GO GREENER-- THIN-FILM PHOTOVOLTAIC SYSTEM AT LAMMA POWER STATION

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Abstract

To strive for sustainable clean power generation for improving regional air quality, HK electric has been actively and positively pursuing renewable energy and commissioned the Lamma Winds, Hong Kong's first grid-connected wind power station in Feb 2006. Built upon the success and operating experience of Lamma Winds, HK Electric is keen to explore the solar energy application in Hong Kong by developing a 550kW solar Photovoltaic (PV) system, comprising 5,500 Amorphous Thin Film Photovoltaic (TFPV) modules, each rated at 100W peak. The operation of the utility scale solar PV system would produce about 620,000 kWh of green electricity per annum offsetting annual emission of 520 tonnes of carbon dioxide. This paper presents the development of the project, environmental considerations and performance evaluation of the TFPV system.

Key Words: Photovoltaic, Thin Film Photovoltaic, Crystalline Silicon, Energy Pay-back Time, Irradiance.

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INTRODUCTION

Since its operation in 1890, HK Electric has been one of the leading firms in energy infrastructure supporting the development of Hong Kong. Nowadays, HK Electric has a total installed capacity of 3,736MW, serving more than 560,000 customers with a consistently high supply reliability rating of over 99.999% since 1997. All the electricity is generated primarily from Lamma Power Station and Lamma Power Station Extension of Po Lo Tsui at Lamma Island.

To deliver the commitment to greener future, HK Electric has commissioned additional emission control installations for the existing coal-fired units at Lamma Power Station, including the Flue Gas Desulphurization (FGD) Plants and Low Nitrogen Oxides Burners which can effectively reduce the formation of sulphur dioxide by over 90 percent and nitrogen oxides by over 60 percent respectively. In order to promote a low carbon economy, HK Electric has introduced natural gas as the second primary fuel with the commissioning of its first 335MW combined cycle gas turbine generating unit (CCGT) at Lamma Power Station Extension in 2006, generating greener electricity with the emission of only 50% of carbon dioxide comparing with other conventional coal-fired generating units.

Further to support sustainable development and protecting the environment, HK Electric is highly concerned on the greenhouse gases emissions leading to climate change. In recent years, HK Electric has been actively pursuing the use of renewable energy (RE) aiming at achieving better environment in Hong Kong and supporting Government's Blue Sky Campaign. Following the success of commissioning the first commercial scale wind turbine in 2006, HK Electric continues to explore the introduction of utility scale solar energy project and the feasibility of implementing a 100MW offshore wind farm in the southern waters of Hong Kong. The Wind Turbine and Lamma Power Station of HK Electric are shown in Figure 1.

Fig. 1 – Lamma Power Station and Wind Turbine

GROWING GREENER – SOLAR SYSTEM OF UTILITY SCALE

Solar energy is the most abundant permanent source on the earth while the operation of solar power system emits no gaseous or liquid pollutants and without noise. Based on the local studies, Hong Kong has a significant solar energy resource, with an annual average of 1.29 MWh/m^2 global horizontal radiation. By taking account to the Hong Kong's total land area of 1,098 km^2, a total energy of 133 TWh per year will be available if these areas were all fitted with horizontal PV panels. [1]

Obviously, the area that is actually available for PV panel installation would be much smaller due to other land uses and constraints. In the recent years, small wind turbines and small scale PV systems have been retrofitted in various premises of HK Electric as shown in Fig. 2. In order to demonstrate the corporate social responsibility for further improving the local air quality, HK Electric is striving to explore the introduction of utility scale solar power system in Hong Kong. By harnessing the cleaner solar energy, which is superior in most of the environmental aspects, the impacts of existing operation on the environment would be further minimized and this also reduces our carbon footprint in power generation.

Fig. 2 – Small Scale PV System and wind turbine installed at rooftop of Marsh Road Substation

SITE SELECTION – GREEN PLATFORM IN LAMMA POWER STATION

Hong Kong is a well-known densely populated area and its land is extremely precious. Finding large flat areas at commercial and residential areas suitable for large scale solar system without shading from surrounding high rise buildings and visual intrusion to the residents nearby is arduous.

As a matter of fact, a utility scale solar power station requires a large piece of flat area for installation. Other key factors such as ease of grid connection, visual intrusion to nearby residents and good access for operation and maintenance area were seriously considered in the site selection process. Particularly, for solar power system, the orientation of PV modules and the possible shading situations on the selected locations become the critical factors in the site selection criteria.

As the proposed utility scale solar power system is an environmental enhancement project with no greenhouse gases emission. Undoubtedly, environmental considerations are one of the major assessments in the site selection stage. Various locations in Hong Kong Island including the country side were checked and no suitable site can be located. Eventually, Lamma Power Station is considered as the most suitable site meeting the key factors in selection criteria while without constituting any adverse changes to the environment. The site plan of Lamma Power Station is shown in Figure 3.

Fig. 3 – Site Plan of Lamma Power Station

There are about 20 power station buildings/plants in Lamma Power Station. Considering the layout and orientation of the power station buildings and various technical constraints such as required flat roof area/loading, accessibility, obstruction, connection to system grid, as a whole, PV modules were planned to be installed on the following roofs of Units 1-8 Main Station Buildings:-

i. Units 1-3 Boiler House at EL+80.15
ii. Units 1-6 Bunker Floor at EL+62.00
iii. Units 1-6 Turbine Hall at EL+37.00
iv. Units 7&8 Bunker Floor at EL+62.00
v. Units 7&8 Turbine Hall at EL+37.00
vi. No. 2 Circulating Water Intake Area

In environmental aspect, since there is no change in physical alignment, layout or design of the Power Station with the PV modules in place, it is unlikely to affect the existing or planned community, ecologically important areas or sites of cultural heritage in the Lamma Island. Moreover, the PV technology is proven for tropical applications and inherently does not generate noise and pollutants during construction and operation that are likely to affect any rare, endangered or protected species, important ecological habitat or any cultural heritage.

Meanwhile, the proposed installation areas do not involve any additional reclamation and dredging works during the construction period. There will be no physical change resulting in an increase in the extent of reclamation or dredging affecting water flow or water quality likely to affect ecologically important areas, or disrupting sites of cultural heritage.

The total area of roof areas where PV modules are installed is about 35,000 m². Taking into consideration the space occupied by existing equipment and spaces required for emergency access, operation & maintenance of the PV System and existing plant equipment as well as avoiding shadow from existing equipment on rooftops, it was concluded that installation of 5,500 PV modules with dimension of 1,410 mm (L) × 1,110 mm (W) × 35 mm (D) is technically feasible.

According to geographic location of Hong Kong, PV modules should be installed facing south and tilted at about 22º in order to capture solar irradiance as much as possible. As PV modules to be installed at Lamma Power Station are faced toward seaside, visual impact to residents and visitors nearby is not envisaged. Based on the estimated maximum power of 100W can be generated by each PV module, the total estimated installed capacity of the solar PV system is 550kW approximately.

An aerial view of the solar power system on the rooftops of Units 1-8 Main Station Buildings is shown in Figure 4.

Fig. 4 – Aerial View of Units 1-8 Main Station Buildings and PV System

TECHNOLOGY SELECTION -- GREENER PV MODULE

From the commercialized PV marketplace, PV technologies are generally classified as basic crystalline silicon (c-Si) and thin film technologies. The crystalline silicon is the first generation of PV technology using silicon in forms of ingot, ribbon or wafer as the raw material, which further categorized into monocrystalline silicon and polycrystalline silicon. The second generation of PV technology, thin film technology reduce the amount of material required in creating a solar cell, which further catergorized into thin film silicon and Cadmium Telluride (CdTe) solar cell. The PV technologies were screened initially on their potential impacts on environment. In such, CdTe thin film modules which consist of extremely rare element Tellurium (Te) and toxic substance Cadmium (Cd), were not considered to be adopted in our project because the potential disposal and long term safety issue. Amongst the aforesaid PV technologies, the long established crystalline silicon (c-Si) and also amorphous thin film silicon (a-Si) were chosen as the potential candidate in our PV system, in which their raw material in manufacturing is the abundant silicon. In-depth studies on the performance and environmental aspects for both PV technology candidates have been conducted and reported as below:

a) Performance Aspects

i) Better High Temperature Performance

Among the most popular and proven PV technologies, crystalline silicon technology has been the more preferable choice than amorphous silicon thin film in the PV market due to its higher conversion efficiency. The cell efficiency for typical crystalline module ranges between 11-18%. In contrast, the cell efficiency record of thin film technology is around 7-8%. By solely comparing the cell efficiency of two types of PV technology, crystalline module generates better electricity outputs than thin film module. However, taking into account that all PV modules are rated at Standard Test Condition (STC) of 1000W/m2, 25^{o}C and AM1.5, which the PV modules will be generally only exposed to such conditions for a very limited amount of time during its service life, and therefore STC ratings are only one of the criteria in evaluating the performance of the technology in the real situation [2].

Based on the fundamental differences between c-Si and thin film modules, the temperature coefficient for maximum power output Pm of thin film PV and c-Si PV module are about -0.25% and -0.4 % per ºC rise on module temperature respectively. In the summer time of Hong Kong with generally high irradiance condition, modules temperature can regularly exceed 45ºC, in which a 100 watt thin film module will experience a decrease of 5 watt in its rated power. However, c-Si module with identical rated power would lose 8 watts in the same condition. Therefore, the ability to maintain power output level at high temperature of thin film PV module is better than crystalline PV module and is more suitable for tropical environment like Hong Kong. Studies on comparing the annual energy yield from thin film silicon and crystalline silicon panel in tropical areas showed that thin film produce higher energy yield of more than 20% in the summer and having a performance advantage of 5-10% in winter time have been recorded [3].

ii) Better High Irradiance Performance

In additional to the more favorable temperature coefficient, the spectral response of the thin film Si cell with the solar spectrum makes it more competitive whenever the sun is at its brightest, usually at the time of midday or in the summer which the sunlight is rich in blue light [4]. Figure 5 shows the spectral response (SR) of amorphous silicon thin film technology (a-Si) and crystalline silicon (c-Si) technologies with the standard sunlight spectrum according to IEC 60904-3 for STC measurements [5]. The solar spectrum shifts to shorter wavelengths (more bluish) at the time of midday or in the summer, in which thin film modules have a better matching of its absorption spectrum with the blue-shifted solar spectrum. Compared to the c-Si technology with a reddish absorption spectrum, a-Si thin film module shows an enhanced spectral response and hence higher energy yield at the summer time which electricity is most highly valued.

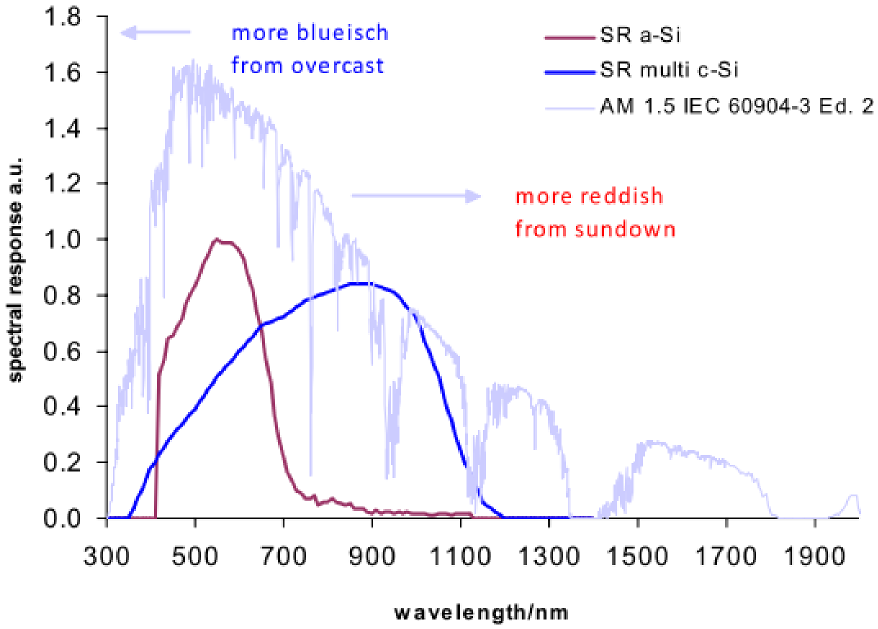


Fig. 5 – Spectral response (SR) of a-Si and C-Si with the standard solar spectrum [4]

iii) Better Weak Light Performance

Even in cloudy sky conditions at low irradiances (100-500 W/m2), sunlight is more diffuse and richer in blue illumination. A-Si modules which have a better spectral match with the outdoor illumination could effectively maintain a high power level compared to c-Si modules [2].

b) Environmental Considerations

i) Energy Payback Time (EPBT)

Thin film PV cells offer substantial advantages on environment aspects over the longer-established crystalline PV materials. In the manufacturing process of PV modules, the thickness of silicon material deposited on thin film PV materials is only about 1/200 of that for crystalline PV materials and hence a-Si require substantially less energy to manufacture. Therefore, the manufacturing cost of a-Si module is substantially lower than that of c-Si module. In term of Energy Payback Time (EPT), which indicates the number of years a PV system has to operate to compensate for the energy it required to produce, install, dismantle and recycle. As shown in figure 6, the EPT of the a-Si thin film PV module is about 1.5 year compared to about 2.8 years for c-Si PV module in the current status, regardless to the balance of system (BOS). Compared to traditional c-Si technology, thin film PV technology is considered as a greener option in production. It is important to note that there is still a high potential for energy efficiency improvements in PV in the future and the EPT for c-Si modules will decrease to 1.8 years and to one years of less for thin film modules, which is very promising.

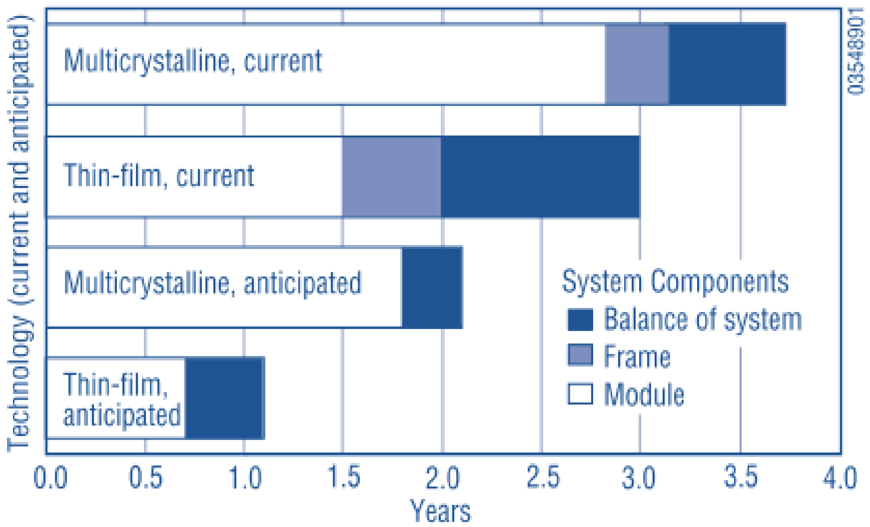


Fig. 6 –Energy Pay-back Time for c-Si and a-Si technologies

ii) Cost Issue

Available information shows that the cost of crystalline PV modules is in some degree higher than thin film PV modules. Their comparison together with other PV technologies is shown in Figure 7.

It is anticipating that thin film PV will continue to increase their market share due to the advantages mentioned above and foreseeable continued improvement of module performance.

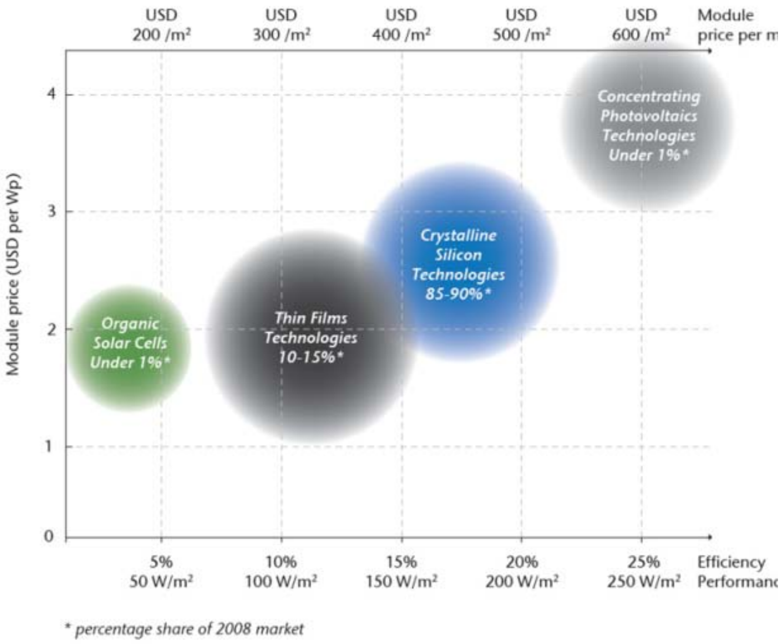


Fig. 7 - Cost of different PV module technologies

iii) Waste Management

In the existing crystalline silicon or thin film PV technologies, it offers a long lifespan of 25 years or more. The environmental effect on the disposal of the retired modules was also evaluated to minimize large quantity of the end-of-life PV waste generated.

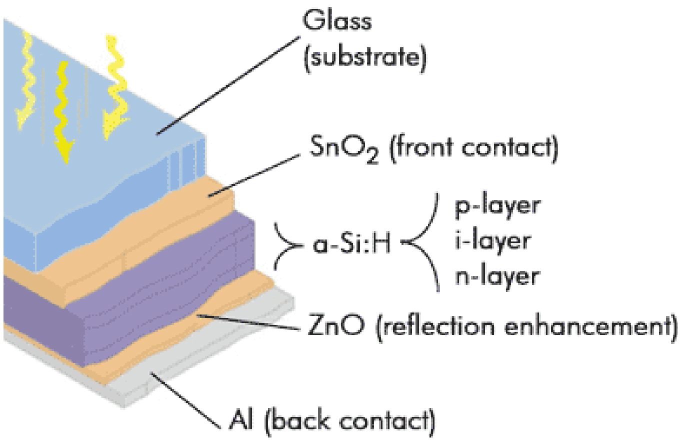


Fig. 8 – Schematic cross-section of typical thin film amorphous Silicon PV cell.

For a better understanding of the basic structure of thin film PV cell, a typical cross section schematic diagram is shown as Figure 8. A thin film amorphous silicon PV cell comprises of a very thin layer of conductive metal called Transparent Conductive Oxide (TCO) such as indium tin oxide, zinc oxide, etc. deposited on the glass substrate as a positive ohmic contact. A layer of p-type semiconductor silicon, undoped silicon and n-type semiconductor silicon are deposited subsequently on the negative ohmic contact made of aluminum.

In the current PV market, a broad range of technologies are available for the recycling and material recovery of the retired PV modules. Along the existing thin film technologies, thin film a-Si modules can be considered as the greenest solar cell, which contains no toxic substances such as cadmium (Cd) existing in the cadmium telluride (CdTe) thin film technology. Moreover, the recycling process is less complicated and more ecological friendly. For a typical a-Si frame module, the front glass can be removed and collected for glass recycling while the main pane with the semiconductor material can be treated in chemical process. Meanwhile, waste from aluminum frames can be transformed into raw material for new frames. The key high value materials in thin film technologies are metals, including indium and tin which employed as the metal ohmic contact for the modules, which could be restored in the chemical thermal treatment. Thus, the environment impact of thin film silicon technology is considered as negligibly small.

Gaining the experience from European countries which were the pioneers of implementing large scale PV system in the world since early 1990s, the development of PV recycling industry has been growing in a significant rate in response to the growing demand for a robust approach to dealing with end-of-life PV modules. In particular, European “PV Cycle Association” is currently representing around 75% of European PV market to provide a focused approach to realizing an adequate recovery system for end-of-life PV modules. Similar growing trend on the development of PV recycling industry is also expected in China in the coming ten years, to meet the demand of the recycling needs on its retired PV modules.

After careful consideration, thin film silicon PV modules are adopted as they are considered more environmentally friendly in production and are superior in gaining better yield in electricity production especially in tropical areas similar to the harsh environment in Lamma Power Station.

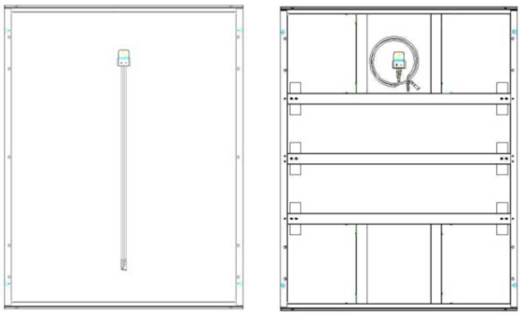
A close view of the PV module installed at the roof of Units 1-3 Boiler House is shown in Figure 9.

Fig. 9 - PV System at roof of Units 1-3 Boiler House

DESIGN FEATURES HIGHLIGHTED

a) Additional Stiffeners on PV modules

The TFPV modules are manufactured and tested according to IEC standards. The maximum mechanical load of the standard module is 2,400 Pa/m². However, to comply with the Wind Code of HKSAR and to meet the prevailing strong wind conditions at roof areas especially for Units 1-3 Boiler House which is about 80 metres above ground, additional stiffeners have been installed at the back of PV module. The maximum mechanical load of the final TFPV module after strengthening is 5,600 N/m². The construction of PV module before and after strengthening is shown in Figure 10.



Before strengthening   After Strengthening

Fig. 10 – Stiffeners of PV modules

b) Pre-fabricated Concrete Block

Pre-fabricated concrete blocks had been specially designed to ensure that PV module will be sitting at 22° after installation and would be freely stood on the roof floor without requiring any site anchoring which damages the existing water-proofing layer on the roof floors. The weights of the concrete blocks have been calculated to be sufficient to sustain the in-situ wind load. Layout of the concrete blocks is shown in Figure 11.

Fig. 11 - Concrete block for PV modules support

All PV modules in the same row are tied together by bolts and nuts for better PV array alignment and increasing the overall dead weight of the whole assembly. The completed PV installation at the roof of Units 1-3 Boiler House is shown in Figure 12.

Vast majority of the construction and fabrication works were carried out offsite in China. The extent of site installation within Lamma Power Station in minimal apart from cabling and screw tightening for fixing the modules onto the pre-fabricated concrete blocks.

Fig. 12 – Completed PV System

ENVIRONMENTAL MONITORING ON ERECTION STAGE

During the construction stage of the 550kW TFPV project, 5,500 pieces of PV modules, 11,000 pieces of concrete blocks, large quantities of PV module fixing accessories, electrical equipment, cables and cable supports were required to be transported to roof areas for installation.

Due to no proper route is available for delivery of material using fort lift and trolleys, a 250 tonne crane had been deployed for transportation of materials from ground level to roof areas. To ensure safe and efficient operation of the 250 tonne, method statement and risk assessment report on the lifting work had been submitted and approved well before work commencement. Lifting of material using the 250 tonne crane is shown in Figure 13.

To minimize the disturbance to the nearby residents during the erection stage of the TFPV project, continuous noise alarm monitoring was carried out to provide early warning to the operators against any possible noise brought by the erection process. Moreover, an existing ambient particulate monitoring network comprising five continuous dust monitoring stations continuously monitor the particulate levels and detect any possible changes during the project construction phase.

Fig. 13 - Lifting of materials by 250 tonne crane

ENVIRONMENTAL BENEFITS

The anticipated annual output of the 550kW TFPV System after computer simulation using solar irradiance and climatic data from NASA and Hong Kong Observatory is 620,000 kWh with the capacity factor of 12.9%.

Comparing with conventional coal fire generating units in Lamma Power Station, the PV system will reduce emission of about 520 tonnes of carbon dioxide per annum which is equivalent to planting 22,000 trees. The amount of sulphur dioxide and nitrogen oxides emissions is also reduced, thus further improving Hong Kong's air quality. A beautiful landscape in Lamma Power Station is shown in Figure 14.

In addition to the reduction of air pollutants, wider use of renewable energies also help in the conservation of conventional fossil fuels and other natural resources that are quickly diminishing. Moreover, it further reduces the wastes such as dust and solid/liquid wastes produced in the mining, cleaning and transportation of traditional fossil fuels.

Fig. 14 – Beautiful landscape in Lamma Power Station

SOCIETAL AND EDUCATIONAL BENEFITS

Additional to improve the local air quality, the project also aimed to raise awareness of climate change and encourage initiatives in promoting better understanding and application of renewable energy within the community. Study tour to the renewable energy power system at Lamma Power Station including the TFPV system and Wind Turbine was opened to the public for application. The response is overwhelming and vistors from a diverse range of backgrounds such as academic, industry and educational sectors have visited the system since the commissioning of the TFPV System on end June, as shown in Figure 15.

Fig. 15 – Visit Photo to +80m level of the TFPV System

INITIAL SYSTEM PERFORMANCE

For verification of PV system performance, solar irradiance meters, ambient and module temperature sensors are installed at each roof areas for acquiring environmental data. All the instruments together with PV inverters and power quality analyzers are connected to the Remote Monitoring Computer at Central Control Room of Lamma Power Station via RS485 communication links.

The Remote Monitoring Computer is industrial grade PC designed for 24 hours continuous operation. The Computer is further connected to Centralized Historical Information System (CHIS) in Lamma Power Station by high speed communication link for long term historical data storage and remote access by PCs in the offices via Corporate LAN.

Present solar irradiance, present electricity output, cumulative electricity production and aerial view of the PV system are repeated to the 42” LCD display at Visitor Centre for introduction of the large scale solar system to visitors.

Since commissioning on July 2010, the 550kW TFPV has demonstrated very good system performance at Lamma Power Station. The monthly production data from the initial 8 months of operation and the average capacity factor (the ratio of actual output of a system to the output at the system’s rated value) are summarized in Figure 16. As can be seen in Figure 21, the electricity output of the system showed its maximum in summer season (Jul 2010 – Oct 2010) and the output reduced accordingly in the winter season (Nov 2010 – Feb 2011). This seasonal variation on the power output showed a typical module performance on the factor on the exposure to sunlight. Cumulative electricity output of 500,063 kWh from the PV system since commissioning in July 2010 was recorded. Moreover, the average capacity factor is around 16% which is better than the design capacity factor of 12.9%.

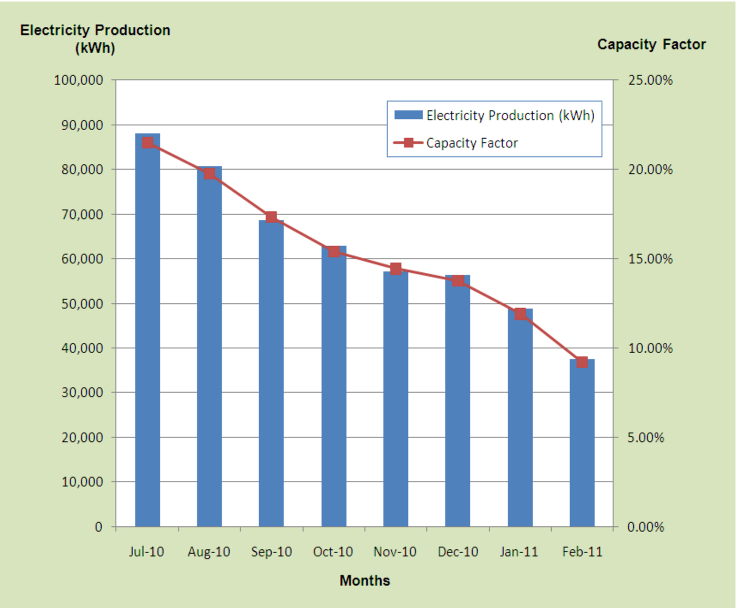
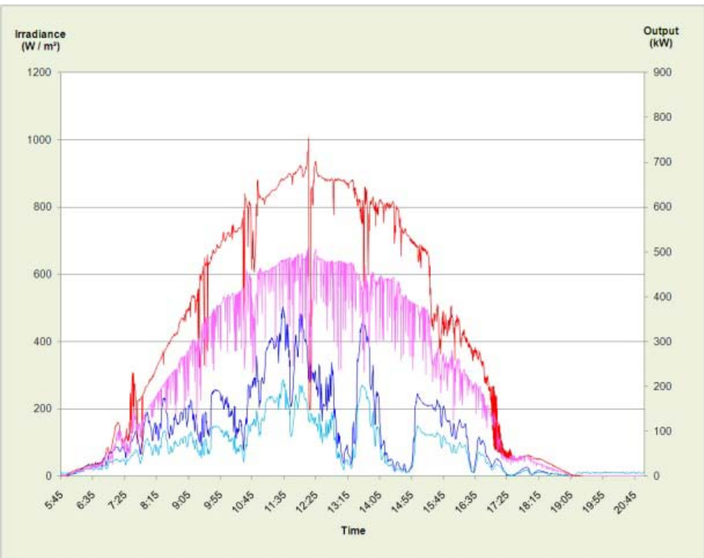


Fig. 16 – Monthly production data and average capacity data of the TFPV System since commissioning on July 2010

To verify the performance of TFPV modules on the weak light condition, comparison of solar irradiance data and the system output for sunny and cloudy/rainy conditions are shown in Figure 17.



Legend

Solar irradiance (Sunny)

Output (Sunny) – total 3,582 kWh

Solar irradiance (Cloudy & rainy)

Output (Cloudy & rainy) – total 1,258 kWh

Fig. 17 – Solar irradiance and system output under sunny, cloudy & rainy conditions

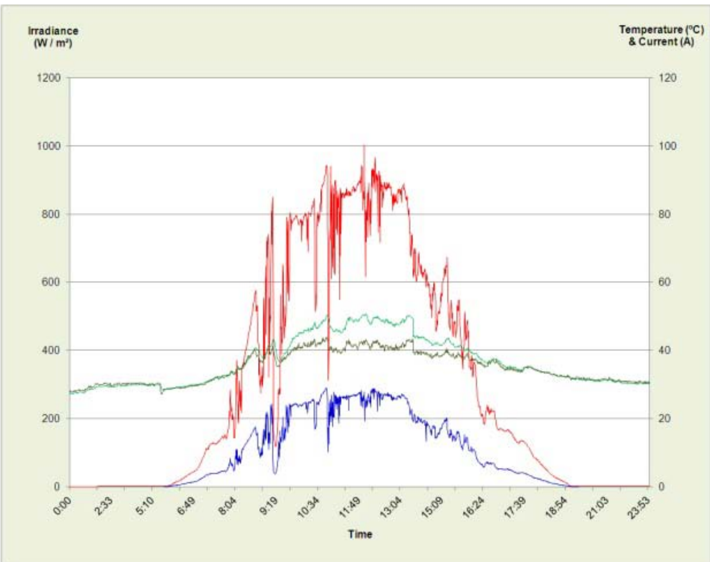
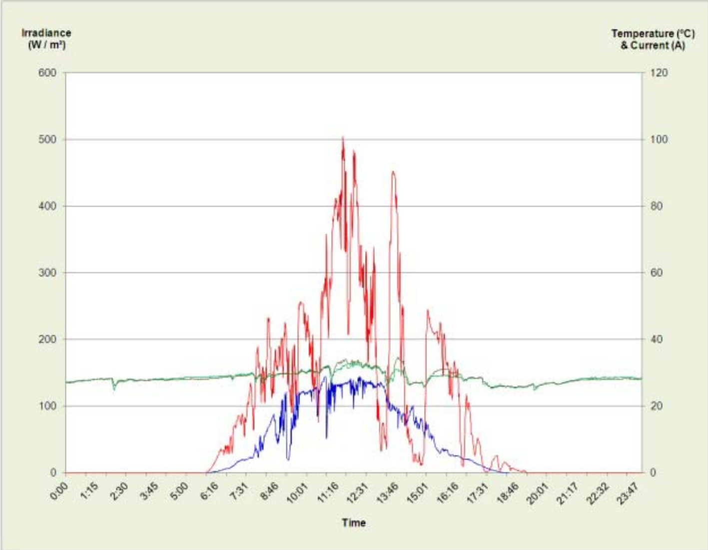


Fig. 18 – Environmental data and PV array current for sunny day



Legend

Solar irradiance

PV module temperature

Ambient temperature

PV array current

Fig. 19 – Environmental data and PV array output current for cloudy and rainy day

It shows that the electricity generated from the TFPV system under cloudy and rainy conditions is around 1/3 of total electricity generated from the system under sunny day with strong solar irradiance, which is very impressive.

To further review the performance of PV module output under high PV module temperature and various weather and seasonal conditions, solar irradiance, ambient temperature and PV module temperature sensors have been installed at each location for data collection.

The solar irradiance, ambient and PV module temperature and PV array output current in sunny, cloudy and rainy days during initial operation phase, which were captured by the sensors, are tabulated in Figures 18 & 19.

Despite not significant, there are some signs that the power output of PV modules somewhat decreases with the increasing module temperature, which verifies one of the typical characteristic of PV modules in its reduction of its rated power generating capacity during high temperature environment.

Considering the environmental aspect on the operation of our TFPV emission free power generating system, there is no increase in air or noise pollutants emission, discharges or waste generation associated with the system's daily operation.

CONCLUDING REMARKS

The successful completion of the solar power project marks another milestone for HK Electric in harnessing renewable energy (RE) for power generation in Hong Kong for better air quality since introduction of wind energy to the city by building and operating the only commercial scale wind power station on Lamma Island in 2006.

The completed 550kW solar power system is currently the largest solar power system in Hong Kong and is also the first large scale project applying amorphous silicon thin-film technology.

Based on initial results, amorphous silicon PV module is considered suitable for use in the site conditions of Lamma Power Station.

HK Electric will continuously evaluate the system performance of the 550kW PV system and the studies on the second phase of the development - expansion of solar power system to achieve a total capacity of 1MW is in progress. More advanced models of TFPV modules offering higher conversion efficiency would be adopted in the future.

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