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Integration of green roof and solar photovoltaic systems

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ABSTRACT

Green roof and solar photovoltaic (PV) systems are two technologies that could contribute to sustainable building development and reduction of greenhouse gas emissions. When they are combined together on the building roof, it can enhance their functions and effectiveness by cooling and shading effects. This paper explains the major findings of a research to study the benefits of integrating green roof and solar PV systems. The important factors affecting the interactions between the two systems are assessed. The thermal and energy effects are analysed by theoretical models, experiments and field studies. A hypothetical case study to retrofit the roof of an existing building in Hong Kong with such integration is carried out to evaluate the practical design issues. The experimental results showed a positive influence for this integration: green roof surface and soil temperatures are reduced from the shading and higher power output of PV panel is achieved from the cooling. The findings of year-round building energy simulation using EnergyPlus for a low rise commercial building indicated that the energy consumption for air conditioning of the integrated system is slightly lower than the stand-alone system and the PV system on integrated approach generates 8.3% more electricity than the stand-a-lone option. The extent of the benefits depends on the system design and how to determine the optimum arrangement for a particular building site.

Keywords: Green roofs, solar photovoltaic, system integration.

1. INTRODUCTION

Green roof and solar photovoltaic (PV) systems are two technologies that could contribute to sustainable building development and reduction of greenhouse gas emissions. Nowadays, some people are interested in developing green roofs for energy saving, reducing storm water runoff and improving building thermal and environmental performance (Castleton, *et al.*, 2010; Hui, 2010; Hui, 2006). Others are interested in adopting solar PV systems at rooftops for renewable power generation (Parida, Iniyan and Goicm, 2011).

Green roofs and roof-mounted solar panels may initially appear as competitors for limited rooftop space (Peck and van der Linde, 2010). But in fact when they are combined together on the building roof, the integration can enhance their functions and effectiveness by cooling and shading effects (Köhler, *et al.*, 2002). It is believed that cooling from evapotranspiration of green roof plants enables a higher efficiency of PV panels, and at the same time, the panels shade the plants from excessive sun exposure and evaporation thus improving plant growth.

Some research studies have been done in different countries to evaluate the energy and thermal performance of green roof and PV systems separately. However, there are very few studies on the integration of both systems for subtropical climates. This paper explains the major findings of a research to study the benefits of integrating green roof and solar PV systems. The important factors affecting the interactions between the two systems are assessed. The thermal and energy effects are analysed by theoretical models, experiments and field studies. A hypothetical case study to retrofit the roof of an existing building in Hong

Kong with such integration is carried out to evaluate the practical design issues. It is hoped that a better understanding of the integration can help promote sustainable building design.

2. BASIC PRINCIPLES

The thermal properties of green roofs, the electrical efficiency of PV panels and the typical arrangement of system integration are described.

2.1 Thermal Properties of Green Roofs

Figure 1 shows the fundamental concepts to explain the thermal properties of green roofs (Hui, 2009). The external climatic factor (solar radiation, external temperature, relative humidity and winds) are reduced as they pass through the foliage of green roof. Large amount of solar energy are absorbed for the growth of plants through their biological functions, such as photosynthesis, respiration, transpiration and evaporation. The heat transfer of green roofs is dominated by four mechanisms (Del Barrio, 1998; Niachou, *et al.*, 2001; Feng, Meng and Zhang, 2010):

(a) Evapo-transpiration
(b) Shading by plants
(c) Thermal insulation
(d) Thermal mass storage

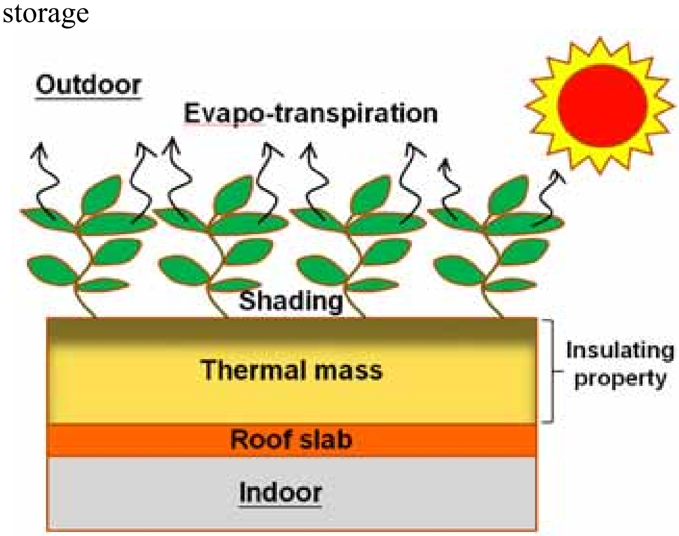


Figure 1. Thermal properties of green roof (Hui, 2009)

The thermal benefits of green roofs can be studied from two aspects (Hui, 2009; Wong, *et al.*, 2003). Firstly, the direct effect to the building (internal) can control roof surface temperature and building heat gain so that the building energy use can be reduced (Castleton, *et al.*, 2010). Secondly, the indirect effect to the surrounding environment (external) can decrease the urban temperature and help mitigate the adverse impacts of urban heat islands.

2.2 Electrical Efficiency of PV Cells

The electrical efficiency (η) of PV cells is the result of the relationship between the power delivered by the cell and the amount of solar irradiation (Meral and Dinçer, 2011; Parida, Iniyan and Goicm 2011). Heat is one of the primary factors that affect the efficiency of roof-mounted PV panels. High rooftop temperatures increase the conductivity of the crystalline semiconductor of PV panel, which in turn inhibits charge separation and lowers the voltage of the solar cell. The high temperature can decrease PV panel productivity by up to 25% and a value of -0.45% per degree celsius can be applied for crystalline silicon PV cells (Peck and van der Linde, 2010; Makrides, *et al.*, 2009). An effective way of improving efficiency and reducing the rate of thermal degradation of a PV module is by reducing the operating temperature of its surface (Meral and Dinçer, 2011).

Another factor influencing the efficiency of PV system is the air pollution or dirt/dust level. Dirt/dust can accumulate on the PV module surface, blocking some of the sunlight and reducing output (Meral and Dinçer, 2011). Kaldellis and Fragos (2011) reported that almost 1.5% efficiency reduction is obtained on a dust-deposed PV panel for ash accumulation on the panel surface reaching 0.4 mg/cm^2. However, it is difficult to generalise and quantify the impact of air pollution on PV system performance because the atmospheric and site conditions may vary significantly.

2.3 System Integration

Initial research by Köhler, *et al.* (2002) showed promising results for green roof and solar PV integration; the electricity generation of PV on green roof is 6% higher than on conventional roofs (Köhler, Wiartalla and Feige, 2007). The green roof cools ambient temperatures around the solar panels, allowing the solar panels to stay cooler and function better. A recent research also confirmed the potential benefit of such integration (Sailor, Wamser and Rosenstiel, 2010). Since green roof can help reduce dust level and improve air quality, the efficiency of PV system could be enhanced but no solid evidence can be found in the literature at present.

On a flat roof with solar PV panels, a green roof installation should be restricted to extensive or low-profile vegetation. The solar panels should be installed above the vegetation level so that the panels are not shaded. Lightweight frames are often used to raise and tilt panels towards the predominant direction of the sun; shade-tolerant vegetation is then planted under the panels. Figure 2 shows an example of green roof and solar PV integration.

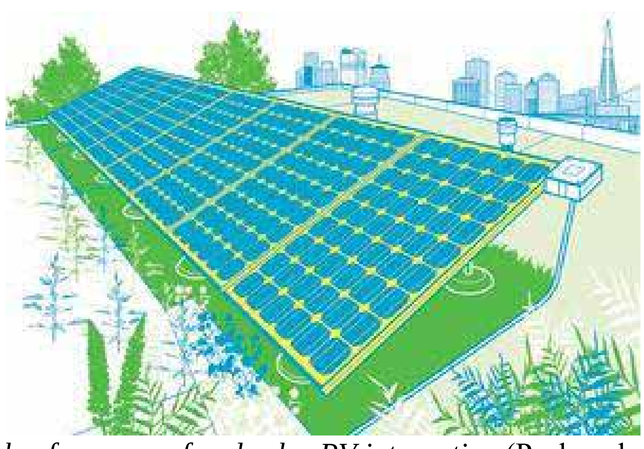


Figure 2. An example of green roof and solar PV integration (Peck and van der Linde, 2010)

The solar panels were mounted on framework which is fixed to plastic boards. The profiled plastic boards are covered with substrate and allow rain water to drain through and vegetation to grow underneath the solar panels. Frames usually have a base (also lightweight) to permit better load distribution. The roof is therefore better protected from damage by point loads. The racking systems for solar panels may be designed so that the green roof layers act as ballast, thereby saving the need for roof penetrations or concrete pavers (Peck and van der Linde, 2010).

3. ENERGY SIMULATION ANALYSIS

To investigate the energy impacts of green roof and solar PV integration, a building energy simulation software, EnergyPlus Version 6.0 (www.energyplus.gov), was used. This software EnergyPlus has a green roof model developed by Sailor (2008) and can calculate the annual energy consumption of the whole building with solar PV systems. Four simulation models were set up using EnergyPlus for comparing the energy performance of green roof, PV and the integrated systems under the Hong Kong climate. Figure 3 shows the basic descriptions of the models. Model number 1 is the base case reference (bare roof) which is a 12-storey office building with a total floor area of 46,320 m^2. Model number 2, 3 and 4 are derived from the base case with green roof and PV systems added.

Figure 3. Four simulation models for the investigation of energy performance

It is assumed that the PV systems of model number 3 and 4 have efficiency of 12% and 13%, respectively. Each PV system covers a roof area of 2,494 m^2. Also, the power generated from the PV system is used for general lighting (i.e. decreases the actual lighting energy use). The leaf area index (LAI) of model number 2 is assumed to be 3 for a typical extensive green roof, whereas the LAI of model number 4 is divided into two parts: LAI = 3 for 30% of roof area (exposed) and LAI = 3.5 for 70% of roof area (under the PV panels).

3.1 Annual Energy Consumption

As the PV system will only affect the lighting energy and the green roof system will affect the building thermal load, it is more effective to assess the energy consumption components of lighting and space conditioning in order to evaluate the energy impacts. Figure 4 indicates the annual energy consumption of lighting and space conditioning for the four models. From the lighting energy consumption, it is found that the PV panels of the integrated system produce 118 GJ more energy than the PV panels on bare roof. As for the space conditioning, the figures for the 4 models are very close. This implies that the green roof system has minimal direct impact on the building energy consumption. It is because the amount of green roof area is small as compared to the total building floor area.

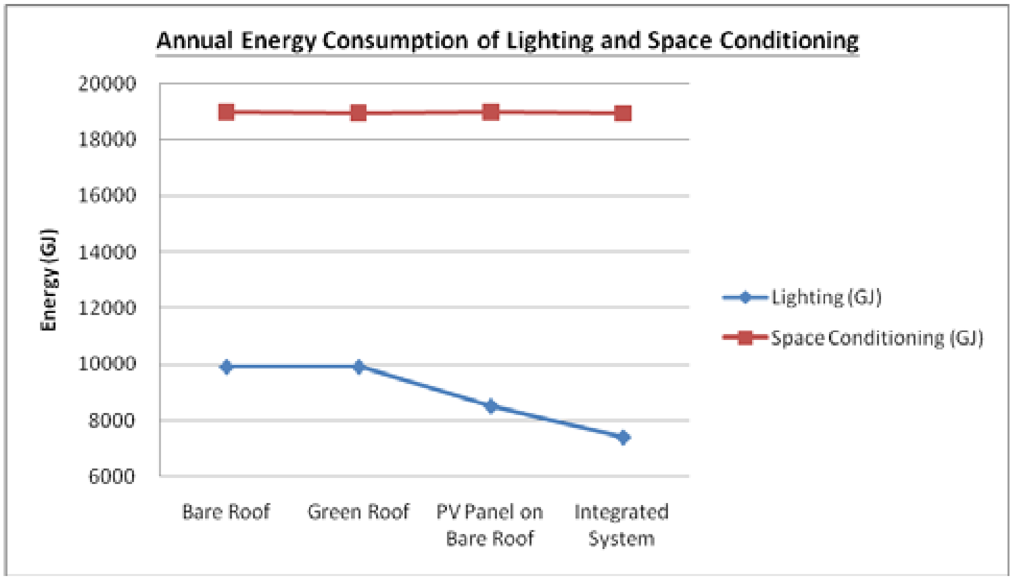


Figure 4. Annual Energy Consumption of Lighting and Space Conditioning

3.2 Monthly Energy Performance

Figure 5 shows the monthly energy generation of the stand-alone PV (model number 3) and green roof integrated PV system (model number 4). It can be seen that the PV systems generate more energy during summer time than winter time due to high value of solar irradiance in summer. For each calendar month, the integrated system produces 8.3% more energy than the stand-alone system because of the efficiency improvement (assumed from 12% to 13%). This amount only considers the direct effect to the building itself. If the indirect effect to the surrounding environment and urban temperature is taken into account, there could be benefits for other buildings too.

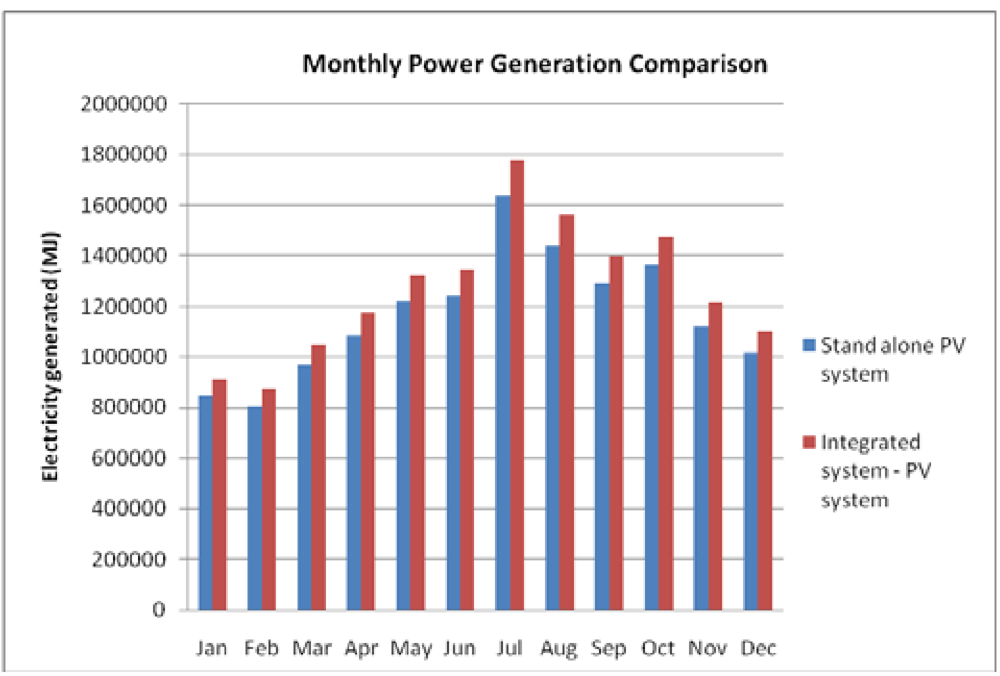
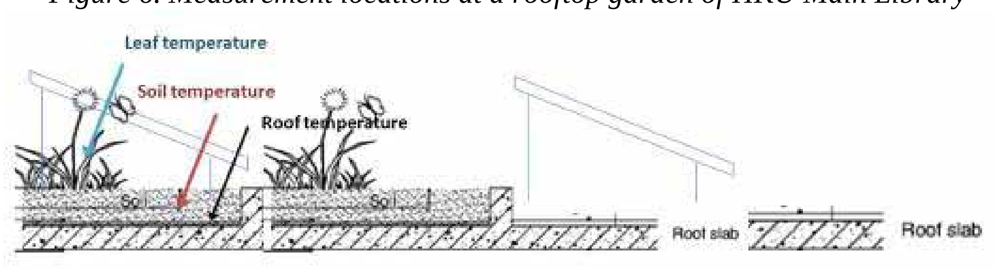


Figure 5. Monthly power generation of stand-alone PV and green roof integrated PV systems

4. FIELD MEASUREMENTS

In order to study the practical design issues of green roof and PV integration, field measurements had been carried out on a rooftop garden of HKU Main Library (see Figure 6) on a sunny day from 11 am to 2 pm. Control experiments were done by using two identical PV panels which were placed on a bare roof and an intensive green roof. Figure 7 shows the four scenarios being assessed. The temperature at different positions and the power output of the PV panels were recorded using temperature sensors, data loggers and multi-meters. Temperature sensors were placed inside the soil layer (about 1 to 2 cm depth), at the soil surface and leaf surface, and on the upper and bottom surfaces of the PV panels.

Figure 6. Measurement locations at a rooftop garden of HKU Main Library



Integrated system Green roof Bare roof with PV Bare roof

Figure 7. Four scenarios being assessed for the field measurements

4.1 Assessment of Temperatures

Figure 8 compares the soil surface temperatures of the integrated system (with shading effect) and the green roof (without shading by PV panels). A temperature difference of about 4 to 5 ºC can be observed. It is believed that this shading effect is important for the healthy growth and well-being of the vegetation especially during the very hot summer period. Hui (2009) has observed at a school green roof project in Hong Kong that the sedum plant can grow better under partial shading near the ventilating fans of the roof. Köhler, Wiartalla and Feige (2007) also found that in the shade of the PV panels, the biomass and number of plant species are significantly higher.

As for the PV panels, the temperature measurements on the upper surfaces indicate that the integrated system (with greening around) has 5 to 11 ºC lower than the bare roof PV system. This temperature difference was observed under bright sunshine when the PV panels were producing high electrical output. In order to assess the total power yield generated by the PV systems, further studies are needed to evaluate the conditions throughout the year.

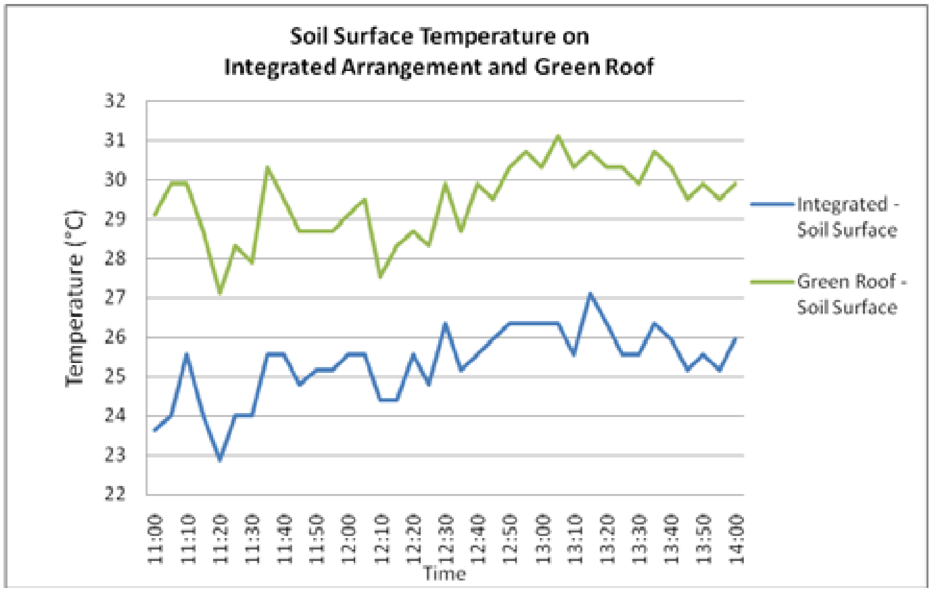


Figure 8. Soil surface temperatures of integrated system and green roof

4.2 Assessment of PV Output

Figure 9 shows the power output of PV panels on bare roof and integrated system. The average power production over the period for integrated system and bare roof PV panel are 32.2W and 33.6W, respectively. In general, the integrated system can give about 4.3% more electricity than the PV on bare roof during measurement period. The temperature evaluation of the PV panels also indicated that the cooling effect by vegetation is quite significant.

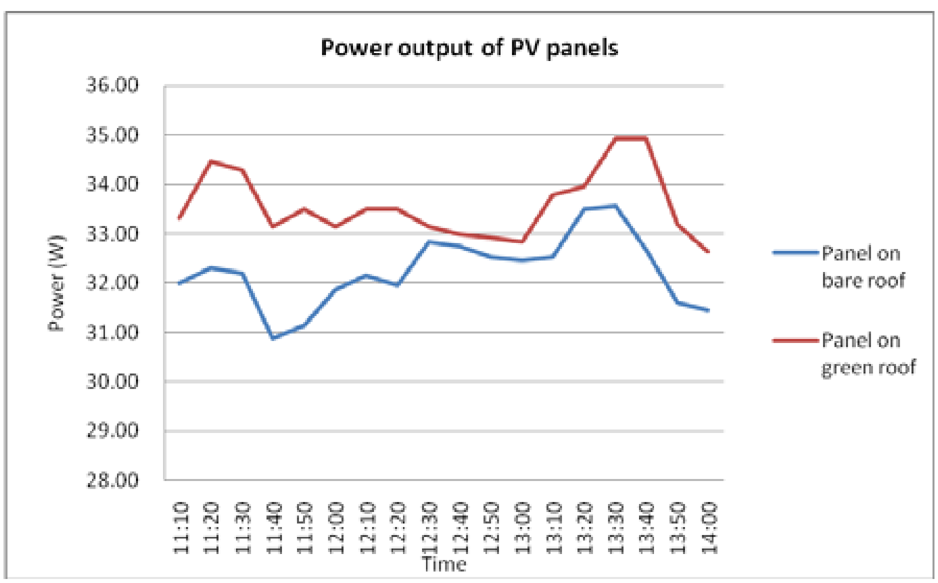


Figure 9. PV power output on bare roof and integrated system

Li, Cheung and Lam (2005) found that the operational performance and efficiency of a PV system in Hong Kong is influenced considerably by the climatic variables, such as solar irradiance availability and ambient temperature. In fact, the PV output is also affected by air pollution or dust level (Meral and Dinçer, 2011) and the surrounding rooftop environment. However, it is not possible to distinguish them from the current measurement results.

5. CASE STUDY

Hong Kong has high-density and high-rise building developments, therefore, the available roof space is often very limited (Hui and Chan, 2008). If it is feasible to apply both green roof and PV systems onto the available roof space, this can facilitate a more effective use of sustainable technologies and help to reduce the total investment costs (Hui, 2010). When this idea is applied to existing buildings, it can provide many benefits to improve the building performance and urban environment, as illustrated in the case study.

5.1 EMSD Headquarters

To evaluate the practical design issues, a hypothetical case study was created to retrofit the roof of an existing building in Hong Kong. This building is the headquarters of the Electrical and Mechanical Services Department (EMSD) and has a roof area of about 7,900 m^2. The roof is made of aluminum sheet modules (known as Kalzip aluminum standing seam roofing system) and a 350 kW grid-connected PV system has been installed on the rooftop (Ho, Chan and Lau, 2007) (see Figure 10). It is proposed that an extensive modular green roof system (using sedum plant) will be installed on the roof by integrating with the Kalzip roofing system. By coordinating the green roof with the existing roofing system, the additional costs can be reduced and the roofing performance ensured.

Figure 10. PV and roof systems at the EMSD Headquarters

5.2 Integration Performance

To assess the building energy benefits of adding the green roof to the EMSD headquarters, an indicator for the energy saving per green roof area (due to thermal benefits of green roof) was developed from the energy simulation results in Section 3. It was determined by dividing the total annual energy reduction in air conditioning loads due to green roof by the total green roof area of the model building. This indicator was found to be 37.32 MJ/m^2.

(a) Green roof performance on annual basis

Assuming the green roof will be installed on 80% of the roof area, by applying the energy saving indicator, the annual energy and cost saving is calculated as shown in Table 1.

Table 1. Green roof performance calculation

Green roof area	6300 m^2 (about 80% total roof area)
Energy saving per green roof area	37.32MJ/m^2 (based on simulation result)
Energy saving due to green roof installation	235,116 MJ
Electricity consumption reduction	65,310 kWh
Annual cost saving	**HK$63,351**

(b) PV system performance on annual basis

Assuming the PV system efficiency improves from 12% to 13% due to cooling effect of the green roof. Additional electricity generated from the PV system and the cost saving are calculated as shown in Table 2. The electricity cost is assumed to be HK$0.97 per kWh. The reference annual final yield is extracted from Ho, Chan and Lau (2007).

Table 2. PV system performance calculation

Parameter	**With Green Roof (Efficiency = 13%)**	**Without Green Roof (Efficiency = 12%)**
Annual final yield (kWh/kWp)	1,021.6	943
Electricity generated (kWh)	357,560	330,050
Cost saving (HK$)	346,833	320,149
Annual cost saving due to green roof :	**HK$26,685**	

It can be seen from the above estimates that the potential energy and cost savings are quite good. There are also other benefits on micro climate, dust level and acoustic performance (during heavy rainfall, the aluminum Kalzip roofing system will generate noise).

6. DISCUSSIONS

It is believed that green roofs and PV system can be used together and there is no clash between them (Köhler, Wiartalla and Feige, 2007). Combining the two technologies in an innovative way to form so called “green roof integrated PV” (Witmer and Brownson, 2010) could bring positive effects to building energy conservation and improving of the surrounding urban environment. The extent of the benefits depends on the system design and how to determine the optimum arrangement for a particular building site. In order to maximize the overall performance of the integrated green roof and PV system, it is essential to study and understand the interactions between them.

6.1 Positive Effects of Green Roofs

The installation of PV panels with green roofs will result in a net cooling of the micro climate that offsets the warming effect of PV panels. In most project situations the additional costs for the extensive green roof could be recovered by the higher electrical power output of the PV system over a few years following installation. To maximize the cooling effect, the layout and spacing of the integrated system must be designed carefully. The size and scale of the greening must be large enough to contribute cooling to the surrounding.

Usually, the PV panel and vegetation should be placed at a close distance so that the cooling by evapo-transpiration can directly influence the solar modules. Green roofs with sprinkler head irrigation could enhance the cooling by increasing the moisture level and producing water mist in the air. If the irrigation system and natural rainfall are properly arranged, the water could help to remove the dirt/dust on the solar panels too.

6.2 Advantages of Solar Panels

The solar panels shade parts of the roof and thereby reduce the sun exposure and high evaporation rates normally experienced on extensive green roofs. The shading will reduce the drought stress for plants and could enhance green roof ecosystem viability by promoting more plant species and biodiversity. This might also enable the use of plants that increase carbon sequestration and carbon gain.

The electricity generated by PV panels can be used to power the water pumps, lighting and other electrical appliances. By proper designing and matching of the electrical loads, it is possible to become self-sufficient on electricity for the building rooftop. This will reduce the costs of electrical wiring and distribution from the supply mains. Together with rainwater harvesting and other renewable technologies, a sustainable system can be created for roof gardens and/or rooftop farming (Hui, 2010).

6.3 Other Considerations

Most design guidelines for green roofs will remind people to check the structural loading and waterproofing membrane before committing to the project (Hui, 2010). The integrated green roof and PV system will have many components and must be assessed carefully for the overall weight and water leakage issues. For existing buildings, the site constraints and limitations might demand designers to select and arrange the system elements (e.g. lightweight and modular) so that the load carrying capacity is not exceeded and construction can be carried out effectively.

Another key issue to consider is related to system maintenance. It should be noted that intensive green roofs or roof gardens have high maintenance requirements, such as watering, fertilizing, trimming and weeding. For a properly installed extensive green roof, once it is well established, its maintenance requirements are usually minimal. Plants for green roofs must be selected with care if the roof is expected to stay more or less maintenance free. For maintenance of PV panels, pathways are needed and this mean also more trampling disturbance of the vegetation.

7. CONCLUSIONS

Integrating green roofs and solar PV systems can enhance their functions and effectiveness by cooling and shading effects. The results of literature theoretical study, field measurements and case study in Hong Kong indicated a positive influence for this integration. It is found from field measurements that green roof surface and soil temperatures are reduced from the PV panel shading and higher power output of PV panel is achieved from the green roof cooling effect. The findings of year-round building energy simulation using EnergyPlus indicated that the energy consumption for air conditioning of the integrated system is slightly lower than the stand-alone system and the PV system on integrated approach generates 8.3% more electricity than the stand-a-lone option. The extent of the benefits depends on the system design and how to determine the optimum arrangement for a particular building site. In general, this research study provides useful hints to understand green roof and PV integration for hot and humid climates.

As we move towards more sustainable buildings, our knowledge of how organic (e.g. greening) and inorganic (e.g. solar PV) technologies can work together will be critical to the long-term success of the society (Peck and van der Linde, 2010).

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