Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong

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**A B S T R A C T**

This paper reports the investigation results of the energy payback time (EPBT) and greenhouse-gas payback time (GPBT) of a rooftop BIPV system (grid-connected) in Hong Kong to measure its sustainability. The 22 kWp PV array is facing south with inclined angle of 22.5°. The hourly solar irradiance and ambient air temperature from 1996 to 2000 were used as weather data input. The annual power output was estimated to be 28,154 kWh. The embodied energy for the whole system in the lifespan was 205,816 kWh, including 71% from PV modules and 29% from balance of system (BOS). The percentage of embodied energy for silicon purification and processing reached 46%. The EPBT of the PV system was 7.3 years, and the GPBT was estimated to be 5.2 years considering fuel mixture composition of local power stations. This paper also discussed the EPBTs for different orientations, ranging from 7.1 years (optimal orientation) to 20.0 years (west-facing vertical PV façade). The results show that the 'sustainability' of a PV system is affected by its installation orientation and location. Choosing locations and orientations with higher incident solar irradiance is one key for the sustainability of BIPV technology applications.

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1. Introduction

The market of photovoltaic (PV) technology has been successful in the past decade. World solar cell production reached a consolidated figure of 3436 megawatts (MW) in 2007, and world solar PV market installation reached a record high of 2826 MW in 2007, representing growth of 62% over the previous year [1]. Generally, PV technology, generating electricity from solar energy, is considered 'sustainable'. However, although PV system operation is free from energy consumption, it consumes a lot of energy during PV manufacturing processes, balance of system (BOS) production, transport, system installation, system retrofitting, and system disposal or recycling in its life cycle. For BOS, it comprises system wiring, electronic and electrical components, foundation, support structure, battery (stand-alone system), and system installation. Life cycle assessment (LCA) is usually used to investigate and evaluate the environmental impacts of a given product or system caused or necessitated by its existence. Therefore, two popular environmental indicators of LCA, the energy payback time (EPBT) and greenhouse-gas payback time (GPBT), can be used to measure the sustainability of PV technology and PV systems.

For the EPBT, simply speaking, it is to analyze the amount of energy the PV system generates and the energy (embodied energy) that is consumed to produce the system in order to see whether they have a net gain of energy to the users in its lifetime and if so to what extent. Wilson and Young [2] investigated the embodied energy payback period of two mono-crystalline PV systems applied to UK buildings, and concluded their EPBTs were 8–12 years. Knapp and Jester [3] studied the EPBTs of mono-crystalline PV system and thin film copper indium diselenide (CIS) PV system in the USA, and showed that the EPBT was 3–4 years and 9–12 years respectively. Battisti and Corrado [4] worked on a grid-connected multi-crystalline PV system in Rome with the EPBT of 3–4 years by using life cycle assessment (LCA) analysis. Crawford et al. [5] investigated the EPBT for three systems, i.e., crystalline silicon PV systems with and without heat recovery unit (HRU) and amorphous silicon PV system with HRU, installed in Sydney, Australia. The results indicated that the hybrid system could halve the EPBT of a traditional crystalline silicon PV system. The estimated EPBTs were far within the predicted PV life of at least 20 years. The paper also concluded that the EPBT depended on the parameters used for the embodied energy calculation, system and module types, installation location, electrical and thermal output, etc.

Nawaz and Tiwari [6] analyzed the EPBT of mono-crystalline PV systems for open field (stand-alone) and building rooftop (BIPV) in India. The research compared the results of EPBT with and without considering BOS and studied the difference of EPBT between macro-level (if life times of battery and PV system are the same) and micro-level (if life times of battery and PV system are not the same). The EPBT was in the range of 7–26 years for different
cases, and the actual EPBT depended on incident solar radiation, sunshine hour, efficiency of PV systems and BOS.

There are other researches which provide us a wide range of EPBT values for different PV systems in different locations. As the EPBT is defined by the embodied energy consumption of a PV system and its BOS divided by its annual energy output of the system, the EPBT calculation of a PV system is affected by many factors. Embodied energy refers to the energy used within the whole life cycle from the extraction of primary resources to the deployment including energy used during the manufacture processes, transportation and installation. Therefore, the type of solar cells (mono-crystalline, multi-crystalline, amorphous, etc.), type of PV module, system location (transport issue), system type (stand-alone system or grid-connected system), system design, system O&M, system retrofiting and system installation methods should all be identified in the embodied energy analysis. Meanwhile, some processes contribute a large portion of the embodied energy while some processes only consume a very little. It is important to investigate the percentage of energy used in some major processes and focus on the main sectors because they have great impacts on the results for calculating the embodied energy and hence the EPBT.

However, it is impossible to gather all the data and understand each step in creating each single component in a PV system, and some simplified assumptions have to be made [7]. For calculating the system annual energy output, the factors, such as local weather conditions (solar irradiance and ambient temperature), the conversion efficiencies and operating performance of PV modules, system efficiency due to battery or inverter and system power losses, orientations of PV modules (including tilted angle), system installation, etc., affect the results [8–10] and should be considered. All above factors should also be updated considering the rapid development of PV industries.

Greenhouse-gas payback time (GPBT) is also used to measure the system or technology sustainability especially when the whole world is tackling the global warming problems by reducing emission of greenhouse gases (GHG) for environmental protection. Using PV is always recommended as one of the best solutions because it does not generate CO2 during the operation. However, it does generate CO2 and other gases during its entire lifecycle such as extraction, production and disposal processes. Therefore, it is important to study the payback period based on the GHG emission to determine the sustainability and ‘greenness’ of the PV system. The GHG payback time (GPBT) is given by the embodied GHG of the system (PV modules) and BOS divided by the GHG produced by a local power plant for the power generated by the PV system [7]. Similar to embodied energy estimation, estimating the embodied GHG is also a great challenge and will have significant impact on the GPBT calculation.

The most common way to express the GHG emission is using the unit of kg CO2 equivalent, kg CO2eq, which is a weighted mass sum of emissions such as CO2, CH4, and NOx. Nawaz and Tiwari [6] used 0.98 kg CO2eq/kWh for electricity generation from coal proposed by Watt et al. [11]. Watt et al. examined the air emissions of grid supply versus grid-connected systems, and grid supply versus grid-connected and off-grid (stand-alone) PV power systems in Australia. The best option in these three cases, in terms of life-cycle air emissions, is grid-connected PV system. Battisti and Corrado [4] used 0.8 kg CO2eq per kWh for electricity generation for their study, and concluded that the GPBT of a multi-crystalline PV system is around 4 years for different system installation topologies. Mason et al. [12] performed a detailed life-cycle analysis of PV systems in USA, and found that the value was 0.0057 kg CO2eq/kWh for the BOS system, 0.024 kg CO2eq/kWh for a grid-connected PV system and 0.02 kg CO2eq/kWh for a residential rooftop system respectively. In addition, for solar cells, Fthenakis and Kim [13] conducted a life cycle assessment (LCA) for thin film CdTe solar cells in the States with the results of 0.018 kg CO2eq/kWh, and the estimation of Raugei et al. [14] was 0.012 kg CO2eq/kWh. Raugei et al. also compared the life-cycle analysis of advanced photovoltaic modules: CdTe and CIS with multi-crystalline silicon. Alesma and de Wild-Scholten [15] gave CO2 equivalent greenhouse gas emission of 6.1 kg CO2eq/m² for array support and cabling.

It can be found that the GPBT results are quite different for different PV systems. Similar to the estimation of EPBT, many factors have to be updated due to the rapid growth of the PV industry, systems should be identified specifically, and location and orientations of PV system have to be addressed before evaluation. For example, due to the advanced technology in PV industry, the production of PV modules becomes cleaner to the environment nowadays [16]. Besides, the CO2 emission of mono-crystalline silicon will decrease from 75 g/kWh in 1997 to 30 g/kWh in 2010. All these factors will affect the GPBT estimation. In addition, the production location also has great affect because different countries generate electricity in different ways. The portion of different materials used in electricity production, so called the mix of electricity, is not equal over the world. For example, the average elec-

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1, C2</td>
<td>parameters</td>
</tr>
<tr>
<td>$E_{BOS,E}$</td>
<td>embodied energy of the BOS</td>
</tr>
<tr>
<td>EI</td>
<td>decommissioning and disposal or other end-of-life energy requirements of PV modules</td>
</tr>
<tr>
<td>$E_{BOS,E}$</td>
<td>embodied energy of the electrical BOS components</td>
</tr>
<tr>
<td>EF</td>
<td>embodied energy of PV module fabrication</td>
</tr>
<tr>
<td>$E_{MBOS}$</td>
<td>embodied energy of the mechanical BOS components</td>
</tr>
<tr>
<td>$E_{Eoutput}$</td>
<td>annual energy output of the system</td>
</tr>
<tr>
<td>$E_{Ep}$</td>
<td>embodied energy of silicon purification and processing</td>
</tr>
<tr>
<td>$E_{Si}$</td>
<td>embodied energy of silicon ingot slicing</td>
</tr>
<tr>
<td>$E_{S,E}$</td>
<td>embodied energy of the system</td>
</tr>
<tr>
<td>ET</td>
<td>energy to transport PV modules from factory to installation site</td>
</tr>
<tr>
<td>$G_{de}$</td>
<td>hourly direct beam solar irradiance on a tilted surface</td>
</tr>
<tr>
<td>$G_{ds}$</td>
<td>hourly diffuse solar irradiance on a tilted surface</td>
</tr>
<tr>
<td>$G_{r}$</td>
<td>hourly reflected solar irradiance</td>
</tr>
<tr>
<td>$G_{0}$</td>
<td>light intensity at standard conditions</td>
</tr>
<tr>
<td>GHBOS</td>
<td>embodied GHG of BOS</td>
</tr>
<tr>
<td>$GHG_{output}$</td>
<td>annual GHG produced by the local power plant for the power generated by the PV system</td>
</tr>
<tr>
<td>$GHG_{s}$</td>
<td>embodied GHG of system</td>
</tr>
<tr>
<td>$I_{m}$</td>
<td>PV module’s maximum operating point current at arbitrary conditions</td>
</tr>
<tr>
<td>Is</td>
<td>short circuit current of the PV Module</td>
</tr>
<tr>
<td>$I_{mp}$</td>
<td>PV module maximum power current at standard conditions</td>
</tr>
<tr>
<td>D</td>
<td>determined by the temperature difference and solar radiation</td>
</tr>
<tr>
<td>$T_{a}$</td>
<td>ambient temperature around PV modules</td>
</tr>
<tr>
<td>$T_{c}$</td>
<td>temperature of PV modules</td>
</tr>
<tr>
<td>$V_{m}$</td>
<td>module optimum operating point voltage at arbitrary conditions</td>
</tr>
<tr>
<td>$V_{mp}$</td>
<td>module maximum power voltage at standard conditions</td>
</tr>
<tr>
<td>$x_{a}$</td>
<td>module current temperature coefficient</td>
</tr>
<tr>
<td>$f_{0}$</td>
<td>module voltage temperature coefficient</td>
</tr>
</tbody>
</table>
The annual energy output of the system, kWh. In Hong Kong, Chow et al. [17] investigated the annual performance of BIPV/water-heating system and Li et al. [18] conducted energy and cost analysis of semi-transparent photovoltaic in office buildings. No local researches were conducted to analyze the energy payback and environmental payback of a roof-mounted BIPV system (mono-crystalline PV module). Therefore, this paper aims to evaluate the EPBT and GPBT of a roof-mounted building-integrated PV system (grid-connected) in Hong Kong, to investigate the impacts of several factors (such as module orientations and local energy mix) on the EPBT and GPBT estimations, and to provide environmental payback time indicators for local PV applications.

2. Methodology

2.1. System description

The roof-mounted PV system (22 kWp) is installed on the roof of Lee Shau Kee Building on The Hong Kong Polytechnic University campus. This is a grid-connected system and all the PV modules face no shading. The orientation of all the PV modules is facing south with an inclined angle of 22.5° (local latitude), as demonstrated in Fig. 1. One hundred and twenty six mono-crystalline PV modules (SQ175-PC) are installed in the system. There are two mounting frames. One is connected with nine PV modules in series and six numbers of parallel strings, and the others is connected with nine PV modules in series and eight numbers of parallel strings.

The rated peak power of each PV module is 175 Wp, and other key characteristics of the mono-crystalline PV module (SQ175-PC) are summarized in Table 1.

2.2. Energy payback time (EPBT) estimation

Energy payback time (EPBT) is calculated by:

\[ \text{EPBT} = \frac{E_{S,E} + E_{BOS,E}}{E_{output}} \]  \hspace{1cm} (1)

where \( E_{S,E} \) is the embodied energy of the system (PV modules), kWh; \( E_{BOS,E} \) is the embodied energy of the BOS, kWh; and \( E_{output} \) is the annual energy output of the system, kWh.

2.2.1. Embodied energy estimation

Embodied energy refers to the energy used within the whole life cycle from the extraction of primary resources to the deployment including manufacturing processes, transportation and installation. In this paper, the embodied energy is divided into two categories, i.e., embodied energy of the system (PV modules) and embodied energy of BOS. The embodied energy of the system (PV modules) is defined by:

\[ E_{S,E} = E_E + E_S + E_F + E_T + E_D \]  \hspace{1cm} (2)

where \( E_E \) is embodied energy of silicon purification and processing, kWh; \( E_S \) is embodied energy of silicon ingot slicing, kWh; \( E_F \) is embodied energy of PV module fabrication, kWh; \( E_T \) is energy to transport PV modules from factory to installation site, kWh; and \( E_D \) is decommissioning and disposal or other end-of-life energy requirements of PV modules kWh.

The balance of system (BOS) is a factor that affecting the embodied energy calculation. When the embodied energy of a PV system is analyzed, the PV module itself is not the only item to be considered even though it contributes to the largest amount of energy. Others components are called the BOS, including electrical BOS components and mechanical BOS components. The electrical BOS components include inverters, electrical wirings and electronic control devices while mechanical BOS components include mounting materials and structures [19]. The embodied energy of the BOS is calculated by:

\[ E_{BOS,E} = E_{BOS,E} + E_{MBOS} \]  \hspace{1cm} (3)

where \( E_{BOS,E} \) is embodied energy of the electrical BOS components, kWh; and \( E_{MBOS} \) is embodied energy of the mechanical BOS components, kWh.

2.2.2. Annual energy output estimation

The annual energy output of a PV system depends on local weather conditions (such as hourly solar irradiance and ambient temperature), operating performance of the PV modules and PV system, system design (such as orientations, grid-connected or stand-alone). The system data collection system was set up in 2008. However, the data collection system hasn’t run successfully for long-term due to property management and grid-connection issues. Therefore, instead of long-term power yield record of the PV system, incident hourly solar irradiance on the module plane and hourly ambient temperatures are used to model the power output of PV modules as weather data input. As the system is a grid-connected one, no storage is considered.

Fig. 1. The 22 kWp roof-mounted PV system.
2.2.2.2. Selection of weather data. As weather data input plays an important role in simulation results, choosing a suitable representative year for the PV system simulation is the first step for the study. The weather is neither completely random nor deterministic. Long-term or typical weather data (such as hourly solar irradiance and hourly ambient temperature) should be chosen as weather data input [20]. Chow et al. [17] performed the annual energy simulation of BIPV/water-heating system based on the hourly Typical Meteorological Year (TMY) weather data of Hong Kong. In this study, the hourly weather data (ambient temperature \( T_a \), total and beam solar irradiances) of Hong Kong from 1996 to 2000 from Hong Kong Observatory were used for system simulations.

2.2.2.2. Modeling of PV modules and PV system. The electricity power generated by photovoltaic (PV) systems is directly related to the solar energy received by the PV panels, while the PV panels can be placed at any orientations and at any tilted angles. Most observatories only offer solar irradiance data on a horizontal plane. The incident solar irradiances on different tilted planes are totally different. For example, in Hong Kong, the radiation difference between a horizontal surface and a tilted surface could reach more than 50% [10,21]. Thus, an estimate of the total solar radiation incident on any sloping surfaces or PV panels at any orientations is needed. The total hourly solar irradiance on a tilted surface, \( G_{tt} \) (W/m²), can be calculated as follows:

\[
G_{tt} = G_{dtt} + G_{dt} + G_t
\]  

where \( G_{dtt} \) is the hourly direct beam solar irradiance on a tilted surface, W/m²; \( G_{dt} \) is the hourly diffuse solar irradiance on a tilted surface, W/m²; and \( G_t \) is the hourly reflected solar irradiance, W/m².

There are estimation methods for the total incident beam solar irradiance and total reflected solar irradiance on an inclined plane. For the estimation of diffuse solar radiation, there are several models, such as Liu & Jordan Model, Hay & Davies Model, Perez Model and Reindl Model. Li et al. [22] also studied the models for predicting the diffuse irradiance on inclined surfaces. In this study, the Perez model [23,24] was chosen as it provided results with high accuracy after validation using Hong Kong weather data [21].

2.2.2.2.3 Modeling of PV modules and PV system. The energy output of PV modules depends on the solar radiation received as well as the PV modules operating performance. The PV module operating performance is related to its specifications, \( I-V \) characteristic and the PV modules temperature. Due to the complexity of simulating the PV module operation, many different parameters are needed and it is difficult to manipulate. Therefore, there are several simplified practical models. Borowy and Salameh [25] introduced one simplified model with which the maximum power output could be calculated for one certain PV module once the radiation on the PV module and the ambient temperature were found. Jones and Underwood [26] provided one simplified model to assess the maximum power generated which had reciprocal relationship with the module temperature and liner multiplying logarithm relationship with the irradiance absorbed by the PV modules. Lu [21] verified and compared these two models, and found that Borowy and Salameh model showed high accuracy when solar radiation and cell temperatures are relatively high. Therefore, for this research, due to the local weather conditions, Borowy and Salameh model, which considers the PV modules’ specifications, \( I-V \) characteristic and the PV modules temperature, was chosen to simulate the power output of PV modules. The formulas for calculating the optimum operating point voltage and current under arbitrary conditions are shown as follows. This model makes use of the specifications of the PV modules offered by the manufacturers, so it offers a very simple way to achieve the power generated by the PV modules.

\[
I_m = I_{sc} \left( 1 - C_1 \left[ \exp \left( \frac{V_m}{C_2 \cdot V_{oc}} \right) - 1 \right] \right) + \Delta I \tag{5}
\]

where \( I_m \) is the PV module’s maximum operating point current at arbitrary conditions (A); \( I_{sc} \) is the short circuit current of the PV Module (A); \( C_1 \) and \( C_2 \) are parameters which can be calculated by the Eqs. (6) and (7) respectively in terms of the specifications of PV modules; \( V_m \) is the module optimum operating point voltage at arbitrary conditions, and can be calculated by the Eq. (8); and \( \Delta I \) is determined by the temperature difference and solar radiation, as described in the Eq. (9).

\[
C_1 = \frac{1 - I_{mp}/I_{sc}}{\exp \left( -V_{mp}/(C_2 \cdot V_{oc}) \right)} \]  

and

\[
C_2 = \frac{V_{mp}/V_{oc} - 1}{\ln(1 - I_{mp}/I_{sc})} \]  

where \( I_{mp} \) is the PV module maximum power current at standard conditions (A); and \( V_{mp} \) is the module maximum power voltage at standard conditions (V).

\[
V_m = V_{mp} \cdot \left( 1 + 0.0539 \cdot \ln \left( \frac{G_t}{G_{0t}} \right) \right) + \beta_0 \cdot \Delta T - R_i \cdot \Delta I \tag{8}
\]

where \( G_t \) is the light intensity at standard conditions (1000 W/m²); and \( \beta_0 \) is the module voltage temperature coefficient (V/°C).

\[
\Delta I = \gamma_0 \cdot \left( \frac{G_t}{G_{0t}} \cdot \Delta T + \left( \frac{G_t}{G_{0t}} - 1 \right) \cdot I_{sc} \right) \]  

where \( \gamma_0 \) is module current temperature coefficient (A/°C); and \( \Delta T = T_i - T_a \). \( T_i \) is the temperature of PV modules, and can be described by:

\[
T_i = T_a + [(NOCT - 20)/800] \cdot G_{dt} \tag{9}
\]

where \( T_a \) is the ambient temperature around PV modules, K; and NOCT is the Normal Operating Cell Temperature, defined as the cell temperature when the module operates under certain conditions (irradiance: 800 W/m²; spectral distribution: AM1.5; ambient temperature: 20 °C; and wind speed >1 m/s) in open circuit. Additionally, the tested parameters of solar cells or PV modules are specified by the manufacturer under the following standard conditions: Irradiance of 1000 W/m²; spectral distribution of AM1.5; and cell temperature (\( T_a \)) of 25 °C.

Table 2 shows the rated parameters of the PV module, SIEMENS SQ175-PC, for the energy output calculation. For the system’s energy efficiency, the average energy efficiency of a Sunny Boy inverter is assumed 94%, and other system losses are assumed 5%.

2.3. Greenhouse-gas payback time (GPBT) estimation

The GHG payback time (GPBT) is given by:

\[
GPBT = \frac{GHG_s + GHG_{BOS}}{GHG_{output}} \]  

where GHG_s is the embodied GHG of system (PV modules), kg CO₂eq; GHG_{BOS} is embodied GHG of BOS, kg CO₂eq; and GHG_{output} is

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (SIEMENS SQ175-PC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open circuit voltage (V_{oc})</td>
<td>44.6 V</td>
</tr>
<tr>
<td>Short circuit current (I_{sc})</td>
<td>5.43A</td>
</tr>
<tr>
<td>Module voltage temperature coefficient (( \beta_0 ))</td>
<td>-0.145 V/°C</td>
</tr>
<tr>
<td>Module current temperature coefficient (( \gamma_0 ))</td>
<td>0.0008 A/°C</td>
</tr>
<tr>
<td>Maximum power voltage (V_{mp})</td>
<td>35.4 V</td>
</tr>
<tr>
<td>Maximum power current (I_{mp})</td>
<td>4.95A</td>
</tr>
<tr>
<td>Nominal operating cell temperature (NOCT)</td>
<td>45.5 °C</td>
</tr>
</tbody>
</table>
annual GHG produced by the local power plant for the power generated by the PV system, kg CO$_{2eq}$.

3. Findings and discussions – EPBT

For the embodied energy of the PV system, we mainly refer to the previous research studies considering the similarity. In this paper, we mainly focuses on the energy output of the PV system as it can affect the EPBT value significantly if the PV system is installed at different places with different orientations.

3.1. Embodied energy of the PV system

Silica is melted, and manufactured into MG-Si and then into EG-Si. Finally, after the Czochralski or other production process, silicon is produced for the solar cell production. Accordingly to the previous researches, the energy required to produce 1 kg MG-Si is 20 kWh [27–29]. The energy to create 1 kg EG-Si is 100 kWh, and there is 90% loss of silicon during this process. In addition, the required energy to make mono-crystalline silicon for the Czochralski process is 290 kWh/kg with 72% mass loss. 1.448 kg mono-crystalline silicon is needed for 1 m$^2$ solar cells, so the required embodied energy for silicon purification and processing for 1 m$^2$ solar cells (or 1.448 kg mono-crystalline silicon) is calculated by:

$$E_F = 290 \times 1.448 + 100 \times 1.448/72\% + 20 \times (1.448/72\%)/90\% = 666 \text{ kWh/m}^2 \quad (12)$$

The silicon ingot is needed to be sliced into wafer. According to the manufacture data, the required energy, $E_s$, to conduct this slicing process is 120 kWh for 1 m$^2$ solar cells [30]. The solar cells are then tested, packed and interconnected with other components to create PV modules. The required energy, $E_p$, to produce 1 m$^2$ PV module is 190 kWh [31]. The PV modules in the system were shipped from Singapore, and the transportation energy use of 0.0002 MJ/(kg km) was chosen for the deep sea transport according to local government study [32]. The transportation energy $E_t$ to transport the PV modules to installation site is estimated to be 25.68 kWh per module. $E_p$ is ignored due to its insignificance.

For the rooftop integrated PV system, the energy requirement is 200 kWh/m$^2$ for making its supporting structure [33]. Besides the supporting structure, 33 kWh/m$^2$ is taken for the embodied energy used in the production of inverters, and 125 kWh/m$^2$ is chosen for all other energy used in system operation and maintenance, electronic components, cables and miscellaneous, etc.

Therefore, the total embodied energy of the 22 kW grid-connected PV system is 205,815.5 kWh, including 59556.45 kWh (29%) from BOS, and 146,259.05 kWh from PV modules (71%). The pie chart of the embodied energy distribution in the case PV system is demonstrated in Fig. 2. The percentage of the embodied energy for silicon purification and processing is the highest, 46%, and the one for BOS should not be neglected (29%).

3.2. Energy output of the PV system

For the 22 kW roof-mounted PV system, facing south with a tilted angle of 22.5°, the annual solar radiation received by the PV array is 266,174 kWh using the weather data from 1996 to 2000, and the annual energy output (AC electricity) is 28,154 kWh. The average efficiency of the PV modules on an annual basis is 10.6%, and the rated standard efficiency of the PV modules from manufacturer is 13.3%. The difference can be partly due to the actual higher cell operating temperature.

The energy output of the PV system could be significantly affected by the orientations of the PV modules. Therefore, different orientations of PV arrays and the corresponding annual energy output are investigated for a similar size PV system in Hong Kong, as given in Table 3. Obviously, for the same size PV system, the energy output could be totally different if the PV modules are installed with different orientations or inclined angles. If the 22 kW PV system is installed on vertical south-facing facade, the system power output is decreased by 45.1% compared that of the case study.

3.3. Energy payback time of the PV system

For the 22 kW roof-mounted PV system, facing south with the tilted angle of 22.5°, the EPBT of the system is estimated to be 7.3 years, which is obviously much shorter than the lifespan of PV modules which is usually 20–30 years. However, when the PV system is installed with different orientations, the estimation results of the EPBT could be totally different, as demonstrated in Fig. 3, ranging from 7.1 years to 20 years. The results show that the EPBT varies greatly with the PV panel orientations and installation locations. For vertical PV façade, the EPBT is much longer, which means less sustainable and should be avoided. However, if the material replacement saving (PV modules are acting as elements of building envelop) and building cooling thermal load saving due to the PV integration with buildings are taken into account, the EPBT should be relatively lower.

In general, choosing good sun exposure places or locations and choosing optimal orientations are the keys to use the PV technology economically and sustainably. To investigate the EPBT of a BIPV system, the building material replacement and thermal performance of the system [33] should also be taken into account, which was not considered in this paper.

4. Findings and discussion – GPBT

4.1. The utility industry in Hong Kong

There are two utility companies in Hong Kong. The one serves the studied building is the CLP Power Hong Kong Limited. Lack of natural resources in Hong Kong, CLP has adopted fuel diversification since the early 1980s, and a variety of fuels has been used to balance supply and price issues including possible cleaner fuels. There are three power stations owned by CLP, namely Castle Peak

<table>
<thead>
<tr>
<th>orientations and inclined angle</th>
<th>Solar radiation received (kWh)</th>
<th>Annual energy output (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facing south 0° (horizontal)</td>
<td>208,947</td>
<td>21,039</td>
</tr>
<tr>
<td>Faceing south 22.5° (case study)</td>
<td>266,174</td>
<td>28,154</td>
</tr>
<tr>
<td>Facing south 30° (optimal angle)</td>
<td>273,989</td>
<td>29,194</td>
</tr>
<tr>
<td>Facing east 90° (vertical)</td>
<td>146,796</td>
<td>15,528</td>
</tr>
<tr>
<td>Facing west 90° (vertical)</td>
<td>103,633</td>
<td>10,961</td>
</tr>
<tr>
<td>Facing west 90° (vertical)</td>
<td>97,160</td>
<td>10,277</td>
</tr>
</tbody>
</table>

Table 3

Annual energy output of the 22 kW PV system for different orientations.
power station, Black Point power station and Penny’s Bay power station. Besides the power generated from the three power stations, CLP employed nuclear energy for electricity production from Guangdong Nuclear Power Station at Daya Bay in 1994, displacing a proportion of our use of coal.

The greenhouse gases produced for power generation depends greatly on the mixture of fuel types. Fig. 4 presented the fuel mixture composition of CLP Power Hong Kong Limited [34] including nuclear energy, coal and natural gas accounting for one third respectively. Based on the data provided by CLP, the greenhouse gas emission rate is about 671 g CO$_2$eq/kWh. The power is relatively clean due to the use of clean fuels, such as nuclear and natural gas.

4.2. Greenhouse-gas payback time of the BIPV system

The annual energy output (AC electricity) of the PV system was estimated to be 28,154 kWh. The equivalent saved CO$_2$ emissions generated from the power station is 28,154 kWh $\times$ 671 g CO$_2$eq/kWh = 18,891 kg of CO$_2$eq.

Regarding the embodied greenhouse gases produced during the cell fabrication processes, 463 kg CO$_2$eq/m$^2$ [4] was chosen for the production of PV modules. For the BOS for rooftop installation, 6.1 kg CO$_2$eq/m$^2$ was estimated for array support and cabling [15], and 125 kg CO$_2$eq/m$^2$ was found for inverters [6]. Greenhouse gas emissions during transportation and disposal are not considered here. The greenhouse gases emitted during the PV system manufacturing and installation is estimated to be 98,834 kg CO$_2$eq. Therefore, the GPBT of the PV system is estimated to be 5.2 years. If the PV system is installed with other orientations, the GPBT will change with the same trend as the EPBT, as demonstrated in Fig. 3. In addition, if the same system is installed in other cities, the GPBT results could be different, which also depends on fuel mixture composition of local power stations. For example, if 0.98 kgCO$_2$eq/kWh for electricity generation from coal is used [11], and then the GPBT of the PV system becomes 3.6 years. Therefore, the energy mix of local power supply utility will also affect the estimation of GPBT of PV applications.

5. Conclusions

This paper reviewed the previous studies of energy payback time (EPBT) and greenhouse-gas payback time (GPBT) for different PV systems. To study the sustainability of a roof-mounted 22 kW BIPV system in Hong Kong, this paper investigated the EPBT and GPBT of the BIPV system in Hong Kong by comparing its EPBT and GPBT with its lifespan by using local weather data from 1996 to 2000.

The embodied energy for the whole system in the lifespan was estimated to be 205,815 kWh with 71% from the embodied energy of PV modules and 29% from the embodied energy of BOS. Nearly half of the embodied energy is for the silicon purification and processing. The EPBT of the PV system is calculated to be 7.3 years which is much shorter than its lifespan of 20–30 years. Considering fuel mixture composition of local power stations, the GPBT is estimated to be 5.2 years. This figure could be much lower if the utility power plants generate power by ‘non-clean’ fuels as the CLP Power Hong Kong Limited aims to provide clean power by the use of clean fuels, such as nuclear and natural gas. However, with the rapid development of PV technologies and other industries, the calculation results could vary with the changing input data.

In conclusion, the roof-mounted 22 kW BIPV system in Hong Kong is truly sustainable and green with a lifespan of 20–30 years. However, if the same capacity PV system is installed at different
orientations or other cities, the results could be totally different. Choosing locations and orientations with higher incident solar irradiance is the key for PV technology applications. Local energy mix (power stations) also affects the estimation of GPBT, which should be taken into account. To provide an overall investigation, for BIPV applications, thermal performance of BIPV systems and building material replacement should also be counted for the EPBT and GPBT estimation, which will definitely lower the BPBT and GPBT. In addition, validation of the estimation results with experimental energy output data after a few years would be conducted as the further work.

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References