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Energy and economic performance of green roof system under future climatic conditions in Hong Kong

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ABSTRACT

In this study, an experimental setup of a green roof system was established on the rooftop of a commercial building for computer model validation. Then a generic office building constructed with green roof was modeled using EnergyPlus and its energy performance was evaluated under different future climatic conditions over three future periods (2011–2030, 2046–2065 and 2080–2099) and two emission scenarios (SRA1B and SRB1). The findings show that a combination of thicker soil layer, lower plant height and higher value of leaf area index (*LAI*) can provide a better thermal insulation effect in a green roof system. The results reveal that a building case with soil thickness of 0.4 m, plant height of 0.05 m and *LAI* of 5 can maintain the year-round A/C energy consumption no more or less than the current level, ranging from −2.4% to −10%, under the future climatic conditions (2011–2030 and 2046–2065, for both emission scenarios). Economic evaluation on the application of green roof was also conducted. Taking into account the replacement cost of a conventional bare roof, the cost payback period is about 10 years. The application of green roof system can act as a potential measure to cope with the impact of climate change.

1. Introduction

Nowadays, people are spending great effort to maintain a pleasant living environment with concern on human health and sustainable development of a city. However, as the energy consumption in developed cities continues to increase, problem such as emission of pollutants from combustion of fossil fuel not only causes adverse effect to the environment but also affects the economic growth [1–3]. As a result, many cities are pursuing a healthy and sustainable living environment. One of the approaches is the use of more planting with vegetation in the urban environment.

However, under the developed layout of a city, it is relatively difficult to search new area for increasing and enhancing the amount of greenery in the urban city. One of the various options is setting up green roofs on buildings. A green roof is a lightweight roofing system with a vegetated space which is structurally integrated on the top of a man-made structure. Green roofs offer a number of merits. In terms of environmental benefit, the urban heat island effect (urban surface layer) can be mitigated since the plants can offer the roof an increased building insulation, protect the buildings from solar radiation and carry out heat energy through evaporation process of the plant and soil [4,5]. Moreover, the air quality can be improved as the vegetation has large surface area for filtering out the fine airborne particles [6,7].

1.1. Application and research of green roof

The use of green roofs is becoming increasingly popular for both new and retrofit buildings in European countries, especially in UK, France and Germany, and some Asian cities such as Singapore and Japan. In London, about 100,000 m^2 green roofs were installed in 2008. Germany adds about 11 million m^2 of green roofs each year and Berlin has between 5 – 30% of roof space greened in different parts of the city. In France, approximately 1 million m^2 of roofs are greened per annum [8].

The Singapore National Parks Board (NParks) had introduced a Skyrise Greenery Incentive Scheme (SGIS) in 2009. Under this Scheme, the NParks would fund up to 50% of the installation costs of green roofs and vertical greenery for all building types approved by NParks that had been granted temporary occupation permit for a minimum period of 6 months [9]. In 2003, the Japan Ministry of Land, Infrastructure and Transport announced a revision on the national nature conservation regulations, mandating all new constructions (multiple dwelling houses and offices buildings) greened at least 20% of their rooftops. This regulation was enforced in 2005 [10].

Various studies are being undertaken with an aim of improving the performance of green roofs. One of the main approaches

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Nomenclature

C_e^g	bulk transfer coefficient for latent heat near ground
C_h^g	bulk transfer coefficient for sensible heat
C_f	bulk transfer coefficient
$c_{p,a}$	specific heat of air at constant pressure (J/kg K)
e_o	windless sensible heat correction factor (2.0 W/m^2)
H_f	foliage sensible heat flux (W/m^2)
H_g	ground sensible heat flux (W/m^2)
$I_{ir}^{\downarrow}$	total incoming long-wave radiation (W/m^2)
$I_s^{\downarrow}$	total incoming short-wave radiation (W/m^2)
L_f	foliage latent heat flux (W/m^2)
L_g	ground latent heat flux (W/m^2)
LAI	Leaf Area Index
l	latent heat of evaporation (J/kg)
q_{af}	mixing ratio of air at foliage interface
$q_{f,sat}$	saturated foliage mixing ratio
q_g	mixing ratio of air at ground surface
r''	foliage surface wetness
T_{af}	air temperature in foliage (K)
T_f	foliage temperature (K)
T_g	ground surface temperature (K)
W_{af}	wind speed at air-foliage interface (m/s)
z	height or depth (m)
α_f	albedo (short-wave reflectivity) of the canopy
α_g	albedo (short-wave reflectivity) of ground surface
ε_f	emissivity of canopy
ε_g	emissivity of the ground surface
ε_1	$\varepsilon_g + \varepsilon_f - \varepsilon_g\varepsilon_f$
ρ_{af}	air density in foliage near atmosphere-foliage interface (kg/m^3)
ρ_{ag}	air density near foliage-ground interface (kg/m^3)
σ	Stefan-Boltzmann constant (W m^{-2} K^{-4})
σ_f	fractional vegetation coverage
κ	soil thermal conductivity of the surface (W/m K)

is experimental work in which planted roof is constructed on the rooftop of a building. Field measurement had been carried out by Wong et al. [11,12] on the roofs of some selected buildings in Singapore to investigate the thermal impact of rooftop garden. On the roof of a low-rise commercial building, a maximum decrease in the surface temperature of 30 °C caused by vegetated plant was found. Moreover, reduced long-wave radiation from the planted roof was observed through comparisons of global temperature and mean radiant temperature (MRT) between a green roof and a bare roof. A maximum reduction in global temperature and MRT were found as 4.1 °C and 4.5 °C, respectively, giving evidence that planted roofs could contribute to the mitigation of urban heat island effect in the urban city.

A test chamber was established and experiments were conducted by Fang [13] for evaluating the thermal reduction effect of plant layers in Taiwan. The study comprises two experiments. The first one was a test chamber with stable light source constructed in an indoor space. The second experiment was performed on the rooftop of a building. Four species of vegetation were planted in pots on a rooftop to confirm the measured data from the first experiment. A chamber of dimensions 40 cm (L) × 10 cm (W) × 70 cm (H) was constructed and covered with thermal insulation in order to prevent interference from atmospheric temperature and light. The plant was located inside the chamber with five thermocouples installed for soil temperature measurement. The thermocouples (K-type) were calibrated with an error margin of ±0.2 °C and placed on a plastic board and connected to a hybrid recorder. A limiting duration of 30 s was allocated per measurement. Two relevant parameters namely coverage ratio and total leaf thickness were found positively correlated with the thermal reduction ratio (TRR). With the measured data, a quantitative TRR map was established that could provide a straightforward guidance on the thermal reduction and planting arrangement for green roofs. The TRR map was confirmed by outdoor experiments using various species of plants on an actual rooftop of a building.

Ouldboukhitine et al. [14] investigated experimentally on three main physical properties of green roof with an aim at identifying the key green roof modeling parameters. The thermo-physical properties of green roof were characterized by the thermal conductivity of substrate with water content for different substrates. Moreover, dynamic vapor sorption technique was adopted to determine the sorption and desorption isotherms for different temperatures and moisture buffer capacities. The porosity range of the substrate in green roof system was also investigated.

A study was conducted by Jim et al. [15,16] to investigate the weather effect on the thermal performance of a retrofitted extensive green roof on a railway station in humid subtropical region. The study revealed that the green roof of area 484 m^2 could bring a potential energy saving of 2.8×10^4 kWh in the air-conditioning system. Moreover, green roof passive cooling was enhanced by high solar radiation and low relative humidity in typical summer sunny days. The findings also indicated that high soil moisture supplemented by irrigation could lower the air and vegetation surface temperature, and dampen the diurnal temperature fluctuations. In addition, a high wind speed could increase the evapotranspiration cooling of the green roof area.

Similar to other fields of study, computer simulation offers its high efficiency and flexibility in research. Advanced building energy simulation software including ESP-r (Environmental Systems Performance-research) and TRNSYS (Transient System Simulation Tool) allow users to develop and incorporate a module of green roof for evaluating the thermal performance of green roof system in a building [17–21]. Traditionally, field measurements were conducted to study green roofs, before modeling approaches were considered. The data collected from field measurement were used for development of a green roof model. The predictive numerical model was then incorporated into an existing building energy simulation software to investigate the thermal and energy performances of buildings with different green roof systems, under various meteorological conditions. The performance evaluation in general showed a significant reduction of building cooling load in summer season. This reduction varied in a range of 12–87% for the roof floor. However, the influence of the green roof system in building heating load was found insignificant.

Another well-known building energy simulation program DOE-2 was used by Wong et al. [22] to study the effects of rooftop garden on the cooling load and annual energy consumption of a five-story hypothetical building in Singapore. Various vegetation plants including turfing, shrubs and trees with different thermal resistances and soil types were modeled using DOE-2 program. The results showed a saving of 0.6–14.5% in the annual energy consumption of air-conditioning system and shrubs was found to be most effective in reducing building energy consumption.

In 2008, a model of energy and moisture balance of vegetated rooftop had been developed and integrated into a building energy simulation program EnergyPlus by Sailor [23]. The development of the model was based on an Army Corps of Engineers' *FASST* vegetation model [24] that solves simultaneously for the foliage surface and soil temperatures at each time step. It is a one-dimensional model that contains energy budgets for both the foliage layer and the ground surface; and tracks the energy and moisture balance within a vegetated soil.