INVESTIGATION ON POTENTIAL, PERFORMANCE AND POLICY OF FEASIBLE SOLAR PV TECHNOLOGIES IN BUILDINGS IN HONG KONG

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Investigation on Potential, Performance and Policy of Feasible Solar PV Technologies in Buildings in Hong Kong

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Certificate of Originality

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ABSTRACT

Hong Kong, as a high-density city whose area reaches 1105 km^2 with more than 7.3 million residents, located in the southeast of China, started to play a significant role in global economic development since last century. The high prosperity and large population no doubt result in huge energy consumption. However, in fact, there is no domestic energy reserves or fossil energy resources in Hong Kong. As a high energy density city and a net energy importer, Hong Kong experiences the dramatic rise in energy consumption and the constantly increasing energy demand poses challenges to the city sustainable development. In addition to the huge energy demand, environmental problems caused by consumption of fossil fuels have also caused widespread concerns, such as the emission of carbon dioxide and the intensification of the greenhouse effect.

From the perspective of economy, energy and environment, one of the possible approaches to deal with the energy challenge is to promote efficient use of energy in buildings. Among various types of building energy consumption systems, space air conditioning and artificial lighting contribute to the considerable proportions. The rapid growth of energy demand and the severe environmental pollution problems becomes one of the local bottlenecks. Therefore, besides promoting energy efficient technologies, another way to alleviate the power supply strain and ameliorate pollutant emission is to utilize renewable energy as alternative in Hong Kong, due to its relatively abundant renewable energy resources, especially solar energy. The local annual solar radiation level of 1290 kWh/m^2 is abundant for solar photovoltaics (PV) application compared with other countries, including Germany, the United Kingdom, and Japan.

Therefore, Hong Kong government has been taking measures to ease the use of electricity pressure and reduce the discharge of the emissions by optimizing the fuel mix for power generation, such as reducing the reliance on fossil fuels, eliminating existing

coal-fired generation units, and raising the utility of non-fossil, low-carbon and cleaner fuels, including RE (renewable energy) and nuclear energy . However, in spite of support measures introduced a decade ago, renewable energy still takes up less than 0.1% of overall installed power capacity in Hong Kong at present, much less than the average figure of 30% in Asia. To boost further local development of renewable energy under the new Scheme of Control Agreements, the government signed a new Scheme of Control Agreement with the two power companies to enter into force in 2018, introducing a plan for on-grid tariff so that the private sector may invest in installing and connecting renewable energy power generation equipment to the public power grid, while the power companies would purchase the electricity generated from these devices at a price higher than the normal tariff to encourage the development of distributed renewable energy. The two local power companies will be required to purchase electricity generated from renewable sources from residential/business users at a premium feed-in tariff ("FiT") for connection to public grid, in line with the practice seen in 110 places across the world. Also, according to our previous researches, it proves that building-integrated solar technologies will become the most feasible sustainable energy forms in Hong Kong. That’s why this thesis focuses on solar energy development in Hong Kong, especially the application of solar energy technology in buildings.

Based on a comprehensive literature review, this thesis aims to find out the research gaps of solar system applications in buildings and to carry out researches in order to provide valuable reference accordingly. In short, we pay much attention on the issues about three 'P's of solar energy development in buildings in Hong Kong, i.e. 'Potential', 'Performance' and 'Policy'. The first main objective of this thesis is to evaluate the application potential of solar energy systems in buildings in Hong Kong. Application potential, obviously, is the most significant factor to identify its possibility of promotion. Then, the application potential of solar systems is divided into four aspects, including market share, energy generation, environmental benefits and cost performance. In particular, after comparing the market in Hong Kong with these in other leading countries, the energy generation of building-integrated photovoltaics (BIPV) was calculated together with its sustainability and environmental benefits. In addition, the Levelised Costs of Energy (LCOE) for BIPV systems were investigated by employing System Advisor Model (SAM). The results present that the calculated $E_{potential}$ (the annual potential energy output of rooftop PV systems in Hong Kong) is about 5981GWh per year which is equal to 14.2% of total electricity use in Hong Kong in 2011, which means the application of BIPV systems can be a practicable renewable energy method in Hong Kong if beneficial policy supports are further provided. The results also show that, BIPV for rooftops, flexible surface thin-film BIPV rooftops and solar PV shading system, are feasible for commercial buildings in Hong Kong. Their LOCEs are about 20% lower than the local electric price. Other types of BIPV systems, such as solar PV facade and semi-transparent PV windows, can be accepted considering the available combined area and the saved building envelop materials.

Previously, there are some researches focusing on one specific performance rather than the overall performance of solar PV systems. Thus, this thesis also aims to evaluate the overall performance of various solar PV systems, including rooftop BIPV systems, shading-type solar PV claddings and a-Si based PV double-skin systems. On one hand, this thesis focused on the power generation and EPBT, GPBT, CO_2 emission rate of different BIPV systems based on Hong Kong domestic geological and climate conditions. On the other hand, the annual overall energy performance (including the power, thermal as well as day lighting performances) of an amorphous silicon (a-Si) based PV window and shading-type PV cladding systems in Hong Kong were also simulated by employing the software of EnergyPlus. For four vertical installation orientations, i.e. facing North, East, West and South, the power generation per unit area all over a year is 317 kWh, 496 kWh, 555 kWh and 504 kWh respectively. For shading-type solar PV claddings, the best orientation and tilt angles for shading-type PV cladding installation in Hong Kong is south facing with tilt angles of 20°. We also found that if the shading PV claddings are connected with an adjustable lighting control system, the energy consumption of artificial lighting could be further reduced significantly.

Then, based on the histories of solar PV system development and application in leading countries, this thesis aims to draw up a series of subsidy policies and incentives to help the local PV industry survive through the early pioneering stage. In this part, an input/output methodology is employed. The histories of solar PV development and application were reviewed as the inputs. Five leading economies in solar PV application, i.e. Japan, Germany, Italy, the USA, and Mainland China, were selected and their subsidies and policies from different eras were collected and analyzed. Then, a policy tools box was generated as the methodology output. Their experiences were referred to while a series of strategies and policies that fit Hong Kong's situation was developed. The conclusions of this thesis could be a practical reference for local researchers as well as policy-makers regarding solar energy application, especially BIPV. The major findings are listed as follows: (1) the BIPV system, which requires little extra installation and land, is a promising way of relieving the increasing financial and environmental costs of fossil fuel energy generation; (2) due to the relatively high initial investment and service costs, it is still difficult for solar PV technology to compete against fossil fuels in Hong Kong's local energy market. The government should release subsidies and sustain policies to help the solar PV industry grow; (3) the service and labor market should be opened up to providers abroad to reduce the installation costs of BIPV systems. Measures must be taken to further improve the efficiency of practitioners so that the soft costs could also be cut; and (4) subsidy of solar PV development with PV electricity grants should be implemented to support the PV business, which is in line with the current feed-in tariff.

Besides, by employing the TRNSYS building energy model, the life-cycle total cost of traditional vapour-compression cooling system, solar electrical cooling system and solar thermal cooling system are also examined and evaluated. The results show that the solar electrical cooling system is available and economical to be applied to supply the cooling for buildings. On the contrary, the solar thermal cooling system is not suitable for providing the cooling. The total cost of solar electrical cooling system could be reduced by 12.3% when compared with the traditional vapour-compression cooling system.

The findings presented in this dissertation can provide a reference for solar energy development and structural adjustment of Hong Kong in the future, and provides a theoretical basis for local energy policy makers to formulate a reasonable energy policy, and the development goal of subsidies in Hong Kong and solar photovoltaic technology.

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PUBLICATION LIST

Journal papers:

[1] **Aotian Song**, Lin Lu, Weilong Zhang (2017). Study on the levelized costs models of solar power generated from different BIPV systems in Hong Kong. To be submitted.

[2] **Aotian Song**, Lin Lu, T. Ma. Life-cycle evaluation of different types of cooling systems in buildings. *Energy Procedia* 142(2017): 1743-1748.

[3] **Aotian Song**, Lin Lu, Man Sing Wong. A Study of Incentive Policies for Building-Integrated Photovoltaic Technology in Hong Kong. *Sustainability MPDI* 2016; 8.

[4] Zhang W.L., L. Lu, J.Q. Peng, **A.T. Song**. Comparison of the overall energy performance of semi-transparent photovoltaic windows and common energy-efficient windows in Hong Kong. *Energy and Buildings* 128(2016): 511-518. (Sep 2016).

[5] Jinqing Peng, Lin Lu, Hongxing Yang, **Aotian Song**. The application potential of Building Integrated Photovoltaic in Hong Kong. *Zero Carbon Building Journal* 2015; 3: 48-55.

Conference papers:

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[2] **Aotian Song**, Lin Lu, Weilong Zhang (2016). Study on the levelized costs of solar power generated from different BIPV systems in Hong Kong. Proceedings of the *11th Conference on Sustainable Development of Energy, Water and Environment System,* Lisbon, Portugal, Sep 2016.

[3] Jinqing Peng, Lin Lu, Hongxing Yang, **Aotian Song**, Tao Ma (2015). Investigation on the overall energy performance of an a-Si based photovoltaic double-skin facade in Hong Kong, Proceedings of the *14th International Conference on Sustainable Energy Technologies,* Nottingham, UK, Aug 2015.

[4] Weilong Zhang, Lin Lu, Jinqing Peng, Aotian Song (2016). Investigation of the Overall Energy Performance of Shading-type solar photovoltaic Claddings in Hong Kong. Proceedings of the 11th *Conference on Sustainable Development of Energy, Water and Environment System,* Lisbon, Portugal, Sep 2016.

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NOMENCLATURE

GHG	greenhouse gas
HAVC	ventilation and air conditioning
RE	renewable energy
PV	photovoltaics
BIPV	building-integrated photovoltaic
BAPV	building-attached photovoltaic
EPBT	energy payback time
GPBT	greenhouse payback time
EYR	energy yield ratios
TMY	typical meteorological year
PV-DSF	photovoltaic double-skin façade
STPV	semi-transparent thin-film PV
LCOE	levelised cost of electricity
MPPT	maximum power point tracking
CHP	heating and power
SAM	system advisor model
CIGS	copper indium gallium selenite
CdTe	cadmium telluride

GIS	geographic information systems
DSM	digital surface model
FIT	feed-in-tariff
LEC	levelized energy cost
PCM	phase change material
PV-TE	photovoltaic and thermoelectric
SHGC	solar heat gain coefficient
PVEG	photovoltaic electricity grant
G_{bt}	hourly beam solar radiation incidence on a tilted surface
G_{tt}	hourly total solar radiation incidence on a tilted surface
G_{dt}	hourly diffuse solar radiation incidence on a tilted surface
G_r	hourly reflected solar radiation
G_{bh}	beam radiation incidence on the horizontal surface
θ	angle of incidence
β	zenith angle
ρ_o	ground reflectance
G_{dh}	diffuse solar radiation incidence on the horizontal surface
G_{th}	total horizontal solar radiation

D	reserved distance between the front and back rows
γ	solar azimuth angle at 9:00 AM during the winter solstice
δ	winter solstice solar declination
ω	winter solstice hour angle at 9:00 AM
α	solar altitude angle
φ	latitude of Hong Kong
H	installation height of PV module
W	width of PV module
$A_{act.}$	potential total active area of PV modules
$A_{pot.}$	potential PV-suitable rooftop area
$A_{occu.}$	installation occupancy area
A_{pv}	area of a single PV module
$E_{potential}$	annual potential energy output of rooftop PV system
$G_{optential}$	annual total solar radiation received
η_{stc}	PV module's energy conversion efficiency
λ	performance ratio of PV systems

A_t cash saving in construction material

$O\&M_t$ annual operating and maintained costs

F_t financial factor

x_j input variables

b_j sensitivity coefficients

nX the number of x_j

ε_k error term defined by $\varepsilon_k = \hat{y} - y_k$

W_{sc} power of solar thermal collector

A_a total aperture area of solar thermal collector

η_{sc} solar-thermal conversion efficiency

I hourly irradiance

CL_{peak} cooling capacity of adsorption chiller

COP_{ad} COP of adsorption chiller

CC_{stc} annualized capital cost of solar thermal collector

CC_{ac} annualized capital cost of adsorption chiller

CL_i	hourly cooling load
$W_{sc,i}$	hourly power of solar thermal collector
A_{pv}	total area of photovoltaic module
η_{pv}	photovoltaic module efficiency
η_{pc}	power conditioning efficiency
I	hourly irradiance
COP_{elec}	COP of electrical chiller
CL_{re}	required cooling load
CL_{ava}	available cooling capacity
TC_{se}	annualized total cost of solar electrical cooling system
CC_{pv}	annualized capital cost of photovoltaic module
CC_{in}	annualized capital cost of inverter
CC_{ch}	annualized capital cost of electrical chiller
OC_{ec}	annual operation cost of electrical chiller
$P_{pv,i}$	hourly power generated by photovoltaic module

I	hourly irradiance
$P_{ch,i}$	the required hourly power consumed by electrical chiller
C_{gp}	electrical price sold to the grid
CL_i	hourly cooling load of building
COP_i	hourly COP of electrical chiller
TC_{te}	total cost of traditional electrical cooling system
CC_{ec}	capital cost of electrical chiller
OC_{ec}	operation cost of electrical chiller
E_{in}	total energy input during the life cycle of the PV system
E_{out}	annual output of the PV system energy
GHG_{in}	embodied GHG of system
GHG_g	annual GHG emission amounts
GHG_{sum}	sum GHG emission of system

CHAPTER 1 INTRODUCTION

1.1 Electricity demand and current situation in Hong Kong

Hong Kong, as a high-density city whose area reached 1105 km^2 and where more than 7.3 million residents lived [1], located in the southeast of China, started to play an important role in the global economic development since last century. Hong Kong has been famous for its relatively high population density and beautiful city appearance. The high prosperity and large population no doubt result in huge energy consumption. However, in fact, there is no domestic energy reserves or fossil energy resources in Hong Kong. As a high energy density city and a net energy importer, Hong Kong experiences the dramatic rise in energy consumption and the constantly increasing energy demand poses challenges to the city sustainable development. In addition to the huge energy demand, environmental problems caused by consumption of fossil fuels have also caused widespread concerns, such as the emission of carbon dioxide and the intensification of the greenhouse effect.

From the perspective of economy, energy and environment, one of the possible approaches to deal with the energy challenge is to promote efficient use of energy in buildings. Among various types of building energy consumption systems, space air conditioning and artificial lighting contribute to the considerable proportions. In Hong Kong, as shown in Fig1.1 &1.2, about 42% of energy and 55% of energy were consumed by heating, ventilation and air conditioning (HVAC) systems and artificial lighting for commercial buildings and residential buildings respectively in the year 2013 [2]. Since Hong Kong is a cooling-dominated area, space cooling represents a significant use of energy in buildings.

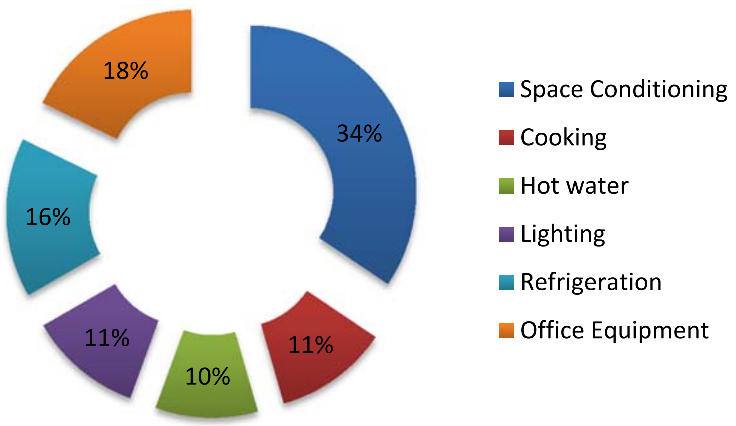


Fig. 1.1 End-use of residential energy in Hong Kong 2013 [2]

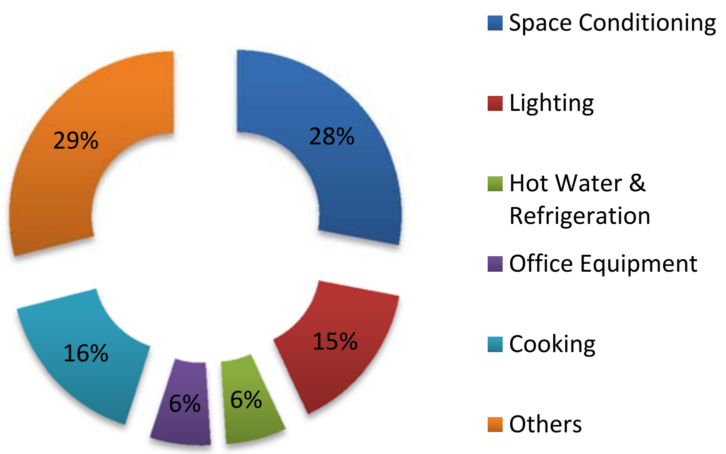


Fig. 1.2 End-use of commercial energy in Hong Kong in 2013[2]

1.2 Conventional power generation and its problems

For now, fossil fuels still take the dominant role in energy sources of Hong Kong. In 2015, the amount of Total Primary Energy Supply was 588,540 TJ, out of which 287,986 TJ was consumed as "energy end-use" within Hong Kong while around 1,899 TJ were produced by renewable energy [3].

It should be noted that with an area of only around 1100 square kilometers, it is impossible for Hong Kong to be self-sufficient in fossil fuel supply. However, the greenhouse gas (GHG) emissions from burning fossil fuels are also a critical environmental issue that attracts attention from the whole society.

In 2011, the total energy use of Hong Kong was 278,618TJ. Renewable energy, including solar energy, wind energy, biogas and biodiesel, only provides 0.8% of energy use, and the rest is provided by fossil fuels (coal, oil and natural gas)[4]. In 2012, the total energy consumption at end-use level in Hong Kong was 287,970 TJ, among which buildings accounted for approximately 90% according to Hong Kong Yearbook of 2014 [5].

In 2009, the electricity mix in Hong Kong comprised of 23% nuclear power plants in Mainland China and 77% traditional thermal power plants from local power plants [6]. In 2010, two electricity companies are operating a total of four power plants, which together supply 77% of electricity for local consumption. In 2011, these four power plants used coal or natural gas as fuel, with coal accounting for 71% of local electricity generation and natural gas 29% [7]. The massive burning of fossil fuels has led to a large amount of greenhouse gas emissions, and greenhouse gases are considered to be the main source of environmental pollution. Fig. 1.1 shows the trend of greenhouse gas emissions in Hong Kong for 1990-2008 years [6], and the annual total greenhouse gas emissions of 42 million tons of 2008. Electricity generation ranked the highest in terms of sectorial contribution to Hong Kong's GHG emissions. For example, it accounts for about 67% of the total emissions of 2008 while thermal power plants accounted for 50%, 25% and 16%, respectively, of SO_2, NO_X and repairable suspended particulates (PM_{10}) emitted in Hong Kong in 2010 [7]. Therefore, the reduction of fossil fuel power plants can effectively alleviate local environmental pollution and greenhouse gas emissions.

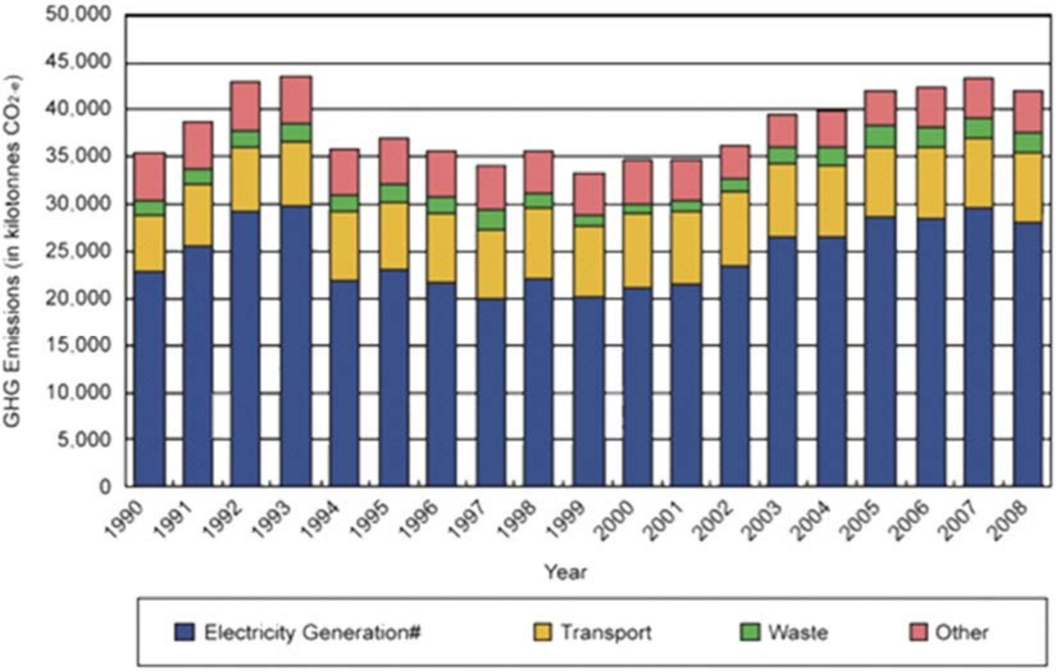


Fig. 1.3 Greenhouse gas emissions from 1990-2008 years in Hong Kong [6]

1.3 Solutions to relieve the power supply strain

The rapid growth of energy demand and the severe environmental pollution problems becomes one of the local bottlenecks. In general, Hong Kong lacks fossil fuel resources, but owns rich renewable energy resources, such as solar energy and wind power. In this context, for a more sustainable future, the Hong Kong Special Administrative Region (HKSAR) Government issued a public consultation document to tackle the challenges of greenhouse gas emissions and climate change in September 2010. This document suggests a target of 50-60% carbon intensity reduction by 2020, compared with 2005, as shown in Table 1.1. In order to achieve this ambitious goal in such a short time, suggestions for improving energy efficiency of power equipment and widely using renewable and low carbon fuel power generation were put forward. The HKSAR government has also set a primary energy target of 50% nuclear, 40% gas, 3%–4% renewable energy, and not more than 10% coal up to 2020 [8]. Thus, as shown in Fig. 1.2, two options were proposed to retrofit fuel mixed power generation by 2023. In Option 1, the fuel ratio of coal should be reduced to less than 10% by 2023, by raising the share of natural gas to 40% for its much lower GHG emissions per kWh electricity generated. Meanwhile, about 30% of electricity would have to be purchased from the Mainland China grid. Moreover, the proportion of renewable energy will rise from 0.1% to 2023 to 3-4% from 2011.

Table 1.1 A road map of greenhouse gas emission reduction for Hong Kong from 2005-2020

	2005	2020	Reduction
Carbon intensity (kg CO_{2-e}/HK dollar)	0.029	0.012-0.015	↓50-60%
Total GHG emissions (million tonnes)	42	28-34	↓19-33%
Per capita GHG emissions (tonnes)	6.2	3.6-4.5	↓27-42%

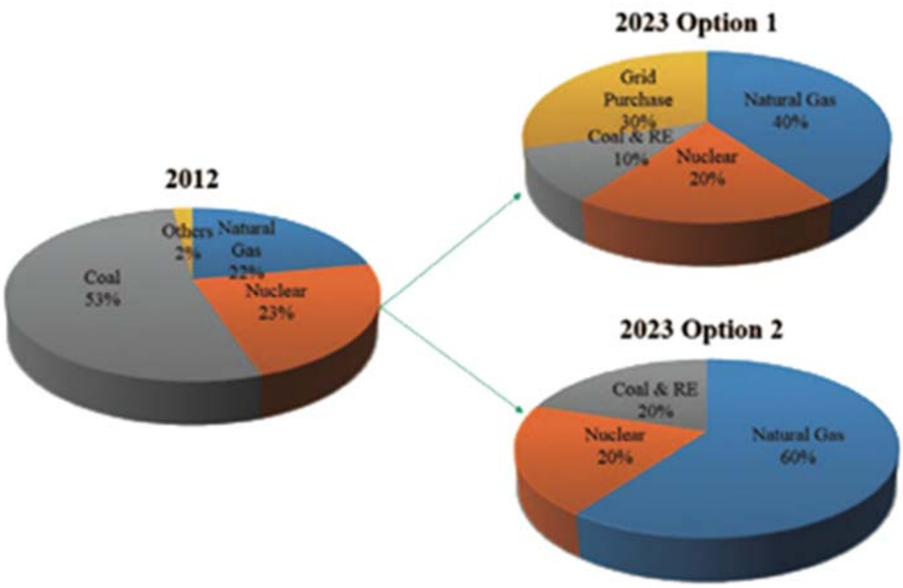


Fig. 1.4 Hong Kong's mixed electricity in 2012 and 2023 [9]

Thus, for Hong Kong government, realizing the optimization of the fuel mix for power generation, especially reducing the reliance on fossil fuels, eliminating existing coal-fired generation units, and raising the utility of non-fossil, low-carbon and cleaner fuels, including RE (renewable energy) and nuclear energy, are an essential path to ease the use of electricity pressure and reduce the discharge of the emissions. The application of sustainable and renewable energy in Hong Kong could be a promising way to reduce the financial and environmental costs of fossil fuels. Carbon intensity in the power sector can be reduced by reducing coal use and by increasing the use of lower carbon content fuels, such as natural gas, nuclear, and renewable energy. The proportion of each energy source in the chosen fuel mix depends on local availability and infrastructure as well as economic affordability. For a more holistic perspective, it would be prudent to also consider the life cycle carbon emissions of each fuel to ensure the effectiveness and sustainability of any proposed choice. With limited fossil fuel resources, Hong Kong's low latitude subtropical climate location offers great potential for sustainable energy application. Currently, the major forms of renewable energy include biomass, solar, wind, hydro, and geothermal. Local scholars have conducted fruitful research work on Hong Kong's sustainable energy application, and came out with quite detailed data about potential sustainable energy applications in Hong Kong.

In Hong Kong, the contribution from renewable energy at present comes mostly from biomass and waste conversion. Ni et al. did a very detailed and complete study on potential renewable energy applications in Hong Kong. They did a statistical analysis and research on three major waste types suitable for energy generation in Hong Kong, including solid waste, sewage sludge, and livestock waste. The hydrogen production per year from organic waste can generate up to 1.1 TWh of electrical energy with satisfactory efficiency, which could satisfy more than 4.0 % of the energy demand for transportation cost [10].

In addition, the local annual solar radiation level of 1290 kWh/m^2 is abundant for solar photovoltaics (PV) application compared with other countries, including Germany, the United Kingdom, and Japan. According to the statistics of Peng and Lu, the annual potential energy output for a rooftop PV system is predicted to be 5981 GWh, which is equal to 14.2% of total electricity used in Hong Kong in 2011 [11]. Gao et al. applied a Multi-Population Genetic Algorithm to investigate the potential offshore wind energy in Hong Kong. They claimed that for the year 2011, the potential offshore wind annual electric generation was about 112.81 * 108 kWh, which is equivalent to 1/4 of the total power end-use in 2011 under the layout-optimized condition. They also found that the wind power potential is the highest in October but the lowest in August [12]. Furthermore, the lack of large running water systems in Hong Kong rules out hydro generation. Exploitable resources in Hong Kong do not support producing electricity from geothermal energy and land availability constraints limit economic opportunities for ground-based wind and solar photovoltaic generation. As stated above, it seems likely that wind power and solar PV power generation will become the most feasible sustainable energy forms in Hong Kong. Therefore, this thesis will mainly focus on the solar PV development in Hong Kong.

1.4 Assessment of the application of solar energy systems in Hong Kong

Hong Kong owned 1800 hours insolation duration in a year [13], and the annual solar irradiation is about 1400 kWh/m^2. It is far higher than the average solar energy in Japan, and much better than Germany.

Solar energy is a clear, non-polluting and inexhaustible source of energy. With the well-developed solar energy technologies, solar energy can be implemented into people's life. Solar energy utilization mainly includes three methods: optical-heat conversion, optical-electricity conversion and optical-chemical conversion, of which the first two are well known. Optical -heat conversion is to use the sunlight to heat the water in tanks for future utilization, which is the most common and basic form of optical-heat conversion. The essence of solar thermal systems is to transform solar radiation into heat energy, mainly used for heating, hot water supply, cooling and power generation, and so on. The principle of optical-electricity conversion is that under light conditions, there is the potential difference between the two ends of the semiconductor p-n junction, which is called the photovoltaic effect. After the semiconductor absorbing photons, resulting in additional electrons and holes, these free carriers in the semiconductor within the local electric field, each moving to the interface layer on both sides of the accumulation, the formation of net space charge and potential difference. The practical application of photovoltaic effect led to the emergence of solar photovoltaics systems, which is a viable renewable power conversion technology.

However, as we know, there is no perfect system and solar PV system has its pitfalls as well. One of the disadvantages of solar PV systems is that they cannot meet electricity demand outside of daylight hours. Therefore, in the case of off-grid or stand-alone applications, power storage is an inseparable part of the photovoltaic power generation (cost issues are ignored) to ensure higher power supply reliability. Therefore, energy storage, also called battery integrated, is one of the key issues to be solved in the roadmap of stand-alone solar PV development [14].

In our study, considering the high building density and scarcity of land, mass installation on fields like in Mainland China, the USA, and some European countries is not practical in Hong Kong. However, with the mature development of solar PV technologies, integrating solar PV systems into the envelope of buildings, especially the rooftop, which is also known as building-integrated photovoltaics (BIPV), offers a great opportunity for renewable energy development in unban cities, such as Hong Kong. Compared with traditional solar PV systems, the BIPV system possesses many merits. It does not occupy land resources. It is also able to supply electricity directly at the place where it is installed. Moreover, the PV elements can be applied as an integral part of the building and can lessen building material consumption. BIPV systems can not only generate electricity for free but also reduce building energy use by absorbing solar radiation and reducing building solar heat gain. From the perspective of sustainability, the EPBT and greenhouse gas payback time (GPBT) of PV systems range from 1.9 to 3.0 and 1.4 to 2.1 years, which are much less than their service life of 30 years. Their energy yield ratios (EYR) distribute from 10 to 15.8, which means that the PV systems can generate power about 10 times than their energy requirement during their lifetime [15]. In terms of GHG emissions, even the highest one, viz. the emission rate of mono-Si PV systems, was still an order of magnitude less than that of fossil fuel-based electricity in Hong Kong, which accounts for about 700 g CO_2-eq/kWh [16].

The first BIPV system in Hong Kong was installed in 1999 and funded by The Industrial Support Fund from the Hong Kong SAR Government. The PV electricity output from this system was stable and never required moving components or anything more than low-key maintenance work during long-term operation. This demonstrates that the solar PV system can provide the best reliability and feasibility of BIPV system in Hong Kong.

In line with the Global Future Report 2013, it is estimated that the global solar PV capacity could reach 400–800 GWp as soon as 2020 and as much as 8000 GWp by 2050, which will save more than 53 million tons of CO_2 emissions [17,18]. By the end of 2015, the Chinese mainland, the largest and fastest developing region in the world, reached 43.5 GWp cumulative installed capacity as compared to only 19.2 GWp in 2013. In the meantime, Germany and Italy have reached 39.7 GWp and 18.9 GWp, representing the largest PV penetration of the electricity demand (7.1% and 8.0%) in the world. Japan and the USA were positioned as the third and fourth in the list with solar PV installation capacity of 34.4 GWp and 25.6 GWp, their annual installation capacities even reached 11 GWp and 7.3 GWp in 2015 [19]. However, solar PV application has not yet been popularized in recent years in Hong Kong. Although solar energy resource in Hong Kong are highly above the world average, the total PV installed capacity is less than 3 MWp and the actual PV electricity generation only reach a negligibly small share of total energy end consumption in Hong Kong.

As to solar cooling technology, it is mainly composed of solar collectors, heat-driven refrigeration devices and auxiliary heat sources. There are two types of technologies: (1) the power generated by optical-electrical conversion technology is used to drive the conventional electric compressor cooling refrigeration. This approach is simple, easy to implement but with high cost; (2) solar energy conversion heat driven refrigeration, which is relatively new but with low cost and without noise and pollution.

1.5 Recently proposed fee-in tariff of solar power in Hong Kong

Recently, to encourage businesses to use environmentally friendly devices, the Hong Kong Government has accelerated the allocation of specified capital expenditures for environmental protection devices from 25 years to five years from 2008. Eligible environmental protection devices include renewable energy power generation devices. The government signed a new Scheme of Control Agreement with the two power companies to enter into force in 2018 in April 2017, introducing a plan for on-grid tariff so that the private sector may invest in installing and connecting renewable energy power generation equipment to the public power grid, while the power companies would purchase the electricity generated from these devices at a price higher than the normal tariff to encourage the development of distributed renewable energy [20].

For the public, implementing a feed-in tariff does not increase the electricity tariffs. On the contrary, introducing more diverse renewable energy sources would reduce future vulnerable increases in gas prices and electricity costs. The public would also benefit from the reduced pollution and avoid hefty health care costs.

1.6 Objectives of the thesis

This thesis aims to examine the three issues, i.e. three ‘P’-- ‘potential’, ’performance’ and ‘policy’, of feasible solar technology, mainly focusing on BIPV technology in Hong Kong. Detailed objectives are provided as below:

1. To evaluate the development potential and energy incentives of building-integrated solar PV systems in Hong Kong. The development potential, obviously, is the most significant factor to identify its possibility of promotion. Then, we divide the development potential and energy incentives of solar systems into four aspects, i.e. market share, power generation, environmental benefits and cost performance.
2. To investigate the levelized cost energy of solar PV systems in Hong Kong, which can serve as a reference for the feed-in tariff of solar PV power for local power company. Meanwhile, according to uncertainty and sensitivity analyses, we can find out the most efficient technical method to improve cell economics.
3. To calculate overall energy performance of various solar PV systems, i.e. rooftop solar PV systems, shading-type solar PV claddings and a-Si based PV double-skin systems.
4. To summarize and learn from the histories of solar PV system development and application in solar PV leading countries, and to draw up a series of subsidy policies and incentives to help the local PV industry surmount from its early pioneering stage.

5. To examine the feasibility of other driven cooling technologies due to the large energy use consumed by air-conditioning cooling systems in Hong Kong.
6. Finally, to analyze the prospect of utilization of solar energy sources and offer a reference for energy development and structural adjustment of Hong Kong in the future.

1.7 Organization of the thesis

Firstly, Chapter 1 analyzes the current situation and tendency of energy and environment in Hong Kong, and puts forward the use of renewable energy to alleviate the increasingly serious energy problems and environmental pollution, combined with the climate characteristics of Hong Kong.

In Chapter 2, a detailed literature review will be presented to introduce the solar PV technology development, solar cooling systems and BIPV systems and to find out the research gap or limitations in local feasible solar technologies. According to the literature review, the research methods of this thesis will be presently accordingly.

Then, the major contents of this dissertation are divided into five main chapters, i.e. Chapter 3, Chapter 4, Chapter 5, Chapter 6 and Chapter 7. In Chapter 3, the potential of solar photovoltaic (PV) applications in buildings in Hong Kong is estimated and assessed. A detailed case study of rooftop PV systems is conducted. In Chapter 4, the impact of the effective lifetime on the LCOE and the energy production is clearly presented. In addition, the presented analysis covers a wide range of PV technological characteristics, and meteorological conditions. Chapter 5 addresses the overall energy performance of different building-integrated solar PV systems, including rooftop solar PV systems, shading-type solar PV claddings and a-Si based PV windows. In Chapter 6, an input/output methodology is employed: The histories of solar PV development and application were reviewed as the inputs while a policy tools box was generated as the methodology output. Afterwards, Chapter 7 aims to newly examine the feasibility of other solar driven cooling technologies in Hong Kong.

Finally, there is a chapter for overall conclusion and recommendation for future research, including conclusions of theoretical and numerical investigations, recommendations for solar PV development in Hong Kong and recommendations for future research.

The findings presented in this dissertation can provide a reference for solar energy development and structural adjustment of Hong Kong in the future, and provides a theoretical basis for local energy policy makers to formulate a reasonable energy policy, and the development goal of subsidies in Hong Kong and solar photovoltaic technology.

CHAPTER 2 LITERATURE REVIEW AND METHODOLOGY

2.1 Introduction

In this chapter, it mainly presents a detailed literature review of the solar PV systems. After having a certain theoretical foundation, we discover the research gaps in the field of solar technology as well. Based on these, we confirm the research direction, tools and methodology.

Following a brief introduction, the literature review and classification of solar PV systems is presented in Section 2.2. Specifically, section 2.2.1 reviews the development of solar PV technology. Section 2.2.2 gives a review of solar cooling technology. Section 2.3 presents the research gaps probed into in this research. Section 2.4 describes the methodology applied in this study. In the end, Section 2.5 summarizes these reviews and methodology in this chapter.

2.2 Literature review on solar systems

2.2.1 Solar PV technology

Solar PV systems can be defined as a combination of several elements to generate electricity from irradiation, which including modules and mechanical and electrical mountings, among others [21]. Systems of different scales, whether a large plant or small distributed, have different components and characteristics in engineering and economics [22,23]. From this point of view, the primary consideration when building a PV system is on-grid versus standalone [24–26], which depends on the margin above the electricity demands. The specific mounting configuration is another significant factor that affects the system’s performance. Rack-mounted and BIPV [27] are two of the main mounted types usually used. In addition, several technologies can be combined with the original PV system in order to improve the efficiency or suitability for multiple environments, such as an maximum power point tracking (MPPT) system [28], battery storage integrated [29–31], and other energy hybrids [32–34].

The most impactful method to improve PV module efficiency must be MPPT technology. MPPT have benefit to raise the power delivered from the PV module to the end uses, and extend the PV operating time. Several MPPT techniques have been developed in recent years, including offline models (also known as model-base method, that the control signals are generated by physical values of the PV panel) [35–38], online method (also known as a model-free method, that the control signals are generated by instantaneous values of the PV output voltage or current) [39], and hybrid method [40].

Currently, the most pressing problem that engineers focus on is the size of batteries, which is a roadblock to commercial use even though many models were established to improve the system's economy [41–44]. However, research focused on energy storage for single-family dwellings indicated that integrated storage might increase by more than 100% annual PV self-consumption [45]. In addition, recent research shows that the PV-battery storage integrated system is still not ready for commercial rollout because suitable PV-batteries are sensitive to all the parameters and the battery will only have an active implication on Net Present Value (NPV) at a low installation cost (e.g., below 750 USD/kWh) [46].

Another method to improve the electrified economy is using PV Hybrid Systems. For residential-scale photovoltaic arrays, the development of small-scale combined heating and power (CHP) systems has provided the opportunity for in-house power backup [47]. Recent work has shown that small-scale CHP and PV technologies can produce significant emission reductions at the residential level [48,49]. Other hybrid systems include PV-Diesel [50,51], PV-Wind [52–54], or PV-Wind-Diesel systems [55–58]. These kinds of hybrid system have lower costs than traditional systems.

A final way to decrease the lifetime cost of a PV system is recycling of PV modules [59]. From the perspective of economics, energy payback time (EPBT) studies have shown great potential savings from recycling the low-efficiency module [60]. Currently there are three kinds of major recycling pathways focused on by researchers, including recycling of manufacturing waste, recycling of end-of-life or used module material, and module remanufacturing and reuse [61]. However, most PV modules are still lack the economic motivation to recycle [62].

In addition to improving components efficiency, research on PV systems has never been interrupted. Along with the BIPV systems popularized, a growing number of people have known its benefits. In recent years, a lot of research has been conducted to investigate the optimization of the energy performance of BIPV systems as well. Yang et al. [63] investigated the impact of PV walls on the cooling load in three cities (Hong Kong, Shanghai and Beijing) via simulation. The results showed that 33%-50% of cooling load could be reduced if PV claddings were integrated on a massive wall. Peng et al carries out A comparable study on the annual thermal performance between normal and PV walls. [64]. The results indicated that about 52.1 kWh/m^2 of thermal energy could be saved per year by replacing normal walls with PV walls. It was also found that the thickness of air duct between PV modules and façade had a great impact on the thermal performance. Yang et al. [65] carried out a simulation study on the energy performance of PV roofs. Comparisons showed a 65% decrease of cooling load using a PV roof instead of a conventional roof. Dominguez et al. [66] studied the influence of rooftop PV panels on annual heating and cooling load reduction in San Diego, California. Compared with the roofs without photovoltaic panels, photovoltaic roofing can reduce the annual refrigeration capacity by 38%. Under the PV module, the heat flux of the roof decreased significantly during the day. At night, however, solar panels cover the ceiling with a higher temperature than the ceiling without a solar panel. Apart from the photovoltaic walls and the photovoltaic roofs, the semitransparent photovoltaic components can also be used as PV glazing [67,68]. An optimum way for BIPV application is to adopt ventilated air gap because this integration would not only improve PV energy conversion efficiency but also reduce cooling load in hot summer [69]. Peng et al. conducted comparative study on the power and thermal performance of a semi-transparent photovoltaic double-skin facade (PV-DSF) [70]. Based on the experimental results, the ventilation modes had a larger effect on thermal performance than power performance. A comprehensive simulation model was developed to investigate the overall energy performance of PV-DSF in Berkeley, California as well [71]. The results indicated that the annual net electricity use of the PV-DSF was much lower than other commonly used windows or facades. Chow et al. [72,73] carried out experimental and theoretical studies on a building-integrated photovoltaic/water heating (BIPV/W) system in Hong Kong. It was reported that the PVT wall could lower the space thermal loads in both summer and winter and compared to BIPV systems, the BIPV/W system has more economic advantages.

Besides, PV modules can integrate with overhang or awning to form shading-type PV claddings as well. An optimal designed shading-type PV cladding not only can provide a considerable amount of electricity but also lessen the electricity use of air conditioning and lighting significantly compared with a normal interior shading device. Thus, it is regarded as one of the most efficient BIPV solutions. Yoo et al. [74,75] examined shading BIPV systems facing south, suggesting that the sun shading type of photovoltaic integration should be applied to power generation and to provide sunshade for buildings. Sun et al. [76, 77] assessed the effect of both tilt angles and surface azimuth angles on the energy performance of shading-type PV claddings. The best orientations and tilt angles for shading-type PV cladding installation in terms of power output and cooling load reduction of building envelops were achieved.

2.2.2 Classification of BIPV systems

Building Integrated Photovoltaics (BIPV) is a technology that uses the photovoltaic effect of semiconductors to directly convert solar energy into electrical energy. It is almost maintenance-free and can be integrated with envelopes of buildings. Compared with wind farms requiring large land arears, the solar PV power generation technology can be directly combined with the building envelope, such as roofs, skylights or facades, to form building-integrated photovoltaic (BIPV) systems [97]. Several tradition types of BIPV can be found in Fig. 2.1. In addition to generating electricity in situ, BIPV systems can also reduce the cooling/heating load of a building [98]. Therefore, due to densely pack high-rise buildings in Hong Kong, the application of the integrated photovoltaic building system is an effective way to promote the energy saving.

In Hong Kong, buildings are consuming about 60% of the total electricity end-uses in Hong Kong and this proportion has increased over recent years [99]. To reduce the building's net electricity use, one of the most effective solutions is to actively develop building-integrated photovoltaic system. Solar PV modules can be integrated with external wall to form a vertical ventilated PV cladding. As the area of external walls is much larger than the rooftop area, this kind of PV cladding is expected to be a main way of BIPV application for this high building density city.

Fig. 2.1 Traditional BIPV Application

The building rooftop PV system is the most typical technology of BIPV. Based on the previous study, this system is likely to provide more than 14% of the power mix of our existing technology, without the need for additional land demand in Hong Kong [100].

Besides rooftops, facades and windows of high-rise buildings are the other suitable places for installing PV systems. Compared with rooftops, the facade and window areas are much larger and can hold more PV installation capacity. All the windows, shading overhangs and the external walls are potential places for integrating with PV modules.

In this study, 5 kinds of BIPV, which can be found in Table 2.1, will be modeled and simulated in System Advisor Model (SAM) [101].

Table 2.1 BIPV systems discussed in this study

Case	Module			Orientation		Module efficiency	Manufacturer
	Type	Area (mm×mm)	Wp (W)	Tilt (deg)	Azimuth (deg)		
mounted rack solar module for Rooftops (BAPV)	C-Si	1640×992	260	0, 23	180	15.9% 15.8-16.3%	TrinaSolar SunTech

flexible surface thin-film BIPV for roofs or facade	CIGS	2598×370	110-130	1/4 arc	180	14.4-17%	Mia Solar
BIPV semi-transparent vertical window(50% transmittance)	A-Si	1000×1000	63	90	180	6.3%	Golden-Glass
BIPV vertical cladding facade	C-Si	1400×1100	100	90	0,90,180,270,360	6.5%	Golden-Glass
BIPV shading system	C-Si CIGS	1640×992	260	31,55	180	15.9%	TrinaSolar SunTech

A normal BIPV system will provide only a part of electricity demand, so grid-connected BIPV is recommended, as shown in Fig. 2.2.

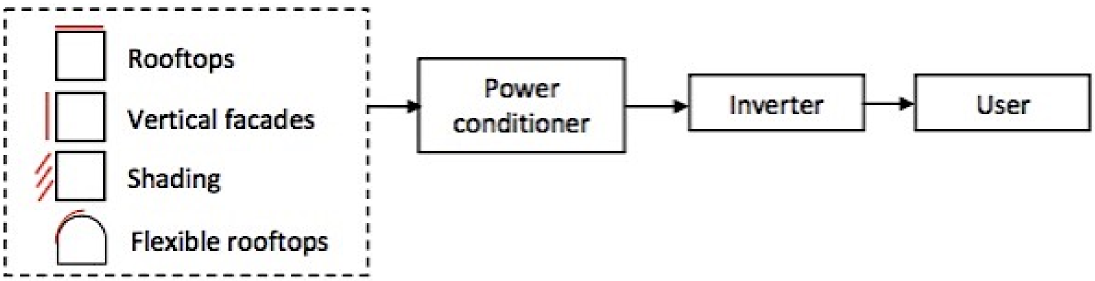


Fig. 2.2 A grid-connected BIPV configuration without batteries

In SAM, the residential (distributed) photovoltaic (detailed) model was used and system parameters were obtained from experiments or assumption. In the chapter 4, a detailed LCOE model and performance analysis will be discussed under the configuration above.

2.2.3 Review of solar cooling technology

Energy consumption of building sector reaches approximately 40% of final energy consumption in the worldwide [78]. For the purpose of cooling, the annual energy demand had reached 14.6% between 1990 and 2000 [79], which is expected to rise in the coming years because of the reduced prices of air-conditioning system and requirement of thermal comfort.

Conventional cooling systems were driven by grid electricity. It may result in several drawbacks: 1) electrical energy is produced by fossil fuels, which leads to emitting a great amount of carbon dioxide to the environment; 2) the electrical grid suffers during the entire cooling season due to the simultaneous and extensive operation of electrically driven chillers [80]. On the contrary, solar cooling system offers a sustainable and reliable solution, which is alternative to conventional cooling system. The solar cooling system can be divided in two main categories: solar thermal cooling and solar electric cooling [81-84]. Currently, the combination of solar thermal collectors with absorption chillers and the combination of photovoltaic module with a traditional compression chiller will be discussed.

In the late years, many researchers had taken the possibility of operating an adsorption chiller with solar energy into account both numerically and experimentally. Miyazaki [85] asserted that the commercial adsorption chillers could operate at the temperature less than 70°Ceffectively. A lumped-parameter model was developed by Yong and Sumathy [86] to investigate the performance of a solar cooling system, which was driven by flat plate collectors of several different types of glazes. It was found that the configurations of glazes had no impact on the performance of the solar cooling system importantly. Qu et al. [87] evaluated a solar thermal cooling and heating system at Carnegie Mellon University to verify the question that how solar energy might be used in providing energy for the operation of a building effectively. Sekret and Turski [88] presented the possibilities of the use of a solar thermal cooling system to supply the cooling in a referential room of 40 m^3 in volume. Experiments on the adsorption ice water generator working conditions and an analysis of the possibilities for using solar thermal cooling system are also presented. Alam et al. [89] investigated the possibility of application of solar cooling system under climatic condition in Tokyo. The system operates with a cooling capacity around 10 kW at noon and achieves a solar COP of approximately 0.3. Du et al. [90] proposed an air-cooled two level ammonia absorption refrigeration system driven by solar hot water. The initial manufacturing and maintenance costs of the solar collector and the absorption chiller can be reduced. The experimental results indicated that the prototype operated smoothly and steadily. Considering that the cooling demand coincided with the availability of solar radiation, Gebreslassie et al. [91] asserted that solar assisted absorption cooling system was a promising alternative to conventional vapor compression cooling system. A decision support tool for solar assisted absorption cooling system based on mathematical programming was proposed. The design accounted for the total cost of the cooling system as well as the associated environmental impact measured over its entire life cycle. Performance of solar energy absorption air conditioning system, installed in the green building of Shanghai Research Institute of Building Science, was investigated by Zhai et al. [92]. The system comprises two adsorption chillers with nominal capacity 8.5 kW each powered by 150 m^2 of solar collectors. The average cooling capacity of the system was 15.3 kW during an 8h operation while the maximum value exceeded 20 kW.

Meanwhile, several researchers had compared the performance of solar thermal cooling systems with solar electrical cooling systems. Noro and Lazzarin [93] compared the performance of solar thermal with electrical cooling systems under Mediterranean weather conditions. The potential of the application of solar cooling systems in an office building was assessed by Porumb et al. [94] in Cluj–Napoca, Romania. The used solar cooling systems contained an absorption chiller associated with solar thermal collectors and an electrical chiller associated with photovoltaic modules. The result illustrated that the annual solar cooling fraction for the solar thermal cooling system was nearly 26.5% while it was about 36.6% for the solar electrical cooling system. A thermodynamic and economical evaluation was conducted by Lazzarin [95] on two solar cooling systems. For the evaluation of solar cooling systems, both the overall system efficiency was considered as well as the capital cost of the two systems. The comparison between the photovoltaic cooling system and solar thermal cooling system was conducted by Eicker et al. [96] on office buildings under different climatic conditions. The result illustrated that the primary energy consumption can be lessened by about 21-70% for both the two system, given the building cooling load and the location.

2.3 Research gap

Although considerable researches have been devoted to solar technology development in buildings, some research gaps in this field are still summarized as below:

(1) Our group has conducted experiments and simulations for some types of BIPV technologies. However, it still lacks of a financial model to evaluate the levelized cost of electricity (LCOE) of different BIPV systems in Hong Kong in order to discuss the commercial feasibility and support the incentive solar policy-making in future.

(2) In the LCOE model, many parameters are involved in an assumption manner, and they affect the LCOE results. But uncertain and sensitivity of the real LCOE is still a research gap up to now.

(3) Little attention has been paid on the overall energy performance of different types of BIPV technologies.

(4) There is a lack of abundant research about energy policy of BIPV, which plays an important role in the PV market of Hong Kong.

(5) Researchers usually worked on improving the efficiency of solar cooling systems previously, but there were still limited numbers of papers focusing on money payback.

2.4 Methodology

As BIPV is a viable solution for commercial buildings and suitable for Hong Kong, many people, especially the policy makers care about its development potential and environmental benefits. In Chapter 3, firstly, we propose related questions, then by assuming the per capita roof area ratio and combined with airborne LiDAR data and spatial analysis, the estimation of total roof area and annual potential energy output of rooftop PV system in Hong Kong is presented.

One of the probable reasons that hinder the popularization of this system is the high installation costs of BIPV systems is much higher than the ones of traditional solar PV systems. However, as NERL mentioned in 2011[102], after considering the saving in original construction material and reduce installation price, BIPV systems are still competitive. Therefore, the LCOEs of different BIPV systems in Hong Kong will be evaluated with a modified model in Chapter 4.

In Chapter 5, a simulation model was developed using EnergyPlus to evaluate the thermal, daylighting and power performance of the a-Si based solar PV windows in Hong Kong. The PV power module, daylighting module as well as window glass module were utilized to simulate the power, daylighting and thermal performances, respectively. The key characteristics of the solar PV window is shown in Table 2.2 and the simulation model of a-Si based solar PV windows is show in Fig. 2.3.

Table 2.2 Key characteristics of the solar PV window

Parameters	Value
Active area, A (m^2)	0.79

Short circuit current, I_{sc} (A)	1.41
Open circuit voltage, V_{oc} (V)	58.6
Current at the maximum power point, I_{mp} (A)	1.1
Voltage at the maximum power point, V_{mp} (V)	42.2

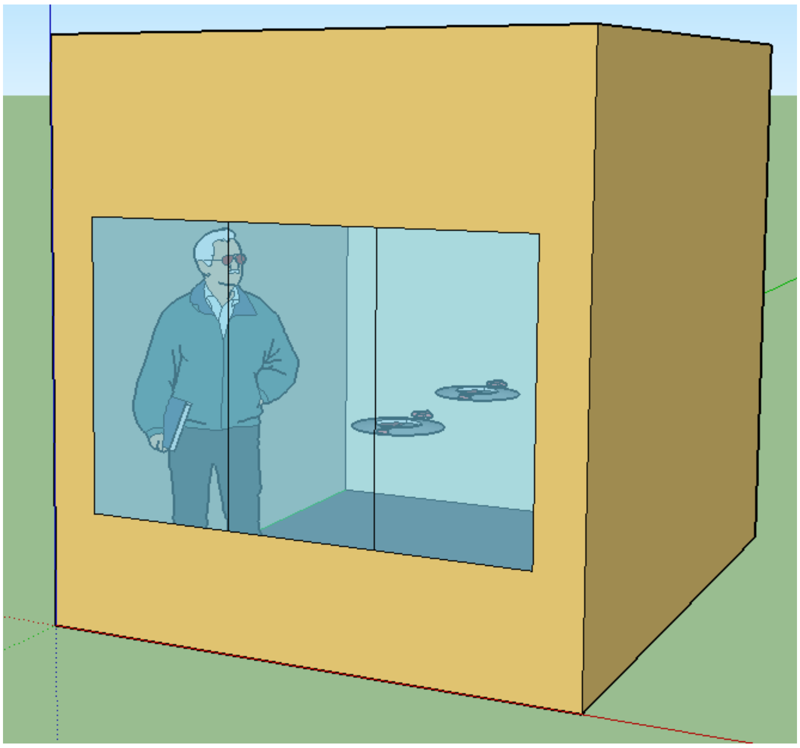


Fig. 2.3 The simulation model of a-Si based solar PV windows

Besides, similar to the simulation model developed for solar PV windows, a simulation model for estimating the energy performance of shading-type PV claddings was developed. The shading-type PV cladding was installed on the wall above the windows with tilt angle of 30˚. The diagrammatic sketch of the office room is shown in Fig. 2.4, and the key characteristics of the PV module are shown in Table 2.3 All the simulation setup was the same as the simulation model for solar PV windows.

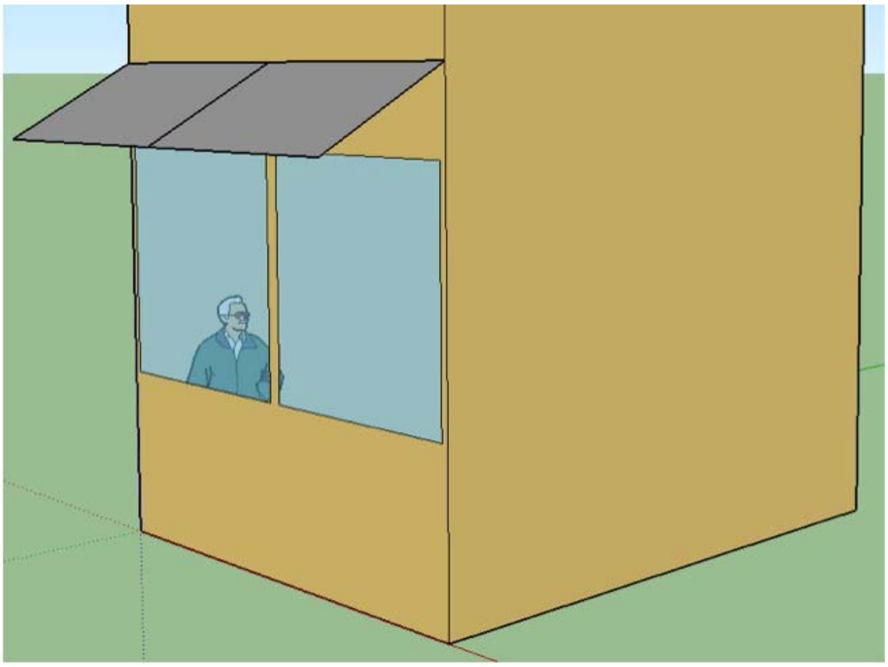


Fig. 2.4 The diagrammatic sketch of the office room

Table 2.3 Key characteristics of PV module

Parameters	Values
Solar cell type	mc-Si
Short circuit current	9.0 A
Open circuit voltage	38.2 V
Current at maximum power	8.5 A
Voltage at maximum power	30.6 V
Dimensions (L × W)	1.65 m^2

Besides, in Chapter 6, a simple input/output methodology is employed. The histories of PV development and application were reviewed as the inputs. Five leading economies in PV application, Japan, Germany, Italy, the USA, and Mainland China, were selected as discussed in the above section. Their subsidies and policies from different eras were collected and analyzed. Then, a policy tools box was generated as the methodology output.

Their experiences were referred to while a series of strategies and policies that fit Hong Kong's situation was developed. It was hoped that the conclusions of this study could serve as a practical reference for local researchers as well as policy-makers.

Lastly, in Chapter 7, the assessment of life cycle costs of the solar electrical cooling system, solar thermal cooling system and traditional cooling system are conducted to verify that which is the best option for buildings in Hong Kong. TRNSYS building energy model is used to calculate the operation cost of these three cooling systems. The originality of this study is mainly the potential of the application of examined three different types of cooling systems in buildings in Hong Kong.

2.5 Summary

This chapter presents a comprehensive literature review on potential solar systems in buildings and finds out the research gaps. The following chapters, in view of the mentioned issues in Section 2.3, aim to carry out the researches and to address the conclusions about potential solar technologies and related energy policy in Hong Kong with the aids of appropriate tools and models mentioned in Section 2.4.

CHAPTER 3 DEVELOPMENT POTENTIAL OF ROOFTOP SOLAR PV SYSTEMS IN HONG KONG

3.1 Introduction

Hong Kong is expected to transform into a city whose fuel structure is made up of non-fossil, cleaner and low-carbon fuels like building-integrated photovoltaic (BIPV) systems because of the limited lands and the high requirement of energy security. Since BIPV technology has the potential of large-scale application in Hong Kong, many people, especially the policy makers are very interested in finding answers to the following questions: (1) How much PV capacity can be installed on the rooftop of buildings in Hong Kong? (2) How much electricity can be generated yearly from these rooftop PV systems? (3) What potential proportion of the total electricity is provided by PV electricity generated by rooftop PV systems? (4) What are the main reasons that restrict the development of PV industry in Hong Kong? (5) What kind of subsidies are suitable for PV installation in Hong Kong? (6) How to determine the intensity of subsidy? (7) What are the environmental benefits of developing rooftop PV systems? Therefore, this chapter aims to provide answers to the above questions as well as suggestions to the local policy makers to promote the rapid development of PV industry in Hong Kong.

Therefore, this chapter aims to examine the development potential and energy incentives of building-integrated solar PV applications in Hong Kong. Section 3.2 gives a description of trends in the global solar PV market, and compares the solar PV market in Hong Kong with these in other PV leading countries. The energy generation and potential of rooftop solar PV system is calculated and presented in Section 3.3, and the sustainability and environmental benefits are discussed.

3.2 Trends in the global solar PV market

Solar photovoltaic technologies have been developing rapidly with great supports from governments all over the world. In 2016, a total of 76.7 GW of solar was installed and connected to the grid, as show in Fig. 3.1[108]. That's the largest amount of solar power that was installed in a year so far and a 50% year-on-year growth over the 51.2 GW added in 2015. China is the most aggressive country in the utilization of solar PV systems and dominated the global solar market in 2016 more than it was the year before. China connected 34.5GW to the grid, a 128% increase over the 15.1 GW it added the year before. This strong growth rate came as a surprise and was triggered by a feed-in-tariff cut in the middle of the year that led Chinese developers to install over 20 GW alone in the first six months of 2016. Then, the United States was the world's second largest solar power market in 2016. The country's annual installed capacity was up 97% year-on-year, resulting in 14.8 GW, compared to 7.5 GW in 2015. Following its demand climax in 2015, the solar market in Japan decreased as anticipated in 2016, despite its nearly 50 GW large pipeline of approved but not yet built utility-scale solar plants.

In recent years, great progress has been made in material science research related to solar cells, leading to continuous improvements in efficiencies of solar cells and PV modules. Fig. 3.2 illustrates the evolution of best research-cell efficiencies [109]. As of October 30, 2017, the best efficiencies of commonly used solar cells, viz. mono-crystalline, multi-crystalline, amorphous silicon, copper indium gallium selenite (CIGS) and cadmium telluride (CdTe), were 27.6%, 22.3%, 14%, 23.3% and 22.1%, respectively.

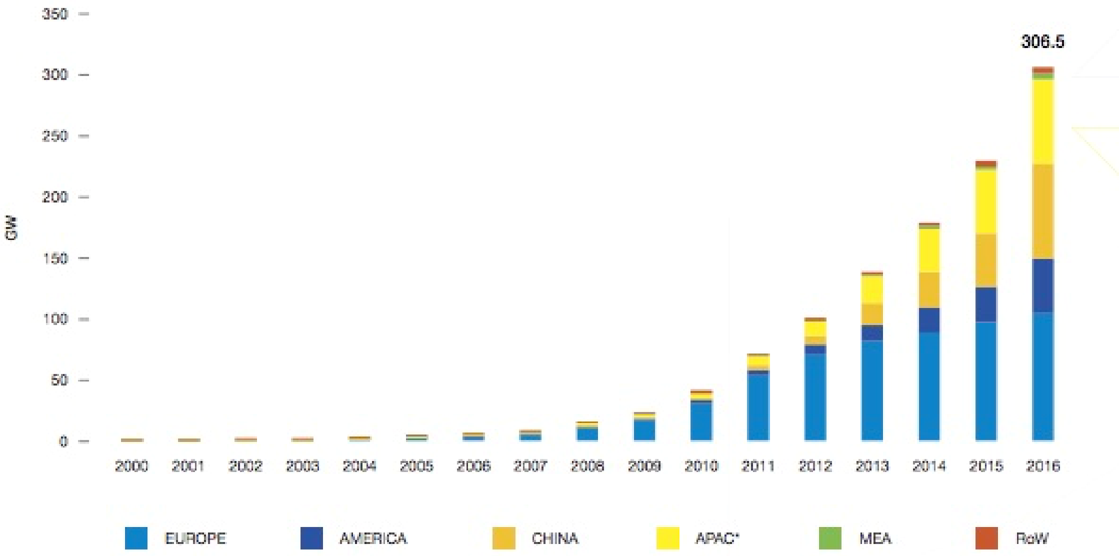


Fig. 3.1 Evolution of global total solar PV installed capacity 2000-2016 [108]

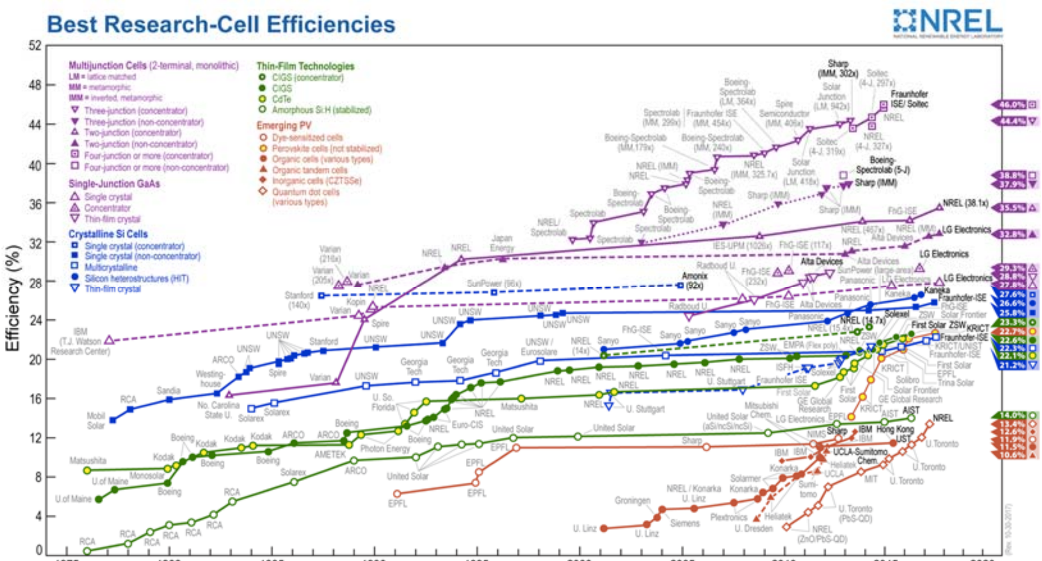


Fig. 3.2 Evolution of the world's best research-cell efficiencies [109]

With worldwide applications of solar PV systems in recent years, there has been an ongoing reduction in solar PV module prices arising from technological progress and economies of scale. Fig. 3.3 shows the historical price trend of photovoltaic components as the global installed capacity increases [110]. The price of PV modules has been lessened to about €0.6/Wp in 2012 from the previous €4/Wp in 2006. The trend shows that if the accumulative capacity of installed capacity is doubled, the price of photovoltaic components will be reduced by 20%. If we continue to vigorously develop products and manufacturing processes, it is expected that the price will continue to decline in accordance with the rules. At the same time, the PV installation costs have fallen significantly— from €5/ Wp in 2006 to €1.64/Wp in 2014 for rooftop installations in Germany with rated outputs of up to 10kWp [111].

According to a recent report from Deutsche Bank [112], the sudden drop of PV installation costs has resulted in solar PV generated electricity becoming competitive with conventional electricity from the grid in at least 19 markets around the world, even without subsidies as shown in Fig. 3.4. Although Hong Kong is not included in the 19 markets, the levelised cost of electricity (LCOE) of solar PV is rapidly approaching parity with conventional electricity in Hong Kong [113], and modest subsidies now could accelerate the adoption of solar PV and stimulate an entirely new industry.

In this study, the potential installation capacity of rooftop solar PV systems in Hong Kong was estimated to be 5.97GWp, and the annual potential energy output was predicted to be 5981GWh. This is equivalent to 14.2% of the total electricity used in Hong Kong in 2011. Hence, local policymakers could develop a more ambitious development target for renewable energy application in the future. Solar PV technology certainly has the potential to meet the target. Although the current cost of PV power generation is relatively high, solar photovoltaic power is expected to compete fully with the traditional power mode in the near future, if the government provides appropriate subsidies, and there are ongoing reductions in the PV system installation costs as well. Therefore, the government should pay more attention to this development, by introducing new policies for encouraging private companies and building occupants to install more BIPV systems.

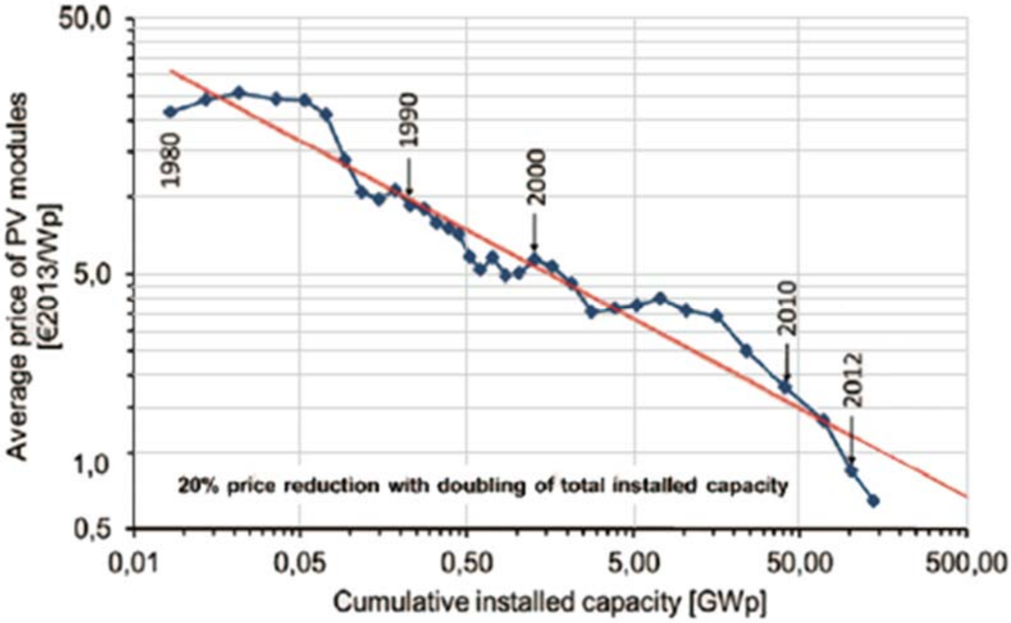


Fig. 3.3 Historical price trends of PV modules varying with the installed capacity [110]

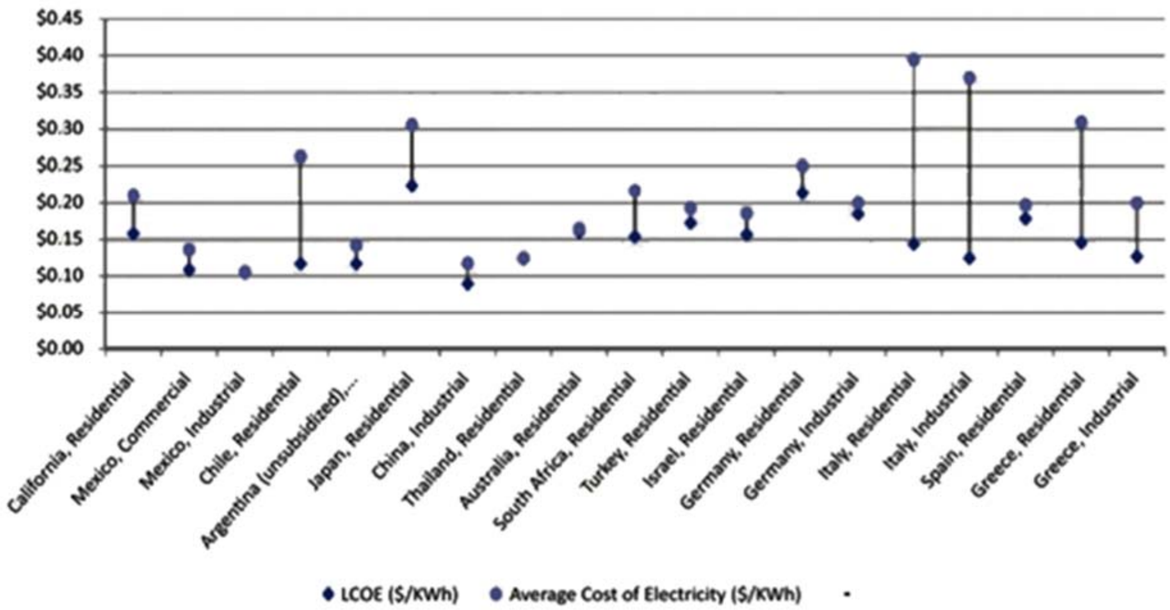


Fig. 3.4 PV achieved parity with grids in 19 markets worldwide [113]

3.3 Development potential and energy incentives of rooftop solar PV system

Building-integrated photovoltaic (BIPV) refers to the use of photovoltaic materials, that is. A solar cell and a photovoltaic module to replace traditional building materials, or exterior walls, in an enclosure, such as a roof, a skylight section. These solar PV modules simultaneously serve as building envelope material and generate power, thus can provide savings in the building material and electricity costs [114]. Compared with common ground mounted solar PV systems, BIPV systems do not occupy any land resources, so they are very suitable for use in cities that lacks land and with high-density buildings, such as Hong Kong.

3.3.1 PV suitable rooftop area

Previous studies have focused on the use of different methods to assess the potential for the development of rooftop photovoltaic systems. The main difference between these methods is how to assess the suitable roof area of the installation of PV systems, which is an assessment of rooftop solar PV potential usually starts with. However, there is little direct statistical information regarding PV-suitable rooftop areas. In recent years, some research methods have been reported for estimating the PV-suitable rooftop area [115,116]. The commonly used methods can be divided into three types, viz. assuming the roof area ratio per capita, aided by geographic information systems (GIS), as well as establishing correlation between the population density and roof area. In this section, the PV-suitable rooftop area was estimated with the first two methods.

Firstly, when it comes to estimate the PV-suitable rooftop from buildings' ground floor areas, the details of the procedure are illustrated in Fig.3.5. The ground floor area is transferred into the gross roof area by using a 'gross roof area to ground floor area' ratio. Then, on the basis of the suitability of the solar roof and the building suitability factor, the roof area of the roof is calculated. Usually, the 'gross roof area to ground floor area' ratio and the solar suitability and architectural suitability factors can be determined by rule of thumb. In this study, these three factors were assumed to be 1.2, 0.55 and 0.7, respectively, to estimate the potential PV-suitable rooftop area in Hong Kong. The total ground floor area of all buildings in Hong Kong account for 117 km^2 [117]. Based on these figures, the potential PV-suitable rooftop area in Hong Kong can be calculated. The results are presented in Table 3.1.

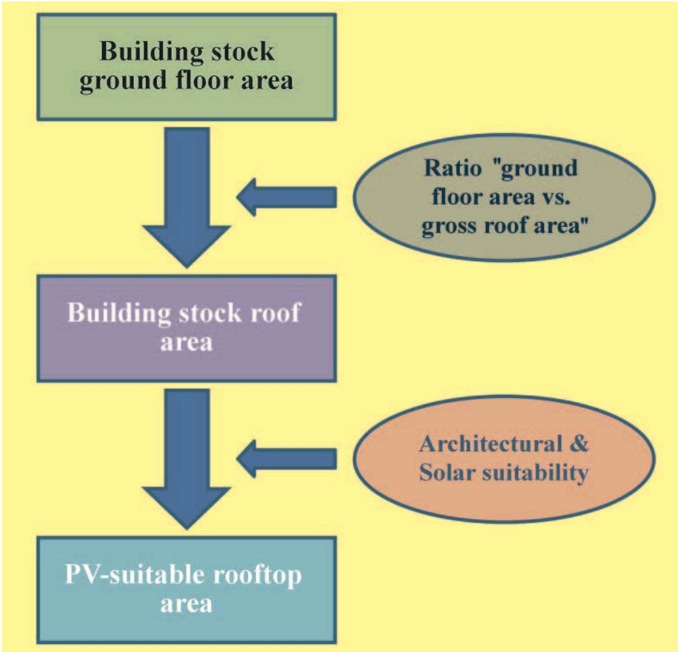


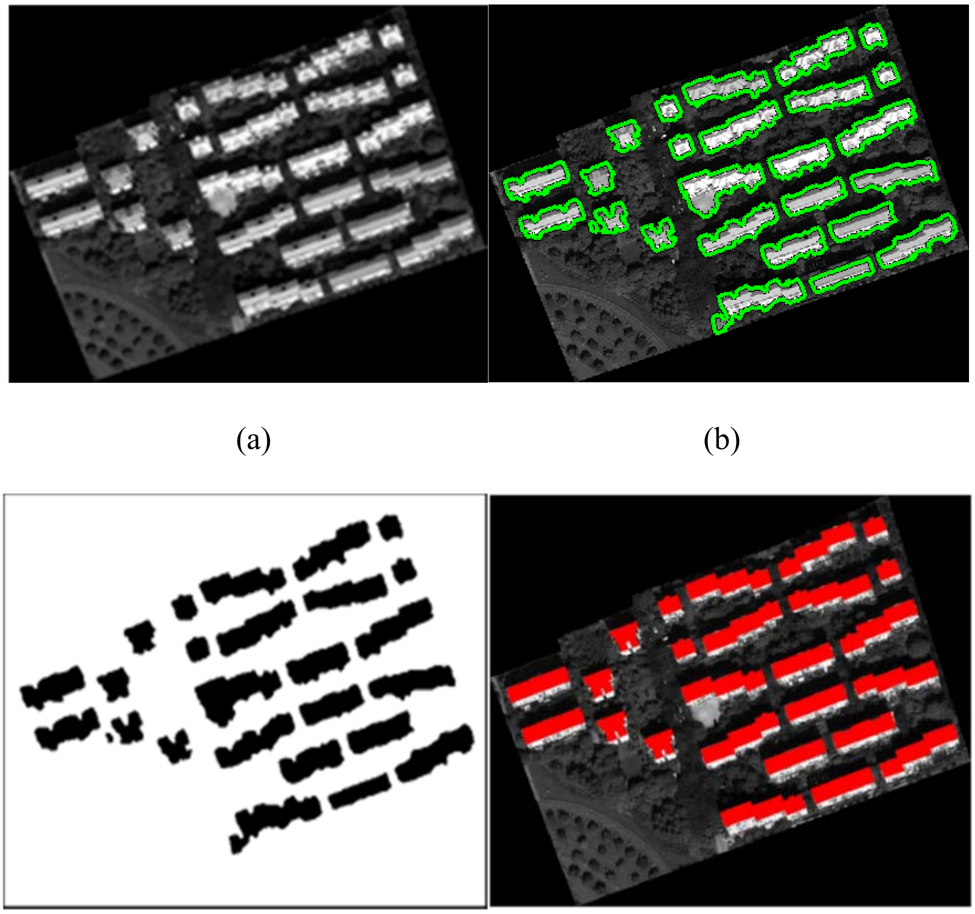
Fig. 3.5 Procedure for estimating potential PV-suitable rooftop area

Table 3.1 The potential PV-suitable rooftop area in Hong Kong

Ground floor area	117 km^2
'Gross roof area to ground floor area' ratio	1.2
Gross roof area	140 km^2
Architectural suitability factor	0.7
Architecturally suitable roof area	98 km^2
Solar suitability factor	0.55
The potential PV-suitable rooftop area	54 km^2

The second method of estimating the potential PV-suitable rooftop area is to combine airborne LiDAR data and spatially analysis. An insolation model was first built based on the Digital Surface Model (DSM) of the study area with parameters of diffuse proportion and transmissivity in 2012. The extraction of the roof area of the PV roof is based on the footprint of the building. Mask the shadow according to the sunshine model. The decision tree method is used to filter the steep slope, the ground feature and the roof barrier.

Therefore, the results were then vectorised and spatially joined; the PV suitable area in the roof can be determined.



(a) (b)

(c) (d)

Fig. 3.6 The extracted final results of the proposed model: (a) shows the original image with 25 building roofs; (b) shows the extracted results with green building outlines; (c) displays the binary results of building roofs; (d) shows the ground truth data.

The rooftop extraction results using this technology are listed in Fig. 3.6 as an example: Fig. 3.6 (a) shows the original image with 25 buildings roofs; Fig. 3.6 (b) presents the extracted results with green building outlines; Fig. 3.6 (c) shows the binary results of building roofs; Fig. 3.6 (d) displays the ground truth data. From these figures, it can be seen that the method is suitable for the recognition and extraction of the roof area. The results show that there are 233,152 buildings suitable for implementing rooftop PV systems in Hong Kong. The suitable roof area of the total photovoltaic was estimated to be 39.2 km^2.

3.3.2 The optimum tilted angle for rooftop PV installation

The energy output of PV system is directly determined by the solar radiation received by PV modules. Therefore, these modules should be installed in the best direction and heading angle to maximize the energy output of PV system. However, most observatories only provide the total solar radiation data on the horizontal plane. Therefore, it is necessary to convert the total solar radiation on the horizontal plane to the incident solar radiation on any inclined surface, and then find the best tilt angle of PV installation on the roof. The hourly total solar radiation incidence on a tilted surface, G_{tt} (W/m2), can be expressed as follows:

$$G_{tt} = G_{bt} + G_{dt} + G_r \tag{3.1}$$

where, G_{bt} is the hourly beam solar radiation incidence on a tilted surface, W/m^2; G_{dt} is the hourly diffuse solar radiation incidence on a tilted surface, W/m^2; and G_r is the hourly reflected solar radiation, W/m^2. G_{bt} and G_r can be given by the following equations, respectively [118].

$$G_{bt} = G_{bh} \times R_b = G_{bh} \times \frac{\cos\theta}{\cos\theta_z} \tag{3.2}$$

$$G_r = \frac{\rho_o}{2} \cdot G_{th} \cdot (1 - \cos\beta) \tag{3.3}$$

where, G_{bh} is the beam radiation incidence on the horizontal surface, it can be extracted from the total horizontal radiation of G_{th} (provided by the Observatory); θ is the angle of incidence; β is the slope angle of PV modules; θ_z is the zenith angle; ρ_o is the ground reflectance.

In this study, the Perez model is adopted to simulate the diffuse solar radiation incidence on any tilted surface. In the Perez Model, the diffuse solar radiation incidence on a tilted surface can be calculated by equation (3.4) [119-120]:

$$G_{dt} = G_{dh} \cdot \left[(1 - F_1) \cdot \left(\frac{1 + \cos \beta}{2} \right) + F_1 \cdot \frac{a}{b} + F_2 \cdot \sin \beta \right] \quad (3.4)$$

where, G_{dh} is the diffuse solar radiation incidence on the horizontal surface, it can be extracted from the total horizontal solar radiation, G_{th}.

In order to maximize the annual solar radiation received by roof PV modules, a FORTRAN program was developed based on the above mathematical models to find the best tilt angle of PV installation on rooftops. The incidence of simulated solar irradiance on the different tilted surfaces in the south direction from 1998 to 2007 was obtained. It is found that the best angle of photovoltaic roof of the installation in Hong Kong is 23 degree, so the average available solar radiation is about 1333 kW / m^2, during ten years. Therefore, in Hong Kong, a potential rooftop photovoltaic system is recommended for installing the maximum annual energy output of the best tilt angle.

3.3.3 Installation potential of rooftop PV systems

In previous studies on the estimation of the potential of photovoltaic cells, there was no consideration of the possible partial shadow of the front row of the photovoltaic module. However, in the actual system, a certain space must be retained between the front and back lines to eliminate this part of the shadow effect. In this study, the distance between the front and back rows of the array ensures that the front row of the photovoltaic components does not cause a partial shadow at the winter solstice from 9:00 a.m. to 3:00

p.m. Fig. 3.7 shows a schematic diagram of the distance between the array of PV modules before and after the calculation. From this diagram, it can be seen that the distance (23 degrees in Hong Kong) of the PV module array with the best inclination angle can be calculated as follows [121]:

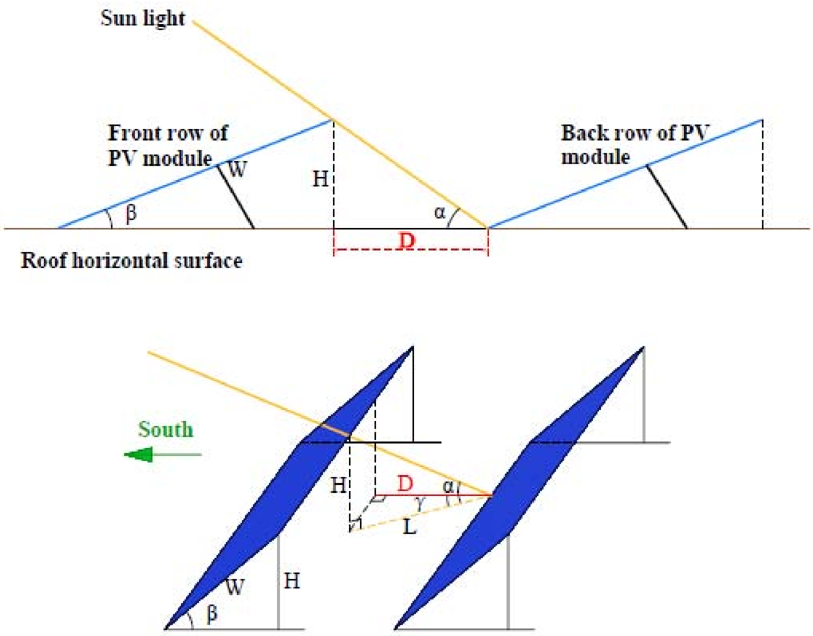


Fig. 3.7 The schematic diagram to calculate the array distance

$$D = \cos\gamma \times L \tag{3.5}$$

where, D is the reserved distance between the front and back rows; γ is the solar azimuth angle at 9:00AM during the winter solstice in Hong Kong. This can be calculated by equations (3.6) and (3.7); L is the projection of sun light on the roof horizontal surface.

$$\sin\gamma = \cos\delta \sin\omega / \cos\alpha \tag{3.6}$$

$$\gamma = \arcsin(\cos\delta \sin\omega / \cos\alpha) \tag{3.7}$$

where δ is the winter solstice solar declination; ω is the winter solstice hour angle at 9:00AM ; α is the solar altitude angle, which can be calculated as follows:

$$\sin\alpha = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega \tag{3.8}$$

$$\alpha = \arcsin(\sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega) \tag{3.9}$$

where φ is the latitude of Hong Kong. The projection of sun light on the roof horizontal surface can be calculated by equations (3.10) and (3.11).

$$L = \mathrm{H}/\tan\alpha \tag{3.10}$$

$$H = \mathrm{W} \times \sin\beta \tag{3.11}$$

where H is installation height of PV module; W is the width of PV module; β is the optimum tilted angle.

Therefore, in order to ensure that there is no partial shadow in the winter solstice PV array line, the layout of PV array should be maintained at the distance between 514 mm.

After taking the reserved array distance into account, installing a single objective PV module would occupy about 2.35m^2 of a rooftop. Equation 3.12 can calculate the total active area of the rooftop PV modules:

$$A_{act.} = \frac{A_{pot.}}{A_{occu.}} \times A_{pv} \tag{3.12}$$

where, $A_{act.}$ is the potential total active area of PV modules; $A_{pot.}$ is the potential PV-suitable rooftop area in Hong Kong; $A_{occu.}$ is the installation occupancy area in Hong

Kong; A_{pv} is the area of a single PV module. For rooftop PV application, the potential total active area of PV modules installed with the optimum tilted angle of 23° was calculated to be 37.4km^2. Thus, the potential installation capacity of rooftop PV systems is estimated to be 5.97GWp in Hong Kong. The potential of annual energy output of rooftop PV systems can be briefly estimated by the following equation:

$$E_{potential} = A_{act.} \times G_{optential} \times \eta_{stc} \times \lambda \tag{3.13}$$

where, $E_{potential}$ is the annual potential energy output of rooftop PV systems in Hong Kong; $G_{optential}$ is the annual total solar radiation received by the PV modules installed with the optimum tilted angle. This is about 1332.7 kWh/m^2; η_{stc} is the PV module's energy conversion efficiency in the standard testing conditions (STC), and the efficiency is 16% as declared by the manufacturer; λ is the performance ratio of PV systems. This ratio considers all losses from converting solar energy into direct current electricity and then inverting the direct current into alternating current electricity. It is assumed to be 0.75 in this study.

The result of calculating $E_{potential}$ is about 5981GWh per year, which is equivalent to 14.86% of the total electricity use in Hong Kong in 2016 [122]. This proportion is much higher than the target set for renewable energy development (3-4%) in Hong Kong. According to this result, local policymakers could develop a more ambitious target for developing renewable energy in future, and solar PV technology certainly has the potential to meet the target. In addition, every year about 3,768,030 tones of GHG emissions can be avoided annually by replacing the equivalent local electricity mix with potential PV electricity (5981GWh) generated by rooftop solar PV systems in Hong Kong. Therefore, according to this result, the policy makers can develop more active renewable energy development goals in the future, and the photovoltaic technology has the potential to achieve the goal. This will greatly change the current energy structure in Hong Kong.

For other types of BIPV technologies, it's hardly to estimate the potentials due to system surrounding conditions, such as the shading effect, etc. However, on the one hand, the development potential of solar PV glazing façade and shading-type solar PV cladding can have even much higher potential than rooftop solar PV systems. On the other hand, the potential electricity only from rooftop PV systems has been equivalent to 14.86% of the total electricity use in Hong Kong in 2016. That means the energy potential of BIPV systems is enormous and noticeable.

3.3.4 Environmental effects and energy payback performance of rooftop PV system

To further study the life cycle environmental effects and energy recovery performance, we carried out life cycle assessment in previous studies to assess the sustainability and environmental friendliness of PV system [123]. Fig. 3.8 presents the results of energy payback time for various rooftop PV systems with different types of solar cells. It was found that the average energy payback time of the five commonly used rooftop PV systems ranged from 1.4-2.7 years, which is far less than the lifespan of PV systems, which is usually about 25 years. The GHG emission rates of solar PV electricity generated by various PV systems are summarized in Fig. 3.9. They ranged from 10.5-50g CO2-eq/kWhe. The mono-Si PV system has the highest GHG emission rate due to its high life-cycle energy requirement, but its GHG emission rate still has an order of magnitude less than that of fossil-based electricity in Hong Kong, which is about 700 g CO2-eq/kWhe. Thereafter, from the perspectives of both energy payback time and GHG emission rate, solar PV electricity is definitely sustainable and environmentally friendly.

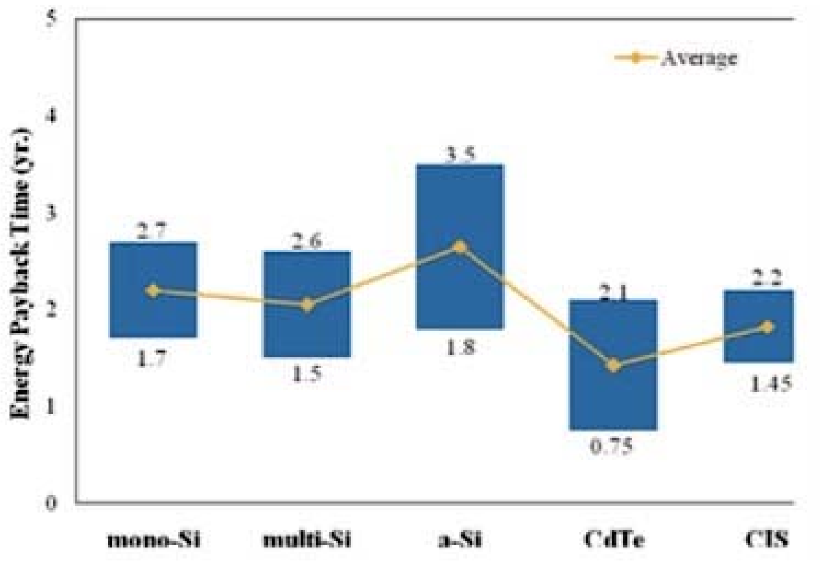


Fig. 3.8 Review of the energy payback time of various solar PV systems

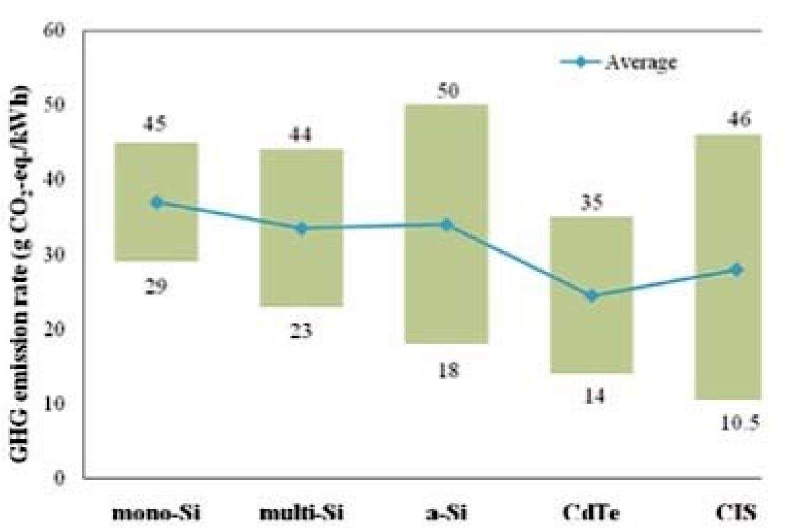


Fig. 3.9 Review of GHG emission rates of PV electricity generated by various PV systems

3.4 Summary

In this chapter, development potential of rooftop PV systems has been evaluated. Firstly, the total roof area of the installed photovoltaic system is estimated by assuming the per capita ratio of the per capita roof area, and using the airborne laser radar data and spatial analysis. The total PV-suitable rooftop area was estimated to be 54 km^2.

Moreover, the result of calculating $E_{potential}$ (the annual potential energy output of rooftop PV systems in Hong Kong) is about 5981GWh per year, which is equivalent to 14.2% of the total electricity use in Hong Kong in 2011. Based on this result, policy makers can develop a more ambitious goal in the future development of renewable energy, photovoltaic technology, of course, is possible to achieve this goal. In addition, each year about 3768030 tons of greenhouse gas emissions can be avoided, replacing the equivalent of local power mixed with the potential photovoltaic roof photovoltaic system in Hong Kong.

Acknowledges:

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CHAPTER 4 THE LEVELIZED COST OF ENERGY OF SOLAR PHOTOVOLTAIC SYSTEMS IN HONG KONG

4.1 Introduction

In power generation, different power generation methods will incur various costs. These costs can be calculated in the case of connection load or power grid. The cost is usually calculated per kilowatt-hour or megawatt hour. It includes the initial capital, the discount rate, and the cost of continuous operation, fuel and maintenance. This kind of calculation helps decision-makers, researchers and others to guide discussions and decisions.

The Levelized Cost of Energy (LCOE) is a measure of power, which tries to compare different modes of electricity in a consistent way. This is an economic assessment that divides the average total cost of generating and operating the power by dividing its life away from the total energy output of the asset over the life. LCOE can also be seen as the lowest average cost of electricity that must be sold to break even during the project。

Feed-in-tariff (FIT), a policy mechanism for subsidizing RE is more effective than alternative supportive schemes in promoting renewable energy technologies, as it provides long-term financial stability for investors [124]. Recent experience from countries around the world suggested that FIT was the most effective policy that promoted the rapid and sustained deployment of renewable energy [125-127].

Therefore, in this chapter, the impact of the effective lifetime on the LCOE and the energy production is clearly presented. In addition, the presented analysis covers a wide range of PV technological characteristics, and meteorological conditions. According to uncertainty and sensitivity analyses, decrease the cell operating temperature is suggested to be the most efficient technical method to improve economics.

4.2 Levelized Cost of Energy

The levelized cost of electricity (LCOE), also known as Levelized Energy Cost (LEC), is the lifespan of the unit generation cost of the net present value to the power generation assets. It is often seen as the average price that the generator must get in the market so that it can achieve a profit and loss balance in its lifetime. This is a first-order economic evaluation of the cost competitiveness of power generation system. The system integrates all costs into its life cycle: initial investment, operation and maintenance, fuel cost and capital cost.

The levelized cost is that value for which an equal-valued fixed revenue delivered over the life of the asset's generating profile would cause the project to break even. This can be roughly calculated as the net present value of all the costs of the total power output of the asset within the life cycle of the asset. [128].

The Levelized Cost of Electricity (LCOE) is given by:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{\left(1+r\right)^t}}{\sum_{t=1}^{n} \frac{F_t}{\left(1+r\right)^t}} \quad (4.1)$$

where, I_t is the investment expenditures in the year t; M_t is the operations and maintenance expenditures in the year t; F_t is the fuel expenditures in the year t; E_t is the electrical energy generated in the year t; r is the discount rate; n is the expected lifetime of system or power station.

Typically the LCOE is calculated over the design lifetime of a plant, which is usually 20 to 40 years, and given in the units of currency per kilowatt-hour or megawatt-day, for example AUD/kWh or EUR/kWh or per megawatt-hour, for example AUD/MWh (as tabulated below)[129]. However, care should be taken in comparing different LCOE studies and the sources of the information as the LCOE for a given energy source is highly dependent on the assumptions, financing terms and technological deployment analyzed [130]. In particular, assumption of capacity factor has significant impact on the calculation of LCOE. Thus, a key requirement for the analysis is a clear statement of the applicability of the analysis based on justified assumptions [130].

The cost of electricity generated by a photovoltaic (PV) system is determined by the capital cost, the discount rate, the variable costs, the level of solar irradiation and the efficiency of solar cells [131]. Meanwhile, the presented LCOEs of BIPV power systems consider the effective lifetime of various BIPV technologies rather than the usual use of the financial lifetime. Therefore, in this study, LCOE is used to calculate the performance of BIPV.

4.3 Case studies of LCOE

Based on the previous equations, the LCOEs are calculated regarding different BIPV system installation costs. Fig.4.1 presents the relationship between BIPV system installation costs and the LCOE of electricity from BIPV systems in Hong Kong. It is shown that the LCOE of solar PV electricity is proportional to the system installation costs and it decreases with the reduction of installation costs. For every $1/Wp decline in the installation costs, the LCOE will drop about 5 cents/kWh. At the moment, for Hong Kong, the installation costs of BIPV systems are roughly $5-6 per peak watt, so the current levelized cost of energy from BIPV system is around 26 cents per kWh (around 2 HK$/kWh). This value is far higher than the local electricity tariff. From the Household Expenditure Survey in October 2009, electricity expenses only account for 1.6% of household expenditure [132]. However, this figure can drop with the decreasing of solar PV installation costs. For example, when the installation costs drops to $3/Wp, the LCOE from BIPV system will drop to 13 cents, which is competitive with local electricity tariff.

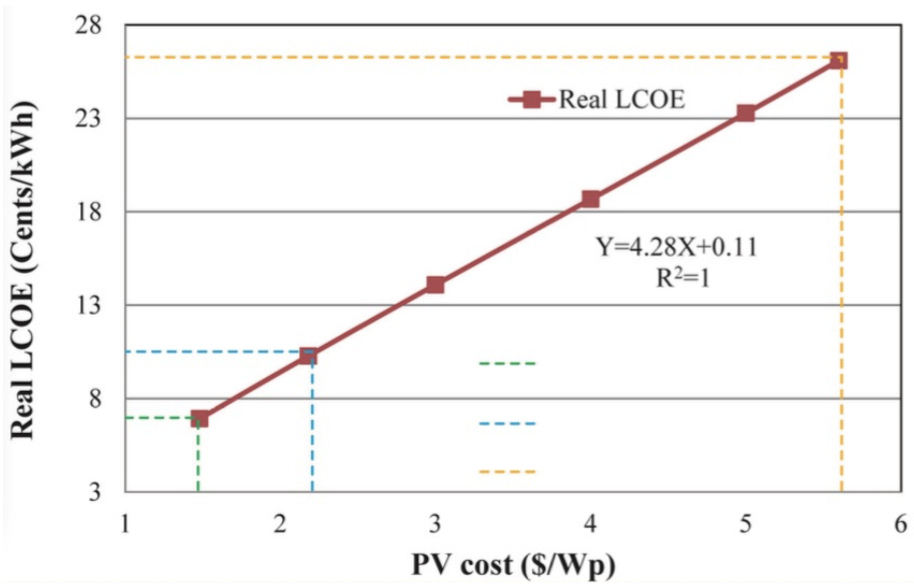


Fig. 4.1 Relationship of solar PV installation costs and LCOE of PV electricity in Hong Kong

In order to further understand the impact of installation costs on the PV systems' LCOE in Hong Kong, the potential LCOEs according to the installation costs in Mainland China, Germany and Hong Kong were analyzed and shown in Fig. 4.2. Case 1 shows the potential LCOE of rooftop solar PV system in Hong Kong if the installation cost is equivalent to that in Mainland China ($1.48/Wp), and the LOCE is about 6.9 cents/kWh. Case 2 gives that the potential LCOE is about 10.3 cents/kWh if the installation cost is equivalent to that of Germany ($2.18/Wp). Case 3 represents the current real LCOE of PV system in Hong Kong. The LCOE is about 26.1 cents/kWh, which is calculated by the current average installation cost of $5.6/Wp. Therefore, we can see that the real LCOE of solar PV system in Hong Kong is very high mainly due to the high local PV installation costs.

Currently, the domestic electricity price in Hong Kong is about 14-23 cents/kWh depending on the amount of electricity consumption [133]. With the rising prices of fossil fuels, the local tariff would rise by about 4% annually. Thus, even with the current high installation costs, the LCOE of PV systems in Hong Kong is probably lower than the retail electricity price after 2 years. If the installation cost is reduced to be equal to that in Germany in the coming few years by reducing the soft costs, the calculated LCOE of 10.3 cents/kWh would be lower than the current retail tariff by 26-55%. With the further cost decreasing of solar PV modules and inverters, the system installation costs in Hong Kong would probably be reduced to be equal to that in Mainland China, and then the calculated LCOE of 6.9 cents would fully compete with other traditional energy sources without subsidy. If the environmental benefits of solar PV electricity, such as much lower GHG emission rates, were also considered, the advantages and competitiveness of solar PV electricity would be further strengthened.

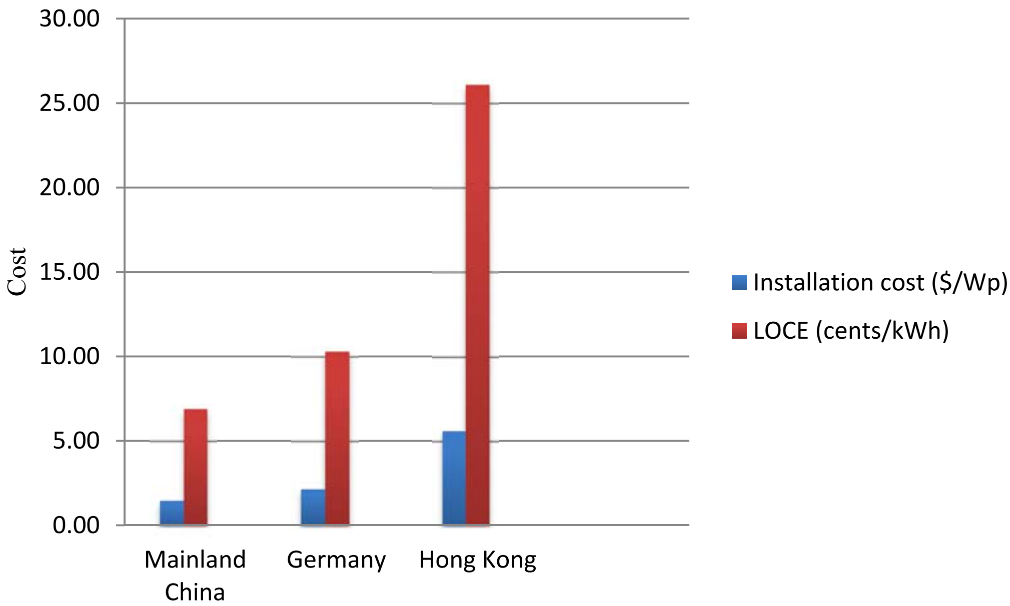


Fig. 4.2 Installation costs in Mainland China, Germany and Hong Kong

4.4 LCOE analysis of BIPV based on SAM

Although BIPV is a viable solution for commercial building, it is not applied widely in Hong Kong. One probable reason may be the installation cost of BIPV is much higher than the ones of traditional solar PV systems. However, as NERL mentioned in 2011[134], after considering the savings in original construction materials and construction costs, BIPV systems can be still competitive. Accordingly, the LCOEs of different BIPV systems in Hong Kong will be evaluated with a modified model and finance assumption in SAM.

The LCOE model with construction material saving consideration is employed to assess the energy finance costs and energy generated during the system lifetime. Based on the estimated LCOE, alternative technologies can be allowed to compare when different scales of operation, investment, or operating time periods exist. Simply, the LCOE can be defined:

$$LCOE = \frac{\sum_{t=0}^{T} C_t / (1+r)^t}{\sum_{t=0}^{T} E_t / (1+r)^t} \tag{4.2}$$

Basically, the costs term C_t includes initial capital investment (via equity or debt financing), interest payments if debt financed, operation and maintenance costs, and cash inflow such as government incentives. Therefore, the net cost term can be modified for financing, taxation and incentives as an extension of the initial definition [135]. Furthermore, for BIPV system, an extra term A_t is suggested to be added as the cash saving in construction material. This part can be simply defined as:

$$A_t = ConstructionMaterials + tranditionalPV - BIPV \tag{4.3}$$

For newly built concrete building, term *At* is about 10% to 20% of the costs of traditional solar PV module [136].

On the other hand, the performance degradation by year d is also considered, the correlation can be defined as:

$$LCOE = \frac{\sum_{t=0}^{T} \left(I_t + O\&M_t + F_t - A_t \right) / \left(1+r \right)^t}{\sum_{t=0}^{T} S_t \left(1-d \right)_t / \left(1+r \right)^t} \quad (4.4)$$

Respectively, I_t is the term of initial capital costs that include module, battery, inverter, other electrical, installation labour and so on, a detailed assumption is list in Table 4.1 and 4.2. The Term $O\&M_t$ is the annual operating and maintained costs, which is usually 1.25% of the total investment, which include 0.25% for insurance. The term F_t is the financial factor presented own capital and loan. In this case, 20% of own capital and 80% of loan with 5% long-term interest is assumed.

Table 4.1 Labour costs per hour in Hong Kong [137]

Occupation	**Average hour Wages** (USD)
Metal worker:	18.58 $/hours
Electrical fitter:	16.88 $/hours
Glazier	19.91 $/hours

Table 4.2 Initial capital assumption

Term			Base	Mean	Ref.
Equipment	Module		PV:0.46-0.74 $/Wp BIPV: 10%-20% off of PV module	PV: 0.60 $/Wp BIPV: 0.48 $/Wp	PVInsight
	Inverter		0.25-0.65 $/Wp dc	0.45 $/Wp dc	
	Other		Wire: 0.17 $/Wp meter, monitor, disconnects: 0.41$/Wp	0.58 $/Wp	NERL
	Overhead		10-30% of equipment cost	20%	assumption
Installation labour	Module	Mounted rack PV for Rooftops:	0.2 hrs Electrical fitter 1.4 hrs Rack worker	0.12 $/Wp	NERL
		Thin-film curve rooftops	0.07 hrs Glazier	0.02 $/Wp	
		Semi-transparent vertical window	0.07 hrs Glazier	0.01 $/Wp	
		Vertical cladding façade	0.5 hrs Glazier	0.04 $/Wp	
		Shading system	0.2 hrs Electrical fitter 1.4 hrs Rack worker	0.12 $/Wp	
	Inverter		6 hours/system Electrical fitter	Fixed 101.28 $	NERL
	other		4.5 hours/system Electrical fitter	Fixed 75.96 $	NERL
	Installer margin and overhead		30%-50% of labour cost	40%	assumption
Other	Permitting and Environmental		1-3% of direct cost	3%	assumption
	Engineering and developer overhead		5%-10% of direct cost	10%	assumption

The LCOEs were calculated in a best estimation manner, which is lower than the conservative method and more useful in policy formulation. The discount rate *r* reflects the risk-adjusted opportunity cost of capital, which combined inflation rate 2.5% and real discount rate 5% in assumption. The tax policy in Hong Kong is easing and will be more beneficial to support solar PV application. So, no tax will be paid in this analysis. Finally, the LCOE results can be simulated and found in Table 4.3 below.

After comparing the electricity price in Hong Kong, which is at least 16.78 cents/kWh for commercial buildings, it can be concluded that the LCOE of BIPV system is competitive. BAPV, thin film BIPV and PV shading systems will be recommended for the development in high priority. Under the limitation of available installation area, BIPV semi-transparent window and vertical facade can provide another choice for users especially for high-rise buildings in Hong Kong whose areas of sidewall are much larger than the rooftop areas.

Table 4. 3 LCOE of different BIPV systems

Case	**Nominal LCOE (**cents/kWh)	**Area of 1 kWp System (m^2)**
Mounted rack solar module for Rooftops (BAPV)	0 deg:11.49	4.9
	23 deg:10.93	
Flexible surface thin-film BIPV for roofs or facade	11.91	7.7
BIPV semi-transparent vertical window(50% transmittance)	17.63	15
BIPV vertical cladding facade	South: 17.90	13.9
	West: 19.71	
	East: 19.80	
	North: 29.83	
BIPV shading system	31 deg: 10.71	4.9

4.5 Uncertainty and Sensitivity Analysis

In the above LCOE model, many parameters are involved in an assumption manner, and they affect the LCOE results. So, a sensitivity analysis is suggested to be performed in order to investigate the uncertainty of the real LCOE. In this way, a sampling-based methodology for uncertainty and sensitivity analysis was employed in our study [138].

The mounted rack solar module for Rooftops (BAPV) case was chosen to be baseline case. Parameters studied in sensitivity were dividing into two groups: technical parameters and financed parameters.

4.5.1 Uncertainty and sensitivity analysis regarding the technical parameters

In technical group, soiling is the accumulation of dust on solar panels that decreases the absorbed irradiation directly and it can degrade the total energy gained from irradiation in a large range, which are summarized in Table 4.5. In addition, the parameters could only affect the power generation of solar PV systems, which are listed in Table 4.4 below. In Hong Kong, rain and wind will occur more often when monsoon climate is obviously than other sites, which means Hong Kong is in a more cleaning panel condition. Besides, the soiling effect could be saturated due to rain, wind or regular cleaning, which means that 7.4% maybe the largest average annual loss.

Table 4.4 Total energy losses due to soiling effect in different studies

Location	Short term	Mid term	Long term
Santiago, Chile	Nearly 0.02%-0. 09% of daily		
Puglia, Italy		6.9% for sandy site 1.1% for compact site in 56 days	
Belgium		3%-4% saturated in 35 days	
Cyprus		3%-4% in 21 days	
Canary Islands, Morocco			Nearly 2%-4% in 150 days
California, U.S.			7.4% in 145 days
U.S.			1.5%-6.2% annual

Table 4.5 Technical parameters

Parameter	Mean	Distribution
Soiling loss	7.4%	Bond in a conversation manner
AC wire loss	1%	Normal distribution δ =0.1%
Total DC wire loss	3.4%	Uniform distribution 2.4% to 4.4%
Nominal operating cell temperature	45%	Normal distribution δ =2%
Temperature coefficient of max power point	-0.45%	Uniform distribution δ =0.05%
Standoff height		1/4 of case 2.5-3.5 inch
		1/4 of case 1.0-2.5 inch
		1/4 of case 0.5-1.0 inch
		1/4 of case less than 0.5 inch
Installation height		Half of case low installation height
		Half of case high installation height

Total DC wire losses include mismatch loss, connections loss, DC wires loss and DC power optimizer loss, which were appropriately from 2.4% to 4.4% in different inverter format by engineering experience.

The uncertainties of nominal operating cell temperature and temperature coefficient are obtained based on manufacturer data, which were usually 2 and 0.5% in respectively.

Mounting configuration and ambient wind will affect the cooling of cell temperature, which will enhance or reduce the effect of temperature degradation. In SAM, four kinds of standoff height configuration and two kinds of installation height configuration are provided in order to calculate the real operating cell temperature empirically.

According to the solar cell efficiency formula:

$$\eta = \frac{V_{oc} I_{sc} FF}{P_{in}} \tag{4.5}$$

The correlation between the ambient temperature of the solar cell and the short-circuit current is not significant, but the short-circuit will increase slightly with the increasing temperature. Both the open circuit voltage and the fill factor decrease with the increasing temperature. The semiconductor band gap width is usually reduced as the temperature rises, and the reduction in the forbidden band width will allow the semiconductor to absorb more photons, resulting in a slight increase in short-circuit current, but the effect is not too great. A significant change in open circuit voltage will decrease the output power and conversion efficiency with the increasing temperature. Silicon solar cells for each rise once and the output power will be reduced by 0.4% to 0.5%.

For the BIPV system, the absorption of part of the heat will increase the temperature of solar panels and lower the solar panel photovoltaic power generation efficiency and the heat will be transferred into the interior space through the building facade, while in the summer to increase the cooling load of the building.

A sampling-based uncertainty and sensitivity analysis method were employed in our study, which based on Latin Hypercube Sampling process. After a thousand times of sampling, the results can be found in Fig. 4.3. It shows that real LCOE with only technical uncertainty is between 10.3 to 11.7 cents/kWh and basically satisfied the normal distribution. Obviously, when the mean value is 10.8 cents/kWh, it corresponds to the highest count value, which is a range about 18% of base cases. Meanwhile, it also shows that this distribution is not as absolutely symmetrical as the normal distribution. Compared to higher than 10.8 cents/kWh, when the value is lower than it, it reaches the maximum point faster, which means the distribution of base cases is more centralized in the range of 10.3 to 10.8 cents/kWh

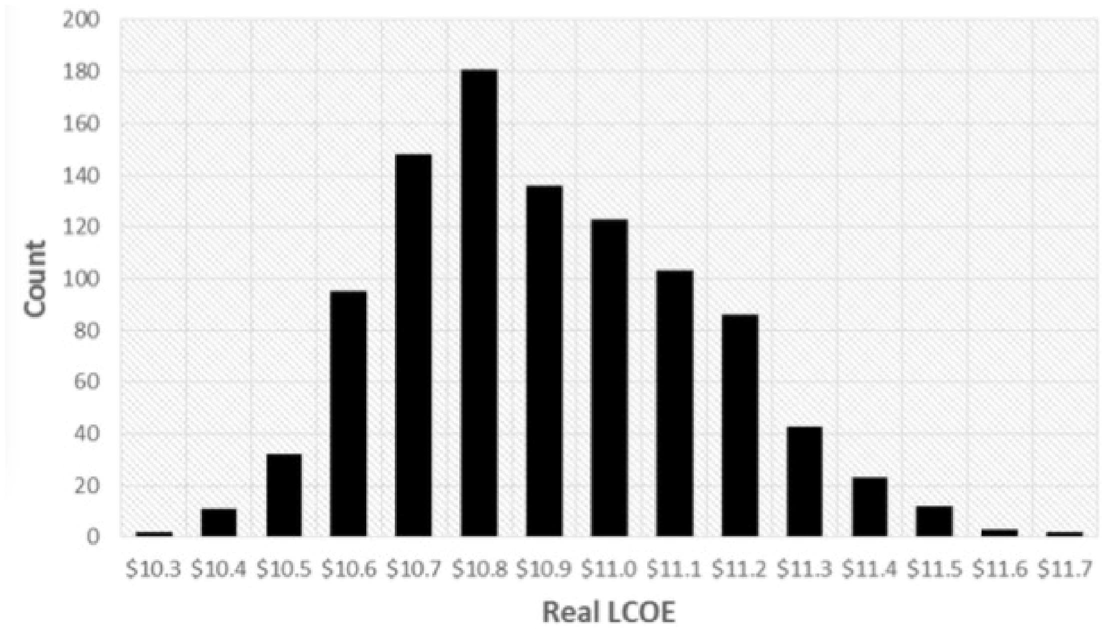


Fig. 4. 3 Histogram of real LCOE with technical uncertainty

The sensitivity analysis is to determine the effects of individual components of inputs on the analysis outcomes contained in outputs. A model of the form:

$$\hat{y} = b_0 + \sum_{j=1}^{nX} b_j x_j \tag{4.6}$$

is developed from the mapping between analysis inputs y and analysis results, where x_j are the input variables under consideration, nX is the number of x_j and b_j are sensitivity coefficients that must be determined. In this way, a specific mapping of $[x_k, y(x_k)]$, $k = 1,2,...,m$, generated from a m time sampling in above, and each $y(x_k)$ becomes:

$$y_k = b_0 + \sum_{j=1}^{n} b_j x_{kj} + \varepsilon_k, k = 1,2,...,m, \tag{4.7}$$

where ε_k is the error term defined by $\varepsilon_k = \hat{y} - y_k$ which is wish to be minimum. According to the least squares approach, b_j can be determined in our case, as shown in

Fig. 4.4. Standoff height and temperature coefficient are obviously have the largest sensitivity coefficient. This is mainly due to the increase of carrier concentration resulting in an increase of internal carrier recombination rate, which means that decreasing the cell temperature, by cooling the panel during operating and choosing the cell materials with lower temperature coefficients are two of the most effective technical methods to improve the economics of solar PV systems.

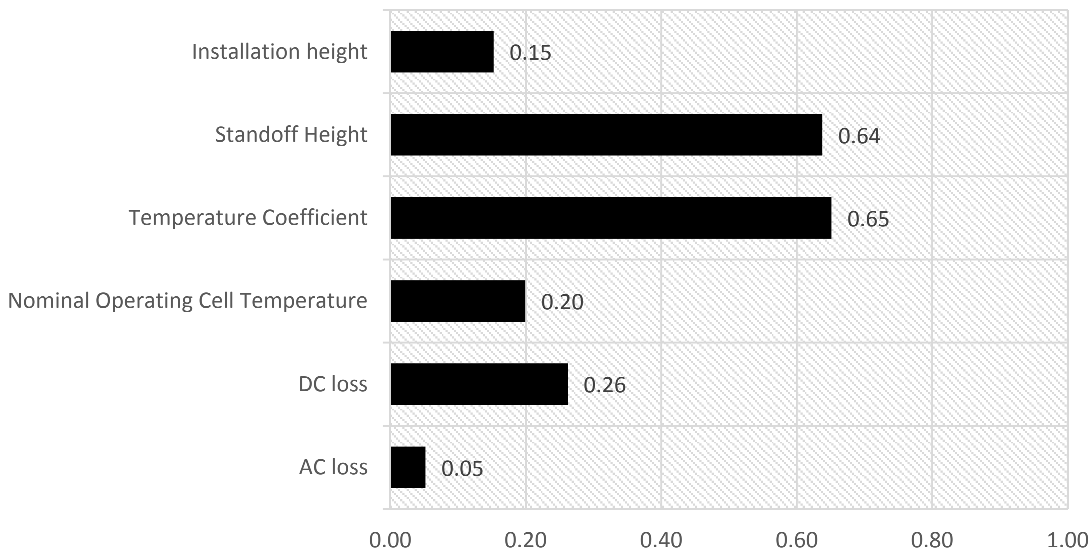


Fig. 4.4 Sensitivity coefficients of technical parameters to the LCOE

As the most important technical parameter with sensitivity coefficient of 0.65, the temperature coefficients for different types of solar PV modules can be totally different. According to Table 4.6, it shows monocrystalline silicon cell is the most sensitive to temperature; polycrystalline silicon cell is less temperature resistant than monocrystalline; amorphous cell can tolerate extreme heat and CdTe and CIS/CIGS cells is relatively low impact on performance.

Table 4.6 Temperature resistance of different types of solar PV modules [139]

Type	Temperature Resistance
Monocrystalline	Performance drops 10-15% at high temperatures
Polycrystalline	Less temperature resistant than monocrystalline
Amorphous	Tolerates extreme heat
CdTe	Relatively low impact on performance
CIS/CIGS	

As the second most important technical parameter with sensitivity coefficient of 0.64, the Standoff Height also plays an important role in promoting the conversion efficiency. To some extent, adjusting the standoff height is to avoid PV modules from direct solar gain, which would reduce the external temperature and the drop of efficiency lead by temperature increase.

In addition, the sensitivity coefficient of reducing DC losses becomes the 3rd position in the LCOE analysis. Without doubt, if high-efficiency components are applied in the PV systems, the DC loss will be reduced accordingly. It is also a hot topic to study how to effectively control the DC loss.

The nominal operating cell temperature is another important factor affecting the LCOE. Therefore, cooling the solar panels and reducing the cell temperature is very important for reducing the LCOE technically. Cooling the solar panels, according to the different cooling mediums, can be divided into air-cooling, liquid cooling, heat pipe cooling, phase change material cooling, and thermoelectric module cooling. Air-cooling is the development of an air passage on the back of the PV panel, passing into a natural or forced airflow and extracting heat by convection. Compared with natural ventilation, the forced ventilation enhances air-cooling to further improve performance. But, the forced ventilation requires a portion of the power to drive the fan, thus affecting net power generation. However, since the air density and the heat capacity are small, the improvement in the actual performance of the air-cooling is limited, which is disadvantageous to the selection. In the high operating cell temperature conditions, liquid cooling is then preferred. Liquid cooling is the adhesion of the pipeline behind the photovoltaic panels, through the series / parallel connection of the forced fluid circulation to effectively carry out thermal energy capture, thereby cooling the photovoltaic cells. Due to the higher specific heat capacity of the coolant used, liquid-based PV cooling is better than air-cooling, and the overall performance of solar PV module is further improved. In addition, liquid-based PV cooling provides less temperature fluctuations than air-cooling. This type of fluid circulation is achieved by the use of a gravity-assisted circulation of the circulation pump. Water is the most commonly used liquid, and the refrigerant is able to carry out phase change at relatively low temperatures recently in many systems. Phase change material (PCM) cooling is another option, and PCM can absorb the heat from operating PV modules and releases the heat at night time. In addition, thermoelectric module cooling is new to convert heat into electricity, help reduce the operating temperature of the PV board and enhance the efficiency of photovoltaic power generation. The coupled solar photovoltaic and thermoelectric (PV-TE) system can make full use of the entire wavelength of sunlight.

For installation height and AC loss, sensitivity efficiencies of these two parameters are much smaller. Especially the AC loss, its sensitivity efficiency is only 5%. Thus, these two parameters are always ignored to simplify and accelerate calculations.

4.5.2 Uncertainty and sensitivity analysis regarding the finance parameters

Furthermore, finance parameters will influence the actual LCOEs more directly than the technical ones. In China, the standard finance arrangement for energy project is about

80% debt and 20% own capital, just like discussed in the base case above. However, the small-scale rooftops PV systems are usually invested by private householders or small and medium companies, and it is difficult for them to borrow capital from commercial bank, especially in Hong Kong. Meantime, the initial capital investment in equipment and installation is the dominating part in total cost when the other is only 2-3% percent annual, which leads to 8 years in payback period at least. In other word, the longer operating period after 8 years, the lower LCOE will be paid. In this way, an LCOE analysis under different debt levels and operating periods is necessary to be conducted.

In this study, there were 6 cases analyzed under different 3 kinds of debt levels, 20% 50% and 80%, and 2 kinds of loan periods, 10 years and 15 years. The results, as shown in Fig. 4.5, indicate that there is a quite disperse distribution than technical uncertainty case. The real LCOEs are in a range between 10.26 and 16.13 cents/kWh, which are 6.1% cheaper and 47.5% more expensive compared to the base case. It also shows that although the changing trends are similar, the longer loan year and a higher debt fraction will decrease the LCOE because the loan rate is lower than the nominal discount rate according to the loose monetary policy. Besides, the decrease caused by increasing debt fraction is more obvious than extending loan debt, which means in the same condition, it should give priority to increase the debt fraction in order to reduce the real LCOE.

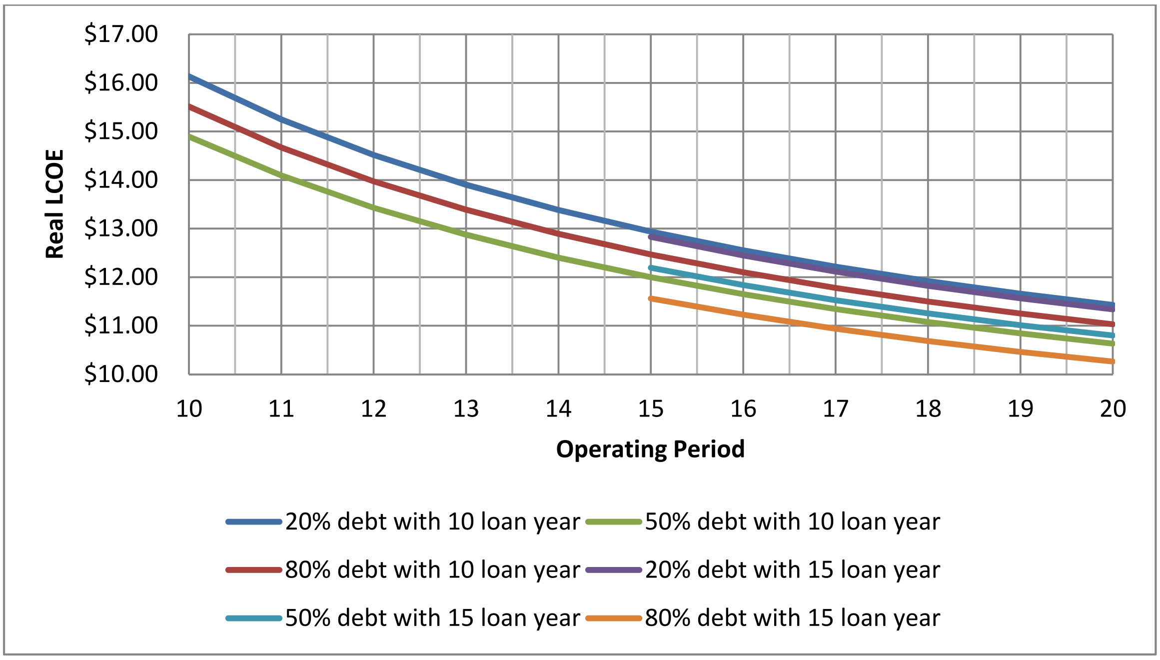


Fig. 4.5 LCOE under different finance conditions

4.6 Summary

By employing the LCOE analytical framework, this chapter estimates and analyzes the LCOEs of different BIPV systems in Hong Kong. The results show that, BIPV for rooftops, flexible surface thin-film BIPV rooftops and shading PV system are feasible for commercial buildings in Hong Kong. Their LOCEs are about 20% lower than the local electricity price. Other types of BIPV systems, such as PV vertical façade and semi-transparent PV windows, can also be recommended if both building envelop material savings and building energy savings can be together considered. Therefore, the application of BIPV systems can be a practicable renewable energy method in Hong Kong if beneficial policy supports are further provided.

In addition, this chapter also conducts the uncertainty and sensitivity analysis of LCOE regarding the technical parameters and finance parameters. There were 6 cases analyzed under different 3 kinds of debt levels, 20% 50% and 80%, and 2 kinds of loan periods, 10 years and 15 years in this chapter. The results indicate that there is a quite disperse distribution than technical uncertainty case. The real LCOEs are in a range between 10.26 to 16.13 cents/kWh, which are 6.1% cheaper and 47.5% more expensive compared to the base case. It also shows that a higher debt fraction will decrease the LCOE because of the lower loan rate than the nominal discount rate due to the loose monetary policy.

CHAPTER 5 OVERALL ENERGY PERFORMANCE OF VARIOUS BIPV SYSTEMS

5.1 Introduction

This chapter addresses the overall energy performance of different building-integrated solar PV systems, including rooftop solar PV systems, shading-type solar PV claddings and a-Si based PV windows.

Firstly, the power generation and EPBT, GPBT and CO2 emission rate of rooftop mounted, shading-type and a-Si based vertical facade BIPV systems were evaluated on the basis of Hong Kong domestic geological and climate conditions. Since the BIPV systems can achieve the building energy efficiency by not only generating electricity in situ, but also reducing the electricity use from air-conditioning systems, this chapter aims to evaluate the overall energy performance of various types of BIPV systems in Hong Kong.

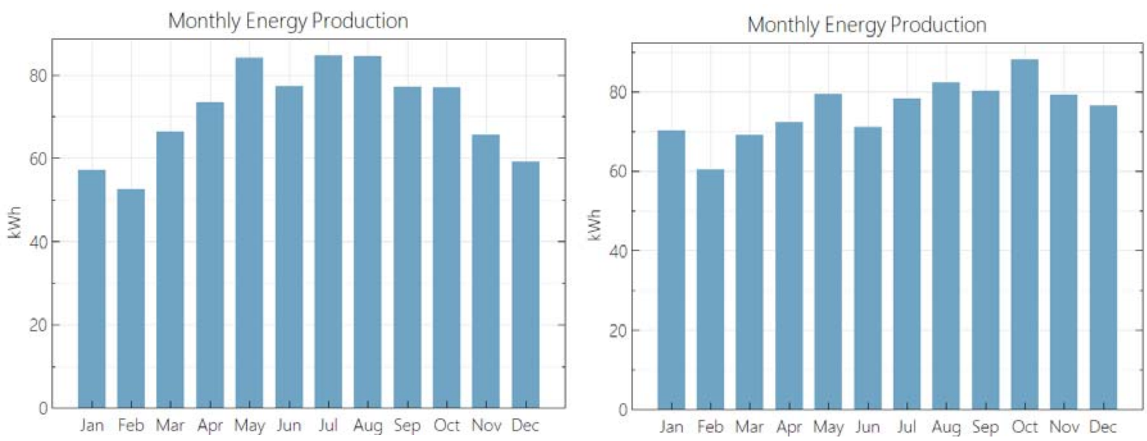
5.2 Power Performance analysis of different BIPV types

5.2.1 Generated Power Estimation

"System Advisor Model" (SAM) [140] is a performance and financial model designed to facilitate decision making for people involved in the renewable energy industry. SAM makes performance predictions and cost of energy estimates for grid-connected power projects based on installation and operating costs and system design parameters which are specified as inputs to the model. SAM includes several libraries of PV performance data and coefficients and solar PV system components, and models the power generation of solar PV systems assuming that these systems deliver power to electricity grids or grid-connected buildings to meet electricity loads. Solar recourse data of a typical-year (TMY) of Hong Kong were imported into the model. Different forms of BAPV (Building Attached Photovoltaic) or BIPV systems were characterized in a few parameters, such as open circuit voltage, short circuit current, maximum power voltage, maximum power current and temperature coefficients. The specific parameters about the BIPV systems discussed in this study are listed in Table 2.1. Then, for ease of calculation, the following assumptions and simplifications were adopted. All PV systems considered in this study were connected to the utility grid.

1. System losses are assumed about 5% soiling loss, 4.4% losses for string inverters and 1% loss for AC wiring.
2. It is assumed that the electricity supply system had an overall conversion efficiency of 31% [141] (viz. the conversion efficiency from thermal energy to electricity is 0.31)

Then monthly power generation of 1kWp with 2 kWh battery system was estimated by SAM model, as shown in Fig 5.1-5.5. The annual energy productions per 1 kW installation for 0 deg tilt and 23 deg tilt configurations are 856 kWh and 904 kWh respectively.



Tilt = 0° Case Tilt=23° Case

Fig. 5.1 Power generated in rooftops case

As shown in Fig. 5.2, for the thin film case, it's hard to estimate the 1/4 arc configuration directly, which is curve irradiation surface. Therefore, an integration method is used to calculate the average power generation at each angle. In this way, the annual energy production is about 946 kWh in this case.

For semitransparent window shows only 613 kWh were generated annually, which has lower efficiency than the above cases, as shown in Fig. 5.3. Although this kind of BIPV system scarified a large part of performance to satisfy the transparent function, it is still economically competitive by saving construction materials and installation labor, which will be presented in the next section.

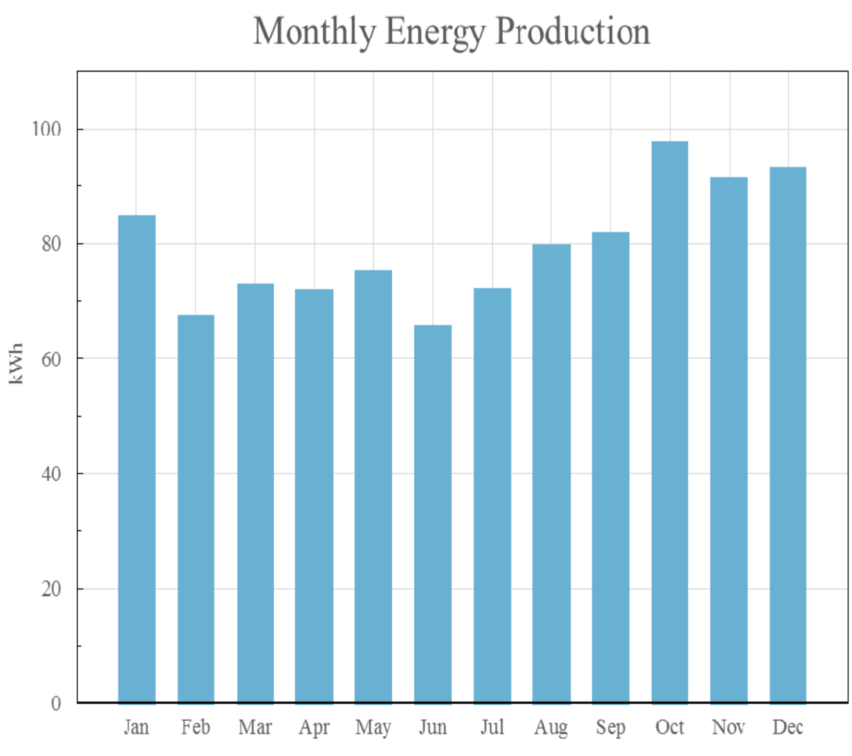


Fig. 5.2 Power generated in BIPV Thin Film case

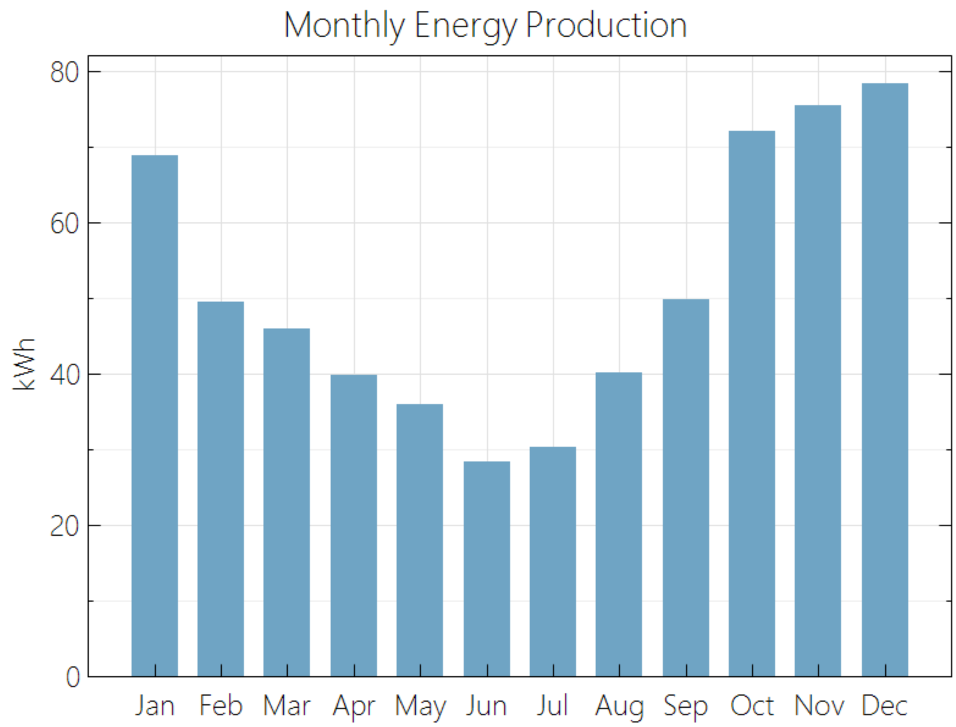
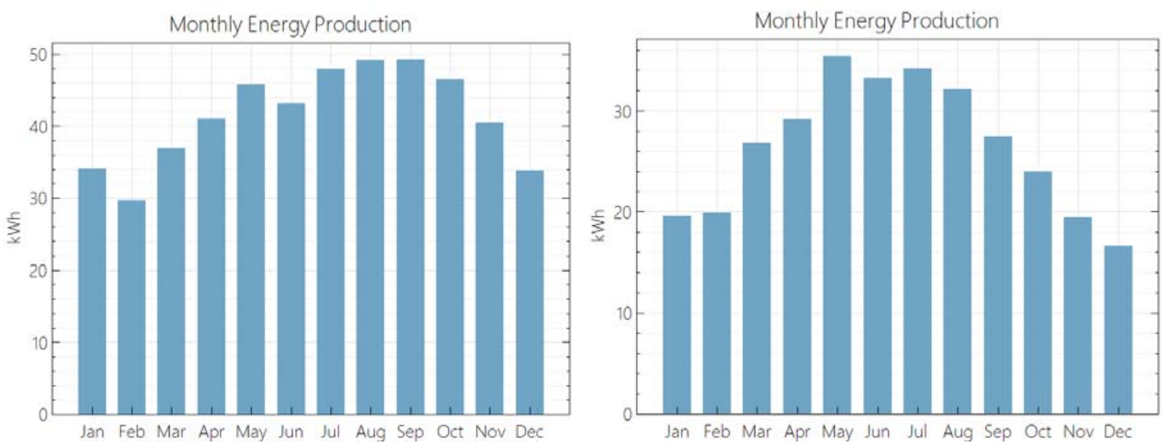


Fig. 5.3 Power generated in BIPV semi-transparent window case

Four kinds of vertical facades were evaluated at different installation orientations with the annual generated power of 317 kWh, 496 kWh, 555 kWh and 504 kWh respectively in facing north, east, south and west. As shown in Fig. 5.4, these results are obviously the poorest, but the largest potential installation area is building facade in densely urban buildings.



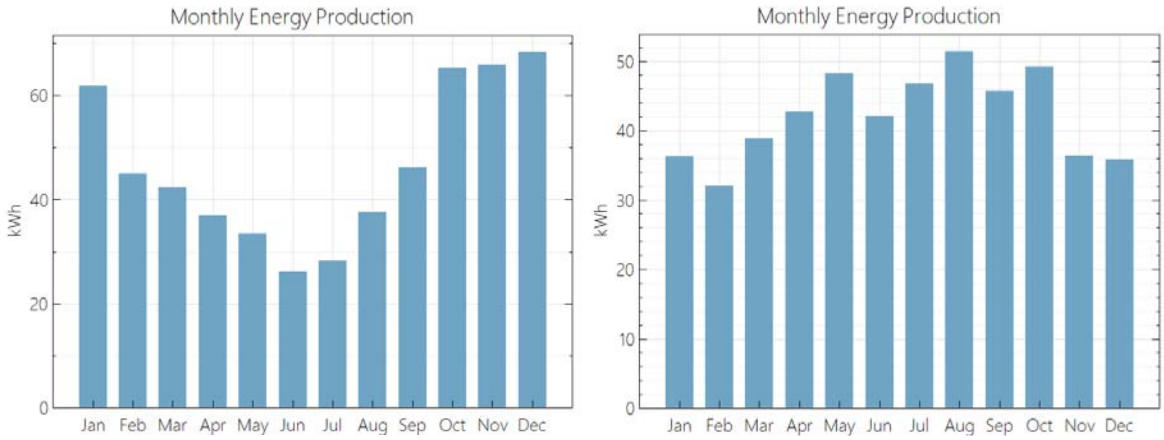


Fig. 5.4 Power generated in Vertical BIPV Facades

Finally, the shading PV systems were estimated to provide 863 kWh and 765 kWh in 31 deg tilt and 55 deg tilt configurations, which is in the middle of all cases. This kind of BIPV system may be the most feasible application, taking the portfolio efficiency, installation area and difficulty into consideration.

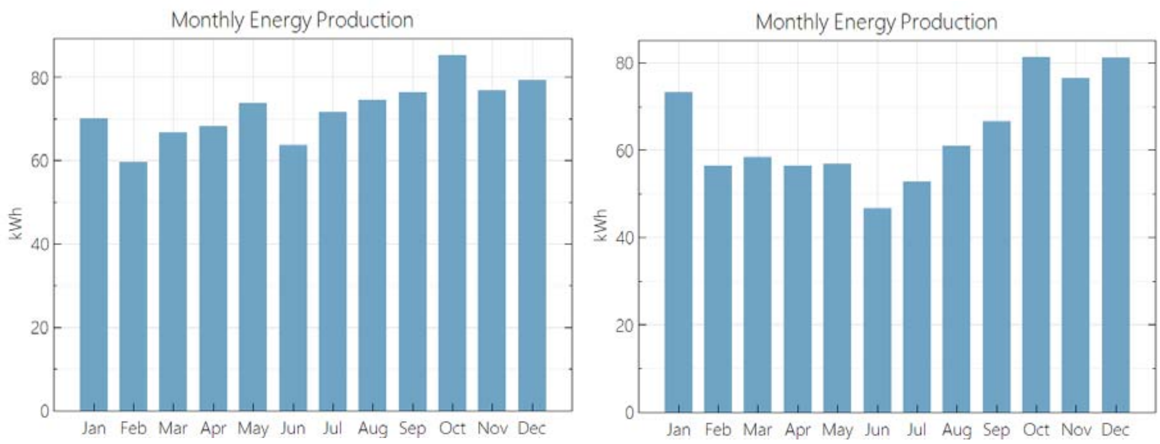


Fig. 5.5 Power generated in BIPV shading case

Besides, the monthly power generation and the primary energy yearly saving of 1kWp with 2 kWh battery systems could be estimated by SAM model, as shown in Table 5.1.

Table 5.1 The annual energy output and the primary energy yearly saving

Type		Energy Output (kWh/year)	Yearly Saving (kWh/year)
Mounted rack solar module for Rooftops (BAPV)	0 deg	856	2761.29
	23 deg	904	2916.13
Flexible surface thin-film BIPV for roofs or facade		946	3051.61
BIPV semi-transparent vertical window(50% transmittance)		613	1977.42
BIPV vertical cladding façade	North	317	1022.58
	East	496	1600.00
	South	555	1790.32
	West	504	1625.81
BIPV shading system	31 deg	863	2783.87
	55 deg	765	2467.74

5.2.2 EPBT, GPBT, and GHG emission rate

One of the metrics that measure the effectiveness of a power generation system is the energy payback time (EPBT), which is defined as the ratio of the total energy input during the life of the system to the annual energy generated by the system, both using the same units, All with primary energy or electricity to express.

$$EPBT = E_{in} / E_{out} \tag{5.1}$$

where, E_{in} is the total energy input during the life cycle of the PV system, including the total energy required for manufacturing, installation, operation and end of the life cycle, removal of the system and external input required for waste disposal; E_{out} is the annual output of the PV system energy. EPBT units are years, obviously the amount of energy to pay the smaller the better.

The energy payback time of the PV system depends on a series of complex conditions. The input energy is related to many factors such as the type of solar cell (monocrystalline silicon, polysilicon, amorphous silicon or other thin film batteries), process, packaging materials and methods, the materials of balance of system (BOS), including boxes, components, etc. In addition to the energy required to install, operate and end the life cycle, to dismantle the system and to dispose of the waste, in particular to consider the energy paid by the person's labor.

The energy output from the PV system is also related to a number of factors such as the service life of solar cells and ancillary components and their performance and efficiency, the types of PV systems (e.g. off-grid systems or grid-connected systems), local geographical and meteorological conditions. Whether the design is reasonable, the square angle is appropriate, the installation process is not proper, maintenance and management of the situation. In addition, there are some indirect factors that are not directly related to the power generation system itself.

The environmental benefit of a BIPV system can also be assessed using the greenhouse-gas payback time (GPBT). The GHG payback time is given by:

$$GPBT = GHG_{in} / GHG_{g} \tag{5.2}$$

where, GHG_{in} is the embodied GHG of system, including PV modules and BOS, kg CO2eq; and GHG_{g} is annual GHG emission amounts in the cases where local power plants generate the power equivalent to that of the PV system, kg CO2eq.

$$GHG_{emissionrate} = GHG_{sum} / E_{sum} \tag{5.3}$$

where GHG_{sum} is the sum emission of system in its lifetime, g CO2eq, E_{sum} is the sum energy output of system, kWh.

The results are shown in Table 5.2. Obviously, as to BIPV semi-transparent vertical windows, north is the direction that has the biggest GHG emission rate and longest EBPT and GPBT, compared with other three directions.

Table 5.2 EPBT, GHG emission rate and GPBT of different BIPV systems

Type		EBPT (year)	GHG emission rate (g/kWh)	GPBT (year)
Mounted rack solar module for Rooftops (BAPV)	0 deg	2.482	708.621	2.457
	23 deg	2.351	670.996	2.058
Flexible surface thin-film BIPV for roofs or facade		0.897	295.941	0.422
BIPV semi-transparent vertical window(50% transmittance)		1.103	239.770	0.317
BIPV vertical cladding façade	North	3.285	735.962	2.819
	East	2.099	470.363	0.893
	South	1.876	420.360	0.729
	West	2.066	462.897	0.867
BIPV shading system	31 deg	2.462	702.874	2.390
	55 deg	2.778	792.915	3.885

5.3 Energy performance of a-Si based STPV windows

5.3.1 Model development

In 2012, about 68% of the total electricity buildings in Hong Kong consumed end-use and this proportion has been increasing over recent years. Among the various types of building energy uses, space air-conditioning has accounted for more than 45% [143]. Windows, as important links between buildings and outdoors, not only allow occupants access to outdoor views but also bring sufficient natural lighting and beautiful building appearance. However, the extensive use of windows also results in negative impact onon building energy use. Thus, it is crucial to develop energy efficient curtain walls/facades which can not only bring sufficient natural lighting but also considerably reduce heat transfer between the outside and the inside of buildings. Semi-transparent PV (STPV) windows/facades, which refer to use semi-transparent PV modules to replace traditional glass windows/facades, have attracted much attention of researchers in recent years due to their good energy efficient performance levels [141-147]. They can not only generate electricity in situ through photovoltaic effect but also significantly reduce the cooling load by effectively blocking solar heat gain [142-151]. Moreover, it can also make full use of daylighting by adjusting the transmittance of PV modules. In this study, a comprehensive simulation model based on EnergyPlus was introduced to simulate the thermal, power and daylighting performances of STPV windows simultaneously, so as to reveal its energy saving potential in Hong Kong.

A simulation model was developed using EnergyPlus to evaluate the thermal, daylighting and power performance of the a-Si based solar PV windows in Hong Kong. The PV power module, daylighting module as well as window glass module were utilized to simulate the power, daylighting and thermal performances, respectively. The key characteristics of the STPV window are shown in Table 5.3 and the simulation model of a-Si based STPV windows is shown in Fig. 2.3. The calculated cooling load was converted into the electricity consumption from air-conditioning system using COP of 2.78. A daylighting reference point was specified in the middle of the room. The designed illuminance was set to be 300 lx. When the daylighting illuminance cannot meet the designed illuminance. The artificial lighting would be turned on to make the illuminance of the reference point meet the design value.

Table 5.3 Key characteristics of the solar PV window

Parameters	Value
Active area, A (m^2)	0.79
Short circuit current, I_{sc} (A)	1.41
Open circuit voltage, V_{oc} (V)	58.6
Current at the maximum power point, I_{mp} (A)	1.1
Voltage at the maximum power point, V_{mp} (V)	42.2

5.3.2 Power output performance

The weather data of typical meteorological year (TMY) in Hong Kong were adopted in this simulation. Fig.5.6 presents the monthly incident solar radiation on the south-facing facade in the typical meteorological year. It is obvious that the south-facing facade received more solar radiation in winter season in Hong Kong. This is because that the latitude of Hong Kong is lower than the Tropic of Cancer, thus the STPV windows installed on the south-facing facade could not receive much solar radiation in summer season. The monthly energy output of the south-facing STPV windows is shown in Fig. 5.7. It is found that energy output in winter season was much more than that in summer season for the south-facing solar PV windows in Hong Kong. The maximum monthly energy output was about 12.1 kWh, occurring in December. The minimum monthly energy output occurred in June, was only 3.8 kWh. The annual energy generation was about 84 kWh.

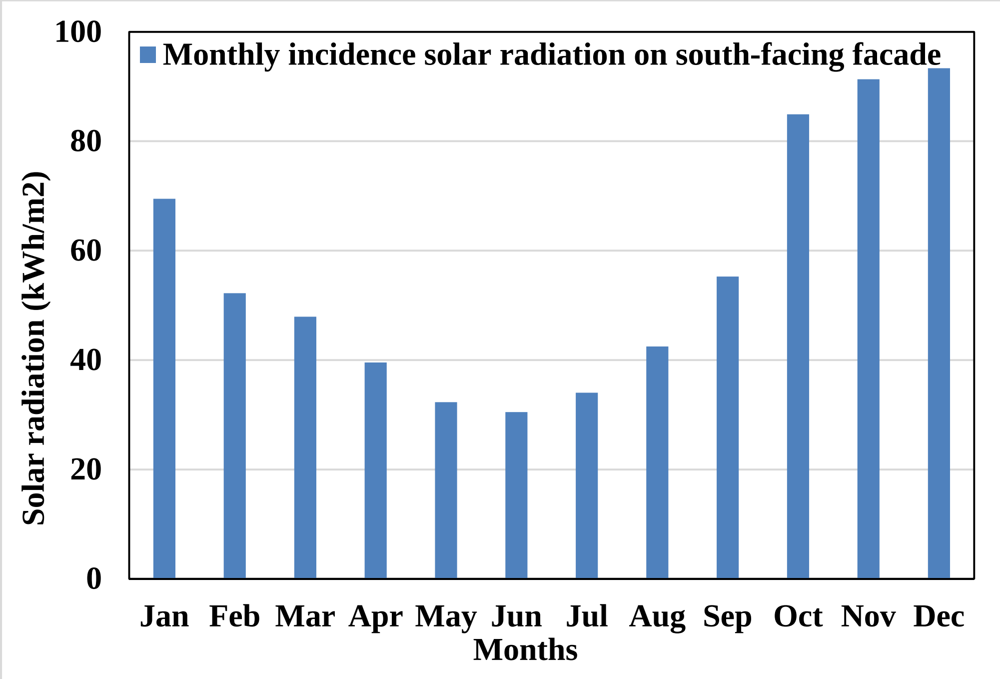


Fig. 5.6 Monthly incident solar radiation on the south-facing facade in TMY in Hong Kong

The maximum power output of the STPV windows in each month was also presented in Fig. 5.7. The results showed that the maximum power output, occurring in December, was about 66.5 W. The minimum power output in June was only 13.0 W because the beam solar radiation was fully obstructed in this month. The annual energy output of per unit area of the STPV window was also calculated, and it was 35.4 kWh/m^2. Fig. 5.8 presents the monthly energy output of per unit area of the solar PV windows. The maximum monthly energy output was about 5.1 kWh/m^2. In order to determine which orientation is the best orientation for STPV window installation in Hong Kong, the annual energy outputs of the STPV windows for east, west and north orientations were simulated. As shown in Fig.5.9, the annual energy output of the solar PV windows varied with orientations. In terms of energy performance, the best orientation for STPV window installation is south, in which the STPV window generates the maximum electricity of

35.4 kWh/m^2 per year. In addition, west facade is more suitable than the east facade for STPV window installation in terms of energy generation in Hong Kong, and north façade is not suitable for STPV window application due to the poor power generation.

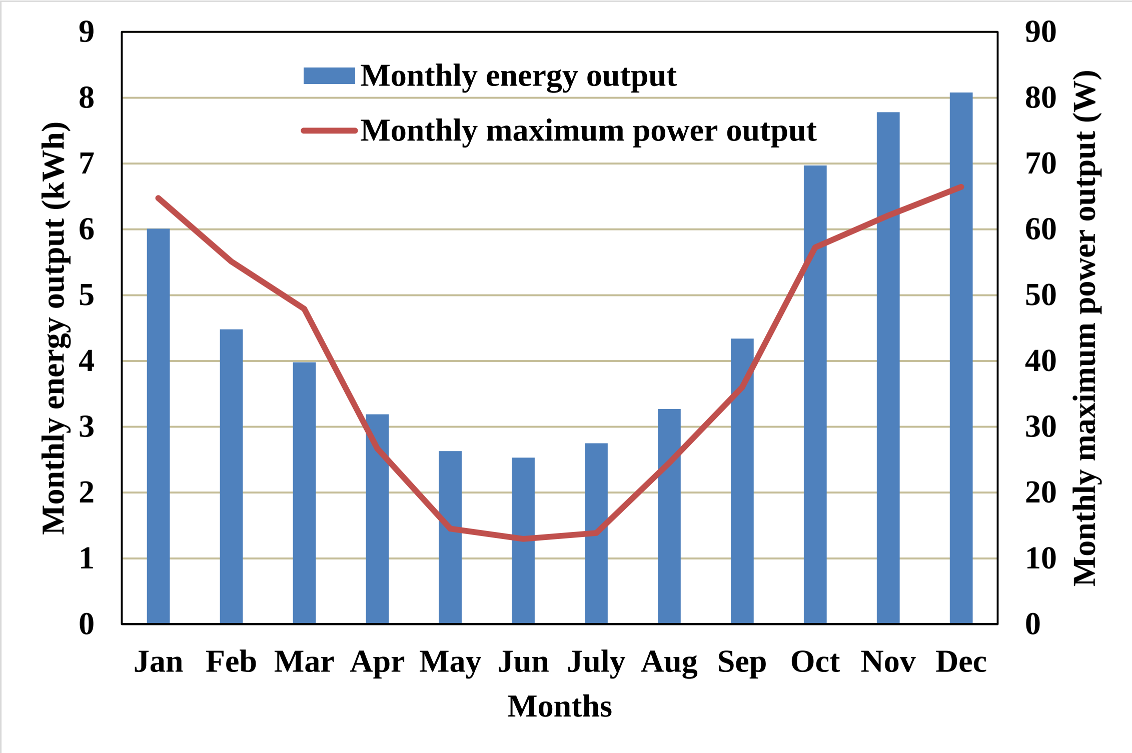


Fig. 5.7 Monthly energy output and the maximum power output of the STPV windows

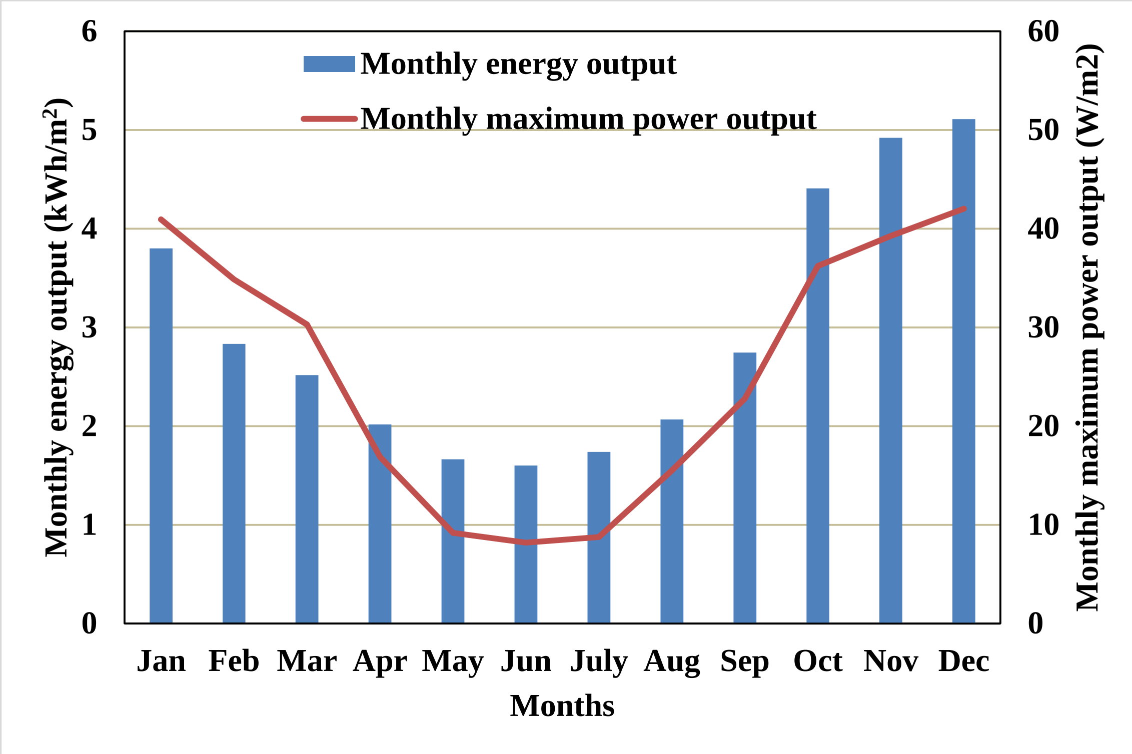


Fig. 5.8 Monthly energy output of and maximum power output per unit area of the STPV windows

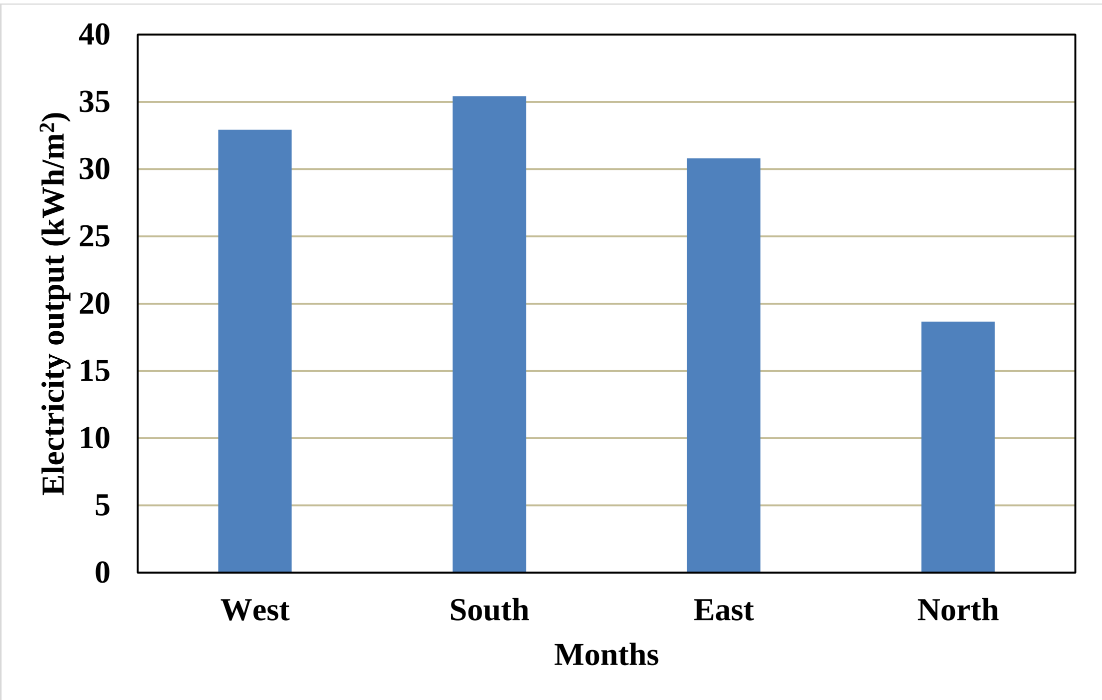


Fig. 5.9 The annual energy outputs of STPV windows in different orientations

5.3.3 Thermal performance

Except for power generation in situ of buildings, solar PV windows could also significantly reduce the building energy use by reducing the air-conditioning cooling/heating loads. As the transmittance of the semi-transparent PV module is low, solar radiation would be blocked significantly when transmitting through the PV module. Fig. 5.10 presents a comparison of the monthly solar energy incident upon the STPV window and the transmitted one. The STPV window reduced the solar radiation energy from 125 W/m^2 to 10 W/m^2 in December. A great amount of solar heat gain was blocked by the PV module, which resulted in a lower solar heat gain coefficient (SHGC) for the STPV windows.

The monthly heat gains and heat loss rates of the ST PV windows are presented in Fig. 5.11. It is found that, generally speaking, the monthly average heat gain rate was low in the middle of the year. The main reasons can be explained by the fact that a large amount of solar radiation was blocked and absorbed by the STPV window and hence, the transmitted solar radiation was reduced dramatically. Thus, the heat gain rate of the STPV window was significantly reduced. Another thing worth to note is that the heat loss rate of the STPV window was very high. This is because that heat loss transferred from interior to exterior in the form of long-wave thermal radiation, but the solar PV window can't block the infrared thermal radiation. In other word, even though the STPV window can absorb and block a large amount of incident solar radiation, especially the visible light, it can't block the thermal radiation emitting from the indoor room to the sky, as its thermal emissivity is high. Thus, for cold climate zones application, double-pane windows should be adopted to enhance the thermal insulation performance of STPV windows.

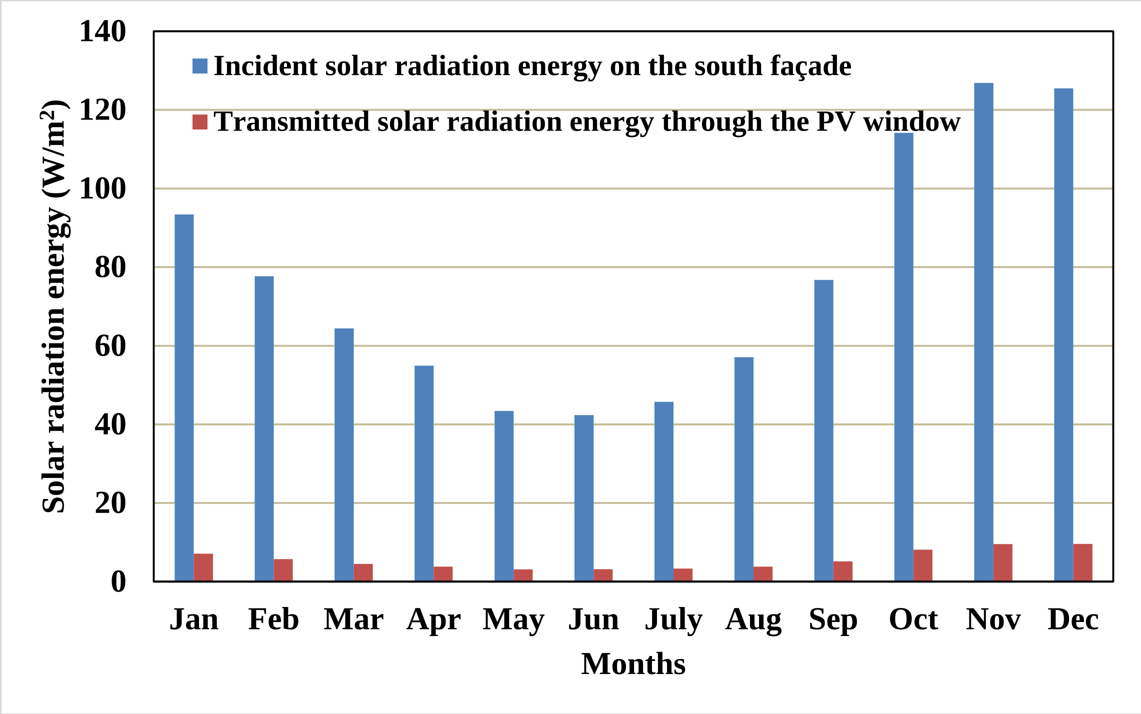


Fig. 5.7 Comparison of the monthly solar energy incident upon and transmitted of the STPV window

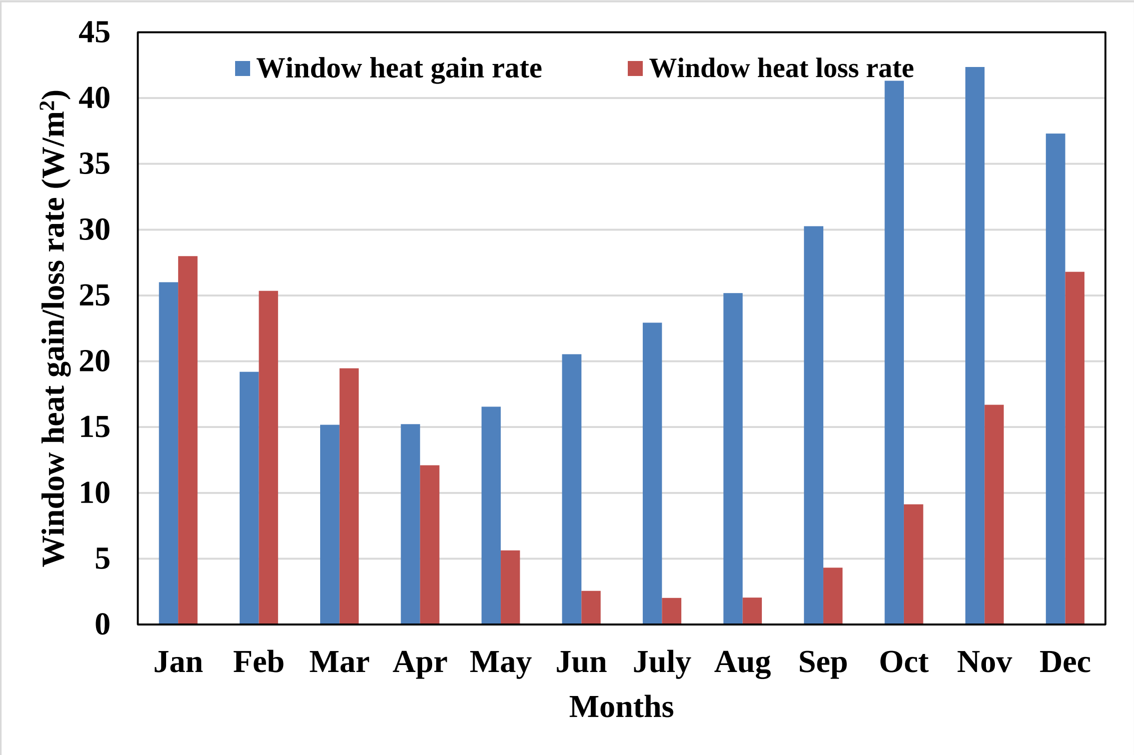


Fig. 5.8 Monthly heat gains and heat loss rates of the STPV windows

Finally, the annual cooling energy use of the room with STPV window in comparison with clear window in different orientations in Hong Kong was simulated, as shown in Fig. 5.12. The largest cooling energy use was observed in the west orientation, followed by the east and south, and the room facing north consumed the least cooling energy. The cooling energy use of the room was significantly reduced using solar PV windows in comparison with clear window. Around 18% of the annual cooling energy could be saved by replacing the clear window with STPV window for west orientation. Therefore, adopting STPV window could achieve great energy savings in Hong Kong.

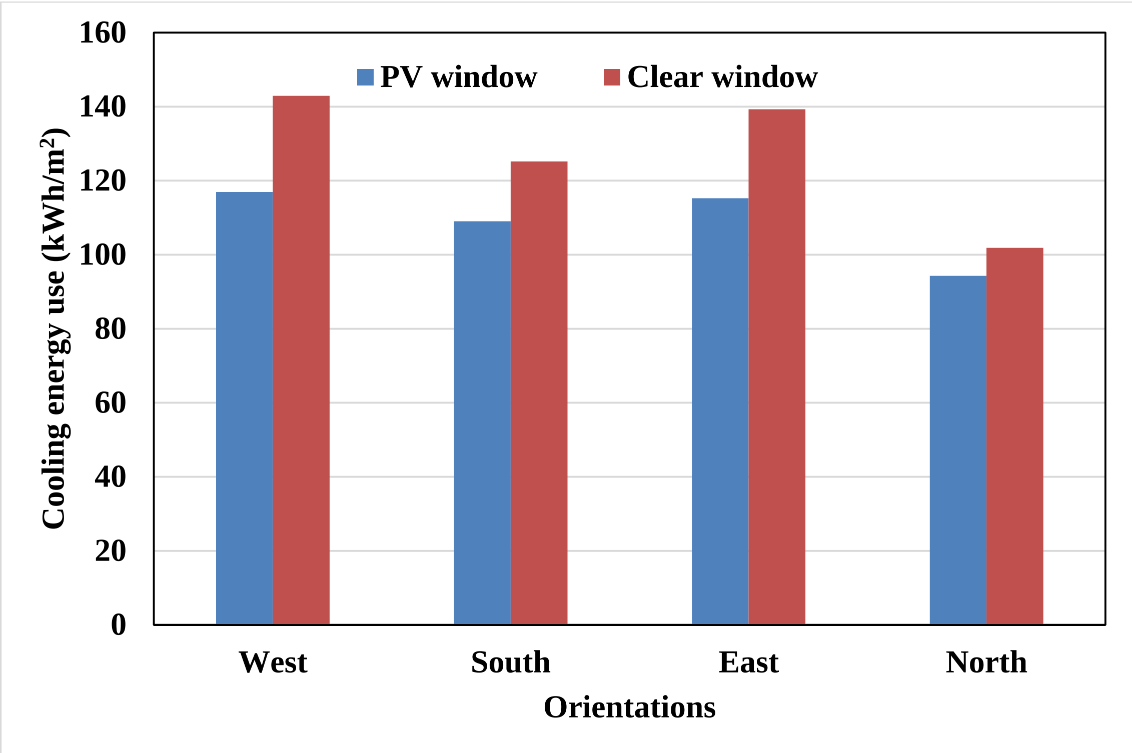


Fig. 5.9 The annual cooling energy use of the room with STPV windows in comparison with clear window in different orientations

5.3.4 Daylight performance

The a-Si PV module could convert a large amount of visible light into electricity and at the same time reduce the solar heat gain significantly. However, the higher the visible light absorptivity of the PV module, the lower the daylighting illuminance in the office room. In order to investigate the impacts of high visible light absorptivity on the daylighting performance of the STPV window, the hourly daylighting illuminance was simulated. Fig. 5.13 presents the monthly average daylighting illuminance. Having the similar trends of the monthly energy output, the STPV window had better daylighting performance in the winter season because the incident solar radiation was much higher in this season in Hong Kong. In December, the monthly average daylighting illuminance level reached 218 lux, which is about one third of the design lighting illuminance of 500 lux.

The variation of monthly average daylighting illuminance would result in a variation of the monthly lighting electricity use with dimming lighting control.

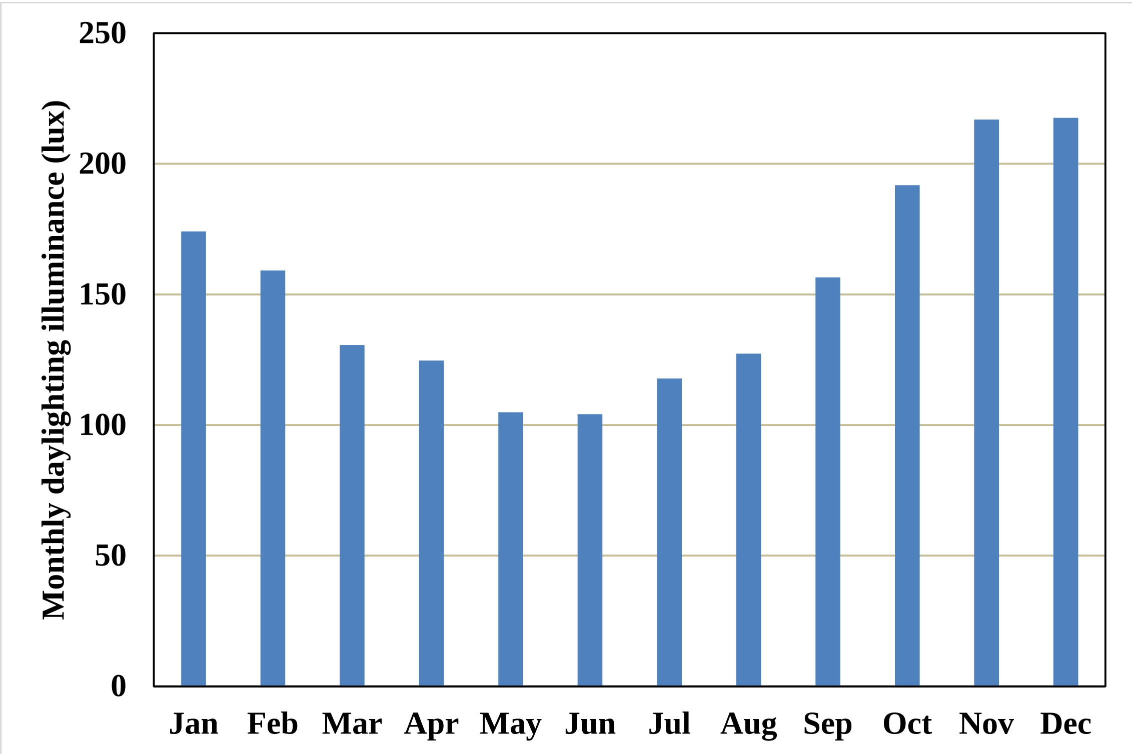


Fig. 5.10 Monthly average daylighting illuminance at the reference point

Fig. 5.14 shows the monthly lighting energy use and the monthly energy output of the STPV windows. From October to January of the whole year, the monthly electrical energy output from the STPV windows was higher than the lighting energy use because the considerable of natural daylight could enter the indoor room in this season. For summer season from July to September, the lighting energy use was significantly larger than the electricity generation. The annual total energy output of the PV windows was about 84 kWh, which was lower than the annual lighting energy use of 100 kWh.

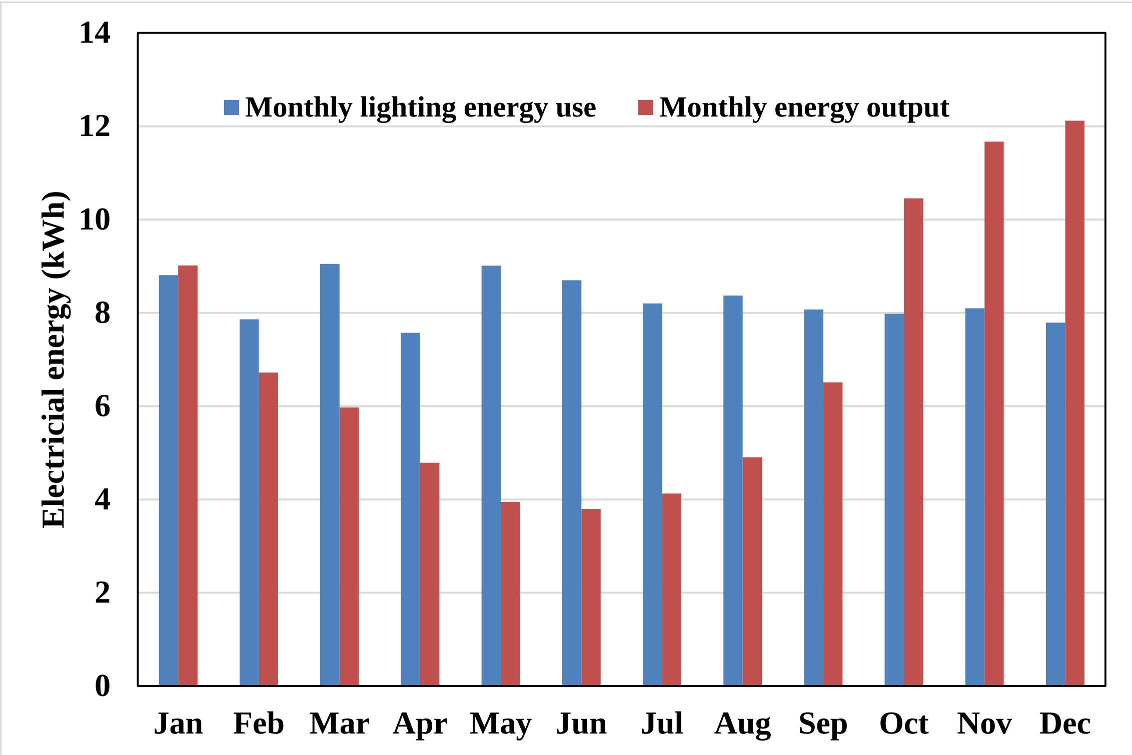


Fig. 5.11 Monthly lighting energy use and energy output of the STPV window

Fig. 5.15 shows that the annual lighting energy use of the room with STPV window in comparison with clear window in different orientations in Hong Kong. Although the STPV windows could reduce the cooling energy use, the lighting energy use increased due to the low solar transmittance of solar PV windows. The annual lighting energy use of the room with clear window was similar for different orientations, while the annual lighting energy use of the room with STPV windows was much larger for north orientation, followed by the east, west and south.

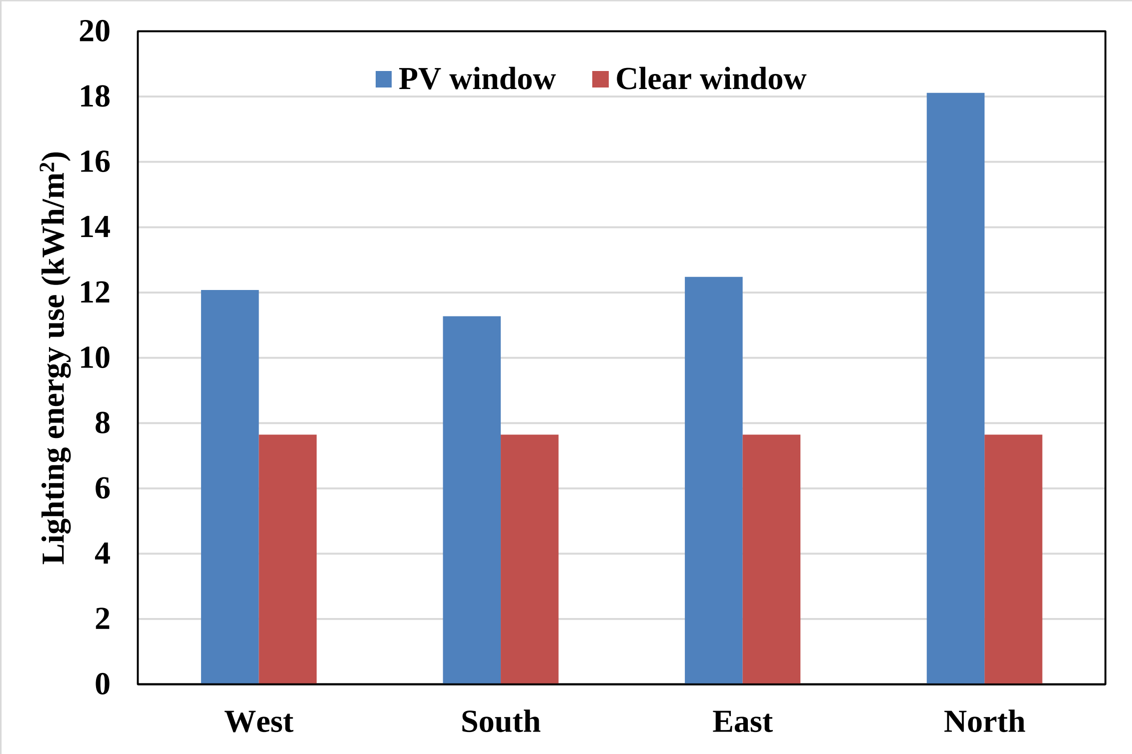


Fig. 5.12 The annual lighting energy use of the room with STPV window in comparison with clear window in different orientations

5.3.5 Overall energy performance in Hong Kong

The annual power, thermal and daylighting performances of the solar PV windows were all simulated in the previous sections. In this section, the overall energy performance of the office room installed with STPV windows was analyzed in comparison with clear window in Hong Kong.

Fig. 5.16 presents the annual net electricity use of the room in different orientations. It can be seen that the overall energy performance of the STPV window was significantly better than the clear window for west, south and east orientations. However, the overall energy performance of STPV window and the clear window was similar for north orientation. The west facing room with STPV window achieve the largest energy saving potential in comparison with the clear window. The annual net electricity use of the west facing room with STPV window and clear window was 118 kWh/m^2 and 151 kWh/m^2. Therefore, around 22% of the electricity could be saved by adopting STPV windows.

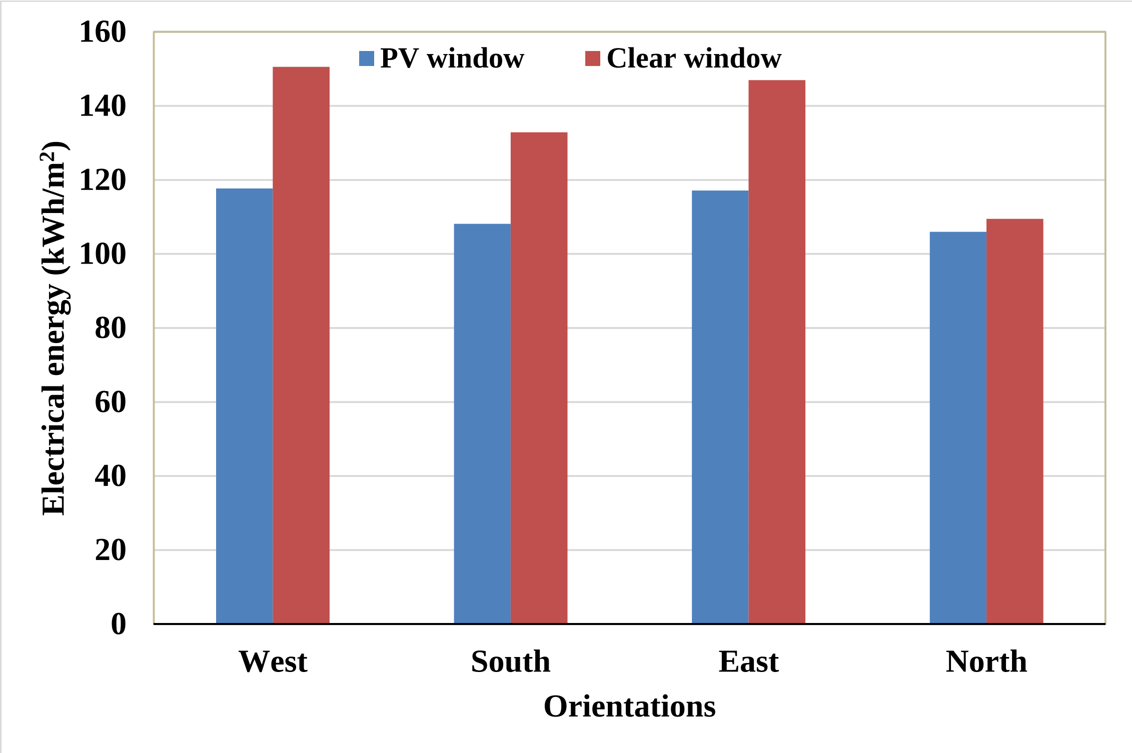


Fig. 5.13 Annual net electricity use of the room in different orientations

5.4 Energy performance of shading-type PV claddings

5.4.1 Model development

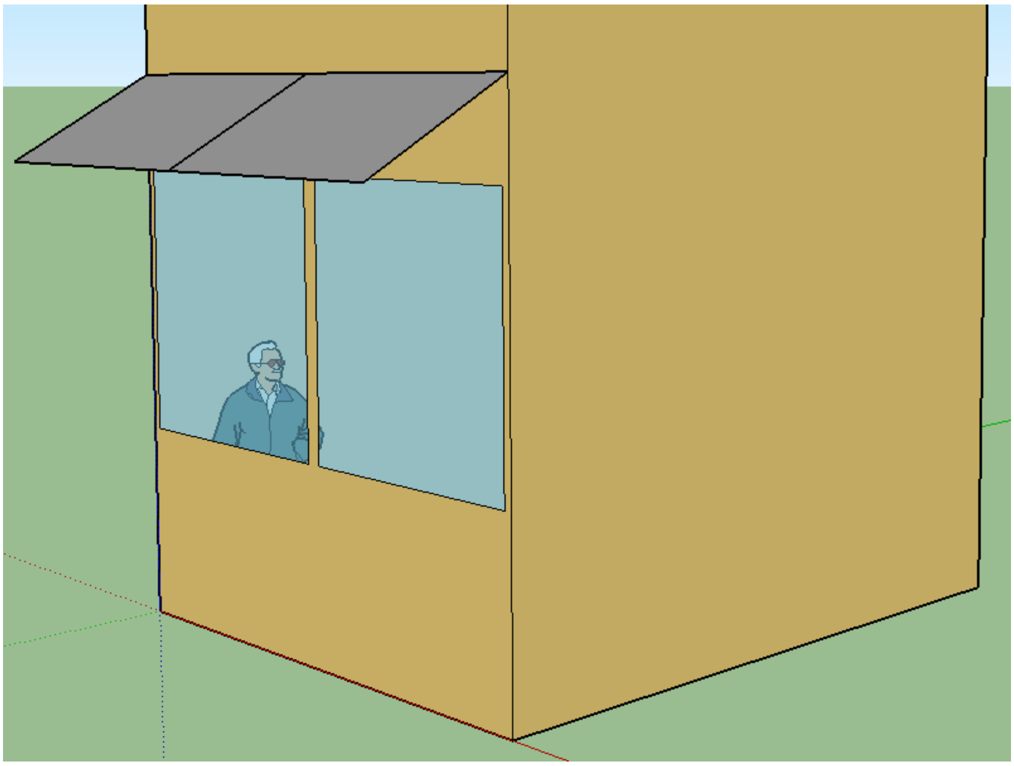


Fig. 5.14 The simulation model of shading-type PV claddings

Besides generating electricity in situ, the shading-type PV claddings could also prevent solar radiation entering the indoor room, which would mitigate the electricity consumption from air-conditioning systems. Similar to the simulation model developed for solar PV windows, a simulation model for estimating the energy performance of shading-type PV claddings was developed. The shading-type PV cladding was installed on the wall above the windows with tilt angle of 30˚. The simulation model of shading-type PV claddings is shown is Fig. 5.18 and the key characteristics of the PV module are shown in Table 5.4. All the simulation setup was the same as the simulation model for STPV windows.

Table 5.4 Key characteristics of PV module

Parameters	Values
Solar cell type	mc-Si
Short circuit current	9.0 A
Open circuit voltage	38.2 V
Current at maximum power	8.5 A
Voltage at maximum power	30.6 V
Dimensions (L × W)	1.65 m^2

5.4.2 Power output performance

Fig. 5.18 presents the monthly energy output and the maximum power output of the shading-type PV claddings. The energy output in the last half year was much higher than that in the first half year. The maximum monthly energy output was 66 kWh in October, while the minimum monthly energy output was only 40 kWh in February. The annual energy generation was about 621 kWh. On the other hand, the maximum power output of the shading-type PV cladding, occurring in February, was about 517 W. The minimum power output in June was only 382 W due to the obstructed beam solar radiation in Hong Kong.

Fig. 5.19 shows the monthly energy output and the maximum power output per unit area of the shading-type PV claddings. It is found that compared to the a-Si PV modules, the monthly energy output of the mc-Si PV modules is significantly higher due to the higher module efficiency. The maximum monthly energy output was about 40 kWh/m^2, while the minimum monthly energy output was 24 kWh/m^2. The annual energy output was around 316 kWh/m^2.

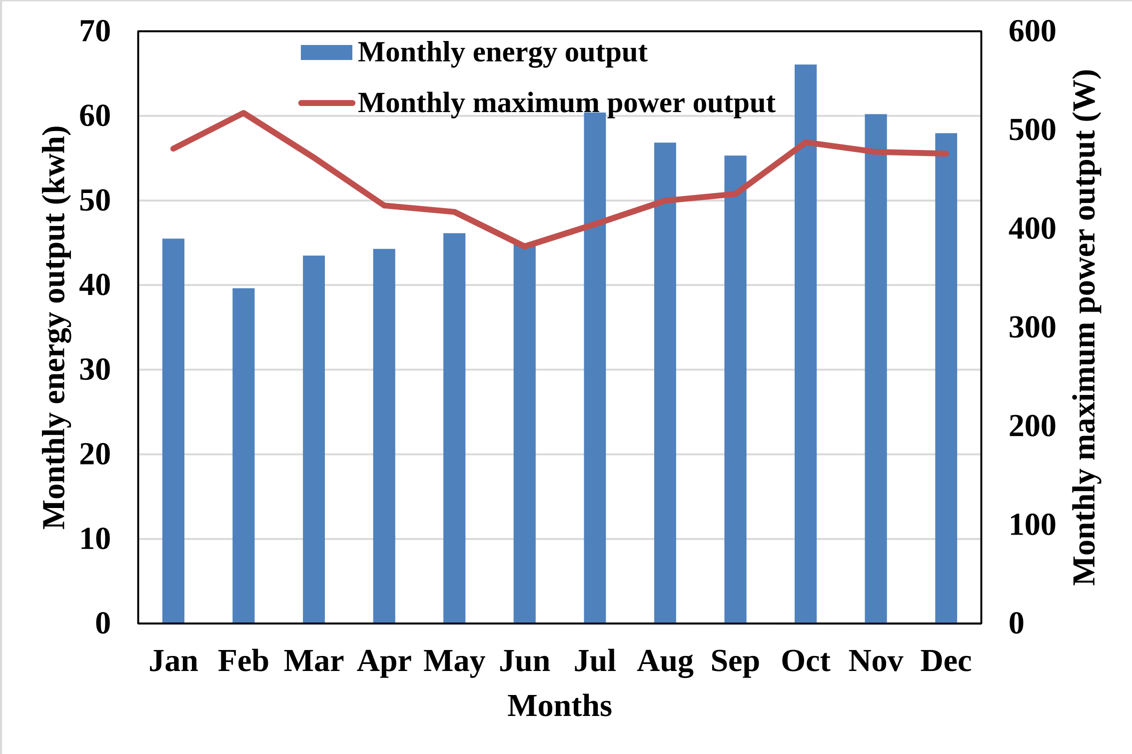


Fig. 5.15 Monthly energy output and the maximum power output of the shading-type PV claddings

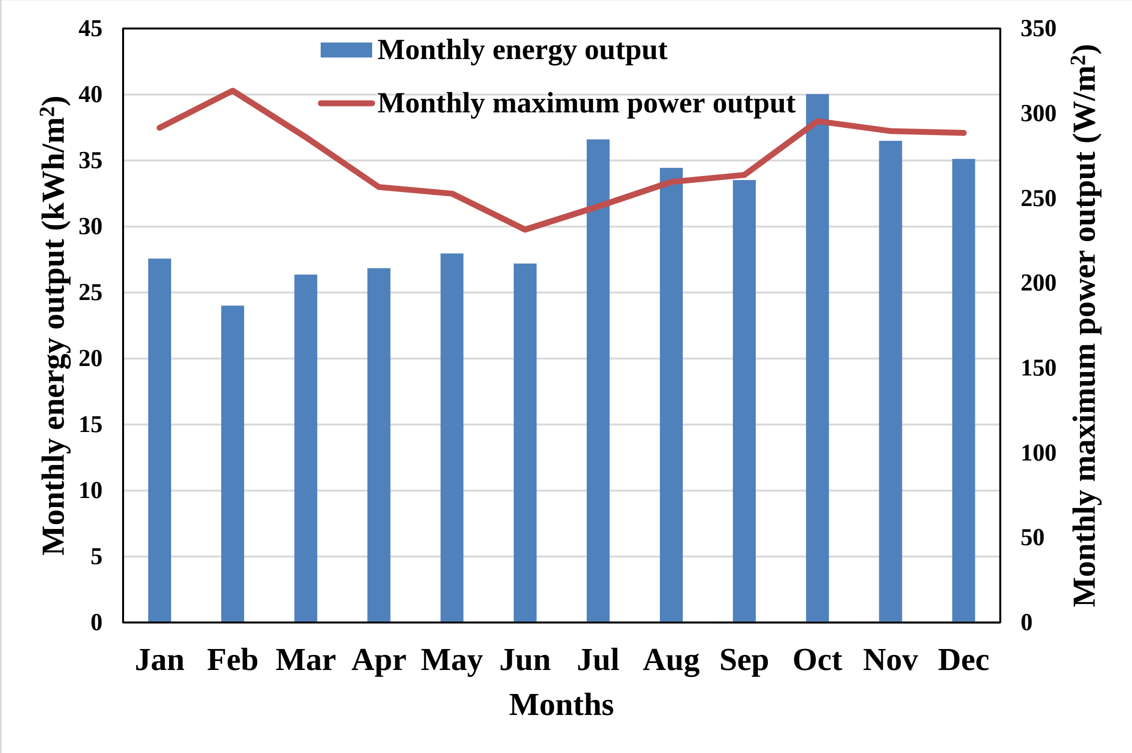


Fig. 5.16 Monthly energy output and the maximum power output per unit area of the shading-type PV claddings

5.4.3 Thermal performance

One of the most important benefit of the shading-type PV claddings is that they can prevent the incoming solar radiation entering the room. Therefore, the thermal performance with and without the shading-type PV claddings was compared. Fig. 5.20 shows the monthly transmitted solar radiation through the windows with and without the shading-type PV claddings. It can be seen that the transmitted solar radiation through the window was significantly reduced using the shading-type PV claddings. The largest reduction ratio of transmitted solar radiation was as high as 50%, occurring in October. The transmitted solar radiation is larger in winter in Hong Kong due to the location and the sun azimuth. The reduction ratio of transmitted solar radiation was lower in summer.

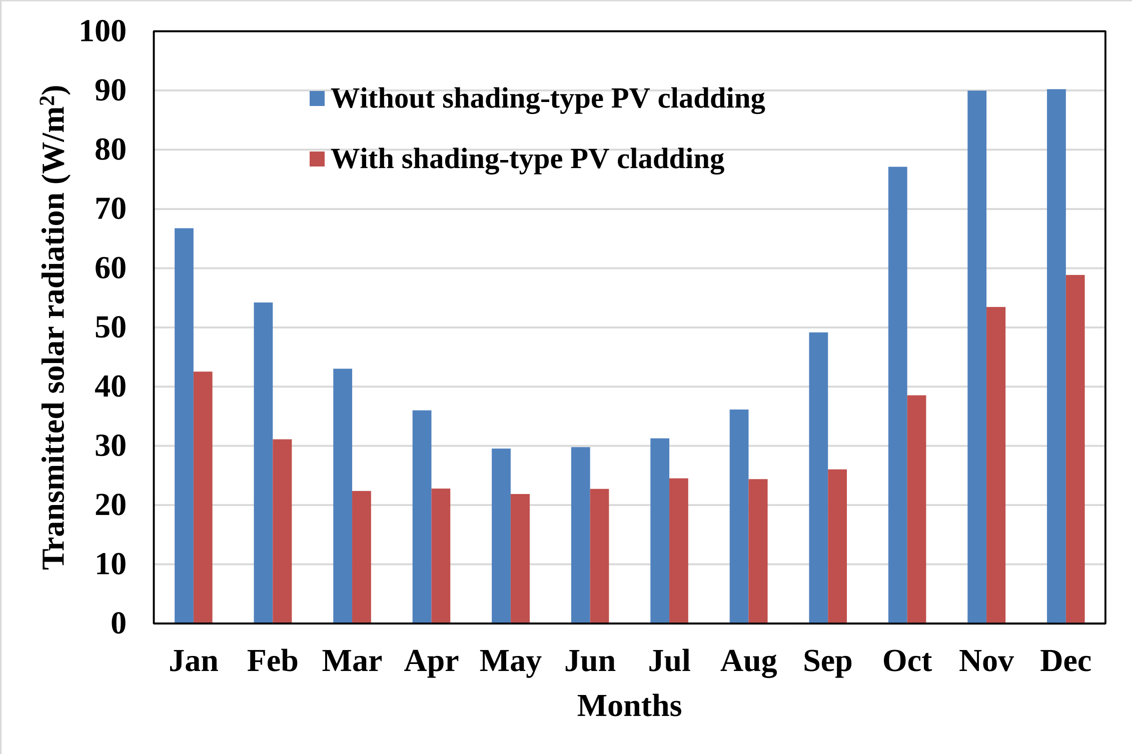


Fig. 5.17 The monthly transmitted solar radiation through the windows with and without shading-type PV claddings

The monthly window heat gain rates with and without the shading-type PV claddings were also compared, as shown in Fig. 5.21. The monthly window heat gain was significantly reduced with the use of the shading-type PV cladding, and therefore, the electricity use from the air-conditioning system could be reduced. The window heat gain rate is larger in summer because of the larger transmitted solar radiation. The largest reduction of window heat gain rate was 60%, occurring in March, while the lowest was 18% in June.

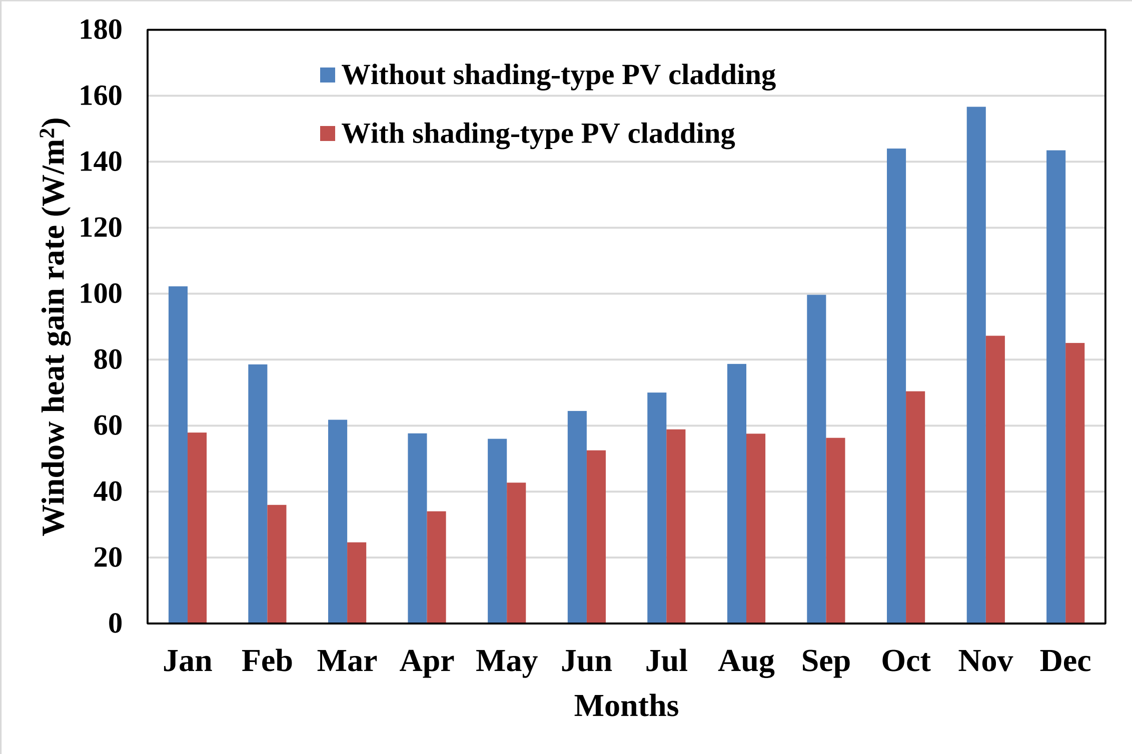


Fig. 5.18 The monthly window heat gain rates with and without shading-type PV claddings

5.5 Summary

In this Chapter, the overall energy performance of different building-integrated solar PV systems, including rooftop solar PV systems, shading-type solar PV claddings and a-Si based STPV windows is evaluated. As to rooftops case, the annual energy productions per 1 kW installation for 0 deg tilt and 23 deg tilt configuration are 856 kWh and 904 kWh respectively due to the higher efficiency of in January and October to December. In thin film case, the annual energy production is about 946 kWh, and for semi-transparent window shows only 613 kWh were generated annually, which has lower efficiency than the above cases. Four kind of vertical facades were evaluated at different installation orientations with the annual generated power of 317 kWh, 496 kWh, 555 kWh and 504 kWh respectively. Finally, the shading PV systems were estimated to provide 863 kWh and 765 kWh in 31 deg tilt and 55 deg tilt configurations, which is in the middle of all cases. This kind of BIPV system may be the most feasible application, taking the portfolio efficiency, installation area and difficulty into consideration.

In addition, the energy performance of a-Si based PV double-skin façade systems was evaluated. The maximum monthly energy output was about 5.1 kWh/m^2. In order to determine which orientation is the best orientation for STPV window installation in Hong Kong, the annual energy outputs of the STPV windows for east, west and north orientations were simulated. The annual energy output of the STPV windows varied with orientations. Taking weather factors into account, the maximum monthly energy output was about 12.1 kWh, occurring in December. The minimum monthly energy output occurred in June, was only 3.8 kWh. The annual energy generation was about 84 kWh. In terms of energy performance, the best orientation for STPV window installation is south, in which the STPV window generates the maximum electricity of 35.4 kWh/m^2/yr. While in terms of thermal performance, the largest cooling energy use was observed in the west orientation, followed by the east and south, and the room facing north consumed the least cooling energy, and around 18% of the annual cooling energy could be saved by replacing the clear window with STPV window for west orientation. Besides, the annual lighting energy use of the room with clear window was similar for different orientations, while the annual lighting energy use of the room with STPV windows was much larger for north orientation, followed by the east, west and south. To sum up, the annual net electricity use of the west facing room with solar PV window and clear window was 118 kWh/m^2 and 151 kWh/m^2. Therefore, adopting STPV windows could save around 22% of the electricity.

Finally, the energy performance of shading-type PV cladding systems was estimated. It is found that compared to the a-Si PV modules, the monthly energy output of the mc-Si PV modules is significantly higher due to the higher module efficiency. The maximum monthly energy output was about 40 kWh/m^2, while the minimum monthly energy output was 24 kWh/m^2. The annual energy output was around 316 kWh/m^2. With respect to its thermal performance, the monthly window heat gain was significantly reduced with the use of the shading-type PV cladding, and therefore, the electricity use from the air-conditioning system could be reduced. The window heat gain rate is larger in summer because of the larger transmitted solar radiation. The largest reduction of window heat gain rate was 60%, occurring in March, while the lowest was 18% in June.

CHAPTER 6 INCENTIVE POLICIES FOR BIPV TECHNOLOGY IN HONG KONG

6.1 Introduction

The installation of sustainable and renewable energy systems is an effective way to reduce Hong Kong's dependence on imported fossil fuels. The solar photovoltaic (PV) technology is due to a perfect solution to Hong Kong's economic geography. By reviewing the history of the development of five leading solar photovoltaic countries, namely, Germany, Japan and Italy, the Chinese mainland and the United States, this chapter is a useful policy kit for the development of photovoltaic power. Based on the previous successful experience and Hong Kong photovoltaic industry unique local conditions, a series of incentive strategies are put forward to help Hong Kong reduce the initial investment in the initial stage, the reasonable subsidies provided during the period of photovoltaic system, promote the use of building integrated photovoltaic system. These results can provide practical reference for local policy makers to promote the application of renewable energy.

In this chapter, an input/output methodology is employed. The histories of solar PV development and application were reviewed as the inputs. Five leading economies in PV application, Japan, Germany, Italy, the USA, and Mainland China, were selected. Their subsidies and policies from different eras were collected and analyzed. Then, a policy tools box was generated as the methodology output. Their experiences were referred and accordingly a series of strategies and policies that fit Hong Kong's situation were developed. It was hoped that the conclusions of this study could serve as a practical reference for local researchers as well as policy-makers.

According to the Global Future Report 2013, it was estimated that the global solar PV capacity could reach 400–800 GWp as soon as 2020 and as much as 8000 GW by 2050, which will save more than 53 million tons of CO_2 emissions [152,153]. By the end of 2015, the Chinese mainland, the largest and fastest developing region in the world, reached 43.5 GWp cumulative installed capacity as compared to only 19.2 GWp in 2013. In the meantime, Germany and Italy have reached 39.7 GWp and 18.9 GWp, representing the largest PV penetration of the electricity demand (7.1% and 8.0%) in the world. Japan and the USA were positioned the third and fourth in the list, having reached 34.4 GW and 25.6 GW with 11 GWp and 7.3 GWp annual installed capacities in 2015 [154]. However, solar PV application has not yet been well developed in Hong Kong in recent years. Although its solar energy resources are above the world average, the total PV installed capacity is less than 3 MWp and the actual PV electricity generation only accounts for a negligibly small share of the total energy end use in Hong Kong. However, as discussed in Chapter 3, for the development potential of usable roof areas with rooftop solar PV systems in Hong Kong, the potential installation capacity can be up to 5.97GWp with estimated annual energy output of 5981 GWh which is equivalent to 14.2% of the total electricity use in Hong Kong in 2011. This proportion is much higher than the target set for renewable energy development (3-4%) in Hong Kong. Therefore, local policymakers could develop a more ambitious target for developing renewable energy in future, and solar PV technology certainly has the potential to meet the target.

6.2 Review of solar PV application process in the leading countries

Since the "Energy Crisis" last century, the major economies started to consider their energy policies carefully. Much more attention was paid to the development of sustainable energy as an acceptable alternative for traditional fossil energy sources. In the following section, five main and representative economies were selected, Japan, Germany, Italy, Mainland China, and the USA. Their solar PV policies are collected and reviewed here. It is hoped that through this research, a series of policies and strategies that fit Hong Kong's situation could be developed.

6.2.1 PV Incentive Policies in Japan

Japan was one of the earliest countries that developed and applied solar photovoltaics. In the early 1980s, the New Energy and Industrial Technology Development Organization started to research and develop solar PV systems, aiming at practical application. In the early 1990s, the basic problems involving the installation and connection of the PV system were solved. The first public support for PV application, the "Net Billing Program", came out in 1992. This program was launched autonomously by 10 domestic electrical enterprises rather than the government to purchase solar PV electricity at a market PV electricity at a market price of 23 JPY/kWh. Soon, afterwards, the Japanese government officially set the price of 23 JPY/kWh. Then, the Japanese government officially approved the Guideline for Grid-connection for PV electricity in 1993 [155].

In 1994, the Japanese government introduced a specific PV program of National Subsidy for Residential Buildings whereby the government subsidized 50% of the solar PV installation cost for those Residential Buildings whereby the government subsidized 50% of the PV installation cost for those with the installed capacity less than 5 KWp, with a ceiling price of 900 JPY/Wp. The subsidy value for installation had been annually adjusted according to market changes. This program greatly promoted the solar PV development in Japan, and, by the time of its termination, the installation cost had declined from 1920 JPY/Wp in 1994 to 661 JPY/Wp in 2005. Although the subsidy value was reduced to 20 JPY/Wp, the domestic solar PV installed capacity in Japan had been over 1422 MWp until the year 2005 [155–157].

However, due to the subsidy value for solar PV installation decreasing and the government failing to follow up with new subsidy policies, the profitability of solar PV electricity generation decreased. As shown in Fig. 5.1, Japan's solar PV market developed slowly especially after the installation subsidy was terminated in 2005, and the growth rate of solar PV installed capacity started to fall. In spite of that, the Japanese government attempted to revive the solar PV market. In 2003, a new renewable energy policy known as Renewable Portfolio Standard (RPS) was introduced and it determined that utility companies had an obligation to purchase a specific percentage (at least 1.35%) of renewable electricity. This policy did not expand with apparent effect, and the new installed capacity was still declining year by year from 2005 to 2008 [158,160]. In 2009, the Japanese government re-executed the subsidy for solar PV installation at 70 JPY/Wp. In November of the same year, the Japanese government introduced a feed-in tariff mechanism for solar PV electricity with 48 JPY/kWh for those installations less than 10 kWp and paid over duration of 10 years. Although the Japanese feed-in tariff was only provided on the surplus of photovoltaic electricity after meeting the residential use, Japan's PV market was revitalized immediately in 2009, and the newly installed capacity was more than double than that of 2008. These two subsidy policies had particularly influenced on the development of BIPV systems, in that more than 90% of solar PV systems were installed on residential buildings [154,160,161].

After the nuclear disaster at Fukushima in 2011, there was more emphasis on the renewable energy development. The Japanese government passed the Act on Purchase of Renewable Energy Sourced Electricity, which created a more comprehensive feed-in tariff mechanism in 2012 and set the targets for solar PV installation that the cumulative installed capacity would increase to 28 GWp in 2020 and reach 50 GWp in 2030. Unlike the previous subsidies, BIPV systems were encouraged to be installed on large commercial and industrial rooftops rather than on residential buildings. Faced with a more generous subsidy, BIPV was becoming more and more profitable in Japan and attracted a large number of investors. As shown in Figure 6.1, the total installed capacity skyrocketed by 351% between 2012 and 2014.

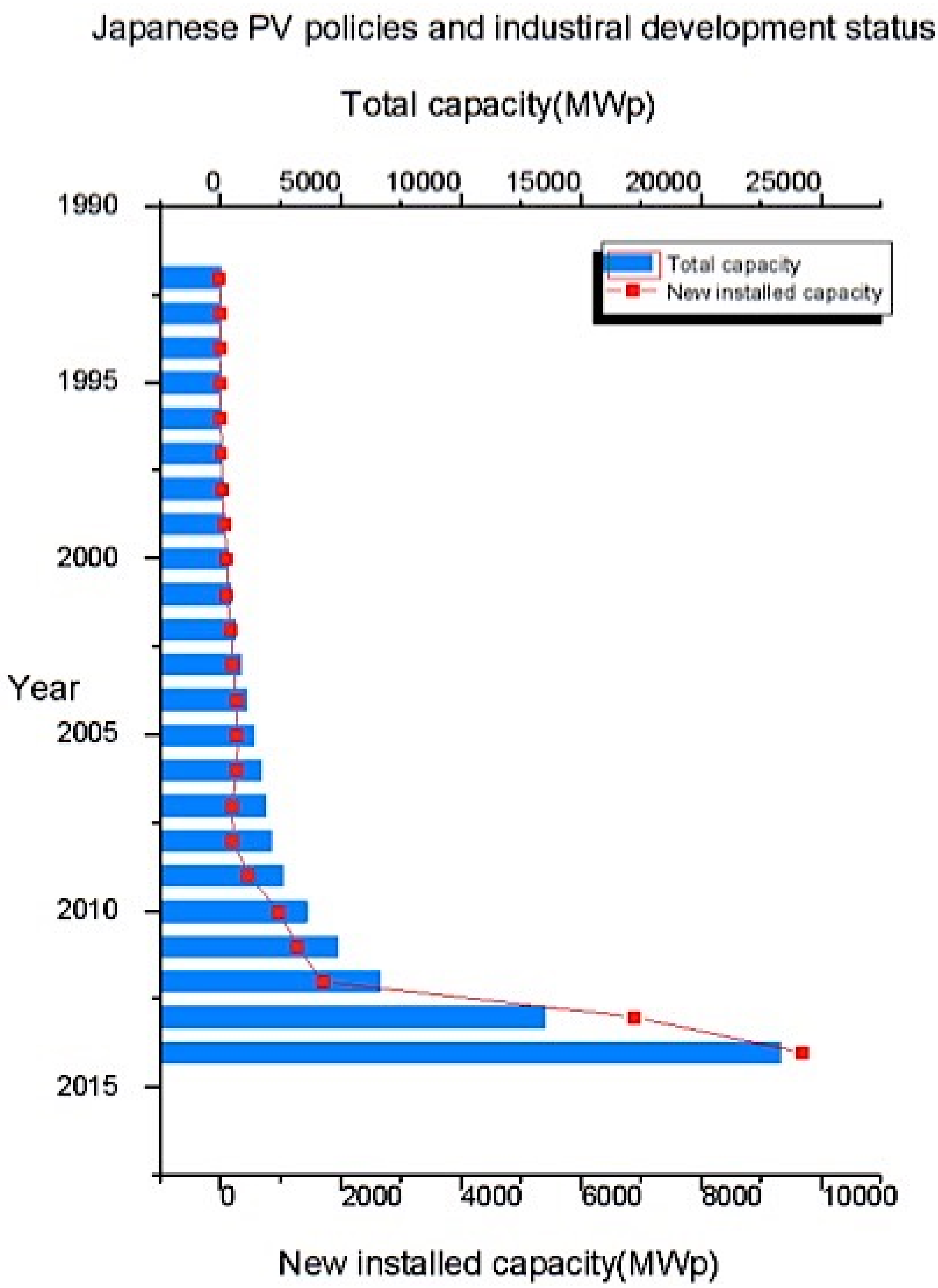


Fig.6.1 PV incentive policies and development trends in Japan [154]

6.2.2 Solar PV Incentive Policies in Germany

Germany was also one of the earliest countries to have widespread solar PV application. The Electricity Feed-in Act of 1991 was the first German governmental PV support scheme that facilitated the development of renewable energy. "The Thousand Solar Roofs Program", the first specific support scheme for the solar PV industry, was formulated the same year and implemented until 1995. It subsidized 70% of the solar PV system's costs for solar roof programs from 1 kWp to 5 kWp [162]. Soon, the Thousand Solar Roofs Program was granted by the state-owned development bank (KfW) between 1999 and 2003. It provided loans at low interest rates for solar PV projects; consequently, the deployment of the Thousand Solar Roof Programs was completed soon and the total installed capacity reached 435 MWp by 2003 [163].

Germany stood out from the old Electricity Feed-in Act and dedicatedly enacted the new tariff for solar PV electricity in the EEG (Erneuerbare Energien Gesetz) Law of 2004, which raised the feed-in tariff from 0.09 EUR/kWh to 0.51 EUR/kWh for a 20-year period for both ground-based and rooftop systems. In order to encourage cost reductions, the feed-in tariff decreased by at least 5% each year, indiscriminate of regions and capacities. The rate of feed-in tariff decline kept increasing in recent years; for instance, a decline of 24% was found in 2011 when the newly installed capacity exceeded 7.4 GWp [164].

After experiencing constant high-speed growth during the past eight years, Germany's renewable policy for solar PV market underwent a great change in 2012 due to the New EEG Law. The major changes included the introduction of a threshold of 52 GWp total installed capacity, the reduction of the feed-in tariff rate to less than 0.14 EUR/kWh, which was a digressive schedule based on the installed capacity, and a limitation on the amount of solar PV electricity exported to the utility grid. These changes represented an effort to transition solar PV to a new, incentive-free policy paradigm [165]. As shown in Fig. 6.2, the growth rate of PV installation capacity plummeted in 2013 and 2014.

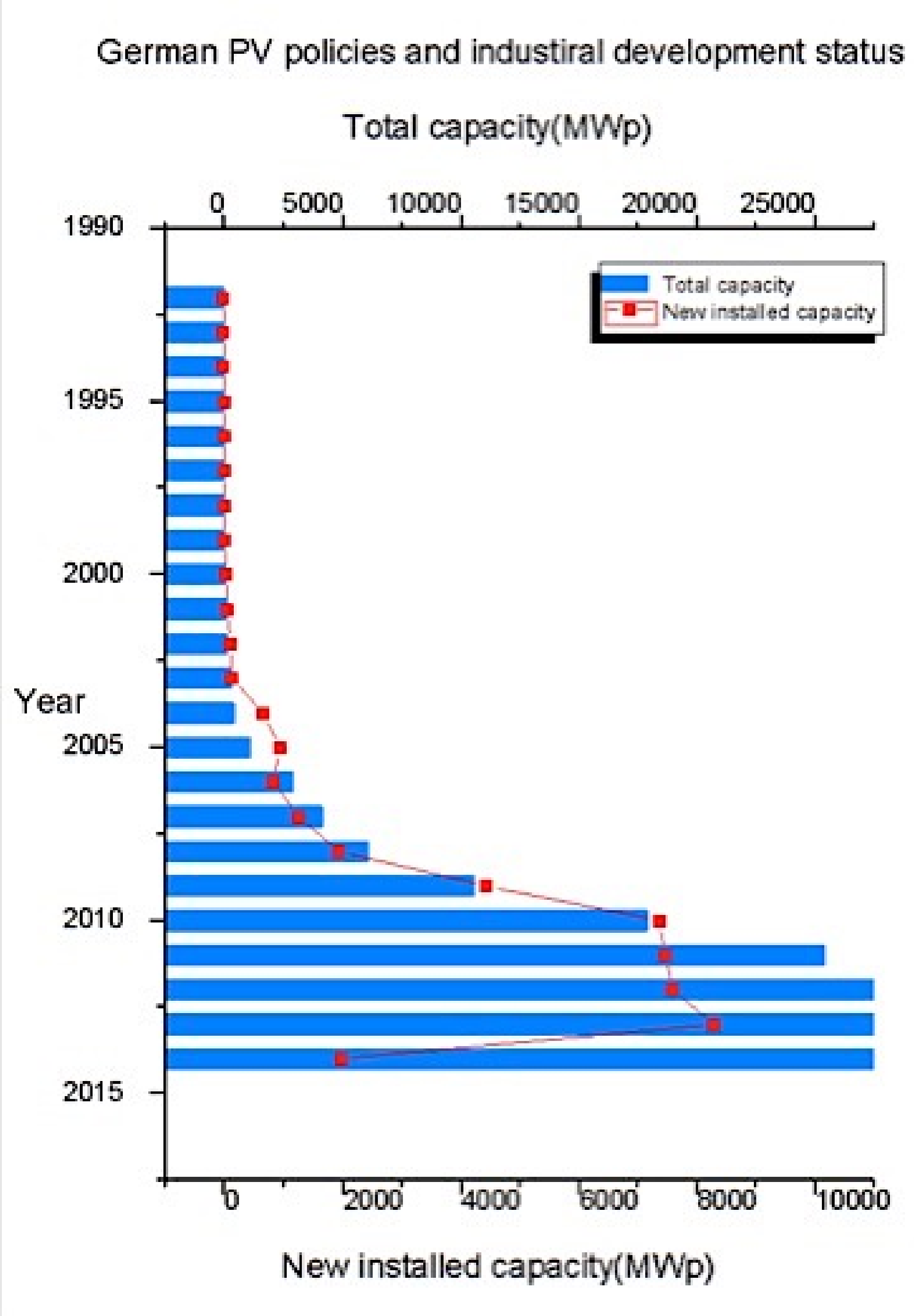


Fig.6.2 PV incentive policies and development trends in Germany

6.2.3 Solar PV Incentive Policies in Italy

Italy has the second largest solar PV capacity in the EU at 18.9 GWp, which corresponded to 9.08% of the national power production at the end of 2015 [166]. However, the pathway of development is quite different from Germany's. The first policy implemented by the government was the "Photovoltaic roofs" program of 2001. This program provided financial support, up to 75% of the total capital costs, to install a solar PV system with peak power between 1 and 20 kWp. In other words, investors could obtain a maximum refund of 8005.08 †/kW on the investment cost of PV systems with nominal power up to 5 kWp, which linearly decreased to 7230.40 †/kW for an installed power of 20 kWp [167]. Unfortunately, although the program brought about 27.0 MWp capacity in 2003, it still had a disadvantage that did not reward the PV system with higher efficiency and electricity generation. Based on the unacceptable cost of replacing or repairing broken equipment at that time, many solar PV systems were turn off after a few years. The producers also had no motivation to spend their resources to maintain their systems [168]. As a result, the installation of PV plants in Italy was unregulated until 2006.

In 2005, in order to put the European Union 2001/77/EC Directive into effect, the Italian government implemented a Feed-in Tariffs scheme to incentivize the PV systems' diffusion, which was called 1st "Conto Energia" [169,170]. In this scheme, PV owners had the possibility of selling the electricity exported to the grid and alternative use of the net metering service for PV systems with a peak power up to 20 kWp. Meanwhile, a premium tariff for the electricity generated by solar PV systems with a peak power up to 1000 kW was provided by the government to solar PV system owners for 20 years. The range of premiums varied from 0.460/kWh to 0.490/kWh for a 3000 kW PV system. This incentive resulted in the 500 MWp PV installations in March 2006.

Then, a new program was carried out in 2007, named 2nd “Conto Energia,” which was set a 1200 MWp target of PV capacity to be installed at a national level [171]. Based on all the terms of the 1st phase, only the premium tariff was modified according to the architectural typologies of the system. Building integrated PV (BIPV) systems and partial BIPVs were selected to receive a higher tariff than other solar PV systems. Meanwhile, a premium tariff de-escalation rate of 2%/year was fixed for PV systems installed after 2008. This incentive prompted a giant growth in the PV investment, and the annual installation capacity reached more than 300 MW in 2007 and 2008. However, at the same time, the tariffs paid by government had reached 110 million euros.

In 2009, the AEEG modified the terms and conditions of net metering service [172] so that covered the fees incurred by customers for withdrawing electricity from the grid. Hourly market price of the electricity exported or imported by solar PV systems was also considered at various hours of the day in a given calendar year. In 2009, the annual installation reached 1.144 GWp, which was more than triple compared with the figure in 2008. The rapid market growth seen in 2008 and 2009 was driven by the changes to the FiT decree, which were adopted in early 2007.

The 3rd “Conto Energia” was carried out in 2010. Besides the regular PV systems, it targeted the installation of Building Integrated PV (BIPV) systems and advanced concentrating PV (CPV) systems, which reached an accumulated capacity of 3500 MW [173]. This movement reduced the tariffs in multiple phases. The government hoped it would not put the development of solar PV at risk in Italy.

The 4th “Conto Energia” [174], which was carried out in June 2011, offered a modified net metering service and simplified purchase and resale arrangements for the electric send into the grid by all kinds of PV systems. At the end of August 2012, this CE was finished. Because the total amount of incentives paid by government reached the target value of 6

M€/year. In 2011, the total installations were schemed to about 3000 to 5000 MWp. To keep investors' confidence in solar PV industry, government decided to maintain registration under the current CE program [175].

After the 4th "Conto Energia" ceased, the 5th "Conto Energia" [176] was implemented, under the condition that the total amount of paid incentives was fixed at the target of 6.7 M€/year. Due to the tight incentive budget, the 5th "Conto Energia" had a short life and ceased by July 2013. The total installation capacity in Italy was 17.08 GWp in 526,000 plant sites in the middle of year 2013.

In general, the Italy case showed intense government promotion in solar PV development but with a heavy debt shouldered by the government. The results showed a rapid but unsustainable growth in solar PV installation.

6.2.4 PV Incentive Policies in Mainland China

Beginning with the enactment of the Renewable Energy Law (REL) in 2005, China has relied on a wide and diverse mix of policy instruments to promote renewable energy growth. PV electricity was identified as the prior renewable energy source to resolve power supply issues in remote rural areas and enhance the utilization of renewable energy in urban areas. The REL set a national target for renewable energy development, and mandated grid electricity companies to purchase all renewable electricity at a price higher than the one of coal-fired electricity. In addition, a specific fund was established to provide additional financial support for renewable energy development, including R&D, pilot projects, rural utilization of renewables, and standard setting and assessment [177].

In order to implement the national strategy of "energy-saving", the Chinese government strengthened supports for solar PV development. In 2009, the ministers of finance and housing and urban–rural development jointly issued "The enforcement advice for promoting solar energy applications in buildings" and "The interim procedures for financial subsidy of solar photovoltaic application in buildings". These two official documents raised China's solar roof program and provided financial subsidies for solar PV installation at 20 RMB/Wp. Additionally, in the middle of 2009, the ministers of finance, science and technology, and national energy administration jointly issued "The notice for implementation of golden sun program" and "The interim procedures for financial subsidy of golden sun program". The Golden sun program clearly stated that the government would undertake 50% of the investment costs for on-grid solar PV systems and 70% for off-grid solar PV systems in remote regions of China. Subsequently, the subsidy of the Golden sun program was adjusted in 2010 so that installation subsidy for BIPV was reduced to 17 RMB/Wp and 13 RMB/Wp for BAPV systems. With the implementation of installation subsidies provided by the solar roof program and the Golden sun program, China's PV industry has developed dramatically since 2009: the cumulative installed capacity increased from 300 MW in 2009 to 17,800 MW in 2013, as shown in Fig. 6.3.

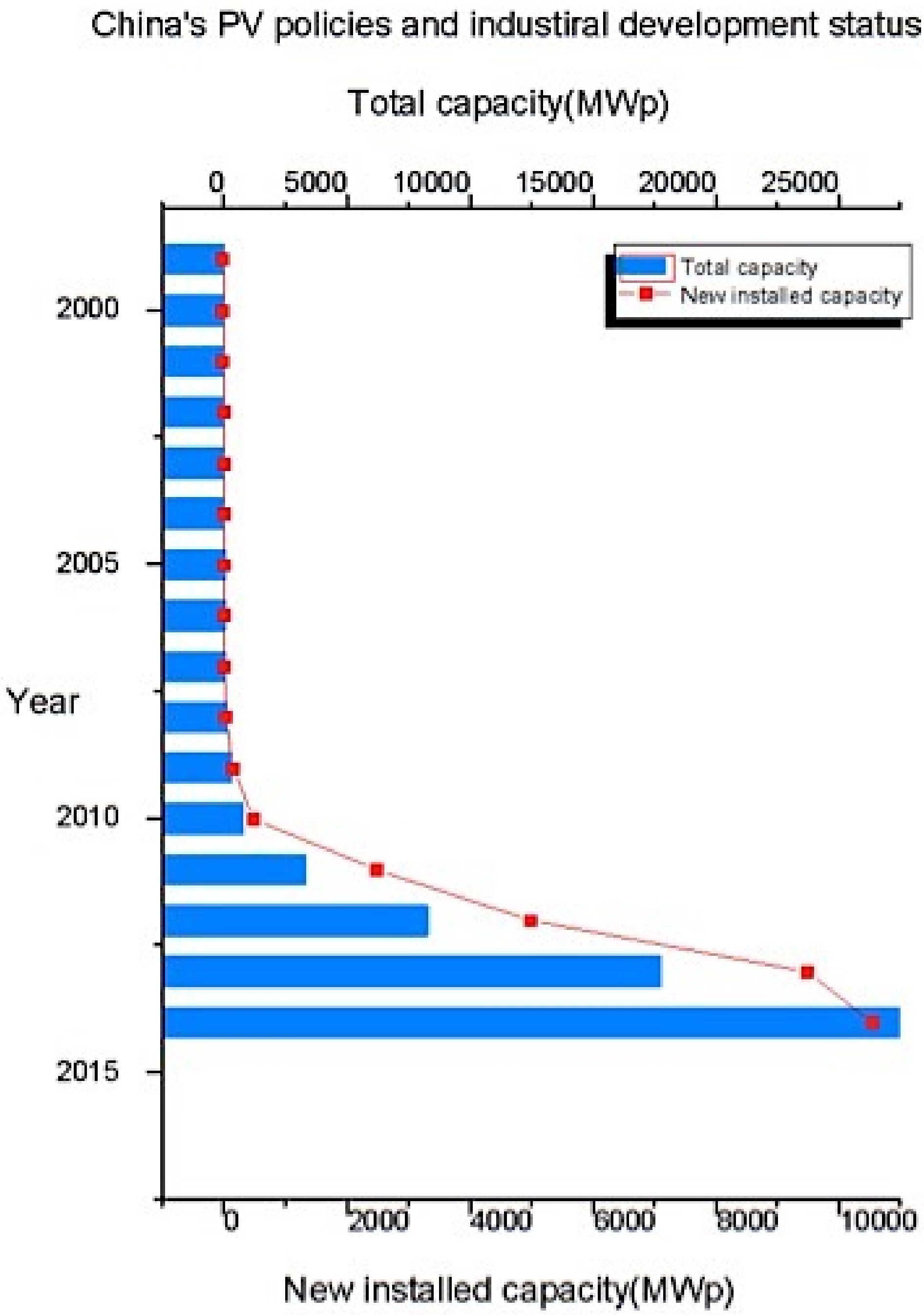


Fig.6.3 PV incentive policies and development trends in Mainland China

The fast progress of the solar PV application, especially the short payback period after being subsidized, greatly stimulated people's motivation to install solar PV systems. For the sake of promoting the healthy and rapid development of the solar PV industry, although the Chinese government gradually reduced subsidies for the Golden sun and solar roof programs, new incentive measures known as solar PV electricity grants (PVEG) were implemented that granted the power generated by distributed PV systems with 0.42 RMB/kWh and provided feed-in tariffs for ground-based PV systems (called the benchmark price) that differed in terms of regional solar energy resource distribution in China [178], as presented in Fig. 6.4. The feed-in tariff rate is 0.9 RMB/kWh for zone I, which has the most abundant solar energy resources; 0.95 RMB/kWh for zone II, which is slightly less abundant than zone I; and 1 RMB/kWh for zones III and VI with relatively poorer solar irradiance.

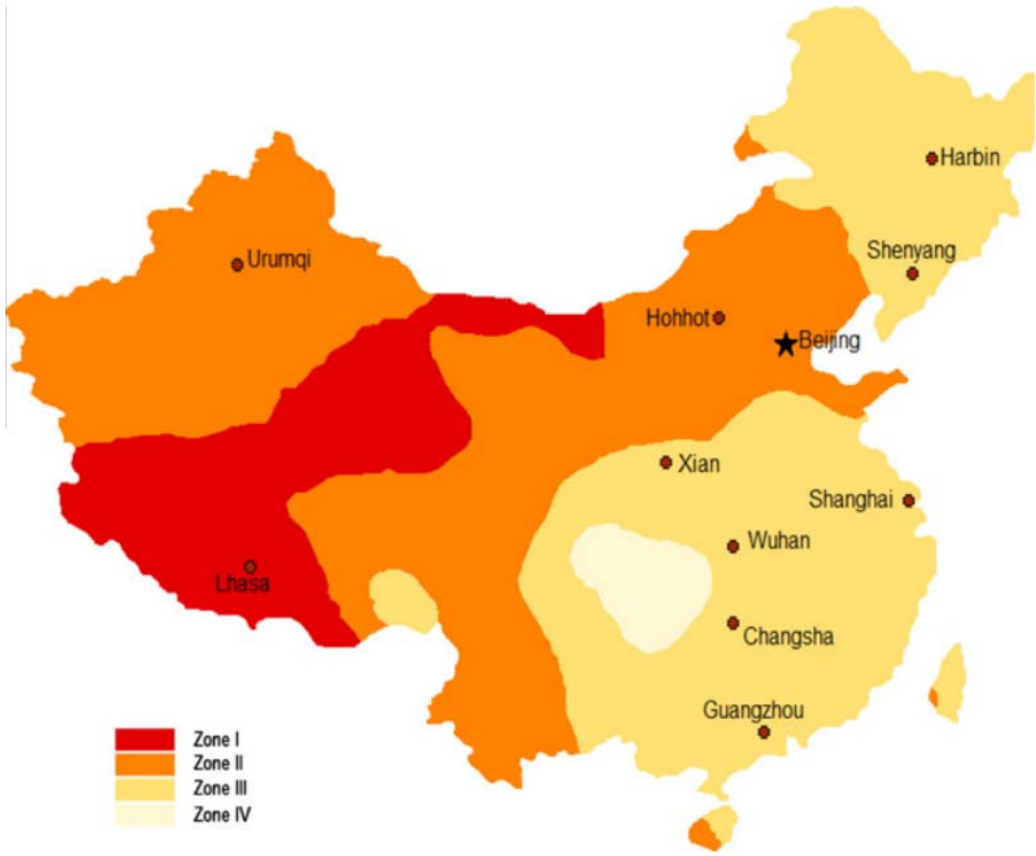


Fig.6.4 Solar energy resource distribution in China

6.2.5 PV Incentive Policies in the USA

The USA has abundant solar energy resources and its PV application ought to be far more developed than that in Europe and Japan. However, due to the lack of sufficient policy supports, the overall maturity of the American PV industry is less advanced than that in Europe and Japan [179]. However, with the increasing scarcity of global energy, the U.S. government had paid much more attention to renewable energy and stepped up efforts to promote the PV industry in recent years.

The first incentive subsidy to renewable energy appeared as early as 1978 in the Public Utility Regulatory Policies Act, which mandated the price standard for electricity sourced from renewable energy in accordance with the avoided cost of fossil fuel. In 1992, the U.S. government passed the U.S. Energy Policy Act, which laid claim to the proportion of renewable energy in electricity demand and allowed renewable energy access to the grid. Furthermore, the new policy was also an offer to subsidize solar PV projects with tax credits.

In the year 2005, the government updated the U.S. Energy Policy Act to set detailed rules for the proportion of renewable energy in electricity demand, should reach 7.5% by 2010. Moreover, the policy also urged governmental buildings to take the lead in using renewable electricity. In addition, the category of items for tax credits extended to investment tax and solar PV equipment and products. Subsequently, the U.S. government formulated the Renewable Energy Incentive Plan, which provided preferential policies on investment and financing for solar PV policies in 2008. This plan included $6 billion to support bank loans and loan guarantees for the PV industry and subsidized PV projects that had been constructed before 2010; and $0.8 billion of energy-saving bonds to support R&D of solar PV technology. At the same time, many states also introduced local renewable energy policies to support the PV industry, such as states' tax credits, high purchasing price to surplus solar electricity, etc. With the development of PV technology, the U.S. government started focusing on promoting the application of BIPV. The 10 million Solar Roofs Program was launched in 2010. Since 2012, the U.S. government has invested $250 million in the construction of solar power rooftops and enlarged the budget on an annual basis, aiming to reach 100 GWp by 2021. From Fig 6.5, it is clear that the incentive policies launched by the U.S. government had worked, and the solar PV application achieved explosive development since 2008. The newly installed capacity increased by nearly 20 times in just six years, making the total installation capacity almost 20 GWp.

In 2008, a global financial crisis hit the U.S. economy hard and caused huge losses. In order to stimulate economic resurgence and create more jobs, the U.S. government enhanced the supports to renewable energy, especially for the solar PV industry, which was known as the Obama Renewable Energy Policy. This policy carved out more in the budget for subsidizing PV industry on the basis of the original support, which aimed at 10% of electricity supply sourced from renewable energy in 2012; this proportion would rise to 25% in 2025.

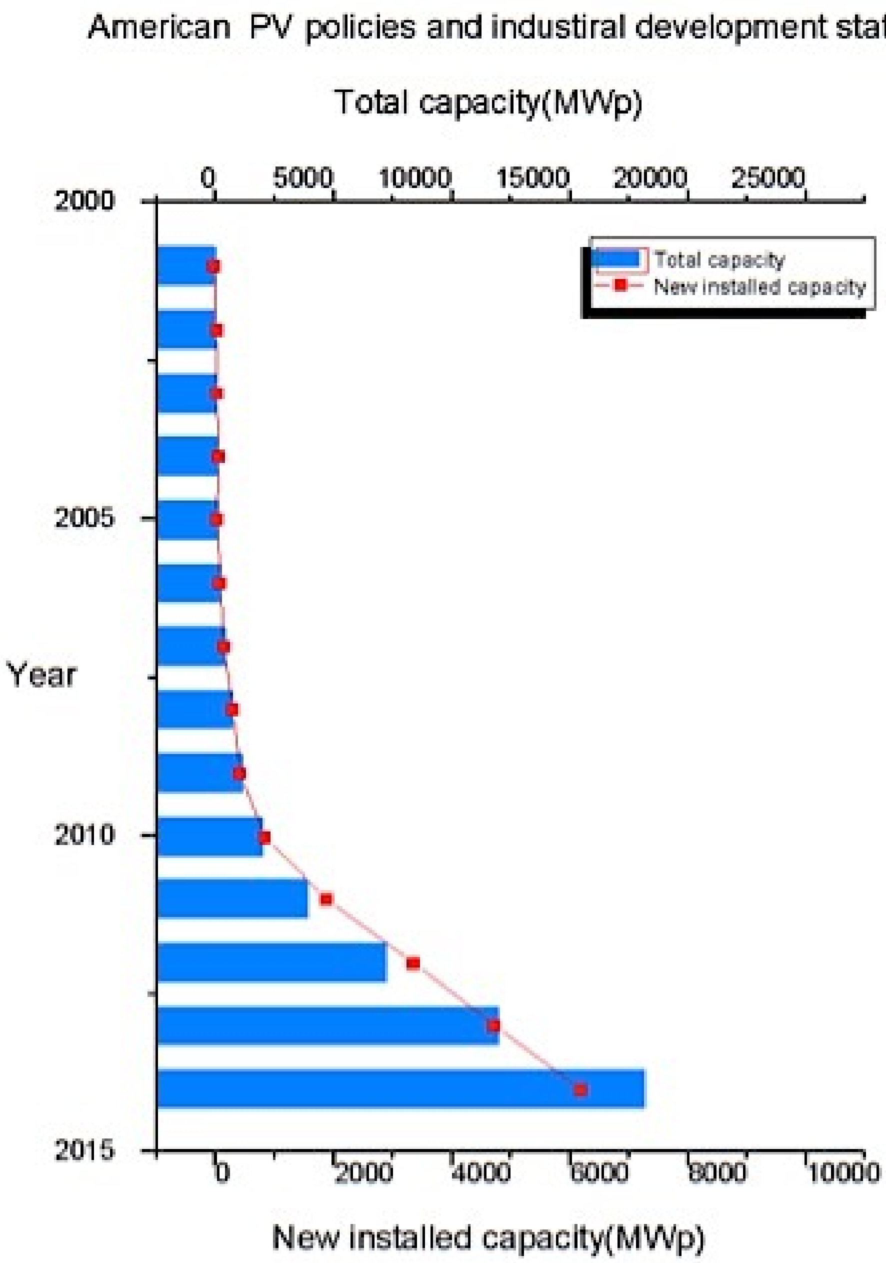


Fig.6.5 PV incentive policies and development trends in the United States

6.3 Lessons Learned from Leading Countries

Following a review of the incentive policy instruments in five leading countries, Germany, Italy, Japan, Mainland China, and the United States, there are lessons we can learn from, which refer to all solar PV systems, not just to BIPV. It is found that their incentive policies could be classified into two main categories.

1. Focusing on helping investors to reduce the investment threshold, for instance, by introducing laws to encourage and formalize the application of solar PV electricity, or subsidizing solar PV installations to reduce initial capital inputs and to reduce the financial costs.
2. Focusing on improving the solar PV investment return, such as a feed-in tariff (FiT), which means that purchasing the PV electricity at a higher price than the domestic tariff is preferred with high priority. This has been the most widely implemented PV electricity incentive in recent years. This kind of incentive encourages the public to transmit all the PV electricity generated to the utility grid. As the return on electricity sales is relatively stable, people are keen on investing in large-scale ground-mounted PV power plants. In addition, PV electricity grant (PVEG), which is more specifically to encourage the distributed PV installation (for example, building-integrated photovoltaics), is another effective incentive measure. PVEG aims to encourage PV electricity used on the spot and the surplus electricity is transmitted to the utility grid. On the one hand, using the electricity generated by PV systems can cut electricity bills; on the other hand, the additional subsidy granted with the use of PV electricity enhances the return rate to investors. Detailed classification of the incentive policies is presented in Tables 6.1 and 6.2.

The effects of each tool are described in more details below.

1. First, the law, though necessary, is the weakest tool because it does not directly create investment but gives investors and householders a “guide” or “roadmap” to take action, which means they will build solar PV systems in the specific technology forms and management mode that the government thought would be beneficial in the long term rather than investment myopia.
2. Secondly, the investment program carried out by the government or company is the strongest tool in the box. This can be proved by the fast increase in capacity after a

program is carried out, such as the annual installed capacity increasing more than three-fold after the start of the Gold sun and 10 million roofs projects in the US in 2009. However, this kind of tool has a limitation when extended to residential PV systems, because the householder or building owner must be persuaded to install the device on the outside of their building even though this product will not affect the appearance of the building.

3. Thirdly, financing measures are only an auxiliary tool to help development. They will be powerful during a period of expansion in an investment program since they will generate a multiplier effect on investment. In addition, a feed-in tariff is another boost to investment programs. These measures will lighten the capital burden on government, in turn releasing more civilian capital to invest in the PV system, which is more suitable for "small government." It crosses economic barriers in a more free-market way. The last tool in the box is PVEG, which is similar to the feed-in tariff above. With the joint efforts of these leading countries in recent years, the hard cost of PV installations has already been dramatically reduced. Therefore, PV technology has become a significant and widely accepted source of renewable energy. Expensive initial investment for installation was no longer a major issue for many countries. In order to quickly promote PV application, governmental supports to increase investment return (for example, Fit and PVEG) have gradually replaced the subsidies of reducing investment capital input to become the mainstream of incentive policies.

Table 6.1 Classification of different solar PV subsidies policies

Investment Support		
Law:	Installation:	Financing:
(1) Feed-in act	(1) Solar roof program	(1) Low interest loan
(2) Guideline for grid connection	(2) National subsidy program	(2) Public guarantee
(3) Renewable portfolio standard	(3) Gold Sun program	(3) Tax abatement
(4) Renewable energy law		
Return Support		
Feed-in tariff:	PV electricity grant:	
(1) Feed-in tariff of EEG law	(1) China's PV electricity grant	
(2) Benchmark price		
(3) Net billing program		
(4) "Conto Energia"		

Table 6.2 The major PV incentive policies implemented by PV leading countries

	Germany	Italy	Japan	Mainland China	USA

1991	➢ Electricity Feed-in Art ➢ 1000 Solar Roofs Program				
1992			➢ Net Billing Program		
1993			➢ Guideline For Grid-connection		
1994			➢ National Subsidy For Residential		
1999	➢ 100000 Solar Roofs Program				
2000					
2001		➢ Photovoltaic roofs			
2003			➢ Renewable Protfolio Standrad		
2004	➢ Feed-in Tariff of EEG law				
2005		➢ 1st "Conto Energia"		➢ Renewable Energy Law	➢ The U.S. Energy Policy Act
2007		➢ 2nd "Conto Energia"			
2008				➢	➢ Renewable Energy Incentive Plan
2009			➢ National Subsidy Program ➢ Feed-in Tariff	➢ Solar Roofs Program ➢ Golden Sun Program	➢ Obama Renewable Energy Policy
2010		➢ 3rd "Conto Energia"			➢ 10 Million Solar Roofs Program
2011		➢ 4th "Conto Energia"			
2012		➢ 5th "Conto Energia"			
2013				➢ Benchmark price (China's Feed-in tariff) ➢ PV Electricity Grant	

6.4 Discussion of the Hong Kong Case

6.4.1 Technology Choice for HK

Hong Kong is a high-density city whose area reaches 1105 km^2 and has more than 7.3 million residents. However, Hong Kong has limited land for installing large-scale solar plants. Thus, Building integrated Photovoltaic (BIPV) systems, small-scale PV systems that can be installed on vertical building façades or rooftops, are suggested in cities such as Hong Kong.

Building Integrated Photovoltaics (BIPV) is almost maintenance-free and can be integrated with outside of buildings, such as roofs, facades, curtain walls, skylights, etc. The building rooftop PV system is the most typical technology of BIPV. Based on the previous study, this kind of system has the potential to generate more than 14% of electricity mix with currently available technology and no extra land requirements in Hong Kong.

6.4.2 Possible Initiatives for Hong Kong

Use of solar PV is a new policy issue in Hong Kong, but the technologies clearly have the ability to reach such a set of objectives. Two potential legal measures to promote development in Hong Kong are suggested: opening the service and labor market to Mainland China, and providing more educational and training resources to workers or engineers.

These points are based on the goal of decreasing the cost of PV system installation. In recent years, global PV markets have been making fast progress toward competitiveness. PV prices decreased and the rise in electricity prices helped to drive momentum toward “dynamic grid parity”, which means that the savings in electricity cost and/or the revenues generated by selling PV electricity on the market are equal to or higher than the long-term cost of installing and financing PV systems. Deutsche Bank's report revealed that solar PV electricity was currently competitive without subsidies in at least 19 markets globally and it expects more markets to reach grid parity in 2015 as solar system prices decline further. Fig. 6.6 clearly demonstrates the declining trend of installation costs worldwide. Hence, if the Hong Kong government introduces appropriate incentive policies, the PV electricity could fully compete with other traditional electricity in Hong Kong by reducing PV installation costs in the near future so as to easily achieve their renewable energy target in 2020.

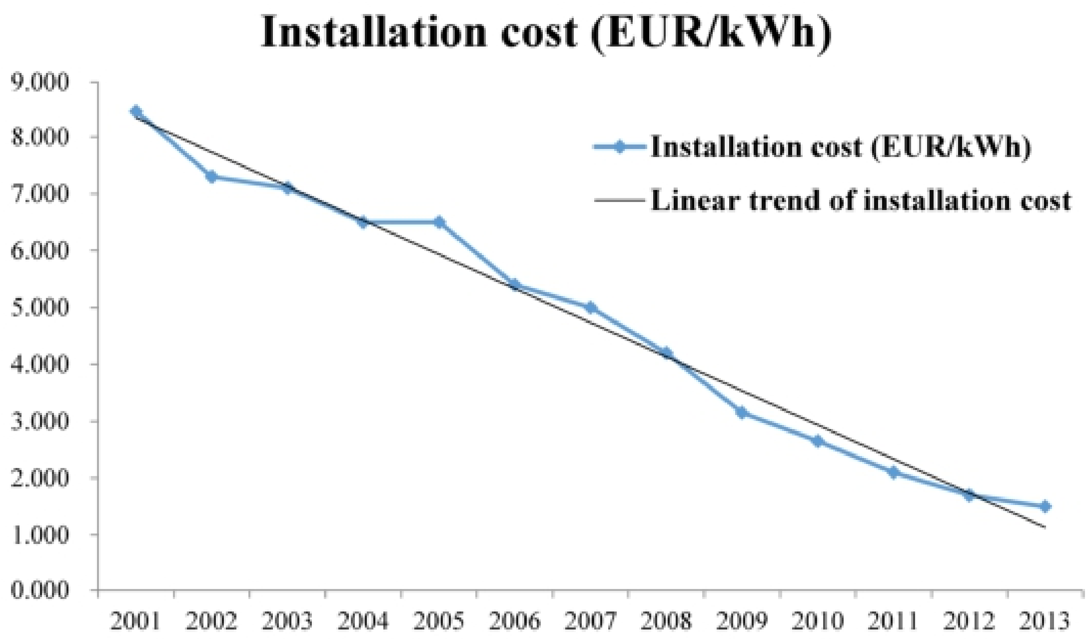


Fig.6.6 Declining trend of PV installation labor cost

Installation cost support incentives, also formularized in investment subsidy, are discussed in this section. This subsidy can be designed to cover a certain percentage of the construction cost or a fixed amount per kWp. The advantage of this measure is the low administrative expense. The disadvantage is that it is hard to control the quality of the installed PV power plant.

Thinking optimistically, a target of 400 MW/year for five years' annual installation is assumed in order to meet the requirement of renewable energy accounting for 3%–4% of total electricity end use by 2020 in Hong Kong, which will be about 1485 to 1980 GWh. The annual power generation per unit is estimated based on a SAM model [180] including a 23 deg tilt south-facing rooftop PV with 15.9% efficiency, which is traditional in the market under Hong Kong's climate and irradiation conditions. An annual degradation of performance is assumed to be 1%, so that the total power generation during a lifetime of 20 years can be estimated. Meantime, the initial unit investment is evaluated from the market price and hypothesized to decrease by 5% each year. At last, the levelized cost of electricity without any subsidy is estimated. The result is shown in the Table 6.3 below.

It can be seen from the results that the LCOE is nearly twice the price of electricity, which is unacceptable for investors. A low level of 20% versus a high level of 60%, and a fixed investment subsidy value of 4 HKD/Wp, which is similar to that in Mainland China, are assumed to be supplied by the government. The results can be found in Table 6.4 below.

Table 6.3 Installation and investment estimated from 2016 to 2020

	2016	2017	2018	2019	2020
Annual new installed capacity (MWp)	400.0	400.0	400.0	400.0	400.0
Accumulated installation capacity (MWp)	400.0	800.0	1200.0	1600.0	2000.0
Estimated annual PV power generation (MWh)	345.2	690.4	1035.6	1380.8	1726.0
Estimated total power generated during lifetime (MWh) of annual installation (GWh)	6285.85	6285.85	6285.85	6285.85	6285.85
Unit investment (HKD/Wp)	23.64	22.46	21.34	20.27	19.26
LOCE (HKD/kWh)	1.50	1.42	1.35	1.29	1.23

Table 6.4 Government subsidies and investments, estimated from 2016 to 2020

Year	2016	2017	2018	2019	2020
Government subsidy in 20% case (Billion HKD)	1.89	1.79	1.70	1.62	1.54
Real investment in 20% case (Billion HKD)	7.56	7.18	6.82	6.48	6.16
LOCE of 20% case (HKD/kWh)	1.20	1.14	1.09	1.03	0.95
Government subsidy in 60% case (Billion HKD)	5.67	5.39	5.12	4.86	4.62
Real investment in 60% case (Billion HKD)	3.78	3.59	3.41	3.24	3.08
LOCE of 60% case (HKD/kWh)	0.60	0.57	0.54	0.52	0.49
Government subsidy in fixed 4 HKD case (Billion HKD)	1.60	1.60	1.60	1.60	1.60
Real investment in fixed 4 HKD case (Billion HKD)	7.86	7.38	6.94	6.51	6.10
LOCE of fixed 4 HKD case (HKD/kWh)	1.25	1.17	1.10	1.04	0.97

As a result, the government total budget is about 8.54, 25.62, and 8.00 billion HKD for low-level, high-level, and fixed level subsidies, respectively. Considering the electricity price for commercial residential is about 0.987 HKD/kWh [181], the LCOE of the 20% case and the fixed value of 4 HKD/kWh will be below the retail price after 2020, which means that solar PV will be economical enough and need no subsidy in competition with other energy sources.

According to the high initial capital investment of PV, it is often a liability. Therefore, the interest rate is the key parameter influencing the investor payback in this kind of long-term return project. If the government can give supports by publishing "Green Bonds", it will decrease the interest rate. In addition, tax benefits are suggested in the case of a PV system installed in conjunction with the purchase or construction of a private home. Moreover, steps should be taken to effectively attract private capital and foreign investment (especially PV suppliers or investors from Mainland China) to develop rooftop PV power plants in Hong Kong by energy management contract (EMC).

A feed-in tariff (FiT), or electricity grant, is an energy supply policy that will offer long-term purchase agreements for the sale of electricity in order to support the development of new renewable energy projects. The core of FiT policy design is determining the payment structure. The suggested payment methodology is based on the actual levelized cost of electric (LCOE) of RE, which means that FiT will cover the gap above the average electricity market price for 20 years. Under the scenario of the electricity retail price remaining at this level for the entire period, the total cost of the FiT plan can be indicated in Table 6.5. This can provide a reference for local feed-in-tariff.

The 0.64 billion HKD cost of FiT will last until 2036 then decrease to 0.17 billion HKD by 2040. Therefore, the total cost of this program will be 12.71 billion HKD.

Table 6.5 Government FiT costs estimated from 2016 to 2020

	2016	2017	2018	2019	2020
Annual new installation capacity (MWp)	400.0	400.0	400.0	400.0	400.0
Accumulated installation capacity (MWp)	400.0	800.0	1200.0	1600.0	2000.0
Estimated annual PV power generation (MWh)	345.2	690.4	1035.6	1380.8	1726.0
Estimated electricity generated during lifetime (MWh) 20 year with 1% degradation per year	6285.85	6285.85	6285.85	6285.85	6285.85
Unit Investment (HKD/Wp)	23.64	22.46	21.34	20.27	19.26
LCOE (HKD/kWh)	1.50	1.42	1.35	1.29	1.22
FiT (HKD/kWh)	0.51	0.44	0.37	0.30	0.23
Total FiT cost to government (Billion HKD)	0.17	0.33	0.45	0.56	0.64

6.4.3 Discussion

We learn from the energy policies of PV leading countries that, although PV investment subsidy requires the least outlay, if investment grants could be subsidized, which is a sort of one-time subsidy, actual electricity generation may become an issue. Therefore, investment subsidies have rarely been implemented in recent years. Instead, providing PV with money return supports became the default.

From the cost-effectiveness point of view, we propose a subsidy for PV development with an electricity grant. It is more suitable for Hong Kong than feed-in tariffs and other forms of investment subsidy because the related legal provisions for solar energy application in Hong Kong are still inadequate. It is difficult for major local utility companies to provide convenient grid-connection services, which is one of the most significant defects that limit the implementation of a feed-in tariff. Moreover, Hong Kong has scarce land resources, which makes it only suitable for small-scale distributed PV systems. Thus, it is especially important to stimulate investors to responsibly operate and maintain their PV systems, and to ensure that each unit of PV electricity generated will contribute to their initiative.

6.5 Summary

In this chapter, the energy policies for five countries leading in solar PV application were studied. Their histories of solar PV system development and application were reviewed and analyzed. Their initiatives towards the popularizing and prosperity of PV application were collected and summarized.

Accordingly, this study proposed a strategy for the incentivizing of BIPV application for Hong Kong PV application. The strategy aims to increase the competitive strength of the PV application, trying to help the relatively frail PV industry survive in the relatively intense free market, and eventually grow up to be a promising local energy solution in the near future.

From the lessons learned from the five forerunners, a series of subsidy policies and incentives were drawn up to help the local PV industry survive through the early pioneering stage. It was hoped that the results could serve as a reference for future policy making. The major findings are listed as follows:

1. The BIPV system, which requires little extra installation and land, is a promising way of relieving the increasing financial and environmental costs of fossil fuel energy generation.
2. Due to the relatively high initial investment and service costs, it is still difficult for PV technology to compete against fossil fuels in Hong Kong's local energy market of. The government should release subsidy and sustain policies to help the PV industry grow.
3. The service and labor market should be opened up to providers abroad to reduce the price. Measures must be taken to further improve the efficiency of practitioners so that the soft costs could also be cut.
4. Subsidy of PV development with PV electricity grants should be implemented to support the PV business.

CHAPTER 7 COST PERFORMANCE OF DIFFERENT TYPES OF SOLAR COOLING SYSTEMS

Besides the solar PV technologies for power generation, the air-conditioning cooling systems for local buildings consume large energy consumption. Therefore, this chapter aims to newly examine the feasibility of other solar driven cooling technologies in Hong Kong.

7.1 Description of the examined cooling system

Cooling system gets a growing market in buildings worldwide, with a particularly significant growth rate observed in commercial buildings. Solar driven cooling system can be a promising alternative to traditional electrical vapor-compression cooling system. It can be used in the combination with solar thermal collectors or photovoltaic collectors to release the duty caused by electrical cooling system. In this study, the performance of three different solar cooling systems is examined, namely: 1) a solar electrical, 2) a solar thermal and 3) a traditional electrical cooling system. The first system employs the solar photovoltaic modules to drive a conventional electrical chiller. The second system uses the solar thermal collectors to drive a heat driven adsorption chiller and the third one utilizes the grid power to feed the electrical chiller. Assessment of life-cycle costs of these three systems is conducted to verify the best option for buildings. A case study in Hong Kong is conducted to assess the three cooling systems.

In this section, assessment of life cycle costs of the solar electrical cooling system, solar thermal cooling system and traditional cooling system are conducted to verify that which is the best option for buildings. TRNSYS building energy model is used to calculate the operation cost of these three cooling systems.

Fig.7.1 shows a conceptual solar thermal cooling system. It includes four parts, i.e. solar thermal collector, storage tank, adsorption chiller and building user. Solar thermal collectors are employed to collect the solar energy and then convert the solar energy into heat. The storage tank, considered as heat transfer medium, receives the heat collected from solar thermal collectors. Adsorption chiller, which is powered by heat, supplies the cooling to the building user. A detailed and comprehensive description of adsorption chiller's operation principle can be found in [181-183].

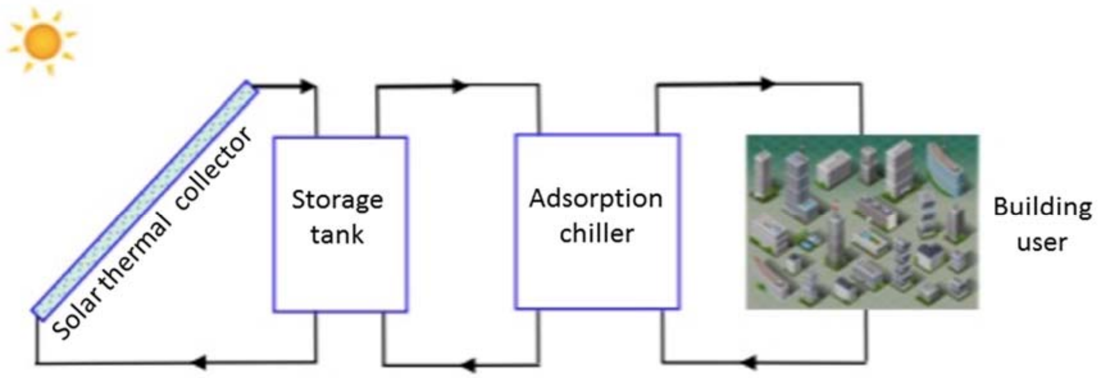


Fig. 7.1 Solar thermal cooling system

Fig.7.2 shows a conceptual solar electrical cooling system. It consists of four main parts, i.e. solar photovoltaic modules, inverter, electrical chiller and building user. The photovoltaic modules are used to collect the solar energy and then convert it into electrical energy. The electricity produced in the PV module is in the type of DC, so the inverter is employed to convert it into AC power which is used to drive the electrical chiller. Then, the chiller supplies the cooling to the building user.

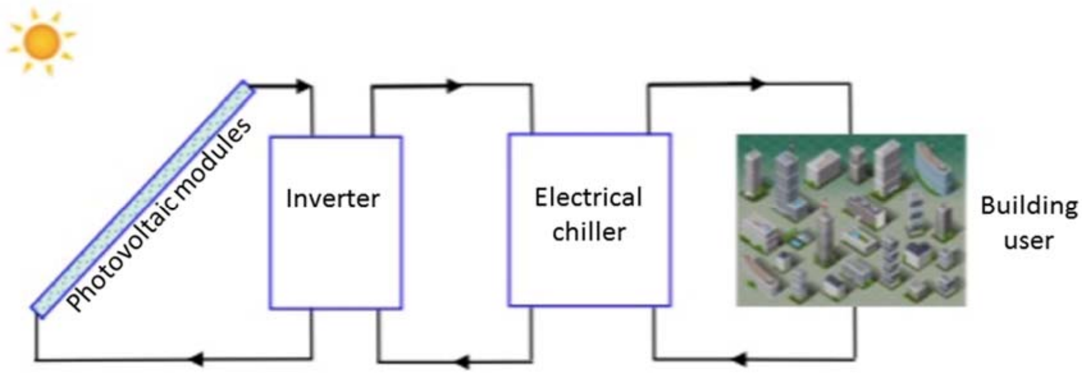


Fig. 7.2 Solar electrical cooling systems

7.2 Model of the examined cooling system

The TRNSYS software is used to model and simulate the hourly cooling load of building based on the typical meteorological (TMY) weather data of Hong Kong. The building energy model could also simulate energy consumption and temperature variations of the system. In this study, the daily working hour of HVAC system is from 8:00am to 18:00pm and the cooling season is from March to November. From December to February, the free cooling is used to supply the cooling to fulfill the thermal comfort.

The solar thermal collection can be computed by Equation (7.1) [185]. In the equation, W_{sc} is the power of solar thermal collector which could be calculated by Equation (7.2), A_a is the total aperture area of solar thermal collector, η_{sc} is the solar-thermal conversion efficiency, I is the hourly irradiance (kWh/m^2), CL_{peak} is the cooling capacity of adsorption chiller, COP_{ad} is the COP of adsorption chiller. The needed aperture area of solar thermal collector can be calculated by Equation (7.3).

$$W_{sc} = A_a \times \eta_{sc} \times I \tag{7.1}$$

$$W_{sc} = \frac{CL_{peak}}{COP_{ad}} \tag{7.2}$$

$$A_a = \frac{CL_{peak}}{COP_{ad} \times \eta_{sc} \times I} \tag{7.3}$$

Based on the annual cooling load distribution, the cooling capacity of adsorption chiller can be determined. Then, the aperture area of solar thermal collector can be obtained according to the cooling capacity of adsorption chiller. The life cycle of the solar thermal collector and adsorption chiller is assumed to be 20 years. The annualized total cost of solar thermal system TC_{st} contains the annualized capital costs of solar thermal collector, storage tank and adsorption chiller and the annual operation cost when the solar thermal collector cannot supply enough heat to adsorption chiller, as shown in Equation (7.4). CC_{stc} is the annualized capital cost of solar thermal collector, CC_{st} is the annualized capital cost of storage tank, CC_{ac} is the annualized capital cost of adsorption chiller, and OC_{ac} is the operation cost of adsorption chiller. The operation cost of adsorption chiller can be calculated by Equation (7.5). Where, CL_i is the hourly cooling load, $W_{sc,i}$ is the hourly power of solar thermal collector.

$$TC_{st} = CC_{stc} + CC_{st} + CC_{ac} + OC_{ac} \tag{7.4}$$

$$OC_{ac} = \sum_{i=1}^{8760} \frac{CL_i}{COP_{ad}} \bullet \max\left(\frac{CL_i - W_{sc,i} \bullet COP_{ad}}{\left| CL_i - W_{sc,i} \bullet COP_{ad} \right|}, 0 \right) \tag{7.5}$$

l) The photovoltaic module power generation can be computed by Equation (7.6). In the equation, A_{pv} is the total area of photovoltaic module (m^2), η_{pv} is the photovoltaic module efficiency, η_{pc} is the power conditioning efficiency, I is the hourly irradiance (kWh/m^2). The total area of photovoltaic module can be calculated by Equation (7.7). COP_{elec} is the COP of electrical chiller.

$$W_{pv} = A_{pv} \times \eta_{pv} \times \eta_{pc} \times I \tag{7.6}$$

$$A_{pv} = \frac{CL_{peak}}{COP_{elec} \cdot \eta_{pv} \cdot \eta_{pc} \cdot I} \tag{7.7}$$

Usually, the COP strongly depends on the operating Part Load Ratio (PLR). Once the other operating parameters such as condensing and evaporating temperatures are maintained at a constant level, the COP is higher when the chillers operate at a larger PLR, as shown in Equation (7.8). Where, D_0-D_3 is the coefficients that can be identified from chiller catalog or field measurement data. The number and size of operating chillers usually determine the PLR. It is simply defined as the ratio of the required cooling load (CL_{re}) to the available cooling capacity (CL_{ava}) (i.e., that of operating chillers) as shown in Equation (7.9).

$$COP_i = D_0 + D_1 + PLR_i + D_2 \cdot PLR_i^2 + D_3 \cdot PLR_i^3 \tag{7.8}$$

$$PLR = \frac{CL_{re}}{CL_{ava}} \tag{7.9}$$

Based on the annual cooling load distribution, the cooling capacity of electrical chiller can be determined and then the total area of photovoltaic module can be obtained. In fact, the peak-cooling load only accounts for a very small proportion of the entire cooling season. Therefore, when the actual cooling load is less than the cooling capacity of electrical chiller, the surplus power generated by the photovoltaic module will be supplied to the power grid. The annualized total cost of solar electrical cooling system TC_{se}

contains the annualized capital cost of photovoltaic module CC_{pv}, inverter CC_{in} and electrical chiller CC_{ch}, the cost of surplus power generated CS_{pv} and the annual operation cost of electrical chiller OC_{ec} when the photovoltaic module cannot supply enough power to electrical chiller, as shown in Equation (7.10).

$$TC_{se} = CC_{pv} + CC_{in} + CC_{ch} + CS_{pv} + OC_{ec} \tag{7.10}$$

The cost of surplus power sold to the power grid can be represented by Equation (7.11), where, $P_{pv,i}$ is the hourly power generated by photovoltaic module, $P_{ch,i}$ is the r enquired hourly power consumed by electrical chiller, C_{gp} is the electrical price sold to the grid. The operation cost of electrical chiller can be calculated by Equation (7.12), where, CL_i is the hourly cooling load of building, COP_i is the hourly COP of electrical chiller.

$$CS_{pv} = \begin{cases} \sum_{i=1}^{8760} C_{gp} \cdot P_{ch,i} \\ \sum_{i=1}^{8760} C_{gp} \cdot \left(P_{pv,i} - \mathrm{P}_{re,i}\right) \end{cases} \tag{7.11}$$

$$OC_{ec} = \begin{cases} \sum_{i=1}^{8760} \frac{CL_i}{COP_i} \\ 0 \end{cases} \tag{7.12}$$

For the traditional electrical cooling system, the total life-cycle cost contains the capital cost of electrical chiller and operation cost, as shown in Equation (7.13). Where, TC_{te} is the total cost of traditional electrical cooling system, CC_{ec} is the capital cost of electrical chiller; and OC_{ec} is the operation cost of electrical chiller. The operation cost of electrical chiller is related to the cooling load and COP, as shown in Equation (7.14). Where, CL_i is the hourly cooling load, COP is the hourly COP of electrical chiller.

$$TC_{te} = CC_{ec} + OC_{ec} \tag{7.13}$$

$$OC_{ec} = \sum_{i=1}^{8760} \frac{CL_i}{COP_i} \tag{7.14}$$

7.3 Case study

Firstly, a case study of an office building was conducted to simulate the performance of photovoltaic air-conditioner (PVAC) in Hong Kong. The simulation model of the PV air-conditioner is constructed using TRNSYS, and the simulation period is 1 y with 1 h steps. The input includes the meteorological data of Hong Kong, air-conditioner operating times of this office building. The output of the simulation model includes the temperature distribution and power profiles influenced by weather conditions. The details of the three main basic modules, namely, the building load, air-conditioner, and PV system are introduced as follows:

The first part is about building module. In this case, the meteorological data of various cities are derived from Meteonorm. The selecting building surface area and building volume are 100 m^2 and 200 m^3, respectively. The building loss coefficient is 5 $kJ/hr.m^2.K$ and the building capacitance is 1000 kJ/K. Plus, the specific heat of building area is 1.007 kJ/Kg.K while the density of building air is 1.2 kg/m^3. Single-zone building model (Type 88) of TRNSYS is implemented for the building simulation.

The second one is HVPC system. PV-powered air-conditioners (AC) are available in the market. These air-conditioners incorporate inner electric converter modules and can be impelled by both PV electricity and grid electricity. For this study, an electric-impelled air-source heat pump (ASHP) is selected as the central air-conditioner system for space heating and cooling. Due to its hot summer and warm winter climate, there is only a cooling demand in Hong Kong. Split system heat pump model (Type 665-8) of TRNSYS is implemented in this case and the total air flow rate is presumed as 300 L/s.

The final key module is about PV system, which is applied as the renewable energy supplier. The system comprises four PV panels connected in parallel and each panel is 1.5 m^2. Then the capacity of selected PV panel is 800W/m^2. PV model for silicon cell (Type 180c) was used to simulate a PV system with MPPT (maximum power point tracking) function. The orientation of the PV panels is due south and the tilted angles of 23° according to the result in Section 3.3.2.

The simulation results are shown as followed. Fig. 7.3 presents the temperature distribution of the whole year. The ambient temperature is derived from Meteonorm while the building temperature is descended with the benefit of HVPC system implemented in this case. Obviously, the refrigeration effect is greatly decreased the high temperature from March to November.

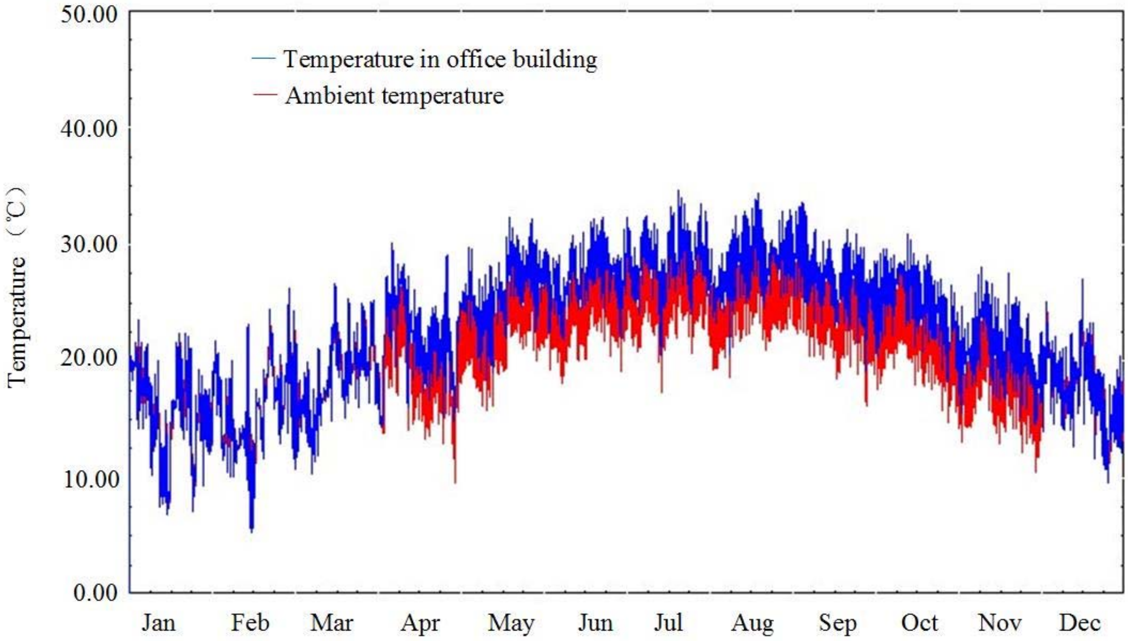


Fig. 7.3 The comparison between ambient temperature and building temperature

The output performance is described in Fig 7.4 and 7.5. The former figure records the total power of PV system of the whole year while the later one compares the average power output by the AC system and PV system during the working hours. It is clear that September and October are the best two months for PVAC system. The power performance of PV system is about 270W/h in this period which accounts more than a half of the total power supplied to AC system.

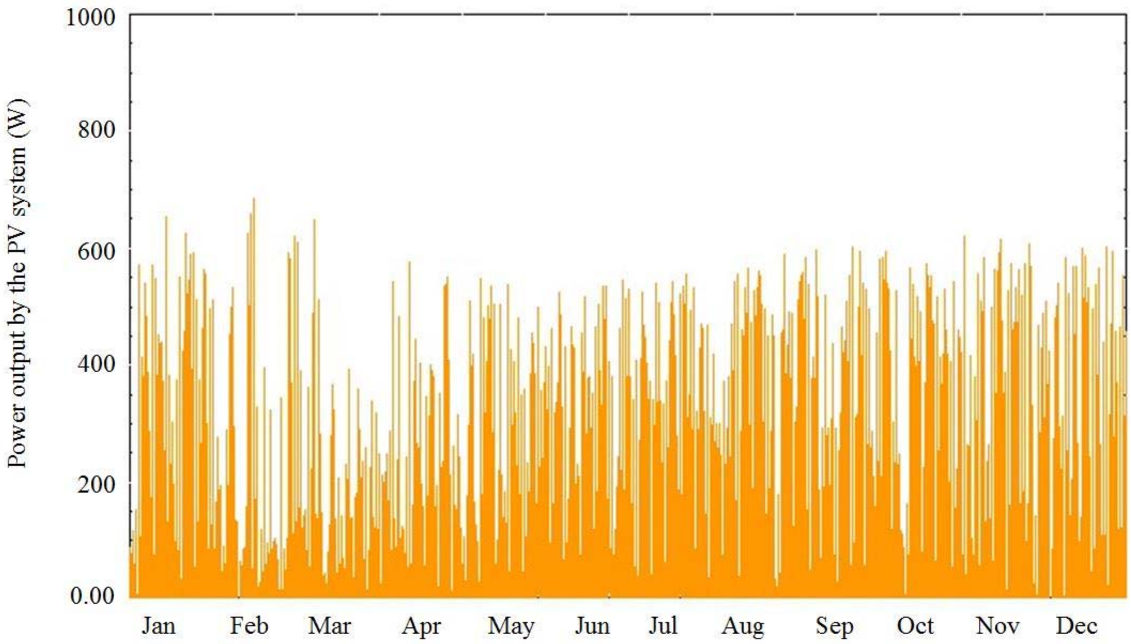


Fig. 7.4 Power output by PV systems

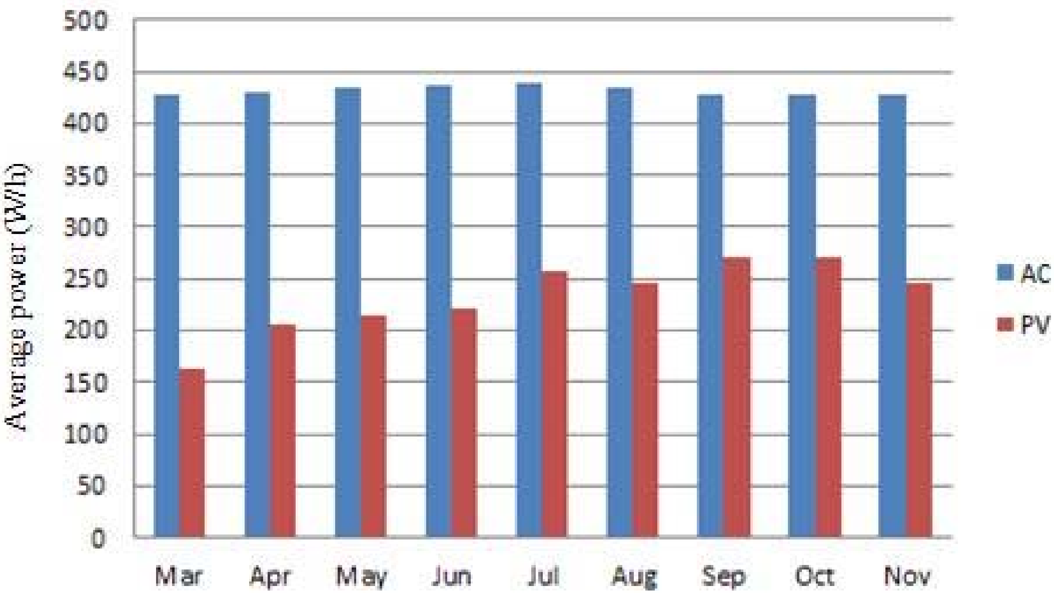


Fig. 7.5 The comparison of power output between PV system and AC system

Then, in order to assess the three cooling systems mentioned in Section 7.1, a case study of a building in Hong Kong is conducted to implement and assess the three cooling systems. The building energy model is used to calculate the annual cooling load and thus the required area of solar thermal collector and photovoltaic module can be determined.

Then, based on the cooling load distribution in July and the whole year, the total costs of the three cooling systems can be obtained. Finally, comparison among the three cooling systems is conducted to select the optimum cooling system which has the least total life-cycle cost.

The required areas of solar thermal collector and photovoltaic module should be determined in advance. As mentioned above, the cooling capacity of adsorption chiller and electrical chiller is assumed to be 1000kW. According to Equation 7.3 and 7.7, the required areas of solar thermal collector and photovoltaic module are 4800m2 and 5300m2 respectively (i.e., rated COPs of adsorption chiller and electrical chiller are assumed to be 1.1 and 5 respectively).

Annualized capital cost plays an important role in the assessment of cooling systems. The lifespan of the three cooling systems is assumed to be 15 years. Capital costs of adsorption chiller and electrical chiller are 0.83 MHKD and 1 MHKD respectively, referring to the data from a manufacture. For the solar thermal collector and photovoltaic module, the prices are 1600HKD/m^2 and 800HKD/m^2 respectively. The prices of storage tank and inverter are 150,000HKD and 50,000HKD respectively. Considering the above prices, the annualized capital costs of solar thermal cooling system, solar electrical cooling system and traditional cooling system are 722,000HKD, 440,000HKD and 84,000HKD respectively. Besides, the electricity price used in this study is 1 HKD/kW (note: 1 USD=7.75 HKD), which is the typical rate in Hong Kong. And the electrical price sold to the grid is assumed to be 0.8HKD/kW.

Take July as an example to assess the three cooling systems. Fig. 7.6 shows the power generated by PV, the operation cost of electrical chiller and the power sold to grid. It can be observed that the electrical chiller should consume a lot of power from grid for several hours every day. And a great amount of power generated by PV could be sold to the power grid. The power sold to grid and the operation cost are 31,687 HKD and 40,877 HKD respectively. Considering the capital cost of solar electrical cooling system, the total cost of this cooling system in July is 39,190 HKD. Fig.7.7 presents the operation cost of adsorption chiller and heat generated by solar thermal collector. It can be observed that the operation cost of adsorption chiller is larger than that of electrical chiller. And a great amount of heat is generated by the solar thermal collector and it cannot be fully used when the cooling supplied by the adsorption chiller (i.e., the heat comes from solar thermal collector) cannot fulfill the cooling demand. The total cost of solar thermal cooling system in July is 160,000HKD. For the traditional electrical cooling system, the total cost in July is 72,592HKD. It can be observed that the total cost of solar electrical system is the lowest when compared with the other two cooling systems.

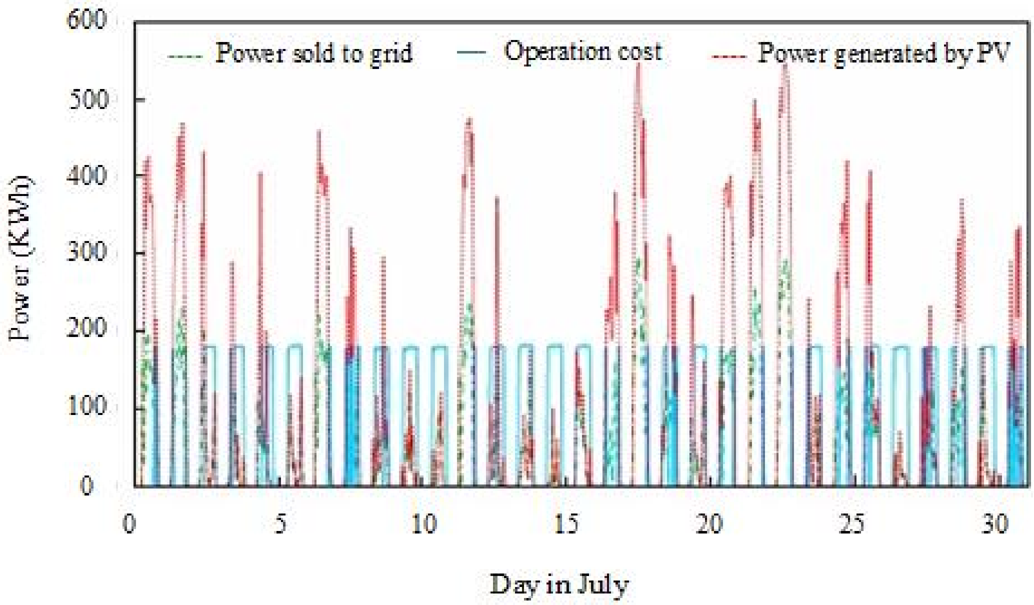


Fig. 7.6 Power output by solar electrical cooling system

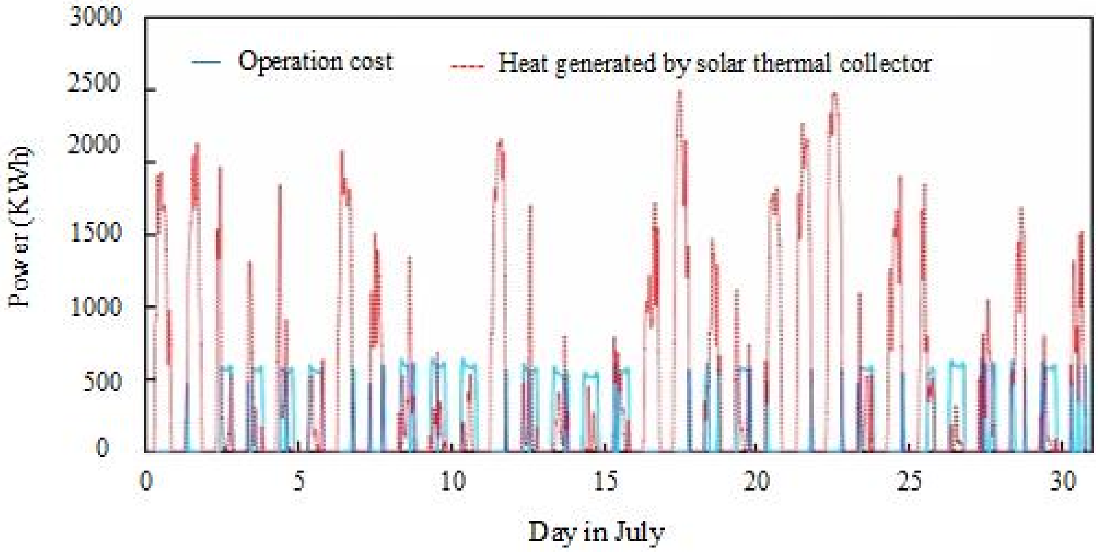


Fig. 7.7 Power output by solar thermal cooling system

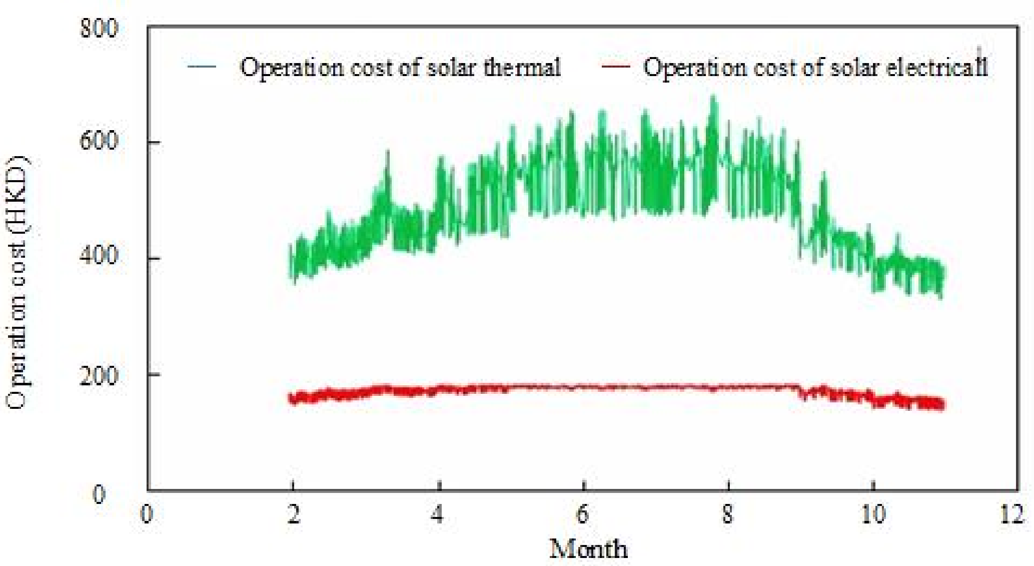


Fig. 7.8 Operation costs of solar thermal cooling system and solar electrical cooling system

Table 7.1 gives the capital cost and operation cost of the three systems. It can be observed that the annual total cost of solar thermal cooling system is the largest among the three systems. Both the operation cost and the capital cost of solar thermal cooling system are the largest. For the traditional cooling system, the operation cost and the capital cost are 804,892HKD and 84,000HKD respectively. The operation cost and capital cost of solar electrical cooling system are 339,523HKD and 440,000HKD respectively. And it can be reduced by about 12.3% when compared with the traditional cooling system. In Hong Kong, the solar electrical cooling system is available to supply the cooling for the building and the solar thermal cooling system is not available to supply the cooling for the building.

Table 7.1 Total costs of the three cooling systems

	Operation cost （HKD）	Capital cost (HKD)	Total cost (HKD)
Traditional cooling system	804,892	84,000	888,892
Solar thermal cooling system	925,791	722,000	1,647,791
Solar electrical cooling system	339,523	440,000	779,523

7.4 Summary

In this chapter, by employing the TRNSYS building energy model, the life-cycle total cost of traditional cooling system, solar thermal cooling system and solar electrical cooling system are evaluated and firstly examined. The results show that the solar electrical cooling system is available and economical to be used to supply the cooling for the building in Hong Kong. On the contrary, the solar thermal cooling system is not suitable to be used for supplying the cooling. The total cost of solar electrical cooling system could be reduced by 12.3% when compared with the traditional cooling system.

Thus, solar PV and solar PV cooling systems have much application potential and are likely to play a vital role in saving energy and reducing greenhouse gas emissions in Hong Kong.

CHAPTER 8 CONCLUSION

8.1 Conclusions of theoretical and numerical investigations

In Chapter 3, the development potential and energy incentives of rooftop solar PV system in Hong Kong is estimated and assessed. Through assuming the roof area ratio per capita and combining airborne LiDAR data and spatially analysis, the total rooftop area, which is available for installing PV systems, was estimated. The total PV-suitable rooftop area was estimated to be 54 km^2. Moreover, the result of calculating (the annual potential energy output of rooftop PV systems in Hong Kong) is about 5,981 GWh per year, which is equivalent to 14.2% of the total electricity use in Hong Kong in 2011. Based on this result, policy makers can develop a more ambitious goal in the future development of renewable energy, photovoltaic technology, of course, is possible to achieve this goal. In addition, each year about 3,768,030 tons of greenhouse gas emissions can be avoided, replacing the equivalent of local power mixed with the potential photovoltaic roof photovoltaic system generated electricity (5981 (small-scale) in Hong Kong.

In Chapter 4, the impact of the effective lifetime on the LCOE and the energy production is clearly presented. The result shows that, BIPV for rooftops, flexible surface thin-film BIPV rooftops and shading system are feasible for commercial buildings in Hong Kong. Their LOCEs are about 20% lower than local electric price. Other types of BIPV systems, such as PV façade and semi-transparent windows, can be accepted considering the available combined area and the saved envelop materials. The application of BIPV system can be a practicable renewable energy method in Hong Kong if beneficial policy supports are further provided. In addition, this chapter also conducts the uncertainty and sensitivity analysis of LCOE regarding the technical parameters and finance parameters. It shows that a higher debt fraction will decrease the LCOE because of the lower loan rate than the nominal discount rate due to the loose monetary policy.

Chapter 5 addresses about the performance on different solar systems, including BIPV systems, shading-type solar PV claddings and a-Si based PV double-skin systems. The results show that for a-Si based PV double-skin façade systems, the maximum monthly energy output was about 5.1 kWh/m; the annual net electricity use of the west facing room with solar PV window and clear window was 118 kWh/m^2 and 151 kWh/m^2; adopting solar PV windows could save around 22% of the electricity. Then, in terms of energy performance, the best orientation for solar PV window installation is south while in terms of thermal performance, the largest cooling energy use was observed in the west orientation. For shading-type PV cladding systems, the monthly energy output of the mc-Si PV modules is significantly higher due to the higher module efficiency. With respect to its thermal performance, the monthly window heat gain was significantly reduced with the use of the shading-type PV cladding. The maximum monthly energy output was about 40 kWh/m^2, while the minimum monthly energy output was 24 kWh/m^2, and the annual energy output was around 316 kWh/m^2.

Incentive policy for BIPV technology in Hong Kong is presented in Chapter 6. Five countries leading in solar PV application were studied in this chapter. Their histories of PV system development and application were reviewed and analyzed. Their initiatives toward the popularizing and prosperity of PV application were collected and summarized.

Besides, by employing the TRNSYS building energy model, the life-cycle total cost of traditional cooling system, solar thermal cooling system and solar electrical cooling system are evaluated in Chapter 7. The results show that the solar electrical cooling system is available and economical to be used to supply the cooling for the building. On the contrary, the solar thermal cooling system is not suitable to be used for supplying the cooling. And, the total cost of solar electrical cooling system could be reduced by 12.3% when compared with the traditional cooling system.

Thus, solar PV and cooling systems have much application potential and are likely to play a vital role in saving energy and reducing greenhouse gas emissions in Hong Kong. Accordingly, this study proposed a strategy for the incentivizing of BIPV application for Hong Kong PV application. The strategy aims to increase the competitive strength of the PV application, trying to help the relatively frail PV industry survive in the relatively intense free market, and eventually grow up to be a promising local energy solution in the near future. From the lessons learned from the four forerunners, a series of subsidy policies and incentives was drawn up to help the local PV industry survive through the early pioneering stage. It was hoped that the results could serve as a reference for future policy making.

8.2 Recommendations for PV Development in Hong Kong

Based on the above analysis, policymakers should formulate relevant policies to further reduce the soft cost of PV system and provide appropriate subsidies or incoming electricity prices. Based on the installation cost and comparison of different countries and regions, the following suggestions are put forward for the installation costs and promotion of PV applications in Hong Kong:

1. The government should provide appropriate subsidies and tariff preferences, increase the installed PV system and expand the scale of PV applications. The LCOE of PV is higher than that of retail price users. The effect of large-scale application is beneficial to further reduce both hardware cost and non-hardware cost. After the development of the photovoltaic power system to a certain cost scale, the subsidy will be reduced year by year.
2. The introduction of more intense competition mechanisms, such as the opening of photovoltaic enterprises in mainland China and the installation of photovoltaic systems by labor in Hong Kong.

3. To train workers and engineers to improve work efficiency and to develop more effective installation methods.
4. To simplify the processes of grid-connection and reduce the related soft costs as much as possible.
5. Effectively attracting private capital and foreign investment (well established PV suppliers or investors from Mainland China) to develop rooftop PV power plants in Hong Kong by the way of energy management contract (EMC).
6. Using rooftops or shading PV system for commercial buildings in Hong Kong as much as possible;
7. Choosing cooling condition like air, water, PCM, or thermoelectric module cooling according to actual condition;
8. Loose monetary policy, providing corporations with more money for longer time;

8.3 Recommendation for future research

There are two limitations in this study.

First, the price used in this study of PV module and BIPV may be underestimated due to the lack of scale effect in Hong Kong. In other words, the actual LCOE may increase in local PV construction industry.

Second, this study is established based on the newly built buildings. However, in rebuilt project, fees of old structure and materials removal should be considered which would be a large part of costs

These two limitations should be taken into serious account in future study.

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