Appendix T

THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

Renewable Energy Applications on the Green Deck

(Final Report)

By Prof. Yang Hong-xing

Co-investigators: Dr Ma Tao, Dr Lu Lin & Dr Qi Ronghui

Renewable Energy Research Group

Department of Building Services Engineering

December 2014

Renewable energy applications on the Green Deck

Prof. Hongxing Yang
The Renewable Energy Research Group
The Hong Kong Polytechnic University

In this project, we have investigated the potential of solar and wind power generations and the energy consumption of the proposed Green Deck project, and evaluated the economic feasibility and environmental benefit of PV installation on this deck. Given that wind speed is too low for economic power generation in this urban area with high-rise buildings, wind power is not recommended. Therefore, two schemes for PV installation are proposed in this study. If the PV panels can only be installed above the deck, it can supply 66% of energy for the deck (Scheme 1). If the roofs or facades of other buildings developed together with the deck are allowed for PV installation, it can meet 100% of energy consumption of the deck (Scheme 2). It is highly possible to achieve a 'net-zero-energy consumption' deck. To develop a real "green" deck, it is proposed to use the Scheme 2. In addition, this proposal of using renewable energy on the deck is evaluated to be economically feasible after considering future tariff increase and environmental factors.

1 Introduction

The objective of this study is to develop a zero-energy consumption/zero-carbon emission Green Deck by integrating feasible renewable energy technologies. This study aims to estimate the future energy consumption of the project and the potential of solar and wind energy generations for achieving the target of zero energy consumption and zero greenhouse gas emissions of the Green Deck.

Locating at a low latitude area (22-23°), Hong Kong is suitable for solar energy application, especially solar photovoltaic integration in buildings in urban environment. The annual mean daily global solar radiation is 14.5 MJ/m^2, much better than most of the areas in Japan and Germany where a lot of solar energy projects have been developed. As shown in Table 1, a comparison of available solar radiation is made with other countries and cities. Our solar energy resource is really not poor! It is thus proposed to use solar energy for power generation in this project. This report gives the details of the investigation.

Table 1 Comparisons of annual mean daily global solar radiation at different locations

Location	London	America SW	America NE	Australia	Germany	Japan	China NW	**Hong Kong**
Radiation (MJ/m2)	9	19.8	9	19.2	9.8	13.1	22.3	**14.5**

2 Estimation of energy consumption

For this proposed green deck, electricity will be mainly used for ventilation, air-conditioning and lighting of the midlevel walkways/bus waiting lobbies and ground-level bus stations. The local traffic in ground floor is very busy and the average daily vehicle traffic volume was estimated as 116,753 in 2013 [1]. Furthermore, as this area is linked to the Hung Hom railway station and bus station, as a very busy traffic centre, the flow rate of people on and below the deck will be huge, which is estimated as more than ten thousands in busy hours.

In order to dilute the pollution generated by passing cars in the covered space below the deck, large amount of fresh air is needed for ventilation. Besides, more lighting energy consumption is required due to the coverage. In hot weather days, air conditioning is also required in the densely waiting area of buses. It is thus necessary to estimate the energy consumption first if the area is covered for developing the Green Deck.

The natural ventilation strategy for the Green Deck proposed by Prof. Niu Jianlei [2] has been considered in this study, however, it is not enough to dilute all pollutions below the deck through natural ventilation. Hybrid natural and mechanical ventilation, therefore, is employed in this study. To estimate the energy consumption of the mechanical ventilation, the main calculation method is shown as follows according to the specifications for Design of Ventilation and Lighting of Highway Tunnel in China [3]:

(1). Calculation of the CO emission rate of passing cars:

$$Q_{CO} = \frac{1}{3.6\times10^6}\cdot q_{CO}\cdot f_a\cdot f_d\cdot f_h\cdot f_{iv}\cdot L\cdot\sum_{m=1}^{n}(N_m\cdot f_m) \tag{1}$$

where Q means the ventilation rate, m^3/h, and q_{CO} is the CO standard emission rate by the passing cars. N_m is the design traffic volume for a particular type of vehicle. f means the parameter for the type, velocity, density, elevation, etc. of vehicles. L is the length of traffic lane under the deck.

(2). The maximum CO concentration. In this study, the concentration is set as 250 ppm.

(3). With the CO emission rate, the required ventilation quantity could be calculated by

$$Q_{req(CO)} = \frac{Q_{CO}}{\delta}\cdot\frac{p_0}{p}\cdot\frac{T}{T_0}\times10^6 \tag{2}$$

where p is the design pressure and T means the local temperature in summer.

(4). The effect of natural ventilation:

$$\Delta p_m = (1+\zeta_e+\lambda_r\cdot\frac{L}{D_r})\cdot\frac{\rho}{2}\cdot v_n^2 \tag{3}$$

where v_n means the ventilation rate caused by natural ventilation, and D_r is the equivalent diameter for the traffic lane under the deck.

(5). Calculation of the ventilation quantity for blowers:

$$Q_b = \frac{Q_r}{2\rho^a v_r^2}(\sqrt{a^2\rho\cdot v_r^2+4\Delta p_b}-a) \tag{4}$$

where $a = \dfrac{K_b\cdot v_b\cdot\cos\beta}{v_r}-2$

(6).Calculation of the shaft power for axial fans:

$$S_{kw} = \frac{Q_a\cdot p_{tot}}{1000\eta}\cdot(\frac{273+t_0}{273+t_1})\cdot\frac{p_1}{p_0} \tag{5}$$

where p_{tot} means the total pressure for axial fans, t_0 and t_1 mean the standard temperature and surrounding temperature of the fans. p_1 is the surrounding pressure for fans.

(7). The energy consumption of the axial fans:

$$M_1 = \frac{S_{kw}}{\eta_m}\cdot k \tag{6}$$

where M means the electricity consumption, kWh; k is a safety factor, usually 1-1.5.

In hot weather days in summer, air conditioning is also required in the densely waiting area of buses. From May to October, several air conditioners are proposed to avoid high space air temperature in the bus waiting areas, and their electricity consumption could be calculated. Figure 1 illustrates the locations of the proposed air conditioners in possible waiting lobbies.

Figure 1 Waiting lobbies requiring air conditioning

More lighting energy consumption is required due to the coverage. To obtain the required illumination level, electricity consumption of the lighting systems in the deck is assumed as $5W/m^2$ from 7:00am to 12:00pm and $2.5W/m^2$ from 0:00am to 6:00am. Besides, only electricity for lighting is used in mid-night and early morning.

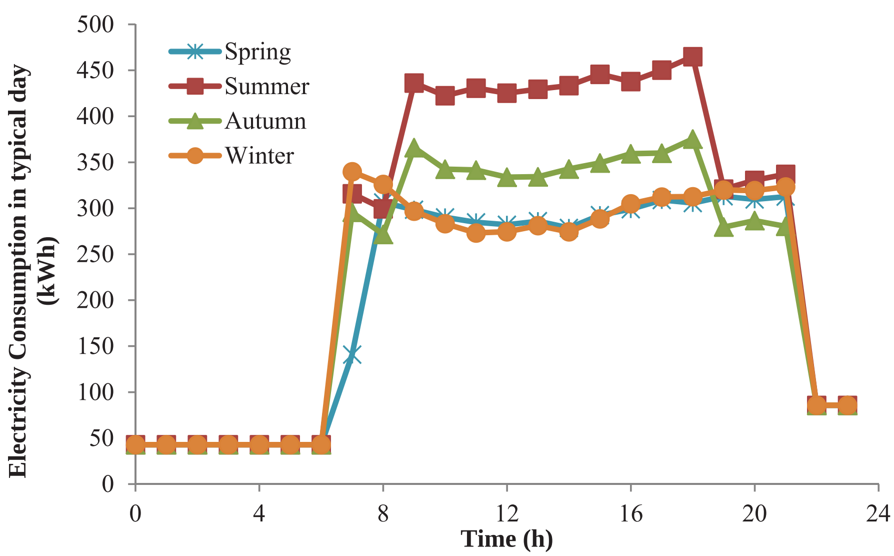

Figure 2 Energy consumption for typical days

By summing the consumptions of mechanical ventilation, air conditioners and lighting, the total electricity requirement of the proposed deck could be derived. Figure 2 indicates the hourly electricity consumption in typical days in spring, summer, autumn and winter. It can be found that there are two peaks in rush hours in the morning and evening every day. As natural wind speed is higher in autumn, less electricity is required for the mechanical ventilation system. The total daily electricity demand is around 6500 kWh in summer, and over 5000 kWh in other seasons.

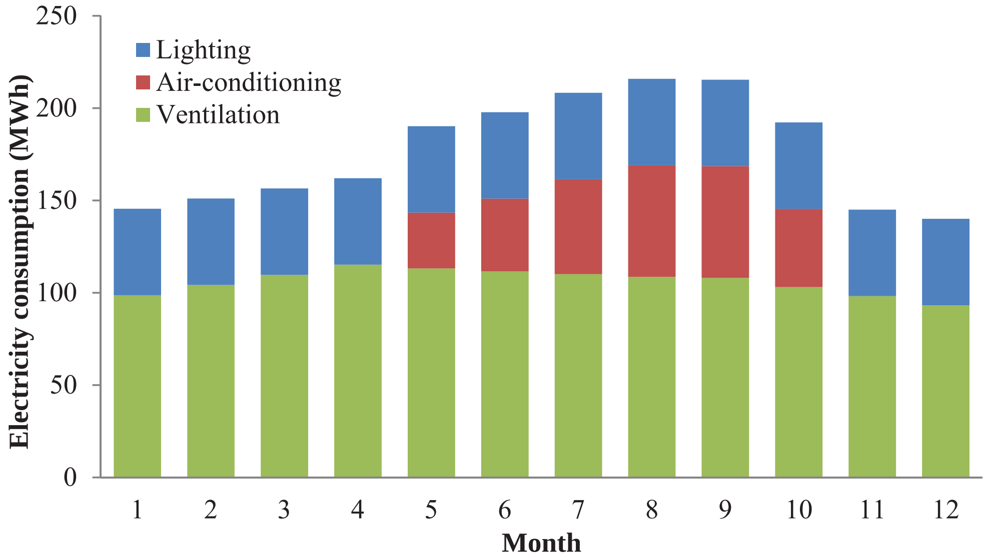

Figure 3 Annual energy consumption

Table 2 Summary of energy consumptions

	Air conditioning	Mechanical ventilation	Lighting
Estimated serving area (m^2)	14,500	15,000	15,000
Estimated energy consumption density (W/m^2)	7-14	9.8-16.9	2.5-5.0
Operation hour	7:00am-24:00pm May-October	7:00am-22:00pm All year	7:00am-23:00pm full-opening 0:00am-6:00am half-opening
Estimated energy consumption (kW)	100-203	147-253	43-86
Remarks	Two air conditioners are required for a waiting lobby, and one air conditioner is required for a bus station.	Mechanical ventilation is required for the waiting lobbies and pedestrian in the midlevel	Lighting is required for the waiting lobbies and pedestrian in the midlevel

The annual energy consumption of the proposed deck is shown in Figure 3. It is found that most energy is consumed for mechanical ventilation. The highest consumption occurs in August, and the consumption is lower in winter. A summary of energy consumption is presented in Table 2. If no renewable energy resource is used, about 5,800 kWh of electricity, would be consumed every day from burning fossil fuels or nuclear energy in local and mainland power plants for the proposed

Green Deck. The total cost of the electrical energy consumption from utility grid could be about HK$2 million in a year, which means the Green Deck project is not “green” if no alternative renewable energy is used. It is thus proposed to use solar and wind energy resources to supply enough renewable electric power to the lighting, ventilation and air-conditioning systems in the future.

3 Evaluation of solar power generation

To achieve the objective of zero carbon emission from the Green Deck, solar photovoltaic modules are proposed to be installed on possible building areas on the deck, e.g. on the roof and vertical façade of the nearby buildings (office buildings, hotels, and apartments), the covers of walkways and other constructions (sports complex, art gallery) in the deck. The power generation from solar photovoltaic could be estimated using the following equation:

$$E = G \cdot \eta \cdot A \cdot \gamma \tag{7}$$

where G is the solar radiation received per square metre (W/m2); η is the energy conversion efficiency of PV systems, A is the installation area of the proposed PV modules (m^2) and γ is the performance ratio of the PV system. The performance ratio considers all losses from converting solar energy into direct current electricity and then inverting the direct current into alternating current electricity. In order to determine this performance ratio, the operation performance of a real rooftop 22 kW*p* PV system located in PolyU campus (Y block) [4] was evaluated. This rooftop PV system faces south with a tilted angle of 22.5 degree, which is close to the optimum tilted angle in this location. The operation data shows that the performance ratio of this PV system is 0.85. Therefore, this figure is also adopted in this study.

To maximize the energy output of PV systems in limited PV-suitable roof areas, the high-efficiency mono-crystalline PV module (STP260S) made by Suntech of China is used in the study. Its characteristics are listed in Table 3 [5].

Table 3 Electric parameters of the STP260S mono-Si PV module

Parameters	**Values**
Solar cell (L×W)	Monocrystalline silicon 156×156 mm
Maximum power at STC (Pmax)	260 W
Optimum operating voltage (Vmp)	30.9 V
Optimum operating current (Imp)	8.42 A
Open circuit voltage (Voc)	37.7 V
Short circuit current (Isc)	8.89 A
Module efficiency	16.00%
No. of cells	60 (6×10)
Dimensions (L×W×T)	1640×992×35 mm

To maximize the power generation, it is assumed that all the PV modules are installed facing south with a tilted angle of about 23° with horizontal surface. To avoid any shading caused by the front rows of the PV modules, certain space has to be reserved between the front and back rows. According to our previous research [5], after considering the interval distance, the installation area for the selected PV module is 2.35 m^2. For the PV panels instated on vertical facade, the installation area can be equal to its original size, i.e. 1.64 m^2.

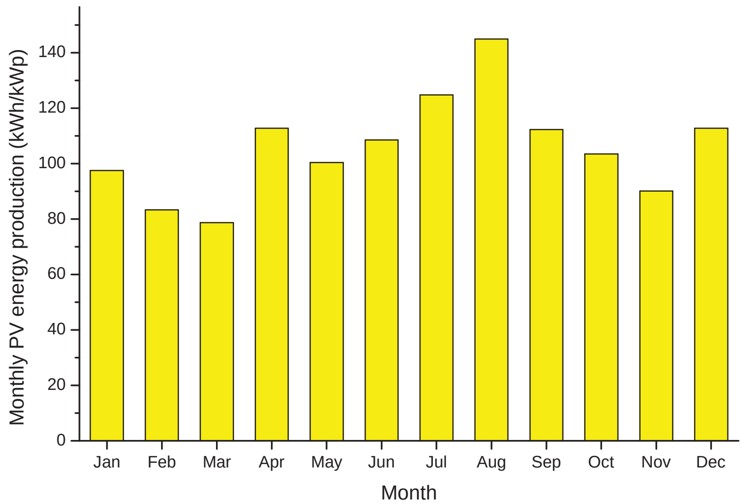

Figure 4 Power generation of 1 kWp PV panel in different months

Based on Eq. (7) and our previous experimental test [6], the electricity generated from 1 kWp PV panel is 1,545 kWh/year if installed on the roof with optimum angle and 778 kWh/year if installed in vertical facades. The simulated power production from 1 kW*p* PV on the roof in different months is presented in Figure 4. It is obvious that the PV output is obviously higher in summer than in winter due to better solar radiation and suitable azimuth angle. This is a favorable characteristic since electricity demand is higher as well in summer due to higher electric load for ventilation, lighting and air-conditioning in the deck.

A PV system is highly dependent on the available installation area. In our previous report, the roofs of the Hong Kong Coliseum and the university buildings in PolyU campus are proposed for PV installation, but these areas may not be used since they are not within the green deck boundary.

Therefore, only the roofs of walkways and other constructions, such as sports complex, art gallery can also be installed with solar panels. The walkways on this deck are the major contributor for PV installation, using the technology so-called ‘solar covered walkways system’.

Therefore, the total potential area above the deck including walkways and other constructions is estimated as 8175m^2, about 19% of the deck area (Figure 5). Therefore, based on above calculation, about 904kWp PV system can be installed, indicating that it can generate 1400 MWh electricity per year, which can cover about 66% of total energy demand of the proposed Green Deck.

If the roofs and vertical façades in the extended deck such as office buildings, hotels, and apartments can be used to install PV panels for power generation, the targets of ‘net zero energy consumption’ and ‘100% renewable energy’ can be achieved.

Figure 5 Possible PV installations on the Green Deck

Therefore, two schemes are proposed in this study. If the PV panels can only be installed above the deck, such PV system can supply 66% of energy for the deck (Scheme 1). If other roofs or facades developed together with the Green Deck are allowed for PV installation, such PV system can supply 100% of energy for the deck (Scheme 2).

The PV system is a grid connected PV system. When solar resource is good during sunshine hours and the power output rate is higher than the load demand of the Green Deck, the extra solar PV power can be exported to local utility grid. When the PV power generation is lower than the demand of the Green Deck, the deficit could be covered by the grid.

Therefore, on an annual basis, the amount of renewable energy power generated on the site is about 66% (Scheme 1) and 100% (Scheme 2) of the total amount of energy consumption of the deck. In Scheme 2, it may also achieve an 'energy-plus deck' as the power generated by the PV arrays may produce a surplus of energy over the year.

4 Economic and environmental evaluation of the PV application

The economic feasibility of the proposed photovoltaic application on the Green Deck has been evaluated with respect to the life cycle cost and cost of energy. A life cycle cost is the total cost of ownership of machinery and equipment, which takes into account the costs of acquisition, operation, maintenance, replacement, and/or decommissioning. The life cycle cost analysis is the most straightforward and easy-to-interpreted measure of cost estimation and economic analysis.

The economic feasibility of an energy generation project can be evaluated using various metrics, while the levelized cost of energy (LCOE) is most often used. The LCOE methodology is an abstraction from reality and is used as a benchmarking or ranking tool to assess the cost-effectiveness of different energy generation technologies. Calculating the LCOE requires considerations of the cost of the energy generating system and the energy generated over its lifetime to provide a cost in $/kWh (or $/MWh or cents/kWh).

Usually, the LCOE can be thought of as the price at which this kind of energy must be sold to achieve cost-recovery over its life cycle. The LCOE of a PV system can be calculated according to the following equation.

$$LCOE = \frac{TAC}{E_{Load}} \tag{8}$$

where TAC is the total annualized cost ($/year), which is the sum of the annualized cost of individual system components; E_{Load} is the total amount of electrical load that the system serves per year (kWh). Based on our previous study, the cost of PV modules and inverters is considered as 1 and 0.5 US$/Wp, respectively. In addition, the hardware cost including cables, cable connection, steel supporting frames, switches, combiner boxes, monitor system and so on, can be assumed as 1.6 US$/W based on the fact that all hardware in Hong Kong has to be imported and the local typhoons mean that much stronger supporting frame is necessary for PV installation. The soft costs, such as labor cost, permitting fees, supply chain costs and project coordination costs, operating overheads as well as the demand for profits, is assumed as 2.5US$/W.

Therefore, the calculated LCOE of the PV installation on the Green Deck is 0.217US$/kWh, i.e. 1.681HK$/kWh. Currently, the general service tariff in Hong Kong is 0.973-1.206 HK$/kWh depending on the amount of electricity consumption and actual fuel cost of the power supply company [7]. However, with rising price of fossil fuels, the tariff would increase for about 5% annually. Therefore, the LCOE of the PV systems on the Green Deck is probably lower than the retail electricity price 5-10 years later, based on the fact of energy shortage and increasing price of fossil fuels. In addition, if considering the environmental cost (penalty associated with pollutant), the economic benefit of the PV systems would be much more significant.

Over dependence on fossil fuels for power generation is alarming. Therefore, the avoided emissions of pollutants, in particular the greenhouse gas, have also been examined in this study. The utilization of fossil fuels for power generation will emit a lot of greenhouse gases, which will pollute our environment and cause global warming. The emission factor from fossil fuel power stations in Hong Kong is 0.79kgCO_2-e/kWh [8]. Therefore, if the Green Deck is powered by the proposed renewable energy, considerable quantity of 1,670 tons CO_2 can be avoided annually. It is clear that investments in renewables are imperative to mitigate both energy shortages and environmental pollution.

5 Assessment of wind power generation

According to our previous research [9], wind energy power generation is also possible in urban areas of Hong Kong, particularly for a hybrid solar-wind application. The potential wind energy above this Green Deck has been evaluated. The result indicates that if a 50kW Seaforth wind turbine is installed close to the seaside, the average daily power generation could be about 115kWh, and yearly output can reach to 42MWh. The monthly energy production from the wind turbine is shown in Figure 6.

However, since the wind turbine will be located in an urban area, the wind speed is reduced by the high-rise buildings. The local wind speed at the proposed deck is very low for economic wind power generation. Therefore wind power is not recommended for the deck.

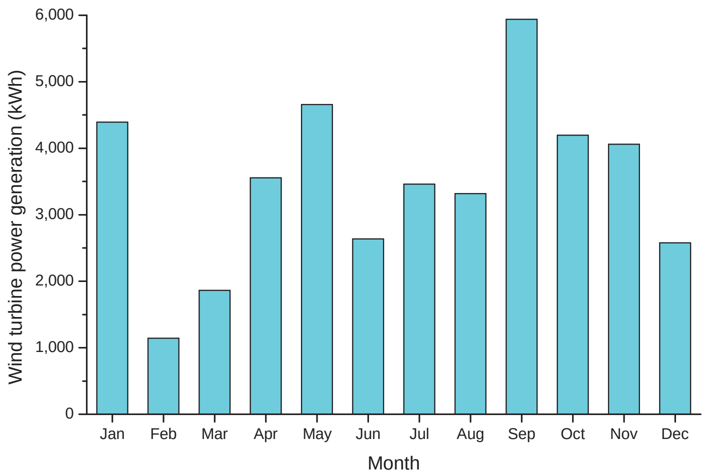

Figure 6 Wind turbine power generation in different months (rated capacity: 50kWp)

6 Conclusions

In this project, we have investigated the potential of solar and wind power generations and the energy consumption of the proposed Green Deck project, and evaluated the economic feasibility and environmental benefit of PV installation on this deck. Given that wind speed is too low for economic power generation in this urban area with high-rise buildings, wind power is not recommended. Therefore, two schemes for PV installation are proposed in this study. If the PV panels can only be installed above the deck, it can supply 66% of energy for the deck (Scheme 1). If the roofs or facades of other buildings developed together with the deck are allowed for PV installation, it can meet 100% of energy consumption of the deck (Scheme 2). It is highly possible to achieve a 'net-zero-energy consumption' deck. To develop a real "green" deck, it is proposed to use the Scheme 2. In addition, this proposal of using renewable energy on the deck is evaluated to be economically feasible after considering future tariff increase and environmental factors.

References

1. *South China Morning Post. Drivers facing three more years of jams in Cross-Harbour Tunnel. 19 February 2014.* .
2. Wu, Y. and J. Niu, *Ventilation strategies for bus passenger waiting areas and boarding passages*, in *Green Deck Final Report* 2014.
3. *Specifications for Design of Ventilation and Lighting of Highway Tunnel (Industry standard of the People's Republic of China).* 1999.
4. Ma, T., H. Yang, and L. Lu, *Development of a model to simulate the performance characteristics of crystalline silicon photovoltaic modules/strings/arrays.* Solar Energy, 2014. **100**(0): p. 31-41.
5. Peng, J. and L. Lu, *Investigation on the development potential of rooftop PV system in Hong Kong and its environmental benefits.* Renewable and Sustainable Energy Reviews, 2013. **27**(0): p. 149-162.
6. Yang, H., et al., *Grid-connected building-integrated photovoltaics: a Hong Kong case study.* Solar Energy, 2004. **76**(1–3): p. 55-59.
7. *www.clponline.com.hk/MyBusiness/CustomerService/TariffOverview/GeneralServiceTariff*.

8. K.H. Leung, M., *Carbon Footprint Management Toolkit for Sustainable Low-Carbon Living*. 2013.
9. Lu, L. and K. Sun, *Wind power evaluation and utilization over a reference high-rise building in urban area.* Energy and Buildings, 2014. **68, Part A**(0): p. 339-350.