BUILD SIMUL (2018) 11: 421–434
https://doi.org/10.1007/s12273-017-0415-7

Research Article

Building Thermal, Lighting, and Acoustics Modeling

Comparing reduction of building cooling load through green roofs and green walls by EnergyPlus simulations

Kalani C. Dahanayake, Cheuk Lun Chow (✉)

Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, China

Abstract

Green roofs (GRs) and green walls (GWs) are good strategies for urban greenery. This study explores the cooling load benefits of GRs and GWs simultaneously for comparison. EnergyPlus simulation programme is used for estimating annual cooling load reduction for different buildings and scenarios in Hong Kong. In simulating GR, a built-in thermal model is used. For GWs, a self-developed thermal model is used, which has been developed and validated in our previous study. The simulation covers a single-storey building and two multi-storey buildings, each with four different coverage areas for GR and GWs. The GWs are assumed to be on building facade facing the west, east, north, and south. Results reveal that both GRs and GWs are capable of protecting building envelop from reaching higher temperatures and of reducing cooling load. In a single-storey building with an equal area of GR and GW, GR is more effective in energy saving. However, in a multi-storey building GR can provide energy benefits only to the topmost floor. An equal area of GW can provide benefits to multiple floors, which may result in higher benefit. Furthermore, the available area for GWs is larger. When considering the effect of orientation of GW, the west-facing GW contributes to the highest annual energy saving. It should be noted that the effect of orientation may differ with location and climatic conditions, and also with the shading effect of surrounding buildings. Therefore, installation of GRs or GWs should be considered case by case, taking into consideration the scale and surroundings of the building, the climatic condition, and area of greenery coverage.

Keywords

green roofs,
green walls,
cooling load,
EnergyPlus,
orientation,
greenery cover

Article History

Received: 17 May 2017
Revised: 14 August 2017
Accepted: 11 September 2017

1 Introduction

Rapid urbanization has transformed cities into concrete jungles leading to miscellaneous environmental issues. Very limited urban areas remain as green spaces in crowded cities. The change of material properties such as thermal conductivity, heat capacity, and surface emissivity, together with the increase of energy consumption, has led to increasing in air temperature and more pronounced heat island effect in urban settings (Hong and Lin 2014; Pierangioli et al. 2017). Urban greening is getting popular in congested cities as a solution for these emerging environmental issues. Among different forms of urban greening, green roofs (GRs) and green walls (GWs) are most suitable for congested cities since they do not require a land space. Apart from aesthetic appearance, they also provide a wide range of environmental and economic benefits (Dahanayake and Chow 2015).

Unutilized rooftop surfaces can be converted into GR by planting vegetation on a growing medium (substrate) (Kokogiannakis et al. 2014; Moradpour et al. 2017). They generally consist of a number of layers including vegetation, substrate, filter material, root barriers, insulation and an irrigation and drainage system. GRs can be classified into intensive and extensive GRs. Intensive GRs consist of a thicker substrate layer (>20 mm) which can accommodate shrubs and even small trees. In contrast, extensive GRs consist of thin a substrate layer (<15 mm) which can only accommodate grasses and moss (Silva et al. 2016). Thus, intensive GRs are cable of accommodating a wide variety of plant types compared to extensive GRs. On the other hand, intensive GRs require higher maintenance and capital cost and higher structural stability of the building (Berardi 2016).

The construction of GWs is very similar to GRs, but with the substrate attached vertically onto the walls of the building. However, traditional GWs are less sophisticated, usually accommodating self-climbing plants or hanging down plants,

E-mail: cheuchow@cityu.edu.hk

and the substrate is located at the ground level or at elevated levels. They require considerable time for growing and may reach only a limited height of the building (Dahanayake and Chow 2017). Modern GWs consist of structural elements to hold the plants and growing medium. These enable the use of a wide range of plants and facilitate these plants in reaching higher elevations of the building facade (Dahanayake and Chow 2015, 2017). Modern GWs are known as modular living walls, hydroponic systems, vegetation mats etc., depending on the characteristics of vegetation and substrate (Dahanayake and Chow 2015).

Both GRs and GWs provide thermal benefits via controlling heat gain transferred to the building. The controlling of thermal microclimate using GRs and GWs can be explained in four mechanisms, namely; insulation, evapotranspiration, shading and wind barrier effect (Sailor 2008). Since GRs and GWs consist of a number of layers they enhance thermal insulation of the building envelope. Insulation effect depends upon many factors, such as foliage density, thickness of substrate and their thermal properties (Sailor and Hagos 2011). On the other hand, evapotranspiration effect due to the vegetation and substrate creates a cooling effect in the surrounding. Evapotranspiration is referred to the evaporation of water in the soil and transpiration of vegetation by absorbing the heat from the surrounding. This process transforms sensible energy into latent energy and it also increases the humidity level in the surrounding. Evapotranspiration is influenced by plant species, irrigation regime and climatic conditions (Dahanayake and Chow 2017). Plants also create a shading effect by intercepting solar radiation. The shading capacity of plants is usually characterised by illuminance and shade factor. The wind barrier effect is the ability to prevent the wind directly reaching the building envelope. Usually, plants contribute to reduce wind velocity and affect the envelope thermal efficiency.

Thermal benefits of GRs and GWs are extended to building level as well as urban microclimate level. They contribute to reducing the exterior surface temperature of building envelope and pedestrian level cooling (Ouldboukhitine et al. 2014; Morakinyo et al. 2017). In the building level, controlling of surface temperature results in regulation of indoor air temperature and ultimately contributing to cooling load reduction. The degree of thermal benefits depends upon plant characteristics, substrate properties, building envelope and weather and climatic conditions (Ferroukhi et al. 2016; Silva et al. 2016).

2 An overview of thermal performance of GR and GW

A number of experimental studies have investigated the cooling load benefits of GR and GW. For instance, Ouldboukhitine et al. (2014) showed that in France GR reduces exterior surface temperature up to 20 °C. Similar results are obtained by Karachaliou et al. (2016) and Foustalieraki et al. (2017) in Greece, where these studies showed that GR can reduce exterior surface temperature up to 15 °C and 21.9 °C respectively. A study by Wong et al. (2003) showed that in Singapore GR can reduce exterior roof surface temperature up to 30 °C. A study in Hong Kong, China showed that presence of GR can reduce the inside temperature up to 3.4 °C (Tam et al. 2016). Coma et al. (2016) showed that during the summer period in Spain, extensive GR reduces energy consumption up to 16.7%. These studies adequately prove that the GRs can significantly reduce the exterior surface temperature and control the heat transfer into the building.

Similar experimental results are obtained for GWs. A study in Wuhan, China (Chen et al. 2013) showed that during summer season GW can reduce the exterior surface temperature of walls up to 20.8 °C. In Italy (warm temperature) exterior surface temperature reduction is up to 20 °C (Mazzali et al. 2013). For Hong Kong, China reduction is 16 °C during the summer period (Cheng et al. 2010). In Singapore, the surface temperature reduction of 10 °C is achieved (Wong et al. 2010). These results emphasis the exterior surface temperature reduction capability of GRs and GWs.

In addition, a number of simulation studies have also shown the thermal performance of GRs and GWs (Kokogiannakis et al. 2014; Hong and Lin 2014; Moradpour et al. 2017). The concept of GWs is relatively new and only limited number of simulation studies can be found. Some of the building energy simulation tools such as EnergyPlus consist with a validated built-in GR module (DOE 2015), facilitating simulation of GRs. However, at the moment most of the building simulation tools do not facilitate simulation of GWs. Table 1 summarises a number of simulation studies and their key findings. As shown most of the GR studies are conducted using EnergyPlus simulations. For GWs, researchers have used self-developed models. These simulation studies show the energy saving capability of GRs and GWs under different climatic conditions.

All these studies are based on either GR or GW separately. In the present study, the effect of both GRs and GWs on building cooling load is analysed and compared. The study is based on simulations using EnergyPlus, which is a widely accepted building simulation software. EnergyPlus consists of a built-in module capable of evaluating the thermal effect of GRs. The thermal effect of GW is evaluated using the EnergyPlus in conjunction with a self-developed module which has been validated in our previous study (Dahanayake and Chow 2017) which is explained under Section 3.1. It has been shown that GWs can provide energy benefits to the building through controlling the exterior surface

Table 1 Findings of simulation studies of GRs and GWs

Reference	System description	Location	Model/software	Key findings
Green roofs				
Sailor 2008	Intensive and extensive green roofs	Florida	Green roof module implemented in EnergyPlus program	The model presented here represents a significant advance in building design capabilities within the building energy modeling community
Jaffal et al. 2012	Extensive green roof	France	A mathematical model coupled with TRNSYS	The annual energy demand was reduced by 6%
Costanzo et al. 2016	Extensive green roof	Italy	EnergyPlus program	GR can reduce exterior surface temperature up to 20 °C
Karachaliou et al. 2016	Intensive green roof	Athens, Greece	EnergyPlus program	Annual cooling and heating loads of the building reduced by 19% and 11% respectively
Silva et al. 2016	Intensive and extensive green roofs	Mediterranean climate	EnergyPlus program	Semi-intensive and intensive green roofs energy use is 60%–70% and 45%–60% lower than black and white roofs, respectively
Morakinyo et al. 2017	Intensive and extensive green roofs	Cairo, Hong Kong, Tokyo, Paris	Co-simulation approach with ENVI-met and EnergyPlus	Maximum of 5.2% cooling demand reduction in hot-dry climate with full-intensive GR while the least saving of 0.1% was found with semi-extensive green-roof in temperate climate
Foustalieraki et al. 2017	Medium scale green roof	Athens, Greece	EnergyPlus program	Overall saving of 15.1% for a whole year on the energy consumption
Zeng et al. 2017	Green roofs with different parameters	Four climate zones in China	EnergyPlus program	Optimal parameters of GR were found as 0.3 m of soil thickness and 0.5 of LAI (leaf area index)
Tian et al. 2017	Extensive green roof	Chongqing, China	A mathematical model based on heat fluxes	The short-wave radiation is the major heat gain for GR. During the day, the main heat transfer ways for GR is latent heat transfer on canopy
Green walls				
Di and Wang 1999	Traditional green facade	Beijing, China	Self-developed mathematical model	Peak cooling load reduction of GW is 28%
Stec et al. 2005	Double-skin green facade	The Netherlands	Self-developed mathematical model	Cooling load reduction of GW is about 20%
Kontoleon and Eumorfopoulou 2010	Traditional green facade	Greek region during the cooling period	Self-developed thermal-network model	Cooling load reductions are found as 20.08%, 18.17%, 7.60% and 4.65% respectively for west, east, south and north orientations
Susorova et al. 2013	Traditional green facade	Chicago	Self-developed mathematical model	GW can improve its effective thermal resistance up to 0.7 $m^2 \cdot K/W$, depending on a range of inputs
Scarpa et al. 2014	Living wall	Temperate climate	Self-developed mathematical model	Developed model show a good agreement with the measurements, 0.7 were obtained for the Nash–Sutcliffe efficiency index (NSEC) index
Djedjig et al. 2015	Living wall	Mediterranean climate	Self-developed green envelope model coupled with TRNSYS	The average bias of the simulation through one summer month is only 0.22 °C for the vegetated facade with a mean-root- square error of 1.42 °C
Davis and Hirmer 2015	Living wall	UK	A mathematical model based on the FAO-56 Penman Monteith Equation	A promising correlation between the mathematical model and empirical experiment, but suggested that either the relative humidity level was lower than estimated
Carlos 2015	Living wall	Portugal	EnergyPlus simulations after it was validated against other studies	GWs effective in lowering the thermal losses through north, east and west walls during winter period, thus it can improve the energy efficiency of the building mainly by insulation effect
Dahanayake and Chow 2017	Living wall	Hong Kong	Self-developed module integrated into EnergyPlus	Maximum of 26 °C reduction in exterior surface temperature of facade and 3% reduction of annual cooling energy consumption

temperature of walls. The current study is extended to check the effect of the scale of the building, area of greenery coverage and the orientation, with a comparison of the effectiveness of GRs and GWs. Simulations were carried out on single-storey building and two multi-storey buildings, each with four different coverage areas for GRs and GWs. Furthermore, GWs were simulated for each of the building facade orientations: west, east, north, and south. The findings of the study provide an insight on potential cooling load benefits with respect to the scale, coverage and orientation of the GRs or GWs.

3 Methodology

3.1 Thermal modelling of GR and GW

This study uses EnergyPlus simulations to model both GRs and GWs. EnergyPlus is a widely accepted open-source energy simulation package based on the fundamental heat balance principle (DOE 2015). It can simulate indoor thermal environments together with mechanical and electrical systems incorporating building descriptions. EnergyPlus consists of a built-in module for simulating GRs. This built-in module was developed by Sailor (2008) based on the heat balance principle of the soil layer and vegetation layer, and validated by field measurement. The main heat fluxes included in the module are illustrated in Fig. 1.

The built-in GR module of EnergyPlus is developed for low-sloped exterior surfaces like roofs and it is not recommended for high-sloped exterior surfaces like walls. Also, currently EnergyPlus allows defining only one material as a green roof layer (DOE 2015). Adopting the model from the roof to wall will ignore the differences between horizontal and vertical surfaces, especially the effect of gravity and irrigation requirements (Malys et al. 2014). Therefore, EnergyPlus GR module, is not appropriate for simulating GWs on vertical surfaces. Malys et al. (2014) developed an evapotranspiration model, which accounts for the irrigation of GWs. This evapotranspiration model is integrated into our GW module. This GW module simulates the thermal effect of GW using a mathematical model based on heat balance principle of plant layer and the substrate layer. It accounts for short-wave radiation absorption by foliage and by soil, long-wave radiation exchange within plant canopy, latent heat flux by evapotranspiration in foliage and substrate, sensible heat flux exchange with air in the canopy and substrate (Fig. 1). It has been integrated with EnergyPlus using Energy Management System (EMS) feature enabling customized simulations. This self-developed GW module can simulate the energy benefits of GW together with EnergyPlus building models, which is validated in our previous study (Dahanayake and Chow 2017).

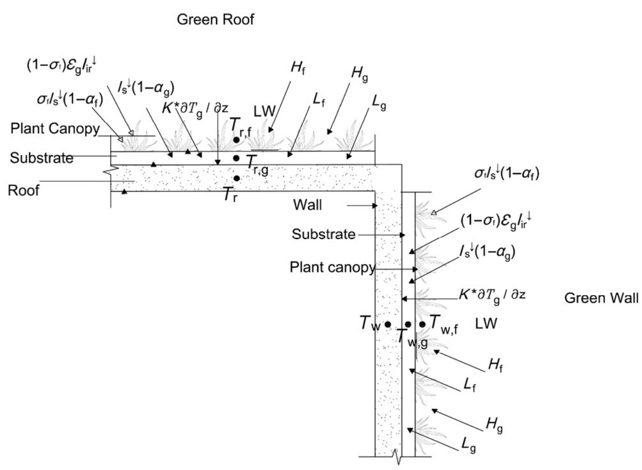

Fig. 1 Heat fluxes in GR (green roof) and GW (green wall). I_s: short-wave radiation, I_{ir}: long-wave radiation, L: latent heat flux, H: sensible heat flux, LW: exchange of long-wave radiation within the canopy, σ_f: fractional vegetation cover, α: albedo (short-wave reflectivity), ε: long-wave emissivity, K: thermal conductivity, z: thickness, T: temperature, g: substrate, f: foliage, w: wall, r: roof

3.2 Error analysis

Errors may associate with each phase of computational modelling and simulation. It should be recognizable and should not be due to lack of knowledge. In some instances, it may be deemed acceptable for analysis requirements or to minimise excessive computational cost. EnergyPlus GR module is a well-established module used by many researchers for GR related studies (Costanzo et al. 2016; Morakinyo et al. 2017; Foustalieraki et al. 2017). Sailor (2008) found that the average bias of the simulation was 2.9 °C with Root Mean Square Error (RMSE) of 4.1 °C. However, some parameters such as the leaf area index (LAI) and stomatal resistance are not quantified in these experiments which would have been helpful for further reduction in the bias error (Sailor 2008). Another experimental study was carried out by Moody and Sailor (2013) to validate the seasonal soil surface temperature output of green roof model. It is found that RMSE is 2.5 °C, 2.4 °C and 3.5 °C for winter, spring and summer seasons respectively. It is suggested that relative agreement and the ability for the model to track diurnal and seasonal variations appear to provide sufficient confidence that the model performs adequately (Moody and Sailor 2013).

The self-developed GW module is validated for indoor air temperature with GWs and the exterior surface temperature of a wall with GWs against a reported experimental study in Hong Kong (Pan and Chu 2016) with good agreement (R^2 = 0.81, R^2 = 0.81) in our previous study (Dahanayake and Chow 2017). Figure 2 illustrates the comparison of measured and modelled exterior surface temperatures of a wall with GW and indoor air temperature with GWs. The RMSE is 0.45 °C and 0.86 °C, respectively for the exterior surface temperature of GW and indoor air temperature with GW.

From the experiment study in Hong Kong (Pan and Chu 2016) it is estimated that GW contributed to an energy saving of 16% (134 kWh) in the period of June to September. The energy saving on a typical summer day was about 1.3 kWh. Simulation resulted in an energy saving of 15% (127 kWh) from June to September. On the hottest summer day, the saving by simulation was 1.37 kWh. This shows

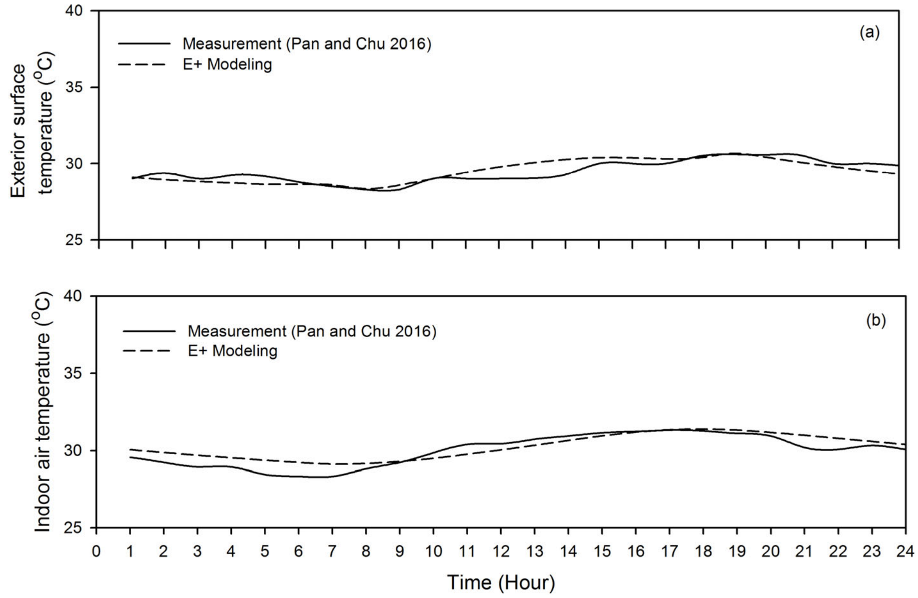

Fig. 2 Measured and modelled values of GW: (a) exterior surface temperature, (b) indoor air temperature

that simulation using EnergyPlus incorporating the self-developed GW module can reasonably predict energy saving through GW.

3.3 Description of the cases in simulation

Three cases are considered in the simulation: Case A, Case B, and Case C. Case A is the experimental setup in the Hong Kong study (Pan and Chu 2016), which was previously used for validating the GW module. This is a single-storey flat with a floor area of 19.3 m^3. Case B and Case C, are hypothetical high-rise buildings with height 100 m and 200 m, respectively. Weather data such as dry bulb temperature, wet bulb temperature, relative humidity, wind speed, wind direction and solar radiation are used in the EnergyPlus weather files of Hong Kong. Hong Kong has a hot-humid climate, located at latitude 22° 19′ N and longitude 114°10′ E. However, it should be noted that EnergyPlus weather files do not account for microclimate of the building neighbourhood, such as the effect of urbanisation. Thus, the results do not include the effect of the surrounding environment.

Similar thermal properties are used for simulating the plant layer and soil layer for both GR and GW. Most of the plant species including grasses, ferns, shrubs, conifers, and succulents are commonly used in both GWs and GRs. The leaf area index (LAI) is the most critical parameter in defining the thermal effect of plants. LAI is defined as the one-sided leaf area per unit ground surface area and is used to characterize set of plants (Morakinyo et al. 2017; Pérez et al. 2017). The LAI can range from 0.001 to 5 (DOE 2015). This study uses LAI = 3, which is a typical value for GRs and GWs. GRs can accommodate a wide range of plants with different heights from grasses/ground covers to small trees depending on the substrate thickness. However, GWs have limitations with the height of plants and substrate thickness since they are integrated into a vertical surface. Therefore, in this study plant height is taken as 0.3 m and substrate thickness, as 0.1 m, which are appropriate conditions for both GRs and GWs. Details of the GR and GW are presented in Table 2.

Case A

Details of the building in Case A are presented in Table 2. Different scenarios have been simulated to understand the effect of area of GR or GW cover and orientation of GW. Simulations have been performed for testing four areas of green coverages: 6.5 m^2, 4.9 m^2, 3.2 m^2 and 1.6 m^2 for GR and GWs. The area is based on the 100%, 75%, 50% and 25% of one wall. For GW, each area of greenery coverage is tested for walls facing north, south, east and west, separately. Altogether this gives twenty (4 areas × 5 orientations) different scenarios. For each scenario, an annual cooling load is obtained and compared with a reference condition for a building without greenery.

Case B

Case B is a hypothetical building of 50 m (L) × 50 m (W) × 100 m (H). The window-wall ratio is taken as 50% for each facade, resulting in equal substrate area in each facade and the roof. Table 2 provides more details of Case B. Twenty simulations are performed with four greenery coverages of 2500 m^2, 1875 m^2, 1250 m^2 and 625 m^2 for GR for each orientation of GWs. These areas are equal to 100%, 75%, 50% and 25% of each wall. Figure 3 illustrates the area of coverages of GRs and GWs.

Case C

Case C is a hypothetical building like Case B, but with the height doubled. Similar to Case A and B, twenty simulations

Table 2 Case details in simulation

Case A	
Dimensions	2.99 m (L) × 2.35 m (W) × 2.75 m (H)
HVAC system	Decentralized (VAV) terminal unit: system efficiency=80%, cooling set point=24 °C, and heating set point=20 °C
Greenery coverages areas considered	6.5 m^2, 4.9 m^2, 3.2 m^2, 1.6 m^2 (areas are calculated based on the 100%, 75%, 50% and 25%, respectively of west facade)
Case B and Case C	
Case B: dimensions	50 m (L) × 50 m (W) × 100 m (H)
Case C: dimensions	50 m (L) × 50 m (W) × 200 m (H)
Window-wall ratio	50% on all facades
Type of building	Office
Floor height	3 m
HVAC systems details	Decentralized (VAV) terminal unit: system efficiency=80%, cooling set point=24 °C, and heating set point=20 °C
Internal heat gains	People: 18.6 m^2/person with activity level of 117 W/person Lights: 10.8 W/m^2, with surface mount fluorescent lighting Electrical equipment: 10.8 W/m^2, with 0.5 fraction radiant
Greenery coverages areas considered	2500 m^2, 1875 m^2, 1250 m^2 and 625 m^2 (areas are calculated based on the 100%, 75%, 50% and 25%, respectively of roof surface)
Details of green roof and green wall (Sailor and Hagos 2011; DOE 2015)	
Height of plants	0.3 m
Leaf area index (LAI)	3
Leaf emissivity	0.9
Leaf reflectivity	0.2
Substrate thickness	0.1 m
Conductivity of dry soil	0.4 W/(m·K)
Thermal absorption of soil	0.96

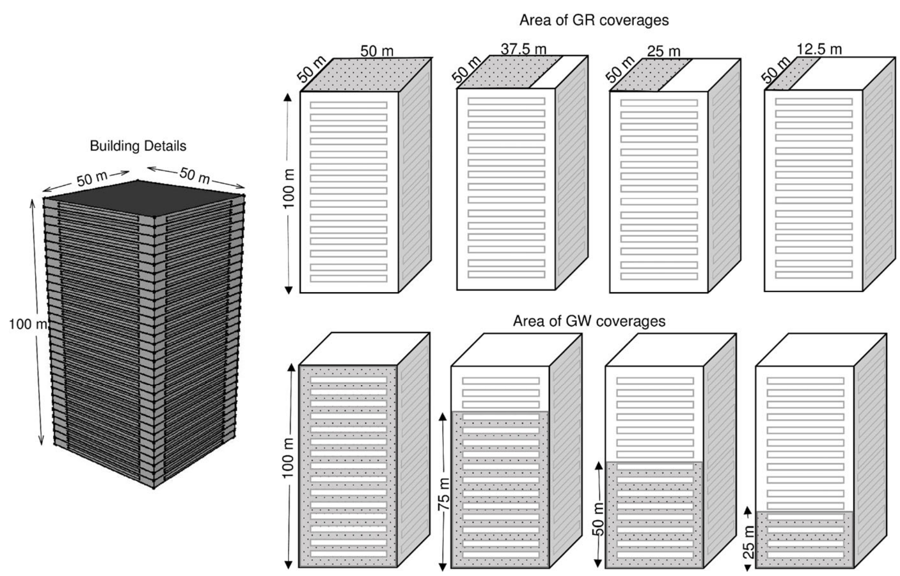

Fig. 3 Areas of coverage of GR and GW for Case B (Note that the window-wall ratio is taken as 50% for each facade)

are performed. The GR coverage areas include 2500 m², 1875 m², 1250 m² and 625 m² which are 100%, 75%, 50% and 25%, respectively of roof area. The height of the building enables higher coverage area for GWs, with 5000 m², 3750 m², 2500 m² and 1250 m² in each orientation, corresponding to 100%, 75%, 50% and 25% of each wall. The manner of coverage is similar to that shown in Fig. 3.

4 Results and discussion

4.1 Thermal effect of GR and GW

The exterior surface temperatures of GR and GW could provide some idea of the effect of these greeneries. Figure 4 shows the exterior surface temperatures of GR and GW (on west-facing wall) of Case A, compared with those of the roof and the wall without greeneries (conventional building) on the hottest summer day, 1st of July as per the EnergyPlus weather files. The surface temperature at the soil surface is considered as the exterior surface temperature of GR or GW. Case B and Case C also show a similar trend. The conventional roof reaches higher surface temperatures during day hours while GR remains in lower temperature values and shows a steady thermal behaviour. The peak surface temperature value of GR is 21.6 °C lower compared to a conventional roof. This shows that GR can significantly reduce the exterior surface temperature during summer periods.

Similar findings can be seen in real experimental data available in other publications. For instance, Ouldboukhitine et al. (2014) obtained a reduction up to 20 °C of exterior surface temperature using GR in La Rochelle, France. Experimental studies in Athens by Karachaliou et al. (2016) and Foustalieraki et al. (2017) showed that the exterior surface temperature of the roof can be reduced up to 15 °C and 21.9 °C, respectively using greenery covers. A study in Singapore (Wong et al. 2003) showed an even higher reduction of exterior roof surface temperature, up to 30 °C which depends upon the density LAI of plants. Another experimental study in Singapore showed that (Tan et al. 2017) green roofs can significantly reduce the heat transmission into the building and the difference is up to 17.7 °C compared to an average concrete surface temperature. Thus, our simulation results agree with the previous experimental findings.

GW shows similar behaviour with steady thermal behaviour. Other orientations show similar behaviour. The west-facing facade is exposed to direct sunlight during afternoon hours and thus the temperature rises rapidly and reaches its peak value in the afternoon. The exterior surface temperature of GW also increases during day hours, but the peak temperature of GW is 15.4 °C lower than the peak value for the conventional wall. Nevertheless, the rise of surface temperature is steady and gradual since 8:00 hour. These results show that both GR and GW have steady thermal behaviour and they are cable of protecting building envelope from reaching higher temperatures.

Previous experimental findings of GWs, have reported similar findings. A study in Hong Kong (Cheng et al. 2010) found that GW reduces up to 16 °C during the summer period. Exterior surface temperature reduction of 20.8 °C and 10 °C were reported respectively in Wuhan, China (Chen et al. 2013) and in Singapore (Wong et al. 2010). Liang et al. (2014) also showed that GWs can significantly reduce surface temperature as well as mean radiant temperature. A study in temperature climate in Italy (Mazzali et al. 2013) also reported with reduction of exterior temperature up to 20 °C. These results evidence the capability of exterior surface temperature reduction using GWs.

Hourly exterior surface temperature variation shows a compatible trend with previous simulation studies. For instance, Jaffal et al. (2012) modelled GR on the hottest summer day for temperature climate and found that the exterior surface temperature reduction through GR is about 30 °C, compared to the conventional roof. During the night time the temperature of GR and conventional roof remains close values and during the day time, conventional roof reaches a higher peak value. This trend is notable in our study as well.

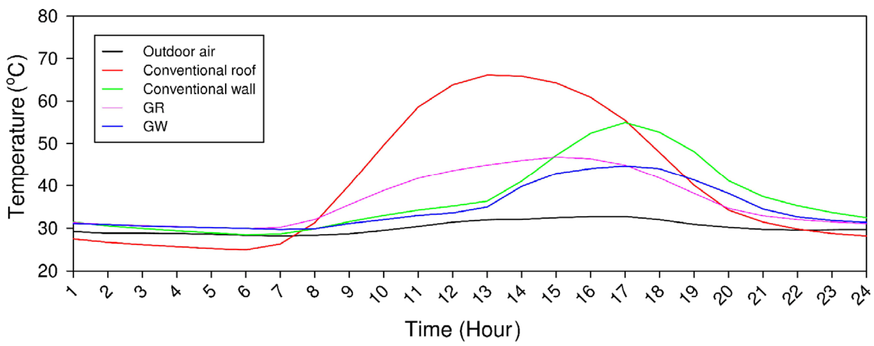

Fig. 4 Exterior surface temperatures on a hot summer day in Case A, with GW on west-facing wall

4.2 Cooling load reduction with GR and GW—Case A

4.2.1 Cooling load reduction in different seasons

To compare the effect of GRs and GWs, the monthly cooling load is obtained with GR and with GW in each orientation with the same area of greenery coverage. The cooling load reduction is obtained by comparing to a reference building without greenery. Figure 5 shows the cooling load reduction with 4.9 m^2 of greenery cover of GR and GW in each orientation. The results show that both GRs and GWs contribute to a reduction in cooling load, with different values depending on orientation. GR results in higher reduction compared to GW in its all orientations.

The simulation results in the present study show that energy saving is higher during summer months (June – August) than in winter months (December – February), with maximum reduction in July. It should be noted that in Hong Kong, even during winter period the outdoor air temperature reaches high values, thus demanding cooling. The cooling load reduction in July is 18.3% for GR and 11.7%, 11%, 6.6% and 4.8% for west-facing, east-facing, north-facing and south-facing orientations, respectively of GW. However, when the GW is on south-facing facade the highest saving is found in October. During winter the sun's path is more southerly, thus south-facing facade receives more sunlight in winter.

The exterior surface temperature of building envelope provides a clear explanation of the effect of orientation on cooling load reduction. Figure 6 shows the monthly average exterior surface temperature. Roof reaches higher exterior surface temperatures compared to the facades, with the peak in July. The west-facing, east-facing, and north-facing facades have a similar trend in temperature variation, with the north-facing facade having the lowest and west-facing facade having the highest temperature values. However, the south-facing facade reaches higher temperatures in winter months, with the peak value in October. This clearly shows that cooling load reduction through greenery cover increases with the exterior surface temperature.

Previous studies have reported similar findings of cooling load reduction through GRs and GWs. For example, Silva et al. (2016) showed that GRs are capable of providing energy benefits in hotter outdoor conditions in Portugal. Berardi (2016) showed that full GR with LAI = 2 and 0.3 m soil depth resulted in 1.8% – 2.9% of energy reduction. Another study by Coma et al. (2016) recorded 2.2% and 16.7% energy reduction through two GRs during summer. As shown in Table 1, annual energy saving through GR ranges from around 6% (Jaffal et al. 2012) to 70% (Silva et al. 2016). Similarly, previous experimental studies have also recorded cooling load benefits through GWs during summer periods (Chen et al. 2013; Pan and Chu 2016). A simulation by Wong et al. (2009) showed that GW can

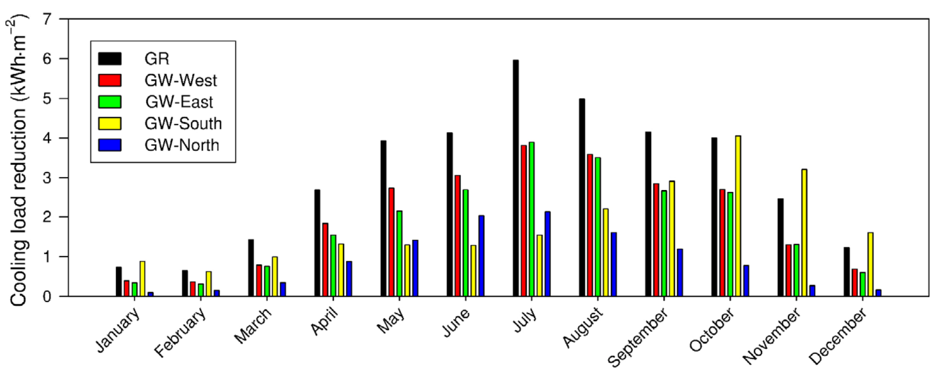

Fig. 5 Monthly cooling load reduction with GR and GW—Case A

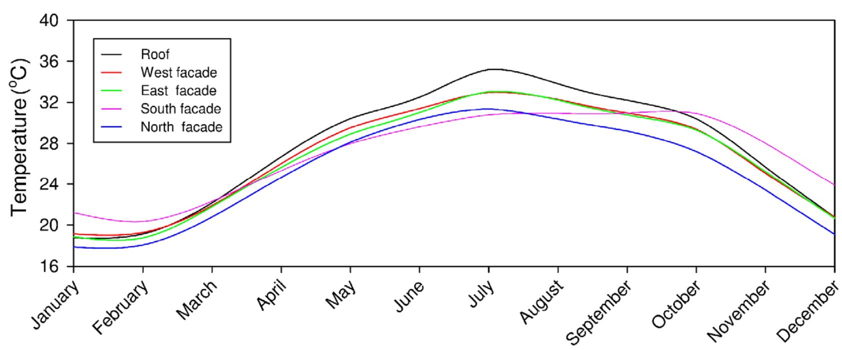

Fig. 6 Monthly exterior surface temperature of reference building without greeneries—Case A

reduce cooling load up to 31% in Singapore weather condition. It should be noted that the percentage of saving greatly depends upon external factors such as building type, scale, and environmental factors. When considering the monthly variation of energy saving it is consistent with the previous experimental study by Coma et al. (2017), which showed that when solar radiation is higher GW can provide higher energy saving. A simulation study (Alexandri and Jones 2008) showed that the temperature decrease through greenery cover negatively correlates with the solar radiation a surface receives. Thus, when a GW or GR receives higher solar radiation, the thermal benefits increases. These results highlight the capability of cooling load reduction through GRs and GWs.

4.2.2 *Effect of area of greenery coverage*

To study the effect of greenery coverage area, different coverages are tested for the roof and each orientation of walls. The annual cooling load is obtained for each case. Selected coverage areas include 6.5 m^2, 4.9 m^2, 3.2 m^2, 1.6 m^2. Annual cooling load reduction can be expressed in percentage as y_r and y_w using Eq. (1) and Eq. (2) for GR and GW.

$$y_r = \frac{E_0 - E_r}{E_0} \times 100\% \quad (1)$$

$$y_w = \frac{E_0 - E_w}{E_0} \times 100\% \quad (2)$$

where E_0 = annual cooling load without greenery, E_r = annual cooling load with GR, E_w = annual cooling load with GW, y_r = percentage annual cooling load reduction with GR (%), y_w = percentage annual cooling load reduction with GW (%).

Figure 7 shows the relationship between y_r and y_w with the area of GR (A_r) and the area of GW (A_w). The y_w values for west-facing, east-facing, south-facing and north-facing orientations are $y_{w,W}$ = 0.3209$A_{w,W}$, $y_{w,E}$ = 0.3021$A_{w,E}$, $y_{w,S}$ = 0.294$A_{w,S}$, and $y_{w,N}$ = 0.1487$A_{w,N}$ respectively. It shows that y_r and y_w correlate linearly with A_r and A_w. This regression analysis can be used in predicting the y_r or y_w value for given A_r and A_w. The regression line of GR has the highest slope (y_r = 0.4837A_r), which means that it provides higher cooling benefits compared to GWs. Among the orientations of GWs, the west-facing facade results in the highest saving, followed by the east-facing, south-facing, and north-facing facade, respectively.

These results agree with the experimental results of previous studies. Cooling load reduction capacity of GWs depends upon the orientation. Few studies have shown the impact of orientation. For instance experiments by Pérez et al. (2017), in the Mediterranean climate and, by Cuce

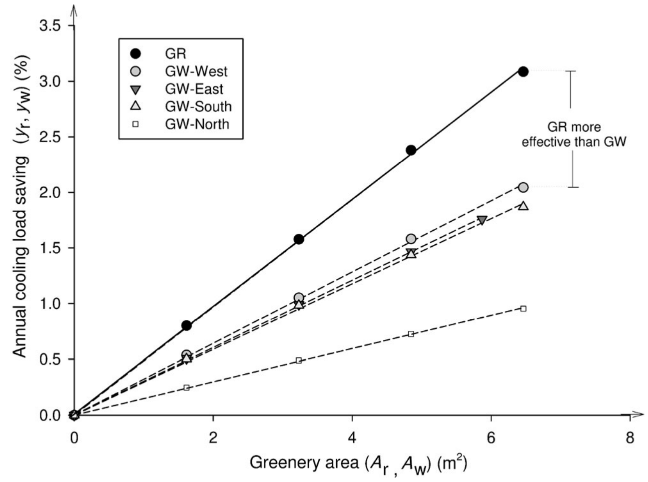

Fig. 7 Relationship between y_r and y_w and A_r and A_w —Case A

(2017) in Temperate climate showed that GW can reduce the exterior surface temperature in all orientations, but the cooling load benefits vary (Cuce 2017). According to Pérez et al. (2017), the highest exterior surface temperature reduction was recorded at 12:15 h, 15.45 h, and 19.00 h respectively for east-facing, south-facing and north-facing orientations. An experimental study by Coma et al. (2017), under the Mediterranean climatic condition, also showed that GW in the south-facing orientation led to the highest temperature reduction during winter. A simulation study by Kontoleon and Eumorfopoulou (2010) showed that cooling load reductions are 20.08%, 18.17%, 7.60% and 4.65% respectively for west, east, south and north orientations. Our results are compatible with these findings emphasising that the orientation which receives highest solar radiation (west-facing orientation) provides the highest temperature reduction and during the winter season it is south-facing orientation. A simulation study in Portugal (Carlos 2015) showed that GWs in south-facing orientation may increase in building heating load requirement during the winter period. However, it depends upon the climatic condition. In such case use of deciduous plants will help to receive solar radiation into the building during the winter period.

4.3 Cooling load reduction by GR and GW—Case B

Monthly cooling load saving of Case B with 2500 m^2 of greenery cover for GR and GW in each orientation is presented in Fig. 8. Unlike the single-storey flat in Case A, GW contributed to higher energy saving compared with GR. On the other hand, the effect of orientation of the GW shows a similar trend. The GWs in west-facing and east-facing walls provide higher energy saving during summer months. The highest saving is found in July, amounting to 1.2% for GR and 2.1%, 2.0%, 1.2% and 0.94% respectively for east,

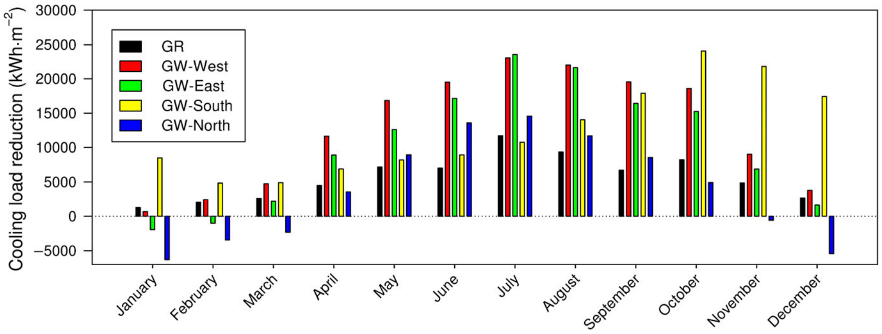

Fig. 8 Monthly cooling load reduction with GR and GW—Case B

west, north and south orientations. As expected, GW in the south-facing facade results in a higher saving in winter months with the peak saving in October. The GW in the north-facing facade shows least energy saving. Under solar radiation, the cooling effect results from evapotranspiration of GW. In absence of solar radiation, GW may act as a thermal insulator for increasing the indoor air temperature. The negative values in cooling load reduction for the winter period (Fig. 8) mean that cooling load is increased. This increase in loading is used to compensate for the higher indoor temperature due to the insulating effect of GW.

4.3.1 *Floor-wise cooling load reduction*

To understand the effect of GR in detail the floor-wise cooling load saving is obtained for each GR coverage. For all cases, highest saving is located on the top floor of the building, as expected. For instance, with 100% GR coverage, 0.72% of energy saving is found on the highest floor, while 0.6% saving is found on the second highest floor and only 0.01% in the third highest floor. The effect on lower floors is negligible. It should also be noted that cooling load reduction is proportional to the area of greenery cover. The floor-wise effect of GR is illustrated in Fig. 9. This shows that in a multi-storey building GR can create a considerable effect on energy consumption only in the topmost floors.

Figure 10 illustrates the floor-wise cooling load reduction due to GW on the west-facing facade. GW in other orientations shows a similar trend. The main difference between GR and GW is that similar area of GW can affect energy consumption on multiple floors. For instance, 100% cover in GR mainly affects the highest floors, whereas 100% cover of GW (same area as in GR) can impact on all the floors in the building. When a particular floor has a GW, it also contributes to a slight saving (around 0.01%) in the adjacent top floor with bare walls.

4.3.2 *Effect of area of greenery coverage*

Figure 11 shows the y_r and y_w values obtained by varying the area of GR and GWs. Selected greenery areas include 2500 m^2, 1875 m^2, 1250 m^2 and 625 m^2. The y_w value for the west-facing, east-facing, south-facing and north-facing orientations can be given as $y_{w,W} = 0.0007A_{w,W}$, $y_{w,E} = 0.0005A_{w,E}$, $y_{w,S} = 0.0006A_{w,S}$ and $y_{w,N} = 0.0002A_{w,N}$ respectively. As expected, y_r and y_w for Case B bear a linear relationship with the A_r and A_w. It is obvious that higher greenery coverage results in higher y_r and y_w. Unlike in Case A, the regression line for the west-facing facade shows the highest slope, which is more than double of that for GR. This means that in Case B, GW on the west-facing wall contributes higher cooling load reduction compared to GR. As shown previously in high-rise buildings, GR significantly affects the top floor, whereas GW provides benefits to a number of floors. Therefore,

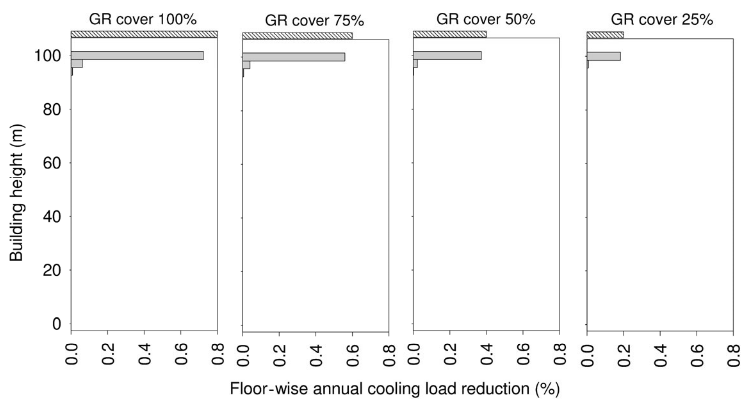

Fig. 9 Floor-wise annual cooling load reduction through GR for Case B

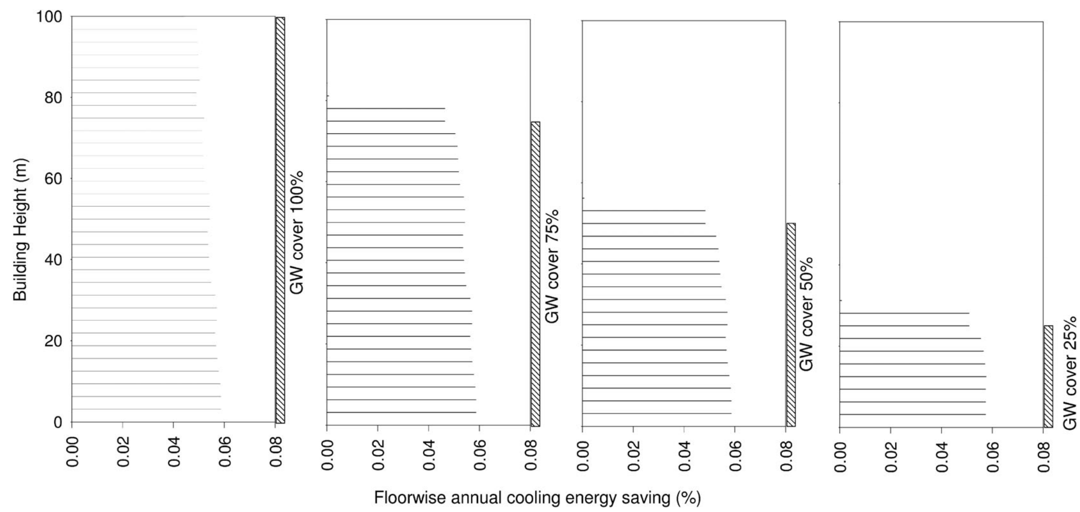

Fig. 10 Floor-wise annual cooling load reduction due to GW on west-facing wall in Case B

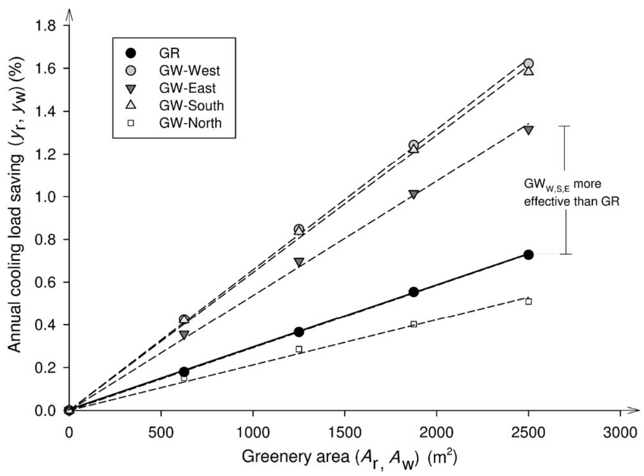

Fig. 11 Relationship between y_r and y_w and A_r and A_w—Case B

cumulative saving through GW is higher compared to GR. However, GW on the north orientation shows the least benefit, even lower than GR.

The effect of greenery coverage is not comprehensively studied at the current scope of research. However, some GR related studies have shown that full-cover of GRs are much effective in cooling load reduction than semi-cover green roofs (Kokogiannakis et al. 2014; Monteiro et al. 2016). For Hong Kong, the peak cooling load reduction was around 2% with semi-extensive GRs, whereas reduction was around 3% for full-extensive GRs (Morakinyo et al. 2017). These results emphasis that the higher greenery cover provides higher benefits.

4.4 Effect of building height on cooling load reduction by GR and GW

The effect of building height is explored with Case B and Case C, in which the building height is doubled in the latter one. The available area of GWs increases with increased building height. The absolute annual cooling load reduction with GR and GW are designated as Y_r and Y_w and are given by Eq. (3) and Eq. (4).

$$Y_r = E_0 - E_r \tag{3}$$

$$Y_w = E_0 - E_w \tag{4}$$

Figure 12 shows the relationship between Y_r and Y_w and A_r and A_w in Case B and Case C. Note that the roof area is 2500 m^2 for both cases, but the total facade area is increased to 5000 m^2 (50 m × 200 m × 0.5) in Case C. Since the GR area is equal for both cases cooling load reduction with GR shows similar value. Equal greenery coverage areas result in similar saving in both cases, but in Case C it is slightly lower. For instance, 2500 m^2 of GW on the west-facing facade results in load reduction of 61 kWh·m^{-2} and 60 kWh·m^{-2}, respectively, for Case B and Case C. In Case C, full greenery coverage (5000 m^2) of west-facing facade results in load reduction of 113 kWh·m^{-2}, which is 88% increase of saving. GW on the south-facing orientation results in 59 kWh·m^{-2} for 2500 m^2 greenery coverage for both cases. On the other hand, 5000 m^2 greenery coverage in Case C results in reduction of 109 kWh·m^{-2}. These results show that increase of building height provides a higher potential of cooling load reduction with GW.

5 Conclusions

This study compares the cooling load reduction through GRs and GWs by varying the area of greenery cover on a single-storey building and two high-rise buildings in Hong Kong by simulations using EnergyPlus. Both GRs and GWs

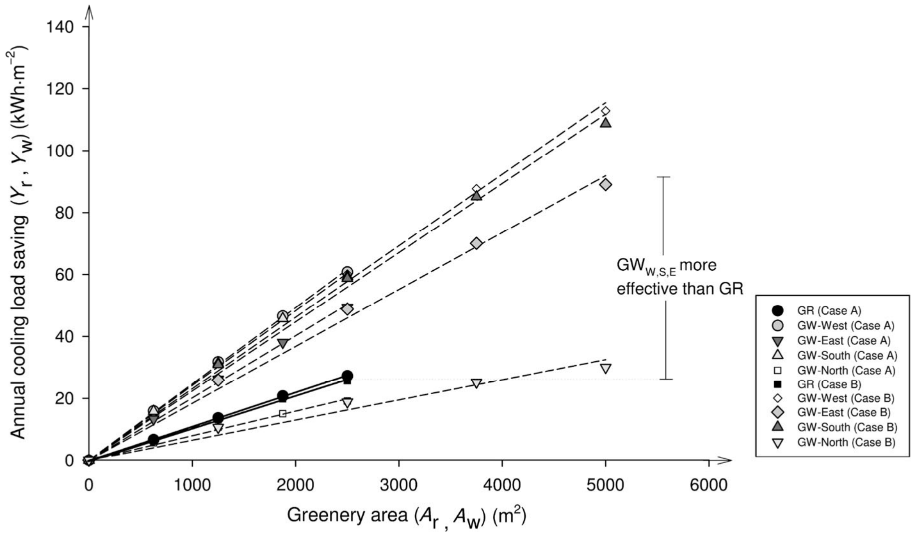

Fig. 12 Comparison of relationship between Y_r and Y_w and A_r and A_w in Case B and Case C

can prevent building surface temperatures from reaching higher values and thereby reduce the cooling load. In general, the reduction is higher during summer period for both GRs and GWs. The monthly cooling load reduction follows a very similar trend as the monthly average surface temperature of the facade. When considering the single-storey building, GR contributes to higher cooling load reduction compared with GWs of the same area. However, when considering multi-storey buildings, GWs on the west-facing, east-facing and south-facing orientations contribute to higher reduction than GR. For both scenarios, GWs on the north-facing facades show the least benefit. In a multi-storey building, the effect of GR is significant only on the topmost floors. However, an equal area of GW can reduce the cooling load on multiple floors, enabling higher benefit. In addition, with the increase of building height more area is available for GW, whereas the area for GR is limited. The effect of orientation of GWs shows a similar trend for both single-storey building and multi-storey building. The west-facing, east-facing, and north-facing orientations show higher saving during summer months in Hong Kong with peak saving in July. The south-facing orientation shows higher saving in winter months in Hong Kong with the peak in October. In overall, the west-facing orientation results in the highest cooling load reduction and the north-facing orientation, the least. For all scenarios cooling load reduction is proportional to the area of greenery coverage. In summary, this study suggests that both GRs GWs effectively reduce cooling load. The decision on choosing GR or GW should be carefully considered in terms of (i) the area of greenery coverage, (ii) the orientation, (iii) the scale of the building, (iv) the surrounding environment, and (v) the geographical location, to maximize the benefits.

Acknowledgements

The work described in this paper was supported by the Hong Kong PhD Fellowship Scheme at the City University of Hong Kong and a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. 11274516).

References

Alexandri E, Jones P (2008). Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment*, 43: 480–493.

Berardi U (2016). The outdoor microclimate benefits and energy saving resulting from green roofs retrofits. *Energy and Buildings*, 121: 217–229.

Carlos JS (2015). Simulation assessment of living wall thermal performance in winter in the climate of Portugal. *Building Simulation*, 8: 3–11.

Chen Q, Li B, Liu X (2013). An experimental evaluation of the living wall system in hot and humid climate. *Energy and Buildings*, 61: 298–307.

Cheng CY, Cheung KKS, Chu LM (2010). Thermal performance of a vegetated cladding system on facade walls. *Building and Environment*, 45: 1779–1787.

Coma J, Pérez G, Solé C, Castell A, Cabeza LF (2016). Thermal assessment of extensive green roofs as passive tool for energy savings in buildings. *Renewable Energy*, 85: 1106–1115.

Coma J, Pérez G, de Gracia A, Burés S, Urrestarazu M, Cabeza LF (2017). Vertical greenery systems for energy savings in buildings: A comparative study between green walls and green facades. *Building and Environment*, 111: 228–237.

Costanzo V, Evola G, Marletta L (2016). Energy savings in buildings or UHI mitigation? Comparison between green roofs and cool roofs. *Energy and Buildings*, 114: 247–255.

Cuce E (2017). Thermal regulation impact of green walls: An experimental and numerical investigation. *Applied Energy*, 194: 247–254.

Dahanayake KWDKC, Chow CL (2015). A brief discussion on current vertical greenery systems in Hong Kong: The way forward. In: Proceedings of the 14th International Conference on Sustainable Energy Technologies (SET2015), Nottingham, UK, pp. 136–147.

Dahanayake KWDKC, Chow CL (2017). Studying the potential of energy saving through vertical greenery systems: Using EnergyPlus simulation program. *Energy and Buildings*, 138: 47–59.

Davis MM, Hirmer S (2015). The potential for vertical gardens as evaporative coolers: An adaptation of the "Penman Monteith Equation." *Building and Environment*, 92: 135–141.

Di HF, Wang DN (1999). Cooling effect of ivy on a wall. *Experimental Heat Transfer*, 12: 235–245.

Djedjig R, Bozonnet E, Belarbi R (2015). Analysis of thermal effects of vegetated envelopes: Integration of a validated model in a building energy simulation program. *Energy and Buildings*, 86: 93–103.

DOE (2015). EnergyPlus Energy Simulation Software. Available at https://energyplus.net.

Ferroukhi MY, Djedjig R, Limam K, Belarbi R (2016). Hygrothermal behavior modeling of the hygroscopic envelopes of buildings: A dynamic co-simulation approach. *Building Simulation*, 9: 501–512.

Foustalieraki M, Assimakopoulos MN, Santamouris M, Pangalou H (2017). Energy performance of a medium scale green roof system installed on a commercial building using numerical and experimental data recorded during the cold period of the year. *Energy and Buildings*, 135: 33–38.

Hong B, Lin B (2014). Numerical study of the influences of different patterns of the building and green space on micro-scale outdoor thermal comfort and indoor natural ventilation. *Building Simulation*, 7: 525–536.

Jaffal I, Ouldboukhitine S-E, Belarbi R (2012). A comprehensive study of the impact of green roofs on building energy performance. *Renewable Energy*, 43: 157–164.

Karachaliou P, Santamouris M, Pangalou H (2016). Experimental and numerical analysis of the energy performance of a large scale intensive green roof system installed on an office building in Athens. *Energy and Buildings*, 114: 256–264.

Kokogiannakis G, Darkwa J, Yuan K (2014). A combined experimental and simulation method for appraising the energy performance of green roofs in Ningbo's Chinese climate. *Building Simulation*, 7: 13–20.

Kontoleon KJ, Eumorfopoulou EA (2010). The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. *Building and Environment*, 45: 1287–1303.

Liang TC, Wong NH, Jusuf SK (2014). Effects of vertical greenery on mean radiant temperature in the tropical urban environment. *Landscape and Urban Planning*, 127: 52–64.

Malys L, Musy M, Inard C (2014). A hydrothermal model to assess the impact of green walls on urban microclimate and building energy consumption. *Building and Environment*, 73: 187–197.

Mazzali U, Peron F, Romagnoni P, Pulsell RM,Bastianoni S (2013). Experimental investigation on the energy performance of Living Walls in a temperate climate. *Building and Environment*, 64: 57–66.

Monteiro MV, Blanuša T, Verhoef A, Hadley P, Cameron RWF (2016). Relative importance of transpiration rate and leaf morphological traits for the regulation of leaf temperature. *Australian Journal of Botany*, 64: 32–44.

Moody SS, Sailor DJ (2013). Development and application of a building energy performance metric for green roof systems. *Energy and Buildings*, 60: 262–269.

Moradpour M, Afshin H, Farhanieh B (2017). A numerical study of reactive pollutant dispersion in street canyons with green roofs. *Building Simulation*, https://doi.org/10.1007/s12273-017-0373-0.

Morakinyo TE, Dahanayake KWDKC, Ng E, Chow CL (2017). Temperature and cooling demand reduction by green-roof types in different climates and urban densities: A co-simulation parametric study. *Energy and Buildings*, 145: 226–237.

Ouldboukhitine S-E, Belarbi R, Sailor DJ (2014). Experimental and numerical investigation of urban street canyons to evaluate the impact of green roof inside and outside buildings. *Applied Energy*, 114: 273–282.

Pan L, Chu LM (2016). Energy saving potential and life cycle environmental impacts of a vertical greenery system in Hong Kong: A case study. *Building and Environment*, 96: 293–300.

Pérez G, Coma J, Sol S, Cabeza LF (2017). Green facade for energy savings in buildings: The influence of leaf area index and facade orientation on the shadow effect. *Applied Energy*, 187: 424–437.

Pierangioli L, Cellai G, Ferrise R, Trombi G, Bindi M (2017). Effectiveness of passive measures against climate change: Case studies in Central Italy. *Building Simulation*, 10: 459–479.

Sailor DJ (2008). A green roof model for building energy simulation programs. *Energy and Buildings*, 40: 1466–1478.

Sailor DJ, Hagos M (2011). An updated and expanded set of thermal property data for green roof growing media. *Energy and Buildings*, 43: 2298–2303.

Scarpa M, Mazzali U, Peron F (2014). Modeling the energy performance of living walls: Validation against field measurements in temperate climate. *Energy and Buildings*, 79: 155–163.

Silva CM, Gomes MG, Silva M (2016). Green roofs energy performance in Mediterranean climate. *Energy and Buildings*, 116: 318–325.

Stec WJ, van Paassen AHC, Maziarz A (2005). Modelling the double skin facade with plants. *Energy and Buildings*, 37: 419–427.

Susorova I, Angulo M, Bahrami P, Stephens B (2013). A model of vegetated exterior facades for evaluation of wall thermal performance. *Building and Environment*, 67: 1–13.

Tam VWY, Wang J, Le KN (2016). Thermal insulation and cost effectiveness of green-roof systems: An empirical study in Hong Kong. *Building and Environment*, 110: 46–54.

Tan CL, Tan PY, Wong NH, Takasuna H,Kudo T, et al. (2017). Impact of soil and water retention characteristics on green roof thermal performance. *Energy and Buildings*, 152: 830–842.

Tian Y, Bai X, Qi B, Sun L (2017). Study on heat fluxes of green roofs based on an improved heat and mass transfer model. *Energy and Buildings*, 152: 175–184.

Wong NH, Chen Y, Ong CL, Sia A (2003). Investigation of thermal benefits of rooftop garden in the tropical environment. *Building and Environment*, 38: 261–270.

Wong NH, Tan AYK, Tan PY, Wong NC (2009) Energy simulation of vertical greenery systems. *Energy and Buildings*, 41:1401–1408.

Wong NH, Tan AYK, Chen Y, Sekar K, Tan PY, et al. (2010). Thermal evaluation of vertical greenery systems for building walls. *Building and Environment*, 45: 663–672.

Zeng C, Bai X, Sun L, Zhang Y, Yuan Y, et al. (2017). Optimal parameters of green roofs in representative cities of four climate zones in China: A simulation study. *Energy and Buildings*, 150: 118–131.