and 2.22%, respectively (Figure 4). Aluminum usage was the main source of carbon emission, followed by steel and cement usage. These results are similar to those of the other studies, and the highest carbon emission was in the structure part of the PV system [18]. To reduce the total emission of 7.5 kW HCPV, the use of cement should be decreased, and aluminum and steel could be replaced with low carbon metals from suppliers.

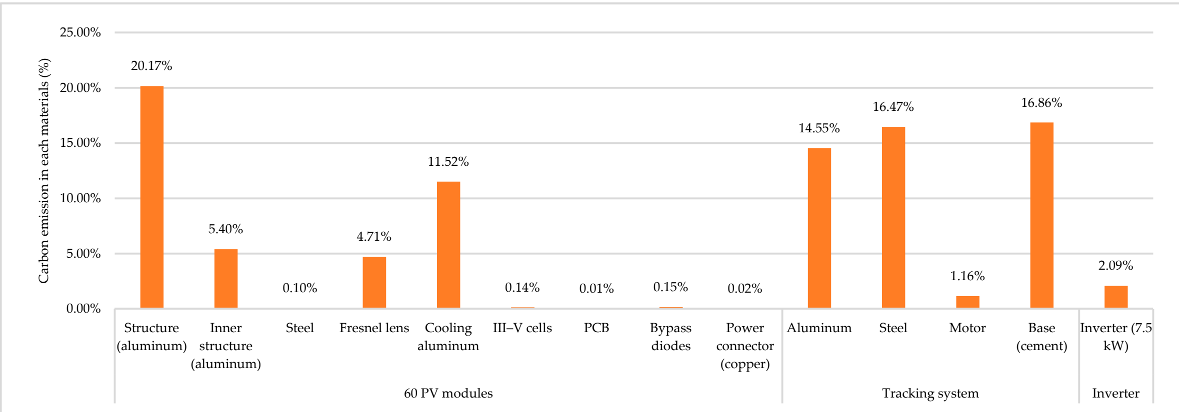

Figure 4. GHG emissions in material input and manufacturing stage in percentage.

The operation and maintenance stage produced the second highest carbon emission in the total life cycle of HCPV because of the replacement of the inverter after 16 and 30 years of HCPV operation and maintenance. The carbon footprint of the replaced inverter and the energy consumption in the operation and maintenance stage for 30 years are 612 kg CO_2eq and 830.94 kgCO_2eq, respectively.

3.2. EPBT of HCPV

CED was calculated using CED 1.80 in Simapro 8.0.2. Table 5 shows the EPBT of each stage in this study, and the HCPV result is 2.51 years in Tauyuan, Taiwan. The material input and manufacturing stage had the highest energy input because of the 60 PV modules and tracking system, followed by the disposal and installation stages.

Table 5. Evaluation of EPBT for HCPV.

	Stages		Energy Input
CED (GJ)	Material input and manufacturing stage	60 PV modules (without cells)	103.32
		III–V cells (2400 cells)	4.568
		Tracking system	84.38
		Inverter	8.23
	Installation stage		0.785
	Disposal stage		5.47
	Total		206.753
$E_{generation}$ (kWh/year)	Energy produced during the operation stage		9070.54
$E_{operation}$ (kWh/year)	Energy consumed during the operation stage		41.975
R (kJ/kWh)	-		8786.4
EPBT (years)	EPBT = $(CED_{total})/[(E_{generation} - E_{operation}) \times R]$		2.61

3.3. Social Benefit of Carbon Reduction by Replacing HCPV

The social cost and social benefit of carbon reduction by replacing 7.5 kW HCPV are shown in Table 6. The SCC per ton of CO_2 was provided by the US EPA. The social cost of HCPV in the average SCC is 1205.9 USD and at the high SCC effect is 3517.23 USD at 3% discount rate. The social benefit of carbon reduction by HCPV under the average SCC and the higher effect of SCC are 0.022 USD per kWh of electricity generation and 0.066 USD per kWh of electricity generation, respectively. The social benefit of carbon reduction by replacing HCPV could help organizations adopt low carbon energy sources for their climate change strategy in communication with external and internal stakeholders. The social benefit of carbon reduction was evaluated in this study, and the social benefits of other environmental aspects may be involved in assessing sustainable alternatives for energy sources to enable better decision making.

Table 6. Social cost of carbon and social benefit of HCPV in Taiwan.

Social Coat of Carbon (USD per Metrics ton of CO_2) in 2015	Average SCC (36) *	Higher Impact of SCC (105) *
SCC of HCPV (USD)	1205.9 **	3517.23 **
Social benefit of carbon reduction by replacing HCPV (USD/kWh)	0.022 **	0.066 **

* In 2007 USD; ** In 2015 USD.

3.4. Analysis of Different Scenarios for HCPV System

3.4.1. Sensitivity Analysis of Scenario L Portfolio

The sensitivity analysis of different DNI values in various Taiwanese regions and six overseas cities were analyzed in this study. Each scenario was compared with the basic scenario to calculate the change in DNI, the carbon footprint of HCPV, and the EPBT of HCPV in percentage (Table 7). Location 15 has the lowest DNI area in Taiwan (521.59 kWh/m^2/year), and Location 31 has the highest DNI area in Taiwan (1200.12 kWh/m^2/year). The highest DNI is in Location H6, with 3322 kWh/m^2/year, which is 2.6 times more than the basic scenario in this study. EPBT and CF would decrease because the total energy generation would increase with the increase in DNI based on Equation (1). The carbon footprint and EPBT of HCPV in low DNI areas are more sensitive than those in high DNI areas. This finding is useful for assessing the carbon footprint of PV systems in the low DNI regions. The sensitivity of EPBT was slightly higher than the carbon footprint when the DNI value was changed, but the difference was below 1%.

Table 7. Carbon footprint and EPBT of HCPV in 30-year life expectancy in various regions.

Location	DNI ($kWh/m^2/year$)	DNI Difference * (%)	Carbon Footprint (kg CO_2eq/kWh)	Carbon Footprint Difference * (%)	EPBT (years)	EPBT Difference * (years)
15	521.59	−42.61%	187.64	74.25%	4.56	74.85%
4	640.94	−29.48%	152.70	41.80%	3.70	42.08%
28	738.03	−18.80%	132.61	23.15%	3.21	23.28%
38	842.06	−7.35%	116.23	7.93%	2.81	7.97%
32	1003.02	10.36%	97.56	−9.39%	2.36	−9.43%
40	1086.24	19.52%	90.10	−16.33%	2.18	−16.39%
31	1200.12	32.05%	81.55	−24.27%	1.97	−24.36%
H2	2278.00	150.65%	42.96	−60.10%	1.04	−60.21%
H3	2668.00	193.56%	36.68	−65.94%	0.89	−66.04%
H6	3322.00	265.52%	29.46	−72.64%	0.68	−72.73%

* Difference of DNI, carbon footprint, and EPBT was compared with the basic scenario.

3.4.2. Sensitivity Analysis of Scenario DR Portfolio

The sensitivity analysis of life expectancy is also important in assessing the carbon footprint of HCPV. Figure 5 shows that the sensitivity of life expectancy in assessing carbon footprint change in percentage at a DNI of 909 $kWh/m^2/year$ without considering different degradation rates. The difference rate of carbon footprint in the short life expectancy (in the basic scenario) was higher than that in the long life expectancy. No difference was observed in the 31st and 46th years because the inverter is replaced in the 15th, 30th, and 45th year, and solar cell replacement also occurs in the 30th year. The result shows that the sensitivity of life expectancy is higher in the short than that in the long PV system lifetime.

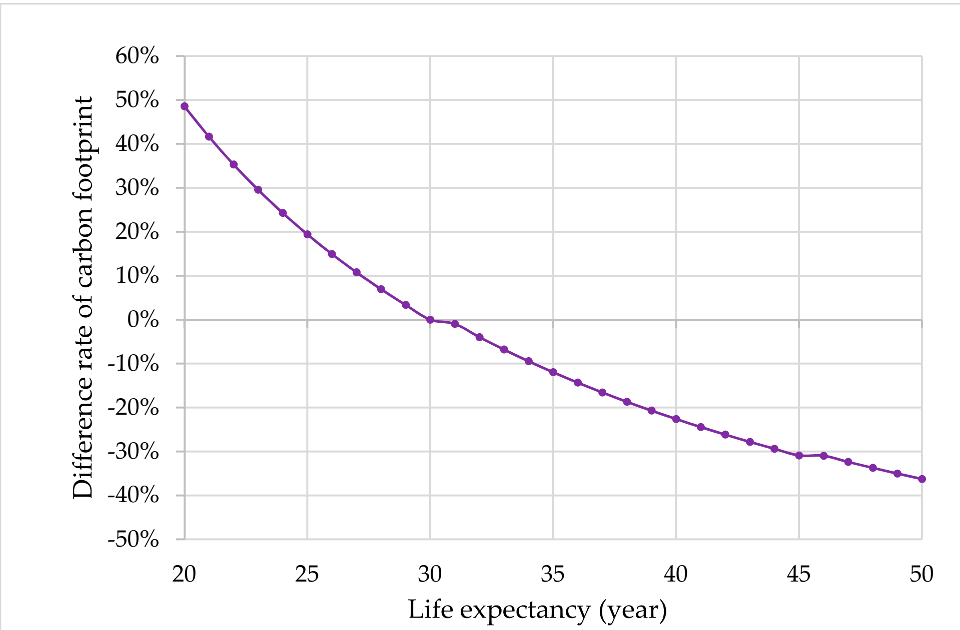

Figure 5. Sensitivity of HCPV in different life expectancies without considering degradation rate.

The total energy generation would be influenced by the lifetime, which also influences the carbon footprint of HCPV. In this section, basic scenario had a DNI and HCPV conversion efficiency of 909 $kWh/m^2/year$ and 30%, respectively, and the sensitivity analysis of scenario LE was compared with the basic scenario. Figure 6 shows the evaluation of the carbon footprint change compared with the basic scenario. When life expectancy is extended from 20 years to 30 years, the increase in carbon footprint percentages at 0.5%, 0.6%, and 0.7% degradation rate assumptions will increase from 5.03% to 7.82%, 6.09% to 9.53%, and 7.17% to 11.30%, respectively. The difference rate of the carbon footprint of HCPV would decrease from the 31st year until the 43rd year of life expectancy because the conversion efficiency of an HCPV system would become 30% after the PV cell replacement in the 31st year according to our assumption. After the 44th year, the difference rate of the carbon footprint of HCPV would increase because of the low energy generation estimate caused by the degradation rate. The results show that a longer life expectancy was assumed under high degradation rate. The difference of carbon footprint without considering the degradation rate would be higher than that at short life expectancy and low degradation rate assumptions. This finding indicates that the degradation rate should not be ignored when evaluating the carbon footprint of a PV system under a long life expectancy assumption. The high difference rate of carbon footprints occurred under high degradation rate at an assumed long life expectancy. However, the short life was assumed during the assessment of the carbon footprint of HCPV, the difference rate would be smaller than that under long life assumption.

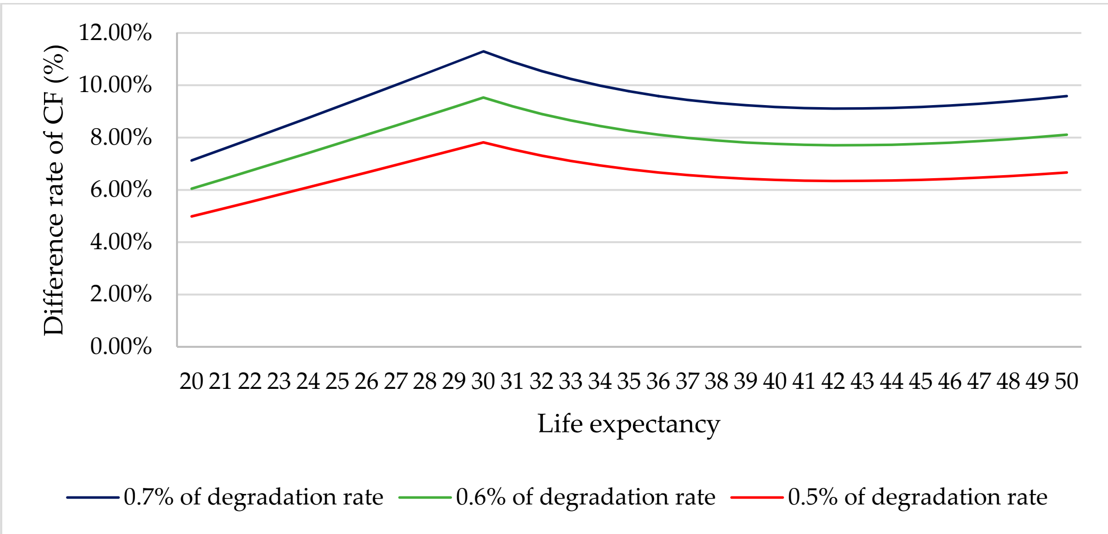

Figure 6. Difference in CF (carbon footprint) compared with the basic scenario by the scenario DR as a percentage.

Figure 7 shows the increasing carbon footprint at different degradation rates. The carbon footprint of HCPV in different degradation rates was compared with the carbon footprint without considering the degradation rate under the same DNI value. The result shows that the difference in carbon footprint in percentage is the same as that in Figure 5. The increasing rates in percentage are the same, but the absolute values of carbon footprint are different at the different degradation rates of HCPV. The increase in carbon footprint under low DNI value was higher than that in high DNI value. A high DNI (i.e., more than 2000 kWh/m^2/year) was assumed. The increase in carbon footprint, which was influenced by the degradation rate, was smaller than the low DNI assumption, but the increase rate of carbon footprint in percentage is the same as that in Figure 6. The highest increase of HCPV carbon footprint occurred in the 30th year because of the lowest energy output when degradation rate was considered during its life expectancy. The increase rate carbon footprint decreased after the 31st year because of the cell replacement.

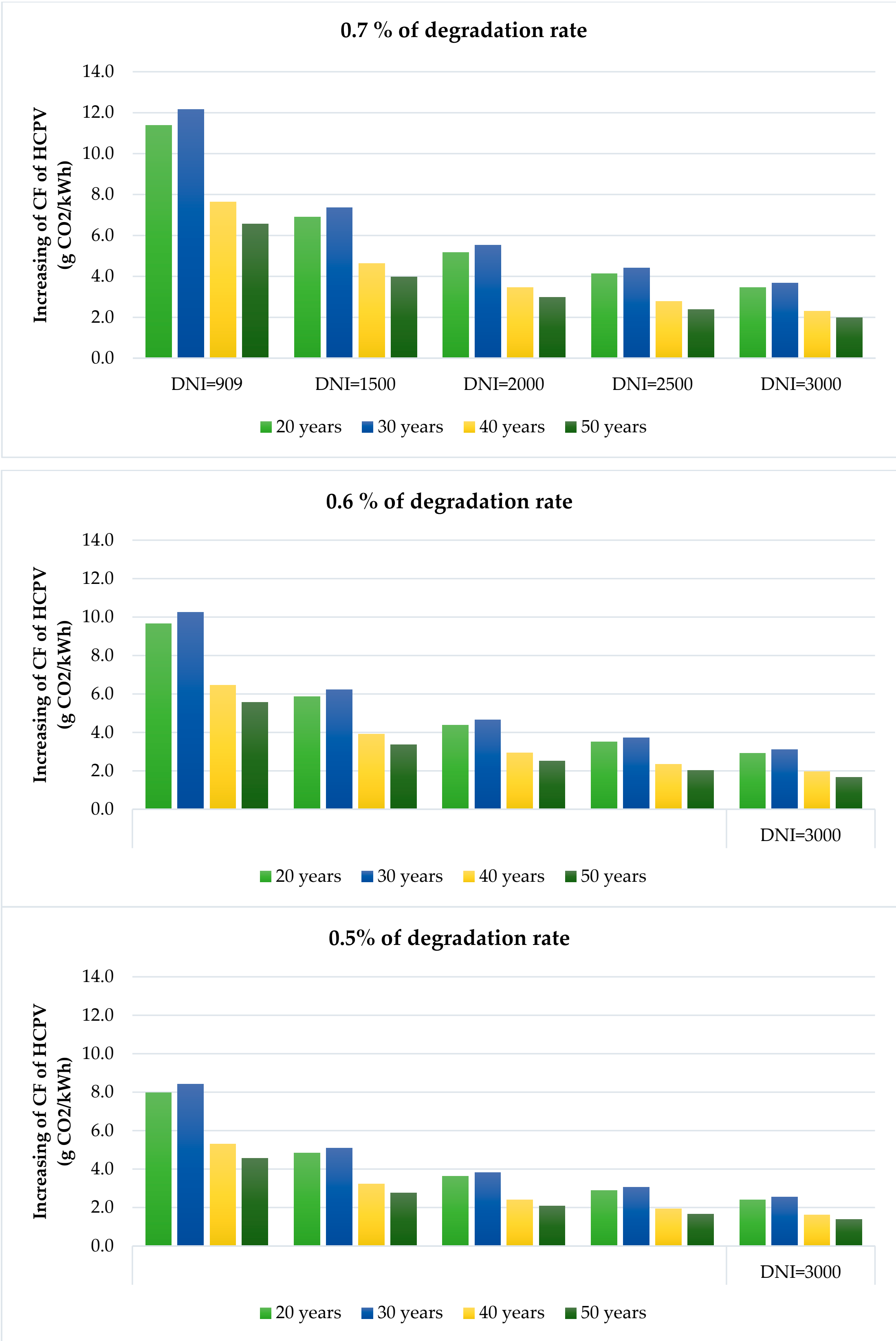

Figure 7. Increasing carbon footprint at different degradation rates (0.5%, 0.6% and 0.7%) under different life expectancies and different DNI values, which was compared with the carbon footprint without considering the degradation rate in assessing HCPV.

The analysis shows that degradation rate should be considered in low DNI location even if the difference rate in percentage remains the same when assessing the carbon footprint of HCPV. Cell replacement can also reduce the difference of carbon footprint when considering degradation in assessing HCPV.

3.5. Comparison of Carbon Footprints of PV Systems

This study compared other PV systems with the HCPV developed by INER (Table 8). The scope and boundary are inconsistent with the studies, but the functional unit and life expectancy are same, which are 1 kWh produced by the PV system and 30 years, respectively. To satisfy the data quality of the LCA methodology, local data and commercial database were employed in the following four studies.

Table 8. Comparison of this study with other PV system assessments.

Carbon Footprint of PV System	This Study (Basic Scenario)	Fthenakis and Kim [12]	Sandwell, Duggan, Nelson and Ekins-Daukes [43]	Kim, Cha, Fthenakis, Sinha and Hur [11]
Scope and Boundary	1. Cradle to grave	1. Cradle to grave	1. Only material input considered	1. Including pre-manufacturing, manufacturing, and use stage
	2. All PV system	2. All PV system	2. PV module	2. PV system
Analyzed aspects	CO_2, EPBT	CO_2, EPBT, Land usage, Water usage	CO_2, EPED, CPBT, LCOE	CO_2, FCC, EPBT, CO_2 PBT
Functional unit	1 kWh produced by PV system	1 kWh produced by PV system	1 kWh produced by HCPV module	1 kWh produced by PV system
Commercial Database	CFCP (Taiwan) Ecoinvent 3.0	Franklin Ecoinvent		Several databases (e.g., AIST, Ecoinvent, First Solar, and KACO)
Analyzed target	7.5 kW HCPV developed by INER	Amonix 7700	1. Fullsun HCPV module. 2. System comprised of 72 Fullsun modules	CdTe PV system
Cell category	III–V cell	III–V cell	III–V cell	CdTe cell
Conversion efficiency of PV	30% of all systems	37% of module System ratio	42% of cell	11.2% of CdTe PV panel
Location (DNI, kWh/m^2/year)	Taoyuan, Taiwan (909)	Las Vegas, USA (2600), Phoenix, USA (2480), Glendale, USA (2570)	Six deployment locations: Pheonix (2482), Seville (2278), Tabuk (2668), Haixi (2409), Alice Springs (2668), Calama (3322)	Malaysia (1810.4)
Life time of system	30 years	30 years	30 years	30 years
Degradation rate of PV module	Degradation rate was not considered in the basic scenario.	Degradation rate was not considered in this study.	Degradation rate was considered to degrade at 0.7% per annum over a lifetime of 30 years.	Degradation rate was considered to degrade at 80% of the initial efficiency at the end of the 30-year life expectancy.
Grid transmission loss	3.74%	Grid transmission loss was considered in A coefficient.	Various loss rates were observed in different locations.	Grid transmission loss was not considered in energy generation.
Carbon footprint (g CO_2eq/kWh)	107.69	26 (Las Vegas, 2009), 27 (Phoenix, 2009), 27 (Glendale, 2009)	9.0 (Phoenix), 9.4 (Seville), 8.3 (Tabuk), 9.8 (Haixi), 8.8 (Alice Springs), 6.5 (Calama)	15.1
EPBT (years)	2.61	0.9 (Las Vegas, 2009), 0.9 (Phoenix, 2009), 0.9 (Glendale, 2009)	0.30 (Phoenix), 0.32 (Seville), 0.28 (Tabuk), 0.33 (Haixi), 0.29 (Alice Springs), 0.22 (Calama)	0.94 year

The carbon footprint of this study is higher than the other carbon footprints of PV systems because of the following reasons.

First, DNI was not discussed in these studies. Furthermore, the total energy generation was high in the low DNI region, and the carbon footprint of the PV system was lower than that in the low DNI region.

Second, the material input in the frame of the PV module and the tracker of the PV system were different in these studies (as shown in Table 9). For the PV module, aluminum was used in the structure/frame of the module by INER, and a large amount of galvanized steel was applied to the frame of PV module by Amonix 7700 [12]. The carbon footprint of aluminum was higher than that of steel under the same weight; if the frame of the module was aluminum, the carbon emission of the PV module would be higher than the steel module [43]. Glass was applied in the Fullsun HCPV module for the Fresnel lens, and the carbon footprint of glass was higher than the PMMA under the same functional unit. The difference in material usage in the components of the PV module led to different hot spots, especially in the frame of the PV module. The recommendation was to search for a low carbon embedded material to comprise the frame of the PV module to reduce the carbon emission. For the tracking system, aluminum (14.55%), steel (16.47%), and cement (16.86%) were the main sources of GHG in the HCPV by INER, whereas steel was the significant source of GHG in the tracker part of Amonix 7700 because steel was the main material in the tracker built by Amonix 7700. Cement, which was heavily used by INER to build the stable foundation of the HCPV system, was the main source of carbon emissions. Therefore, reduce cement use in the tracker building for HCPV would provide a critical improvement of carbon emission reduction.

Table 9. Comparison of hot spots for HCPV system assessments.

GHG Hotspot	This Study (Basic Scenario)	Fthenakis and Kim [12]	Sandwell, Duggan, Nelson and Ekins-Daukes [43]
GHG Hotspot of PV system in a life cycle	Material input and manufacturing stage (93%) *	Material input and manufacturing stage (92.4%) *	Material input and manufacturing stage
	Operation and maintenance stage (5%) *	Transportation of HCPV (4.1%) *	Operation and maintenance stage
	Another stage was less than 1%	Operation and maintenance stage (2.2%) *	Transportation
Hot spot in material input and manufacturing stage	Tracking system (49.04%)*	PV module (52.24%) *	PV module
	PV module (42.22%) *	Tracking system (38.2%) *	Tracking system
	Inverter (2.09%) *	Inverter (1.9%) *	
Materials hot spot in PV module	Aluminum for frame and heat sink (37.09%) *	Aluminum for heat sink (28.2%) *	Aluminum for frame and heat sink (60%) **
	PMMA (4.71%) *	Steel for frame (15.2%) *	Process (24%) **
	Cells (0.14%) *	PMMA (8.2%) *	Glass (10%) **
		Cells (0.6%) *	Others (6%) **
Hot spot in tracking system	Cement for Foundation/base (16.86%) *	Steel for tracker (28.4%) *	-
	Steel for structure (16.47%) *	Hydraulic drive (8.1%) *	
	Aluminum for structure (14.55%) *	Concrete for foundation (0.4%) *	
	Motor (1.16%) *	Motor (0.1%) *	
		Others	

* Percentage of carbon emission in full HCPV system; ** Percentage of carbon emission only in PV module.

The carbon emission from operation and maintenance was the second highest in the full life cycle of the HCPV system in all the studies. A short life was assumed, and less carbon emissions were calculated. The carbon emission of transportation was less than 1% of the total carbon emission in the HCPV by INER because all parts of the HCPV system, which was manufactured in a domestic region, were assumed, except for the PV cells. The transportation distance in the present study is shorter than those in the other studies because the carbon emission is less than the long distribution of the PV system.

The carbon emissions of the installation and disposal stages are similar to those of the other studies, and the main GHG source in the HCPV is from the PV module and the tracking system. The comparison of the three stages is difficult because of the various assumptions regarding the carbon footprint of the HCPV.

4. Conclusions

4.1. Conclusions

The carbon footprint and EPBT of a 7.5-kW HCPV at a DNI value of 909 kW/m^2/year, 30-year life expectancy, and 3.74% of grid transmission loss were 107.69 g CO_2eq/kWh and 2.61 years, respectively. The assessment results in the current study are higher than those in other HCPV studies because the total energy output under the DNI of 909 kW/m^2/year is lower than those in the other studies at high-DNI locations (more than 2000 kWh/m^2/year). The hot spot of GHG emission at the material and manufacturing stage, which accounted for more than 90% GHGs in the total life cycle of HCPV, is similar to that in Amonix 7700 [12]. The analysis of the material input and manufacturing stages revealed that the percentages of GHG emissions in the PV module, tracking system, and inverter were 42%, 49%, and 2% of the total GHG emission, respectively. The social cost and social benefit of carbon reduction were introduced to assess HCPV. The social cost of HCPV in the average SCC and the high effect of SCC were 1205.9 USD and 3517.23 USD in 2015, respectively. The social benefit of carbon reduction by replacing 7.5 kW HCPV in the Taiwan electricity grid in the average and high effects of SCC are 0.022 and 0.066 USD/kWh, respectively.

The sensitivity of life expectancy, DNI value, and degradation rate of HCPV were analyzed by comparing the differences in carbon footprints and EPBT. The influence of low DNI value on carbon footprint and EPBT is higher than that of high DNI value. The sensitivity of life expectancy also showed that the influence under a short HCPV life assumption is higher than that under a long life expectancy. The difference rate of the HCPV carbon footprints would increase with the life expectancy because the annual energy output would decrease as a result of the degradation rate, as considered in the assessment. The higher the assumed degradation rate, the greater the increase in the difference of HCPV carbon footprints. The sensitivity of the degradation rate in low DNI and short lifetime assumption is higher than that in high DNI and long lifetime assumption. To assess the carbon footprint of HCPV systems, the life expectancy and degradation rate of HCPV are considered when the HCPV is installed in a low-DNI region.

4.2. Suggestions and Recommendations

HCPV systems should be installed in high-DNI regions to achieve low carbon emission and low EPBT. When HCPV is installed in lower-DNI regions (DNI equal to 909 kWh/m^2/year), the degradation rate of the PV module cannot be neglected in carbon footprint assessment. The main causes of GHG emission in the PV module are aluminum and cement use in the tracking system. The use of aluminum and cement should be reduced by replacing them with low-carbon-embedded materials for HCPV. The data used in this study were obtained from CFCP. The carbon coefficient value of a material should be improved in the carbon footprint calculation for data quality. The concept of social benefit of carbon reduction by HCPV replacement was introduced in this study. The social benefit can be another indicator that decision makers can use to evaluate the benefits of renewable energy. Moreover, the social benefit concept can be a bridge that connects the social and environmental aspects in the assessment, and to improve the effectiveness of communication between corporate and government stakeholders and the public.

4.3. Directions for Futrue Research

Only carbon emissions, one of numerous environmental effects, were analyzed in this study because of inventory and information limitations. In future research, other environmental effects will be examined, such as eutrophication, acidification, land-use change, resource exploitation, and water use. Additional environmental effects, such as the social cost of carbon and natural capital accounting, could be calculated in monetary units for easy comparison. Several materials were selected in Ecoinvent. The uncertainty of data selection between different databases should be analyzed in the future to improve the accuracy of carbon footprint assessment.

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