Hindawi Publishing Corporation
International Journal of Photoenergy
Volume 2012, Article ID 101968, 9 pages
doi:10.1155/2012/101968

Research Article

Environmental Life-Cycle Analysis of Hybrid Solar Photovoltaic/Thermal Systems for Use in Hong Kong

Tin-Tai Chow[1] and Jie Ji[2]

[1] *BEETRU, Division of Building Science and Technology, City University of Hong Kong, Kowloon, Hong Kong*
[2] *Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230026, China*

Correspondence should be addressed to Tin-Tai Chow, bsttchow@cityu.edu.hk

Received 4 May 2012; Accepted 15 August 2012

Academic Editor: Christophe Menezo

While sheet-and-tube absorber is generally recommended for flat-plate photovoltaic/thermal (PV/T) collector design because of the simplicity and promising performance, the use of rectangular-channel absorber is also tested to be a good alternative. Before a new energy technology, like PV/T, is fully implemented, its environmental superiority over the competing options should be assessed, for instance, by evaluating its consumption levels throughout its production and service life. Although there have been a plenty of environmental life-cycle assessments on the domestic solar hot water systems and PV systems, the related works on hybrid solar PV/T systems have been very few. So far there is no reported work on the assessment of PV/T collector with channel-type absorber design. This paper reports an evaluation of the energy payback time and the greenhouse gas payback time of free-standing and building-integrated PV/T systems in Hong Kong. This is based on two case studies of PV/T collectors with modular channel-type aluminium absorbers. The results confirm the long-term environmental benefits of PV/T applications.

1. Introduction

A photovoltaic/thermal (PV/T) system is a combination of photovoltaic (PV) and solar thermal devices that generate both electricity and heat energy from one integrated system. With solar cells as (part of) the thermal absorber, the hybrid design is able to maximize the energy output from an allocated space reserved for solar application. Air and/or water can be used as the heat removal fluid(s) to lower the solar cell working temperature and to improve the electricity conversion efficiency. Comparatively, the water-type product design provides more effective cooling than the air-type counterpart because of the favorable thermal properties. Those with flat plate collectors meet well the low temperature water heating system requirements. They are also ideal for preheating purposes when hot water at higher temperature is required.

While sheet-and-tube absorber is one common feature in flat-plate collectors, the use of rectangular-channel absorbers also has been examined extensively [1–3]. An aluminum water-in-channel-type PV/T collector design is recommended by the authors, with the prototypes well-tested under both free-standing and building-integrated manners [4, 5]. Through the adoption of the channel absorber design, the potential problem of low fin efficiency can be readily improved. Based on the thermosyphon working principle, the collector performance is found to have geographical dependence and working well at the warmer climate zones. In the Asia Pacific region, most large cities are dominated by air-conditioned buildings where space cooling demands are high. In these buildings, the exposed facades provide very good opportunity for accommodating the building integrated systems, hence, the BiPV/T. When a part of the solar radiation that falls on the building façade is directly converted to useful thermal and electric power, the portion of solar energy transmitted through the external facade is reduced. Hence, the space cooling load is reduced. Through dynamic simulation with the use of experimentally validated system models and the typical meteorological year (TMY) data of Hong Kong, the cost payback time (CPBT) of free-standing and building-integrated PV/T systems were found 12.1 and 13.8 years, respectively [6, 7]. The assessments were taken, respectively, at their best tilted and vertical collector positions for maximizing their system outputs. It is expected that these CPBT will be gradually shortened as the PV technology is in progressive advancement. In this paper, the environmental life-cycle analysis (LCA) of such hybrid solar systems as applied in Hong Kong is reported.

2. Environmental Life-Cycle Analysis

LCA is a technique for assessing various aspects associated with development of a product and its potential impact throughout a product's life [8]. Before a new energy technology is fully implemented, the environmental superiority over competing options can be asserted by evaluating its consumption levels (such as cost investments, energy uses, and GHG emissions) throughout its entire production and service life. In terms of economic analysis, a simplified approach is to ignore the time element so the cost payback time (CPBT) can be used. This is by adding together the cash inflows from successive years until the cumulative cash inflow is the same as the required investment. In analogy to the economical evaluation, two environmental cost-benefit parameters, the energy payback time (EPBT) and greenhouse gas payback time (GPBT), can be used to evaluate the time period after which the real environmental benefit starts [9]. EPBT is the period that a system has to be in operation in order to save the amount of primary energy that has been spent for production, operation, and maintenance of the system. It is the ratio of embodied energy to annual net energy output. In a BiPV/T system, for example,

$$\mathrm{EPBT} = \frac{\sum_{\mathrm{pvt}} + \sum_{\mathrm{bos}} - \sum_{\mathrm{mtl}}}{E_{\mathrm{pv}} + E_t + E_{\mathrm{ac}} - E_{\mathrm{om}}}, \tag{1}$$

where $\sum_{\mathrm{pvt}}$, $\sum_{\mathrm{bos}}$ and $\sum_{\mathrm{mtl}}$, are, respectively, the embodied energy of the PV/T collectors, of the balance of system (BOS), and of the replaced building materials; E_{pv} is the annual useful electricity output, E_t the annual useful heat gain (equivalent), E_{ac} the annual electricity saving of the HVAC system due to the space thermal load reduction, and E_{om} is the annual electricity consumed in system operation and maintenance activities. $\sum_{\mathrm{mtl}}$ and E_{ac} can be omitted in free-stand PV/T system evaluation. Hence,

$$\mathrm{EPBT} = \frac{\sum_{\mathrm{pvt}} + \sum_{\mathrm{bos}}}{E_{\mathrm{pv}} + E_t - E_{\mathrm{om}}}. \tag{2}$$

Similarly, in terms of greenhouse gas (GHG) emission, for BiPV/T

$$\mathrm{GPBT} = \frac{\Omega_{\mathrm{pvt}} + \Omega_{\mathrm{bos}} - \Omega_{\mathrm{mtl}}}{Z_{\mathrm{pv}} + Z_t + Z_{\mathrm{ac}}}, \tag{3}$$

where Ω stands for the embodied GHG (or carbon dioxide equivalent) emission and Z the reduction of annual GHG emission from the local power plant owing to the BiPV/T operation. And for the free-stand system,

$$\mathrm{GPBT} = \frac{\Omega_{\mathrm{pvt}} + \Omega_{\mathrm{bos}}}{Z_{\mathrm{pv}} + Z_t}. \tag{4}$$

Thus EPBT and GPBT are functions of the related energy system performance and their environmental impacts, like those of the power utilities, the building systems, local and overseas manufacturing, and transportation and on-site handling of PV/T collector system as a whole.

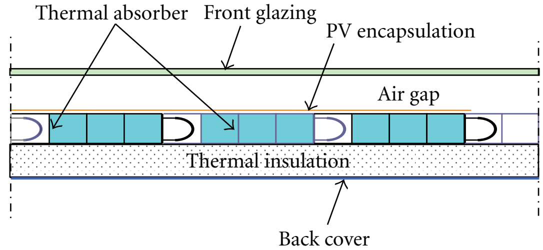

Figure 1: Cross-sectional view of the PV/T collector showing several absorber modules in integration (N.T.S).

Figure 2: Front view of free-stand PV/T collector system.

3. Aluminum Rectangular-Channel PV/T Systems

The sectional view of an aluminum rectangular-channel PV/T collector developed by the authors is shown in Figure 1. It is composed of the following layers: (i) front low-iron glass cover, (ii) crystalline silicon (c-Si) PV encapsulation, (iii) metallic thermal absorber constructed from extruded aluminum, (iv) thermal insulation layer with glass wool, and (v) back-cover steel sheet. The PV encapsulation includes TPT (tedlar-polyester-tedlar) and EVA (ethylene-vinyl acetate) layers at both sides of the solar cells. The rectangular-channel design strengthens the heat transfer and structural durability.

In a free-stand thermosyphon system, the PV/T collector carries a water tank with the natural water circulation via inter-connecting pipes. Figure 2 shows the external view. Water enters the collector at the lower header and leaves via the upper header. Table 1 lists the technical data of this PV/T collector for free-stand applications.

Figure 3: Front view of BiPV/T system with water tank at top of wall.

A BiPV/T system, on the other hand, is composed of an array of PV/T collectors that are integrated to the external wall of an air-conditioned building. See Figure 3 for reference. The water tank is located at the roof-top and the water circulation is again by means of thermosyphon. Table 2 lists the technical data of the BiPV/T wall system in our study.

4. Review of Previous Works on Flat Plate Collector Systems

4.1. Solar Hot Water Systems. The LCA works on domestic solar hot water (DSHW) systems in majority were from EU countries [10–13]. Streicher et al. [10] evaluated the EPBT of solar thermal systems by dividing the system into components. The cumulative energy demand was obtained by multiplying the weight of the main components with their respective cumulative energy demand values. They estimated that in Germany the DSHW systems have EPBT from 1.3 to 2.3 years. In their study, construction credit was given to the collector system in integrated roof-mounting mode. This is for the savings in building materials, transportation, and construction works. The collector itself accounts for 89% and 85% of the total embodied energy in the roof-integrated and open-stand systems, respectively. Tsilingiridis et al. [11] found that in Greece the materials used, including steel and copper, have the major contribution to the environmental impacts. Ardente et al. [12] found that in Italy the indirect emissions (related to production of raw materials) are about 80–90% of the overall GHG releases. Kalogirou [13] worked on a thermosyphon DSHW system in Cyprus. The system thermal performance was evaluated by dynamic simulation program. The LCA determined that 77% of the embodied energy goes to the collector panels, 15% goes to the steel frame, 5% goes to piping, and the remaining accounts for less than 3% of the total. Considerable amounts of GHG can be saved. The EPBT was estimated around 1.1 year.

Outside Europe, the study of Crawford et al. [14] in Australia showed that although the CPBT of DSHW systems can be 10 years or more, the corresponding GPBT can be only around 2.5–5 years. In their study, a conversion factor of 60 kg CO_2 eq/GJ was used to determine the GHG emission

Table 1: Collector and technical design data of free-stand PV/T system.

Design parameters	Data
Glazing (low-iron glass)	
Thickness	0.004 m
Emissivity	0.88
Extinction coefficient	26/m
Refraction index	1.526
Depth of air gap underneath	0.025 m
PV encapsulation (TPT + EVA + solar cell + EVA + TPT + silicon gel)	
Solar cell type	single-crystalline silicon
Cell area	1.11 m^2
Cell electrical efficiency at STC	13%
Solar cell temperature coefficient	0.005/K
Emissivity	0.8
Absorptivity	0.8
Packing factor (wrt glazing)	63%
Thermal absorber (Aluminum)	
No. of flat-box absorber module	15
Absorber module size	0.105 × 1.38 × 0.012 m
No. of header	2
Header size	1.575 × 0.025 (dia.) × 0.002 (thick) m
Thermal insulation layer (glass wool)	
Thickness	0.03 m
Back cover (galvanized iron)	
Thickness	0.001 m
Water tank and connecting pipes	
Water storage capacity	155 kg
Tank length	1.2 m
Tank diameter	0.21 m
Pipe diameter	0.015 m
Thickness of insulation layer at tank	0.025 m
Thickness of insulation layer on pipe	0.02 m

from the cumulative energy of the entire system. Arif [15] evaluated the environmental performance of DSHW systems in India. Based on the 100 litre-per-day and steady year-round usage, the EPBT was estimated 1.6–2.6 years, all depending on the local climates and also the collector materials in use. In the LCA work of Hang et al. [16] on a range of solar hot water systems in USA; dynamic thermal simulation was again applied.

4.2. PV Systems. In the last decades, plenty of works have been reported on life cycle performance of PV systems in both free-stand and building-integrated manners. The

Table 2: Collector and technical design data of BiPV/T system.

Design parameters	Data
Front glazing (low-iron glass)	
Thickness	0.004 m
Surface area	1.61 m^2
Depth of air gap underneath	0.025 m
PV encapsulation (TPT + EVA + solar cell + EVA + TPT + silicon gel)	
Solar cell type	single-crystalline silicon
Cell area	0.81 m^2
Cell electrical efficiency at STC	13%
Solar cell temperature coefficient	0.005/K
Emissivity	0.8
Absorptivity	0.8
Packing factor (wrt glazing)	50%
Thermal absorber (aluminum alloy)	
Thermal capacity	903 kJ/(kg·K)
Density	2702 kg/m^3
Thermal conductivity	237 W/(m·K)
Emissivity	0.8
Absorptivity	0.9
Insulation material (glass wool)	
Thickness	0.03 m
Air gap between insulation layer and building wall	0.02 m
Building wall (brick)	
Thickness	0.15 m
Density	1600 kg/m^3
Thermal capacity	880 J/(kg·K)
Thermal conductivity	1.0 W/(m·K)
Water tank (steel) and connecting pipes (copper)	
Water storage capacity	0.46 m^3
Tank length	1.5 m
Tank diameter	0.54 m
Pipe diameter	0.055 m
Thickness of insulation layer at tank	0.025 m
Thickness of insulation layer on pipe	0.02 m

estimations of EPBT and GPBT have been kept on revising owing to the advancements in PV technology.

The production of a PV module includes the following processes:

(i) silicon purification and processing,

(ii) silicon ingot slicing, and

(iii) PV module fabrication.

Silica is first melted and manufactured into metallurgical-grade silicon (MG-Si), then into electronic silicon (EG-Si) through the Siemen's process or into solar-grade silicon (SoG-Si) through the modified Siemens process [17]. Finally, after the Czochralski process (for sc-Si) or other production process, silicon is made available for the solar cell production. The silicon ingot is needed to be sliced into wafer. The technologies of cell production include etching, doping, screen printing, and coating. The solar cells are then tested, packed, and interconnected with other components to form PV modules.

Alsema [18] studied the EPBT and the GHG emissions of grid-connected PV systems. The cumulative energy demands of sc-Si and mc-Si frameless modules were evaluated as 5700 and 4200 MJ/m^2. Further, it was pointed out that with the implementation of new manufacturing technologies, the above data could be as low as 3200 and 2600 MJ/m^2. Later on, Alsema et al. [19, 20] reviewed the important options that were available for further reduce energy consumption and environment impacts of the PV module production processes. As for BOS, Alsema and Nieuwlaar [21] presented that because of the less use of aluminum in supporting structure, the energy requirement for array support of ground-mounted PV system was about 1800 MJ/m^2, but this could be only 700 MJ/m^2 for rooftop installation; hence rooftop systems should have better potentials for EPBT reduction than ground-mounted systems.

Mason et al. [22] studied the energy contents of the BOS components used in a 3.5 MWp mc-Si PV plant. By integrating the weight of the PV modules with the supports, the embodied energy of the BOS components was found as low as 542 MJ/m^2—a sharp reduction from the previous estimations. Fthenakis and Kim [23] showed that in Japan the primary energy demand for sc-Si PV module was in the range of 4160–15520 MJ/m^2, and the life-cycle GHG emissions rate for PV systems in the United States were from 22 to 49 g CO_2-eq/kWh$_e$.

In Singapore, Kannan et al. studied a 2.7 kWp distributed PV system with sc-Si modules [24]. Specific energy consumptions for the PV modules and the inverters were estimated 16 and 0.17 MWh$_e$/kWp respectively. The manufacturing of solar PV modules accounted for 81% of the life cycle energy use. The aluminium supporting structure accounted for about 10%, and the recycling of aluminium accounted for another 7%. The EPBT was estimated to be 6.74 years. It was claimed that this can be reduced to 3.5 years if the primary energy use on PV module production is reduced by 50%.

In India, Nawaz and Tiwari [25] calculated EPBT by evaluating the energy requirement for manufacturing a sc-Si PV system for open field and rooftop conditions with BOS. Mitigation of CO_2 emissions at macrolevel (where lifetime of battery and PV system are the same) and microlevel of the PV system has also been studied. For a 1 m^2 sc-Si PV system, their estimations give an embodied energy of 666 kWh for silicon purification and processing, 120 kWh for cell fabrication, and 190 kWh for subsequent PV module production. Hence without BOS, the embodied energy was estimated 976 kWh/m^2 and the GHG emission was 27.23 kg/m^2.

In Hong Kong Lu and Yang [26] investigated the EPBT and GPBT of a roof-mounted 22 kW BiPV system. It was found that 71% of the embodied energy on the whole is from the embodied energy of the PV modules, whereas the remaining 29% is from the embodied energy of BOS. The

EPBT of the PV system was then calculated as 7.3 years. Considering the fuel mixture composition of local power stations, the corresponding GPBT is 5.2 years. Further, it was predicted that the possible range of EPBT of BiPV installations in Hong Kong is from 7.1 years (for optimal orientation) to 20 years (for west-facing vertical façade).

Bankier and Gale [27] gave a review of EPBT of roof mounted PV systems reported in the 10-year period (1996–2005). A large range of discrepancy was found. They pointed out that the limitations to the accuracy of the assessments came from the difficulties in determining realistic energy conversion factors, and in determining realistic energy values for human labor. According to their estimation, the appropriate range of EPBT for mc-Si PV module installations should be between 2–8 years. A more recent review was done by Sherwani et al. [28]. The EPBT for sc-Si, mc-Si, and a-Si PV systems have been estimated in the ranges of 3.2–15.5, 1.5–5.7, and 2.5–3.2, years, respectively. Similarly, GHG emissions are 44–280, 9.4–104, and 15.6–50 g CO_2-eq/kWh.

4.3. PV/T Systems. While there have been plenty studies of EPBT and GPBT on solar thermal and PV systems, our literature review shows that those on PV/T systems have been very few. In particular, there is so far no reported work on the assessment of PV/T collectors with channel-type absorber design.

Battisti and Corrado [29] made evaluation based on a conventional mc-Si building-integrated system located in Rome, Italy. An experimental PV/T system with heat recovery for DSHW application was examined. Evaluations were made for alternative heat recovery to replace either natural gas or electricity. Their results give the EPBT and GPBT of PV system as 3.3 and 4.1 years. On the other hand, those of the PV/T systems designed for natural gas replacement are 2.3 and 2.4 years.

Also in Italy, Tripanagnostopoulos et al. [30] evaluated the energy and environmental performance of their modified 3 kWp mc-Si PV and experimental water-cooled PV/T sheet-and-tube collector systems designed for horizontal-roof (free-stand) and tilted-roof (building integrated) installations. The application advantage of the glazed/unglazed PV/T over the PV options was demonstrated through the better LCA performances. The EPBT of the PV and BiPV system were found to be 2.9 and 3.2 years, whereas the GPBT were 2.7 and 3.1 years, respectively. For PV/T system with 35°C operating temperature, the EPBT of the PV/T and BiPV/T options were both 1.6 years, and the GPBT were 1.9 and 2.0 years respectively. The study showed that nearly the whole of the environmental impacts are due to PV module production, aluminium parts (reflectors and heat-recovery-unit) as well as copper parts (for heat-recovery-unit and hydraulic circuit), with barely significant contributions from the other system components, such as support structures or electrical/electronic devices. The disposal phase contribution is again almost negligible.

Dubey and Tiwari [31] carried out an environmental impact analysis of a hybrid PV/T solar water heater for use in the Delhi climate of India. With a glazed sheet-and-tube flat plate collector system designed for pump operation, the EPBT was found 1.3 years.

5. Environmental Analysis of Aluminum Rectangular-Channel PV/T Systems

5.1. EPBT of Free-Stand System. Skillful lamination of solar cell onto thermal absorber with layers of EVA and TPT is needed for PV/T collector production. Aluminum thermal absorber parts are made available by raw material mining and extraction, ingot melting, mechanical extrusion, machining, and assembling into whole piece. The major-component production and assembly processes include front glass (low iron), PV-laminated absorber, insulation material and aluminum frame. The supply was from the mainland. As for the BOS, the electrical BOS components include inverters, electrical wirings, and electronic devices. The mechanical BOS include water storage tank, pipe work, supporting structure, and accessories. The embodied energy to be considered in the LCA include the above during production, plus those related to the required transportation from factory to installation site, construction and testing, decommissioning and disposal, and any other end-of-life energy requirements.

Table 3 summarizes the materials used and cumulative energy of the free-stand PV/T collector system. The cumulative energy intensity of sc-Si PV module was estimated as 976 kWh/m^2, making references to [25, 26]. That of the inverter and electrical parts was taken as 5% of the PV module. The other values of cumulative energy intensity in MJ/unit was obtained from the Hong Kong government EMSD (Electrical and Mechanical Services Department) database that covers the specific (per unit quantity) impact profile due to consumption of materials in the "Cradle-to-As-built" stage [32]. The total cumulative energy comes up to 3041.8 kWh or 1728 kWh/m^2 for this free-stand system. Table 4 shows the distribution of the embodied energy in this case. It can be seen that the hybrid PV/T collector itself accounts for around 80% of the embodied energy. For the BOS, the water tank accounts for 11.4%, the other mechanical components accounts for 7%, whereas the electrical accessories accounts for only 1.8%. $\sum_{\text{pvt}}$ and $\sum_{\text{bos}}$ are then 2429 and 613 kWh, respectively.

With the installation of this PV/T system, two kinds of energy saving are involved: thermal energy for water heating and electrical energy. This will be no air-conditioning saving. A thermal energy saving of 2650 MJ/year and electricity saving of 473 MJ/year give an E_t of 736 kWh/year and an E_{pv} of 398 kWh/year. In the computation, a heat-to-electricity conversion factor of 0.33 has been used. Mainly labor costs were considered in E_{om}. This is estimated as 41 kWh/year and is therefore not significant. With (2), the EPBT is found 2.8 years. This is much shorter than the expected CPBT of 12.1 years reported in our previous work [6]. Assuming that the working life of PV/T system is similar to PV system, that is, 15–30 years in general [29], then it can be concluded that

Table 3: Cumulative energy in free-stand PV/T system.

Materials	Quantity consumed (kg)	Cumulative energy intensity (MJ/unit)	Cumulative energy (kWh)
PV/T collector			
Front glazing			
Low-iron glass ($1.76\,m^2$)	19.7	19.7	107.9
Thermal insulation			
Glass wool	1.69	31.7	14.9
Thermal absorber			
Aluminum absorber	18.3	219	1114.7
Frame and back cover			
Aluminum	1.78	219	108.0
PV Encapsulation			
PV Module	$1.11\,m^2$	976	1083.4
BOS			
Water tank			
Stainless steel tank	4.20	82.2	273.0
Tank insulation (Glass wool)	1.58	31.7	13.9
Aluminum Cladding	0.966	219	58.8
Connecting pipe			
Copper piping (15 mm dia.)	2.4 m	6.33	4.2
Pipe insulation (Glass wool)	0.0627	31.7	0.6
Structural support and accessories			
Steel stand	14.2	29.2	115.2
Pipe fittings and structural joints	7.19	140.0	93.3
Inverter + electric wiring	5% of PV module		54.2
		Total:	3041.8

Table 4: Distribution of embodied energy in PV/T collector systems.

System component description		Free-stand	BiPV/T
PV/T Collector	Mechanical components	44.2	51.8
	Electrical components	35.6	37.7
BOS	Water tank	11.4	4.9
	Pipe and structural supports	7.0	3.8
	Electrical components	1.8	1.9

the EPBT in this case study is an order of magnitude lower than its expected working life.

5.2. BiPV/T System. Table 5 summarizes the materials used and the cumulative energy in the $9.66\,m^2$ BiPV/T case. Accordingly, the values of Z_{pvt} and Z_{bos} are, respectively, 11258 and 1328 kWh. Z_{mtl} is estimated as 594 kWh, making reference to the work of Streicher et al. [10] and adjusted by the cost of living. Taking the advantage of building material replacement, the cumulative energy intensity reduces to $1241\,kWh/m^2$. The embodied energy distribution of this BiPV/T system is also given in Table 4. It can be seen that for this building integrated case the portion of the collector increases to 89%. For the BOS, the water tank accounts for 4.9%, the pipe and supporting components account for 3.8%, and the electrical components remain at less than 2%.

Table 5: Cumulative energy in BiPV/T system.

Materials	Quantity consumed (kg)	Cumulative energy intensity (MJ/unit)	Cumulative energy (kWh)
PV/T collector			
Front glazing			
Low-iron glass ($1.61\,m^2 \times 6$)	99.6	19.7	545.0
Thermal insulation			
Glass wool	9.50	31.7	83.7
Thermal absorber			
Aluminum absorber	86.7	219	5273.8
Frame and back cover			
Aluminum	10.1	219	611.8
PV Encapsulation			
PV Module	$4.86\,m^2$	976	4743.4
BOS			
Water tank			
Stainless steel tank	19.9	82.2	454.0
Insulation (Glass wool)	2.14	31.7	18.8
Aluminum Cladding	1.53	219	93.0
Connecting pipe			
Copper piping (55 mm dia.)	7 m	40.1	77.9
Pipe insulation (Glass wool)	1.07	31.7	9.4
Structural support and accessories			
Pipe fittings and structural parts	5.25	140.0	68.1
Inverter + electric wiring	5% of PV module		237.2
		Total	12585.2

With the installation of this BiPVW system, the annual energy savings include the following:

(i) thermal energy: 2258 kWh (E_t);

(ii) electrical energy: 323 kWh;

(iii) space cooling load: 206 kWh.

By taking the COP of air-conditioning plant as 3.0, E_{pv} and E_{ac} are then 979 and 208 kWh/year, respectively. In this case E_{om} is 246 kWh/year, by estimation. By (1), the EPBT is 3.8 years, which is much shorter than its CPBT of

13.8 years. A longer period of EPBT in this BiPV/T than in the free-stand case is mainly because of its vertical collector position as compared to the best angle of tilt, and also the differences in collector size and solar cell packing factor. A shorter EPBT is expected if ms-Si cell modules were used in the analyses because of the lower energy consumption during the manufacturing process. As a matter of fact, this 3.8 years for vertical-mounted BiPV/T is advantageous as compared to the 7.1 years [26] for an optimal-oriented roof-top BiPV system in Hong Kong.

5.3. GHG Emission Analysis. In our analysis, the thermal energy saving was taken as a save of town gas consumed in the building. The electrical energy saving was taken as a save in purchased electricity from the utilities. Based on the data provided by the Hong Kong government, the territory-wide emission factor of GHG coming from utility power generation is 0.7 kg CO_2-eq/kWh$_e$ including the transmission losses [33]. As for town gas, the emission factors for CO_2, CH_4, and N_2O are, respectively, 2.815 kg/unit, 0.0446 g/unit and 0.0099 g/unit, where 1 unit of town gas is equivalent to 48 MJ consumed. For the free-stand case, the above information gives an annual reduction in GHG emission of 285 kg CO_2-eq. The PV/T system itself does not produce polluting emissions during their daily operation. And in these days, most of the manufacturing activities of products consumed in Hong Kong are taking place in the Mainland, so the emission factor of China can be used in our embodied GHG assessment. In China, the primary energy consumption for power generation is 12.01 MJ/kWh$_e$ and the CO_2 emission rate for coal-fired power plant is 24.7 g CO_2-eq/MJ [34], the embodied GHG intensity of the PV/T collector in this case is therefore 0.297 kg CO_2-eq/kWh cumulative energy. The local emission factor was used for the BOS part since local acquisition was assumed. Accordingly, with (4) this approximation gives a GPBT of 3.2 years for the free-stand system.

Similarly, for the BiPVT system the saving in air-conditioning energy is converted as electricity saving based on a system COP (coefficient of performance) of 3.0. With (3) this gives a GPBT of 4.0 years. The result is again lower than the previously estimated GPBT of 5.2 years for the general performance of BiPV systems in Hong Kong [26].

For completeness, Table 6 shows the technical data in the evaluation of their CPBT. Comparing with the free-stand PV/T case, the BiPV/T system had a lower investment cost on unit collector area basis. This is because on one hand there were building materials saving and there was no requirement on the steel stands which is essential for tilt-mounting of the free-stand PV/T collector. On the other hand, it was benefitted by the economy of scale for mass handling of the system components. During operation, however, the vertical collector position of the BiPV/T system made it disadvantageous in the quantity of year-round solar radiation received by the collector surface. At the same time, there would be greater transmission loss for a centralized energy system. The simulation results showed that the annual useful heat gains of the free-stand and the building integrated

Table 6: Evaluation of cost payback time.

Investment: HK$	Free-stand PV/T [6]	BiPV/T [7]
Water storage tank	400	750
Collector frame and support	400	1800
Modular thermal absorber	600	2700
Solar cells and encapsulation	4000	17500
Inverter	700	1000
Piping, wiring and accessories	300	900
Installation costs	1500	3000
Total system costs (HK$)	7900	27650
Useful energy savings	MJ (kWh)	MJ (kWh)
Thermal energy	2650.4 (736.2)	8127.5 (2257.6)
Electrical energy	473.2 (131.4)	1162.4 (322.9)
Space cooling load	—	742.6 (206.3)
Cost savings: HK$		
Gaseous fuel at HK$0.2/MJ	530.1	1625.5
Electricity at HK$0.95/kWh	124.9	372.0
Annual saving	655.0	1997.5
Cost payback time (CPBT)	12.1 years	13.8 years

Note: USD1 is equivalent to HK$7.8.

cases are 418 kWh/m^2 and 233 kWh/m^2, respectively, on unit glazing area basis. And the electrical energy gains are 118 kWh/m^2 and 66.4 kWh/m^2 on unit PV cell area basis. These came out with the CPBT of 12.1 years for the free-stand case and 13.8 years for the building integrated case.

Our above findings are generally in line with the estimations by other researchers based on their own collector designs and local applications. Nevertheless, it should be noted that the above picture is not static. It is expected that the continuing improvements in material and energy utilization and recycling will change the current environmental profiles. On the other hand, the progression in solar cell performance will also lead to better EPBT and GPBT.

6. Conclusion

An environmental life-cycle assessment has been done to evaluate the energy and environmental profiles of two cases of PV/T system application in Hong Kong. In both cases, aluminum rectangular-channel absorber in association with sc-Si PV encapsulation was adopted in the single-glazed flat-plate PV/T collector design. In our analysis, the cumulative energy inputs and the embodied GHG emissions were determined by established methodology and technical data making reference to reported research works as well as local government publications. The annual thermal and electrical energy outputs were from results of dynamic simulation based on the TMY dataset of Hong Kong and validated PV/T system models. Our estimation shows that the EPBT of the free-stand PV/T system at the best angle of tilt is around 2.8 years, which is an order of magnitude lower than the expected system working life. In the vertical-mounted BiPV/T case, this is 3.8 years which is again considerably better than the general performance of roof-top BiPV system in Hong Kong. The corresponding GPBT of 3.2 and 4.0 years as a result demonstrate the environmental superiority of this PV/T option over many other competing renewable energy systems.

Acknowledgment

The work described in this paper was supported by a Grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project no. CityU112009).

References

[1] B. Sandnes and J. Rekstad, "A photovoltaic/thermal (PV/T) collector with a polymer absorber plate. Experimental study and analytical model," *Solar Energy*, vol. 72, no. 1, pp. 63–73, 2002.

[2] C. Cristofari, G. Notton, P. Poggi, and A. Louche, "Modelling and performance of a copolymer solar water heating collector," *Solar Energy*, vol. 72, no. 2, pp. 99–112, 2002.

[3] Y. Tripanagnostopoulos, T. Nousia, M. Souliotis, and P. Yianoulis, "Hybrid photovoltaic/thermal solar systems," *Solar Energy*, vol. 72, no. 3, pp. 217–234, 2002.

[4] T. T. Chow, J. Ji, and W. He, "Photovoltaic-thermal collector system for domestic application," *Journal of Solar Energy Engineering, Transactions of the ASME*, vol. 129, no. 2, pp. 205–209, 2007.

[5] T. T. Chow, W. He, A. L. S. Chan, K. F. Fong, Z. Lin, and J. Ji, "Computer modeling and experimental validation of a building-integrated photovoltaic and water heating system," *Applied Thermal Engineering*, vol. 28, no. 11-12, pp. 1356–1364, 2008.

[6] T. T. Chow, W. He, J. Ji, and A. L. S. Chan, "Performance evaluation of photovoltaic-thermosyphon system for subtropical climate application," *Solar Energy*, vol. 81, no. 1, pp. 123–130, 2007.

[7] T. T. Chow, A. L. S. Chan, K. F. Fong, Z. Lin, W. He, and J. Ji, "Annual performance of building-integrated photovoltaic/water-heating system for warm climate application," *Applied Energy*, vol. 86, no. 5, pp. 689–696, 2009.

[8] ISO, (International Organization for Standardization) 14040 Standard, Environmental Management-Life cycle Assessment-Principles and Framework, 1997.

[9] G. N. Tiwari and R. K. Mishra, *Advanced Renewable Energy Sources*, RSC Publishing, Cambridge, UK, 2012.

[10] E. Streicher, W. Heidemann, and H. Müller-Steinhagen, "Energy payback time—a key number for the assessment of thermal solar systems," in *Proceedings of EuroSun*, pp. 20–23, Freiburg, Germany, June 2004.

[11] G. Tsilingiridis, G. Martinopoulos, and N. Kyriakis, "Life cycle environmental impact of a thermosyphonic domestic solar hot water system in comparison with electrical and gas water heating," *Renewable Energy*, vol. 29, no. 8, pp. 1277–1288, 2004.

[12] F. Ardente, G. Beccali, M. Cellura, and V. Lo Brano, "Life cycle assessment of a solar thermal collector," *Renewable Energy*, vol. 30, no. 7, pp. 1031–1054, 2005.

[13] S. Kalogirou, "Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters," *Solar Energy*, vol. 83, no. 1, pp. 39–48, 2009.

[14] R. H. Crawford, G. J. Treloar, B. D. Ilozor, and P. E. D. Love, "Comparative greenhouse emissions analysis of domestic solar hot water systems," *Building Research and Information*, vol. 31, no. 1, pp. 34–47, 2003.

[15] M. Arif, "Life cycle analysis and carbon credit earned by solar water heating system," *International Journal of Research in Engineering and Applied Sciences*, vol. 2, no. 2, pp. 1884–1905, 2012.

[16] Y. Hang, M. Qu, and F. Zhao, "Economic and environmental life cycle analysis of solar hot water systems in the United States," *Energy and Buildings*, vol. 45, pp. 181–188, 2012.

[17] N. Jungbluth, "Life cycle assessment of crystalline photovoltaics in the Swiss ecoinvent database," *Progress in Photovoltaics: Research and Applications*, vol. 13, no. 5, pp. 429–446, 2005.

[18] E. A. Alsema, "Energy pay-back time and CO_2 emissions of PV systems," *Progress in Photovoltaics Research and Applications*, vol. 8, pp. 17–25, 2000.

[19] E. A. Alsema, M. J. de Wild-Scholten, and V. M. Fthenakis, "Environmental impacts of PV electricity generation, a critical comparison of energy supply options," in *Proceedings of 21st European Photovoltaic Solar Energy Conference*, Dresden, Germany, 2006.

[20] E. A. Alsema and M. J. de Wild-Scholten, "Reduction of the environmental impacts in crystalline silicon module manufacturing," in *Proceedings of the 22nd European Photovoltaic Solar Energy Conference*, Milan, Italy, 2007.

[21] E. A. Alsema and E. Nieuwlaar, "Energy viability of photovoltaic systems," *Energy Policy*, vol. 28, no. 14, pp. 999–1010, 2000.

[22] J. E. Mason, V. M. Fthenakis, T. Hansen, and H. C. Kim, "Energy payback and life-cycle CO_2 emissions of the BOS in an optimized 3.5MW PV installation," *Progress in Photovoltaics: Research and Applications*, vol. 14, no. 2, pp. 179–190, 2006.

[23] V. M. Fthenakis and H. C. Kim, "Greenhouse-gas emissions from solar electric- and nuclear power: a life-cycle study," *Energy Policy*, vol. 35, no. 4, pp. 2549–2557, 2007.

[24] R. Kannan, K. C. Leong, R. Osman, H. K. Ho, and C. P. Tso, "Life cycle assessment study of solar PV systems: an example of a 2.7 kWp distributed solar PV system in Singapore," *Solar Energy*, vol. 80, no. 5, pp. 555–563, 2006.

[25] I. Nawaz and G. N. Tiwari, "Embodied energy analysis of photovoltaic (PV) system based on macro- and micro-level," *Energy Policy*, vol. 34, no. 17, pp. 3144–3152, 2006.

[26] L. Lu and H. X. Yang, "Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong," *Applied Energy*, vol. 87, no. 12, pp. 3625–3631, 2010.

[27] C. Bankier and S. Gale, "Energy payback of roof mounted photovoltaic cells," *The Environmental Engineer*, vol. 7, no. 4, pp. 11–14, 2006.

[28] A. F. Sherwani, J. A. Usmani, and Varun, "Life cycle assessment of solar PV based electricity generation systems: a review," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 1, pp. 540–544, 2010.

[29] R. Battisti and A. Corrado, "Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology," *Energy*, vol. 30, no. 7, pp. 952–967, 2005.

[30] Y. Tripanagnostopoulos, M. Souliotis, R. Battisti, and A. Corrado, "Energy, cost and LCA results of PV and hybrid PV/T solar systems," *Progress in Photovoltaics: Research and Applications*, vol. 13, no. 3, pp. 235–250, 2005.

[31] S. Dubey and G. N. Tiwari, "Life cycle cost analysis and carbon credit earned by PV/T solar water heater for Delhi climatic conditions," *Open Environmental Sciences*, vol. 2, pp. 15–25, 2008.

[32] Hong Kong Government, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) Tool for Commercial Building Developments in Hong Kong: User Manual, EMSD, Hong Kong SAR Government publication, 2005.

[33] “Hong Kong Government,” Guidelines to Account for and Report on Greenhouse Gas Emission and Removals for Buildings (Commercial, Residential or Institutional Purposes) in Hong Kong, EMSD and EPD, Hong Kong SAR Government publication, 2008.

[34] M. Ito, K. Kato, K. Komoto, T. Kichimi, and K. Kurokawa, “A comparative study on cost and life-cycle analysis for 100 MW very large-scale PV (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and CIS modules,” *Progress in Photovoltaics: Research and Applications*, vol. 16, no. 1, pp. 17–30, 2008.