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Temperature and cooling demand reduction by green-roof types in different climates and urban densities: A co-simulation parametric study

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ABSTRACT

This paper presents a parametric study on the effect of four green-roof types on outdoor/indoor temperature and cooling demand under four different climates and three urban densities using co-simulation approach with ENVI-met and EnergyPlus. Results reveal an outdoor nighttime warming effect of not more than 0.2 °C which is most obvious with the semi-extensive while the outdoor and indoor cooling effect ranges between 0.05–0.6 °C and 0.4–1.4 °C, respectively depending on the green-roof type, urban density and time of the day. These daytime temperature reductions also vary per prevailing climates and follow this order: hot-dry, hot (or warm)-humid, and temperate which can be explained by the interplay between solar intensity/air temperature and relative humidity between the regions. In a hot-humid region, the evaporative cooling potential of greenery is dampened when compared to hot-dry region. This is also true for region with low solar intensity and humidity like the temperate region. In terms of cooling demand reduction, 5.2% was observed in hot-dry climate on the hottest day of the year with full-intensive green-roof while the least saving of 0.1% was found with semi-extensive green-roof in temperate climate. In general, for both outdoor temperature and cooling demand reduction, semi-intensive green-roof was found more effective than its full-extensive counterpart while the higher spatial green-roof is most important for indoor temperature reduction irrespective of the leaf density of the greenery. Therefore, the intent of green-roof installation should be a determining factor for the type and spatial extent to be implemented.

1. Introduction

As a consequence of rapid urbanization, many global cities have been transformed into congested and overpopulated concrete jungles leading to a number of environmental problems such as pollution of its various forms, urban heat island (UHI) and heat stress, among others [1]. The UHI phenomenon basically arises from the heat storage capacity of paved areas, anthropogenic heating and reduction of green spaces leading to higher urban than rural daytime and nighttime air and surface temperatures [2]. In a bid to mitigate or adapt to UHI and heat stress, several countermeasures such as urban greening (i.e. tree-planting, façade greening and roof greening), cool roof, water-retentive materials, modification of urban morphology, insulation of buildings, application of irrigation systems [3,4] have been suggested and are being implemented by urban planners and landscape architects. Urban greening is one of the most effective of these countermeasures as it directly reduces solar gains by surfaces. Of all forms of urban greening, tree-planting is the most efficient and more advocated for ground surface temperature reduction. However, the contribution of roofs' surfaces cannot be overemphasized as they cover more than 20% of the total urban surface [3]. Hence, cooling roof surfaces' temperature could significantly contribute to UHI mitigation, indoor air temperature reduction and lowered cooling energy demand [5,6]. This is even more important due to limitation of ground surface area for ground level tree-planting especially in high-density cities. Therefore, green-roofs though ancient practice, are becoming popular as a potential alternative and means of re-establishing the connection

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between nature and city [7], enhancing the aesthetic appearance of a building [8] and improving environmental quality. Simply put, a green-roof is a roof top used for plantation with the use of a suitable growing medium. In recent years, green-roofs have been getting popular as a suitable technique of introducing greenery into congested cities [9]. Latest technological advancements have enhanced the flexibility and speed of construction of green-roofs enabling them to be integrated into most of the projects. Modern green-roofs are generally consisting with number of layers. These may include vegetation, growth substrate, filter fabric, drainage element, root barrier, insulation and water proofing membrane depending upon the location and the requirements [9–11]. In a broader perspective, green-roofs are classified into intensive and extensive based on the thickness of the substrate layer. Green-roofs with thin substrate layer (<15 cm) are considered as extensive green-roofs. On the other hand, if the substrate is thicker (20–200 cm), they are considered as intensive green-roofs. These layers enhance the insulation capacity of a conventional roof by controlling the heat transfer into the building [12]. In addition, these layers block the solar radiation reaching the building surface. Only limited type of vegetation can be grown in extensive green-roofs such as grass. Intensive green-roofs have more flexibility in accommodating shrubs and small trees. However, they require more attention in structural support, maintenance and irrigation [13,14]. Therefore, extensive green-roofs are widely used in practice due to lower cost and maintenance compared to intensive green-roofs [9]. Solar radiation is the main heat source into the buildings. Integration of vegetation to the building surface is an effective way of controlling this heat gain [15,16] as greenery absorb the solar heat and evaporates water through biological functions and metabolism, a process known as evapotranspiration which essentially creates a cooling effect in the surrounding. The evaporative cooling potential of the vegetation layer may depend upon characteristics of vegetation such as foliage density and leaf thickness [17,18].

Green-roofs have a range of benefits: they improve the microclimate, minimize heat island, lowers the building envelope temperature and reduce energy consumption and peak cooling load of the building at both city, neighborhood and building scale [13,18,19]. Besides, they are known for reducing the risk of flooding by retaining rainwater and delaying the peak flow [20,21] and also helps to control the urban sound pollution [22]. Moreover, they are efficient in absorbing gaseous pollutants including greenhouse gas emissions and helps remove of particulate pollutants thereby contributing to improved urban air quality [23,24].

The performance of green-roofs for urban cooling and energy reduction is dependent on several factors based on findings from previous studies. First, building height and urban density: previous studies [25,26] have shown a negligible cooling effect of extensive and intensive green-roof in medium to high density neighborhood. It has also been established that intensive green-roof provides better environmental and energy reduction benefit than their extensive counterparts mainly due to higher soil depth and leaf density implemented in the former [27]. Another important factor is the geographical location on the green-roof installation. While several studies have investigated the benefit of green-roof, most did so under singular climatic condition and as such their conclusion are restricted with the geographical scope of their study.

In the present study, we concurrently studied the outdoor/indoor temperature and indoor electricity peak changes effected by the implementation of four types of green-roofs see Fig. 1; full-intensive (100% greenery coverage), semi-intensive (50% greenery coverage), full-extensive (100% greenery coverage), and semi-extensive (50% greenery coverage) compared to a conventional roof (with no greenery), under four different climates (i.e. hot-dry, hot-humid, warm-humid and temperate) and three urban densities (High, medium and low) using an integrated modelling approach. While there are several studies on the energy savings or the microclimate effects of green-roofs [28,29], our study represents one of the few where energy and microclimate benefits was investigated concurrently for different green-roof types, urban densities and climates in a neighborhood scale. This was achieved by integrated building energy simulation, EnergyPlus and urban climate model, ENVI-met.

2. Methodology

This section presents our study's scenario development, models' description and methodology of integrating the two modelling tools i.e. EnergyPlus for assessing indoor temperature/electricity peak benefits and ENVI-met model for assessing the outdoor cooling effects by the green-roof retrofit.

2.1. Description of simulation tools

To simulate the micro-climate of our predefined neighborhood, ENVI-met V4, a three-dimensional (3D) non-hydrostatic, micro-climatological, and computational fluid dynamics model which employs the standard $k-\varepsilon$ turbulence model in closing the Reynold Average Navier-Stokes (RANS) equations was employed. ENVI-met has the capability to simulate the surface-plant-atmosphere interactions within or around a complex urban geometry making it a commonly used tool for modelling different urban atmospheric processes including wind flow, turbulence, urban microclimate, pollutant dispersion, radiation fluxes, and soil temperatures. The model has fine resolution grid (0.5 – 10 m) making analyses of small-scale interactions between individual buildings, surfaces and plants possible. Previous studies have employed and validated this model for green-roof related research, for instance, a strong correlation (R^2 = 0.82–0.96) was found between measured and simulated air temperature on rooftops (greened and non-greened) [27,30,31] while a strong agreement (R^2 = 0.79–0.85) have also been noted under tree-shade and/or open-spaces at pedestrian level [32–34] with 20–25% percentage error. Based on these capabilities and validity, ENVI-met can be said to be useful tool for urban planners, architects and urban climatologists who want to simulate the meteorological components of the urban environment. A detailed description of this model with all equations can be found in Bruse and Fleer [35] and Huttner and Bruse [36]. The model is freely available at http://www.envi-met.info.

To simulate the indoor micro-climate and energy use, EnergyPlus, an open source simulation code was adopted. The program enables users to model buildings with mechanical and electrical systems with integrated thermal controls and perform simulations based on real building descriptions. It uses a combination of program modules to simulate the thermal environments of building indoors, which operates based on the fundamental heat balance principle [37,38]. Green-roof module in EnergyPlus based on heat balance equations are developed and validated by Sailor [39]. It is a widely accepted design tool for assessing the likely magnitude of energy saving through green-roofs. The model takes into account, long-wave and short-wave radiation exchange within the plant canopy, convective heat transfers effect of the plant canopy, evapotranspiration and heat conduction in the soil layer. It also enables specifying various aspects of green-roof construction including growing media depth, thermal properties, plant canopy density, plant height, and stomatal conductance and soil moisture conditions [40–42]. Other studies have coupled ENVI-met with EnergyPlus [27,43,44] to concurrently study the interaction between outdoor micro-climate condition and indoor energy use. Specifically, Berardi [27] found ±5% between simulated and

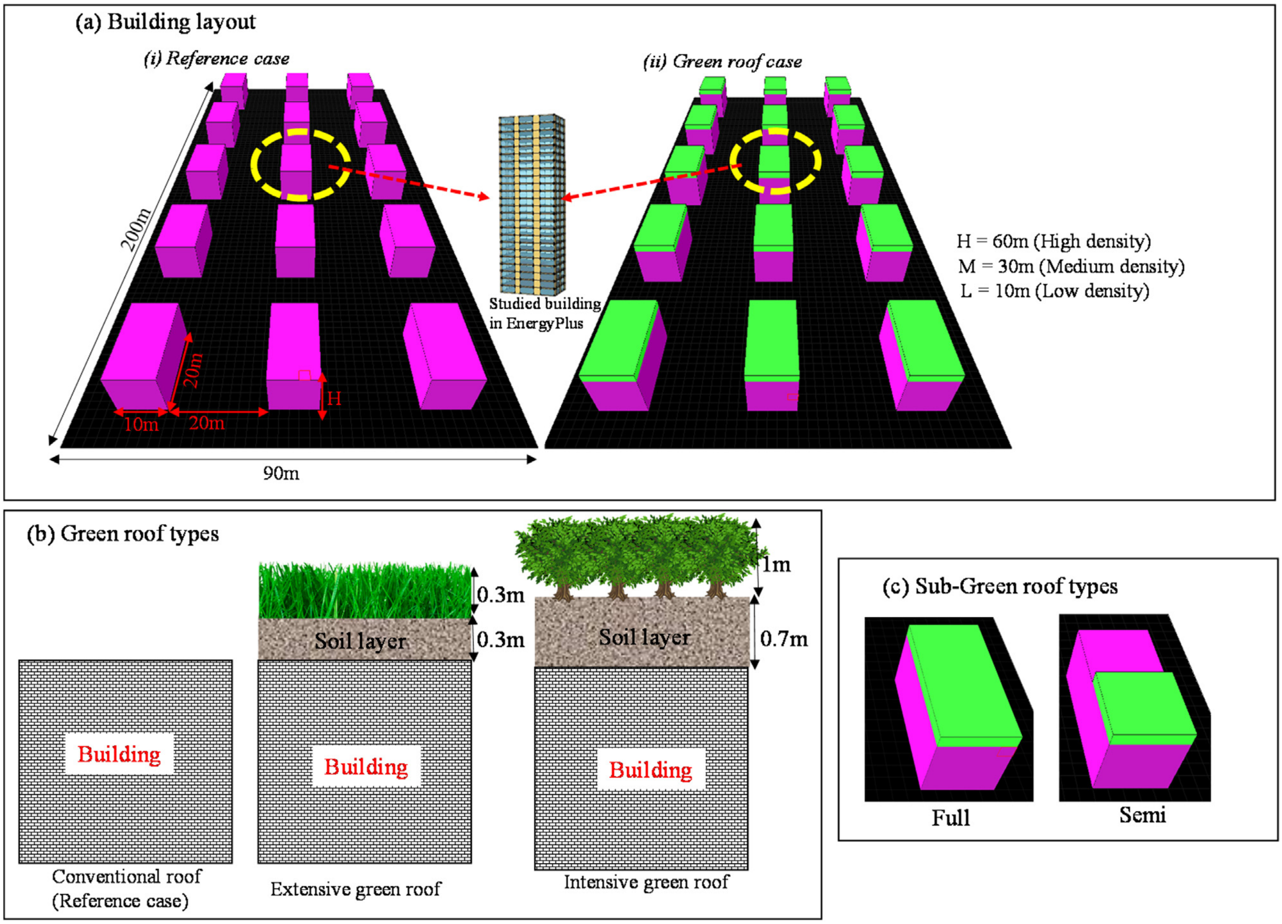

Fig. 1. Schematic diagram of (a) ENVI-met's building/neighborhood layout, (b) green-roof types and (c) sub-green-roof types.

measured monthly energy use using this co-simulation technique. EnergyPlus is freely available at https://energyplus.net/downloads.

2.2. Scenarios' development

Sixty (60) scenarios have been developed to demonstrate the benefit of different green-roofs on outdoor cooling and indoor energy demand reduction under different climates and urban densities using integrated modelling system of EnergyPlus and ENVI-met. A 90 m × 200 m neighborhood with a row layout of buildings was modeled in ENVI-met (see Fig. 1). The buildings are of uniform height of 60 m, 30 m and 10m, representing high, medium and low density neighborhood, respectively (see Fig. 1(a)). Five rooftop types were also tested for each urban density: conventional rooftop (without greenery) was assumed as the reference condition. Others include intensive green-roof composed of 0.7 m soil thickness, 1 m canopy height of leaf area index,[1] LAI = 2 while the extensive roof is contained of grasses of 0.3 m of LAI = 2, soil thickness of 0.3 m (see Fig. 1(b)). Two sub-type of intensive and extensive green-roof were further tested: full-intensive (extensive) was made up of with 100% green coverage while semi-intensive (extensive) which contains somewhat realistic 50% green coverage (see Fig. 1(c)). To analyze the summer microclimate and electricity peak change effects of the green-roofs under different climatic condition, the above scenarios are implemented under four different summer climates and city; arid (hot-dry, Cairo), sub-tropical (hot-humid, Hong Kong), sub-tropical (warm-humid, Tokyo), and oceanic (temperate, Paris) climates based on Koppens climate zone classification. For the indoor energy simulation, the building at the centre of the domain was selected (see Fig. 1(a)) while other scenario selection procedures remain unchanged. The settings of EnergyPlus simulations and ENVI-met simulations are presented in Tables 1 and 2, respectively.

2.3. Models' integration framework

The co-simulation procedures of using ENVI-met simulation results as the boundary conditions of EnergyPlus computation and vice-versa is presented in Fig. 2. The purpose is to harness the strength of one to overcome the drawback of the other. Specifically, ENVI-met does not have the capability of simulating indoor energy use while EnergyPlus is deficient in simulating outdoor micro-climate. For the outdoor micro-climate simulations, each scenario was initialized with weather data (e.g. wind speed, wind direction, ground temperature, relative humidity, radiation and sky condition) from the default EnergyPlus Weather (EPW) file and forced at the model boundary using the model forcing function. However, for the EnergyPlus simulation we did not follow the common practice which is to use a city's representative weather data (EPW file) for the model initialization. We opined that this EPW are not representative of the neighborhood's microclimate as it would not contain the effect or urbanization and surface modification making them not so accurate for energy simulation. Therefore, ENVI-met

[1] LAI is the ratio of total leaf surface area to total ground area for an area with vegetation cover. Note that LAI = LAD (leaf area density which is defined as "total one- sided leaf area (m^2) per unit layer volume (m^3) in each horizontal layer of the plant crown) in this study since the tree/grass canopy falls in with once vertical grid.

Table 1
Settings of EnergyPlus simulations.

Building design	High density – 20 m (L) × 10 m (W) × 60 m (H) Medium density – 20 m (L) × 10 m (W) × 30 m (H) Low density – 20 m (L) × 10 m (W) × 10 m (H)
Type of building	Office
Floor height	2.5 m
Window-wall ratio	60% of each façade
Simulation period	Hottest summer day according to EnergyPlus Weather (EPW) file Cairo – 7th July Hong Kong – 1st July Tokyo – 3rd July Paris – 2nd July
Weather data	Modified EPW files based on ENVI-met simulation separately for low, medium and high urban densities
HVAC system details	Decentralized (VAV) terminal unit in each floor and operates with: system efficiency = 70%, cooling set point = 25 °C, and heating set point = 20 °C
Internal heat gains	People – 18.6 m²/person with activity level of 117 W/person Lights – 10.8 W/m², with surface mount fluorescent lighting Electrical Equipment – 10.8 W/m², with 0.5 fraction radiant
Green-roof design	
Intensive	Height of plants (m) = 1 LAI = 2 Soil thickness (m) = 0.7
Extensive	Height of plants (m) = 0.3 LAI = 2 Soil thickness (m) = 0.3
Full	20 m (L) × 10 m (W)
Semi	10 m (L) × 10 m (W)
General Properties [38,45,46]	Leaf reflectivity = 0.35 Leaf emissivity = 0.95 Minimal stomatal resistance (s/m) = 180 Thermal Conductivity (W/m.K) = 0.90 Density (kg/m³) = 1850 Specific Heat (J/kg.K) = 850 Thermal emissivity = 0.65 Solar Absorptance = 0.35

HVAC = heating ventilating and/or air-conditioning. VAV = Variable Air Volume. LAI = Leaf area Index.

Table 2
Model configuration and initialization parameters' values.

Study location and climate types	Cairo (Hot-dry) Hong Kong (Hot-humid); Tokyo (Warm-humid); & Paris (Temperate)
Simulation period	Peak summer month and day of each location/climate
Simulation duration	24 h
Start time	6:00 a.m.
Spatial resolution	2 m × 2 m × 3 m
Domain size	90 m × 200 m × 120 m
Basic meteorological (wind speed, wind direction, ground temperature, relative humidity radiation and sky condition) input	From EPW file for each location/climate
Green-roof properties and dimension	Similar to Table 1

generated meteorological outputs from thirty-six (30) grid cells located 2 m away and at three height levels around the buildings at the centre of ENVI-met's domain were averaged to reproduce weather data (modified EPW file) for the EnergyPlus simulations following Fahmy et al. [47] and Yang et al. [48]. It is important to mention that modified EPW files are obtained separately for low, medium and high urban density for each considered city. This modification enables use to simulate the effect of urban density on local climate. We consider it as more accurate compared to use of the conventional EPW file. To illustrate this idea, Fig. 3 shows a comparison between air temperature with default and modified EPW (using ENVI-met output) under different urban densities in (a) Hong Kong and (b) Paris as an illustration. Clearly, the effect of urban density can be observed as daytime air temperature is higher with modified than default profile in Hong Kong and otherwise in Paris. Also, the daytime value increases with lower urban density due to higher solar heat gain. The released solar heat at night gets trapped in denser urban geometry resulting in higher nighttime temperature which conforms with the observation of Theeuwes et.al [2]. This difference in default and modified due to urban density effect exist in other climates, and parameters not shown.

3. Results and discussion

3.1. Pedestrian cooling (or warming) effect of green-roofs

To characterize the cooling (or warming effect) of green-roofs, we calculated the pedestrian (1.5 m) air temperature difference at both nighttime (00:00 h) and daytime (15:00 h) as presented

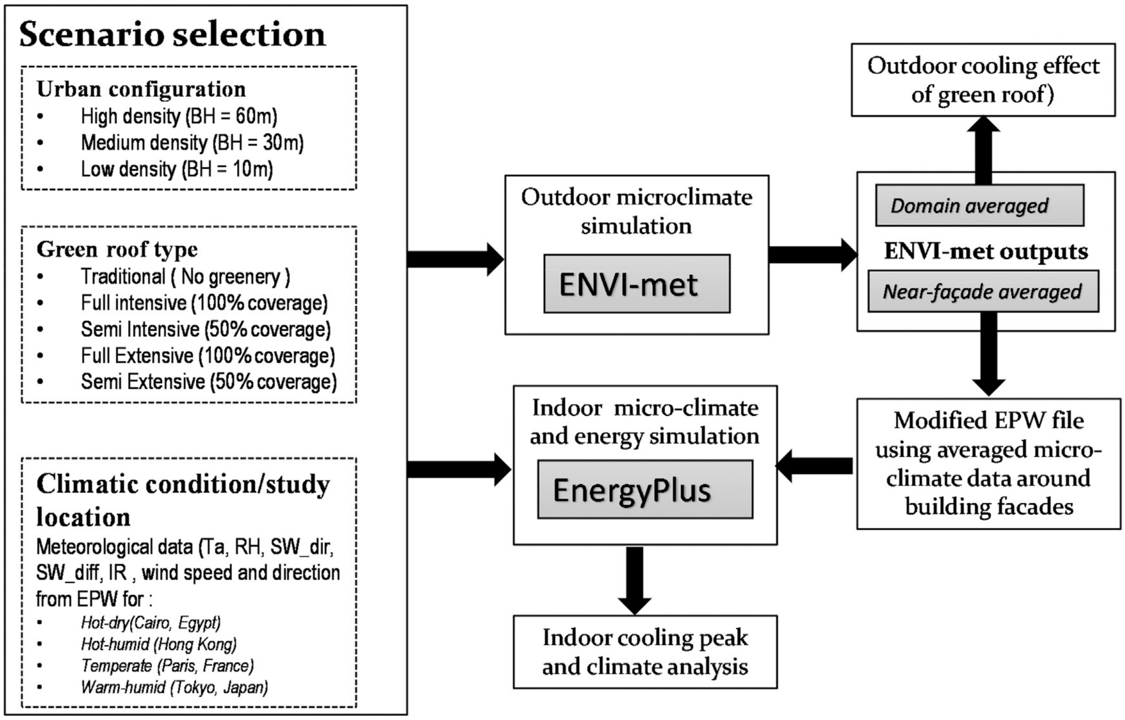

Fig. 2. Study framework and integration of ENVI-met and EnergyPlus.

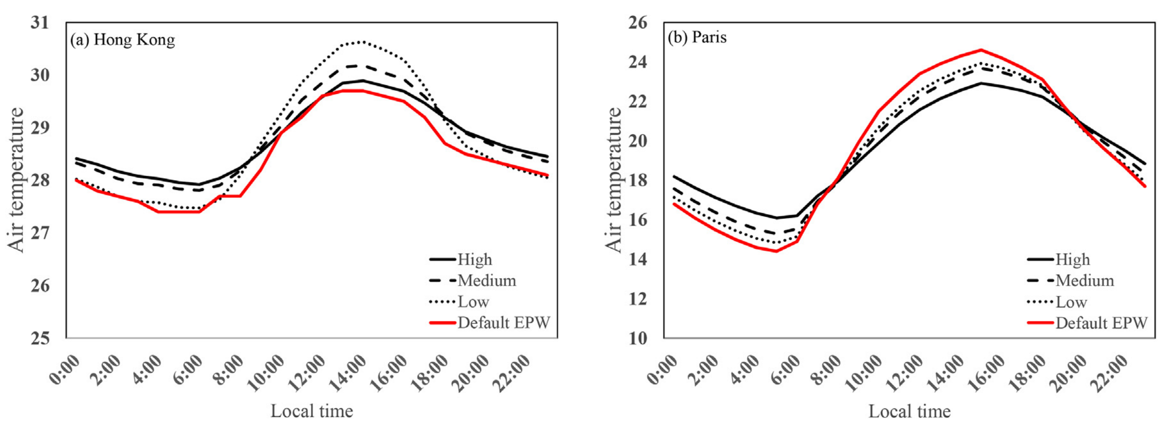

Fig. 3. Comparison between air temperature data in default and modified EPW with different urban densities in (a) Hong Kong and (b) Paris as an illustration.

in Figs. 4 and 5, respectively under different climate conditions and urban densities. Considering all the grids in domain, positive (warming effect) and negative (cooling effect) air temperature difference by green-roof implementation was observed, even though the latter is more spatially pronounced. The warming effect which is more obvious with the semi-extensive is not more than 0.2 °C while the cooling effect ranges between 0.05–0.6 °C depending on the green-roof type, climate, urban density and time of the day. This slight difference should rather not be underemphasized, as it could implies reduction in extreme heat (by 1 °C) which has been associated with human mortality while also reducing the period of warm spell by 50% especially in tropical regions [49], thereby improving overall human wellbeing.

At nighttime, higher spatial and vertical greenery coverage averagely leads to lower cooling effect as seen in Fig. 4. On the average, nighttime urban heat island (UHI) mitigation potential by green-roof types are in this order: semi-extensive, full-extensive, semi-intensive and full-intensive. This could be attributed to higher daytime absorption and nighttime release of energy as green coverage and leaf density reduces, hence warmer air is generated which couples with other heat releases from wall and ground surfaces to increase pedestrian temperature. This is similar to observation from a reduced-scale experiment by Rabah et.al [50] where their results show that during the night the green-roof and wall release the solar radiation absorbed in the afternoon inform of sensible heat resulting in street slightly warmer by about 0.5 °C. It is important to mention that the released warmth could be beneficial in reducing cold stress in high-medium urban density area of temperate region and otherwise for low density areas. In other regions, actual nighttime UHI mitigation mainly under low urban density as observed in our result. Generally, nighttime effect is not significant as temperature difference only ranges between −0.22 – (+0.12) °C and lower than the daytime effect. This observation echoes the significance of solar radiation for improved evaporative cooling which is in line with findings of Sun et al. [51]. Further discussions will be focused on the daytime cooling effect or UHI mitigation as this time

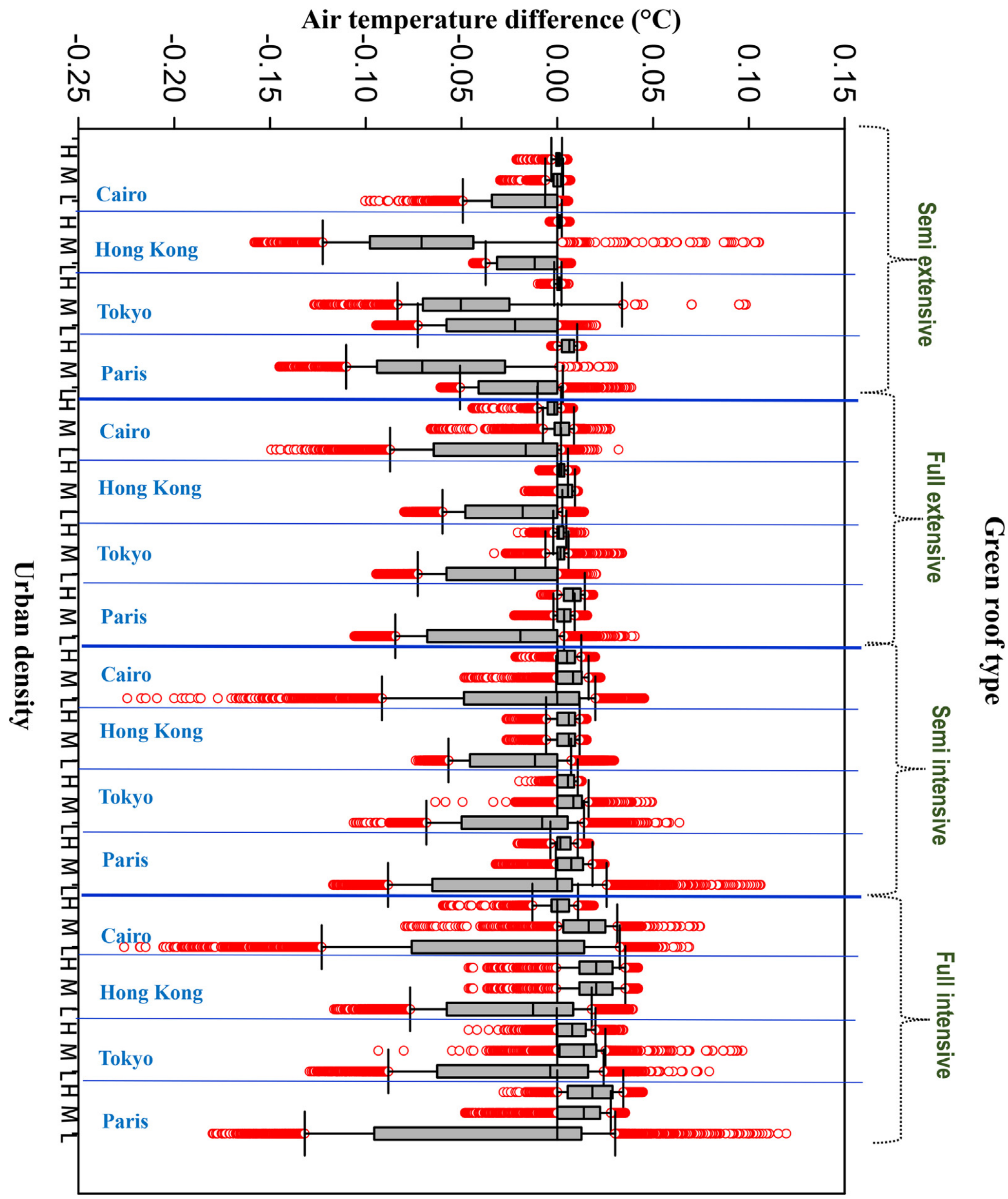

Fig. 4. Effect of green-roof types on nighttime (00:00 h) pedestrian air temperature under different climate and urban density (H: High density; M: Medium density and L: Low density).

represents period of human (outdoor) activity. More importantly, the cooling effect's sensitivity to climatic condition, urban densities and green-roof types will be discussed.

From Fig. 5, the performance of green roof for daytime cooling especially, varies per prevailing climatic condition, this is more apparent with the full-intensive green roof type and follows this order: hot-dry (Cairo), hot-humid (Hong Kong), warm-humid (Tokyo) and temperate (Paris). This order can be explained by the interplay between solar intensity, air temperature and relative humidity between the regions (see Fig. A1). In a hot-humid region like Hong Kong the evaporative cooling potential of greenery is dampened when compared to hot-dry region like Cairo. This is also true for region with low solar intensity and humidity like the temperate Paris. Our observation also follows the conclusion of other previous studies e.g. [50,52] where they likewise observe that the passive cooling effect of vegetation is lower on lower solar intensity and high relative humidity days and region by extension. It is important to mention that the greenery applied have similar soil wetness and physiological condition, as such the irrigation demand or requirement to actualize full cooling potential follows the same order of observed air temperature difference i.e. hot-dry (Cairo), hot-humid (Hong Kong) warm-humid (Tokyo) and temperate (Paris).

In terms of urban density, our results reveals the pedestrian cooling effect of green roof increases with decreasing urban density irrespective of climatic condition and green roof type. This is similar to the conclusion of other previous studies [25,26] where installation of green roof (irrespective of type) in medium and high density neigbourhood have negligible effect on pedestrian cooling.

In terms of the green roof type, our results follows the established conclusion that intensive green roof is more effective than extensive because of higher leaf density and canopy height [7,27]. Further to this, our results shows that intensive is as twice effective than extensive green roof. However, due to restrains in realistic implementation of 100% greenery coverage on rooftops, we tested the effect of each intensive and extensive green roof when

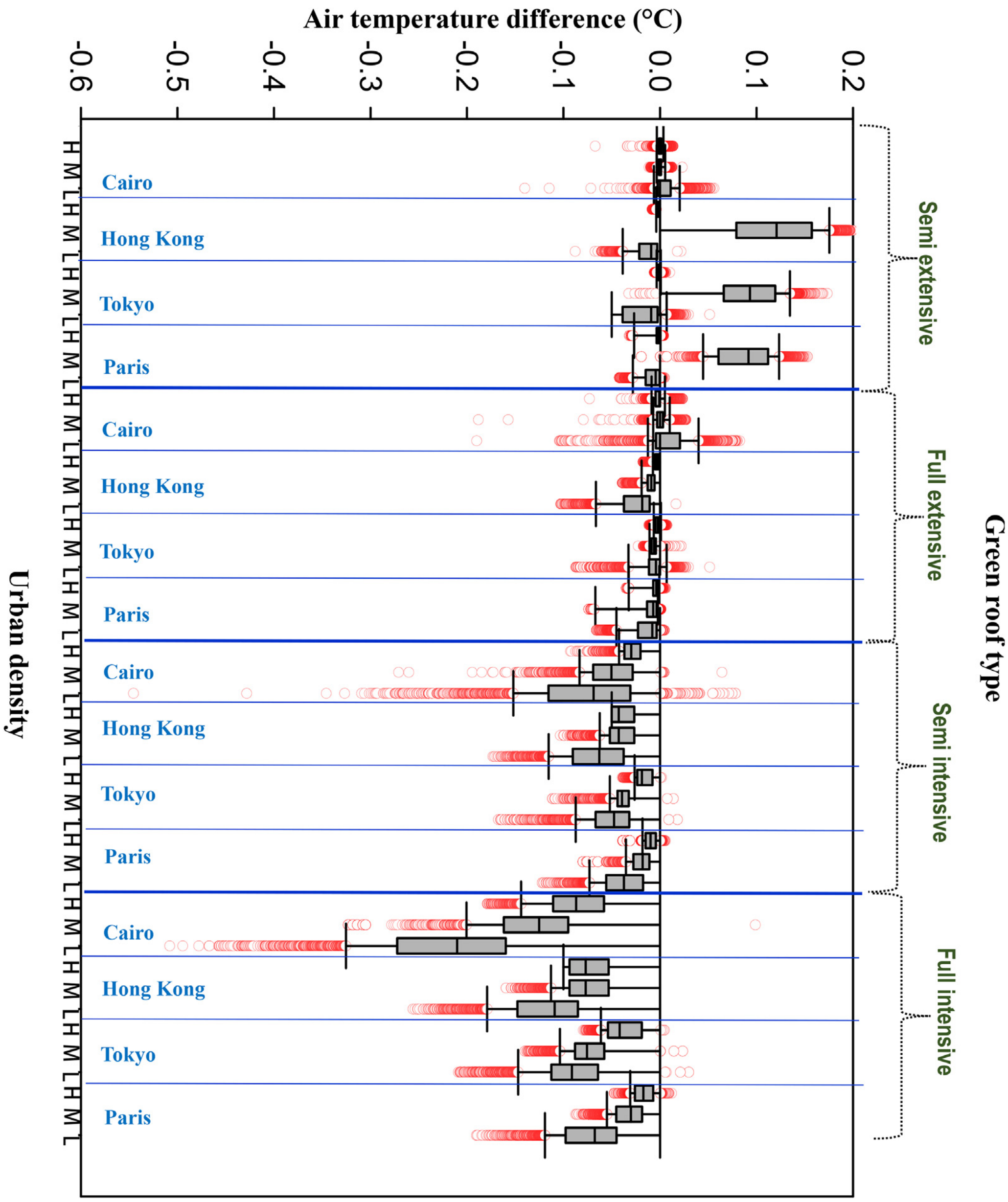

Fig. 5. Effect of green-roof types on daytime (15:00 h) pedestrian air temperature under different climate and urban density (H: High density; M: Medium density and L: Low density).

50% greenery is implemented. Results shows that spatial coverage has lower effect than leaf density and canopy height as we found semi-intensive to result in higher temperature reduction than full-extensive.

3.2. Effect of green-roof on roof surface temperature

Another effect of green-roof implementation is the reduction of roof surface temperature and consequent decrease in downward heat flux, indoor temperature and energy consumption [3,9]. As both of our simulation tools have the capacity to simulate buildings' surface temperature, we have compared the hourly roof surface temperature using data of low-density's reference case (conventional roof). The correlation between the two dataset ranges from $R^2 = 0.92$ to 0.98 (See Fig. 6). However, the absolute difference (green-roof −reference case) is higher with EnergyPlus than ENVI-mets' (Figure not shown). These discrepancies cannot be disconnected from difference in implemented physics and simulation techniques in the models. It should be noted that roof surface temperature in both models doesn't significantly varies with urban density since uniform building heights was assumed hence no shadow-shading effect on any of the building roof surface. Further discussion will be based on ENVI-met's result (for low urban density) since it provides better visualization of this parameter than EnergyPlus.

Like air temperature, the roof surface temperature reduction (at 12:00 noon when the sun is overhead) by green-roofs also varies with climate and green-roof type (see Fig. 7). The maximum reduction was ~14 °C, ~10 °C, 8.5 °C and 7 °C in Cairo, Hong Kong, Tokyo and Paris, respectively with full-intensive green-roof. For semi-intensive, the portion with greenery has similar reduction as their "full" counterpart while the greenery-free portion experiences insignificant difference. Surface temperature reduction is two times higher with intensive than extensive green-roof principally due to higher leaf density. These results emphasis that green-roof are effective in exterior surface temperature reduction of roof

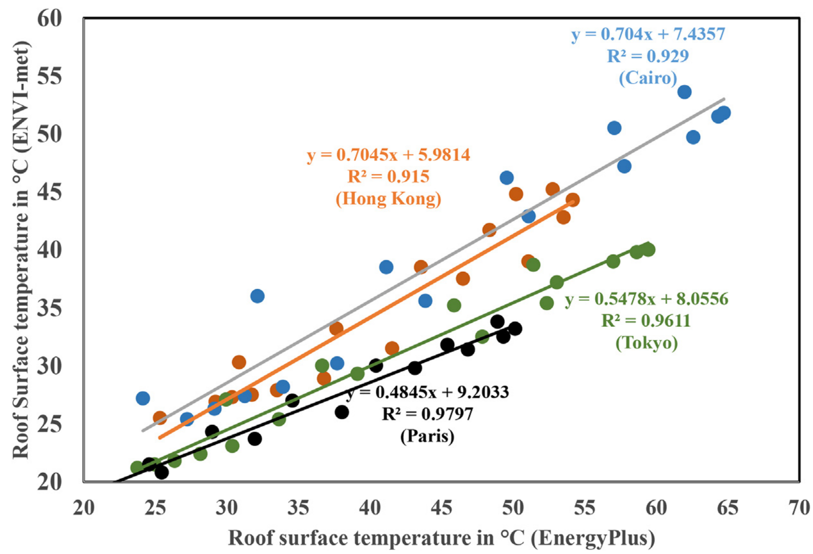

Fig. 6. Relationship between ENVI-met and EnergyPlus simulated hourly roof surface temperature for the four climates.

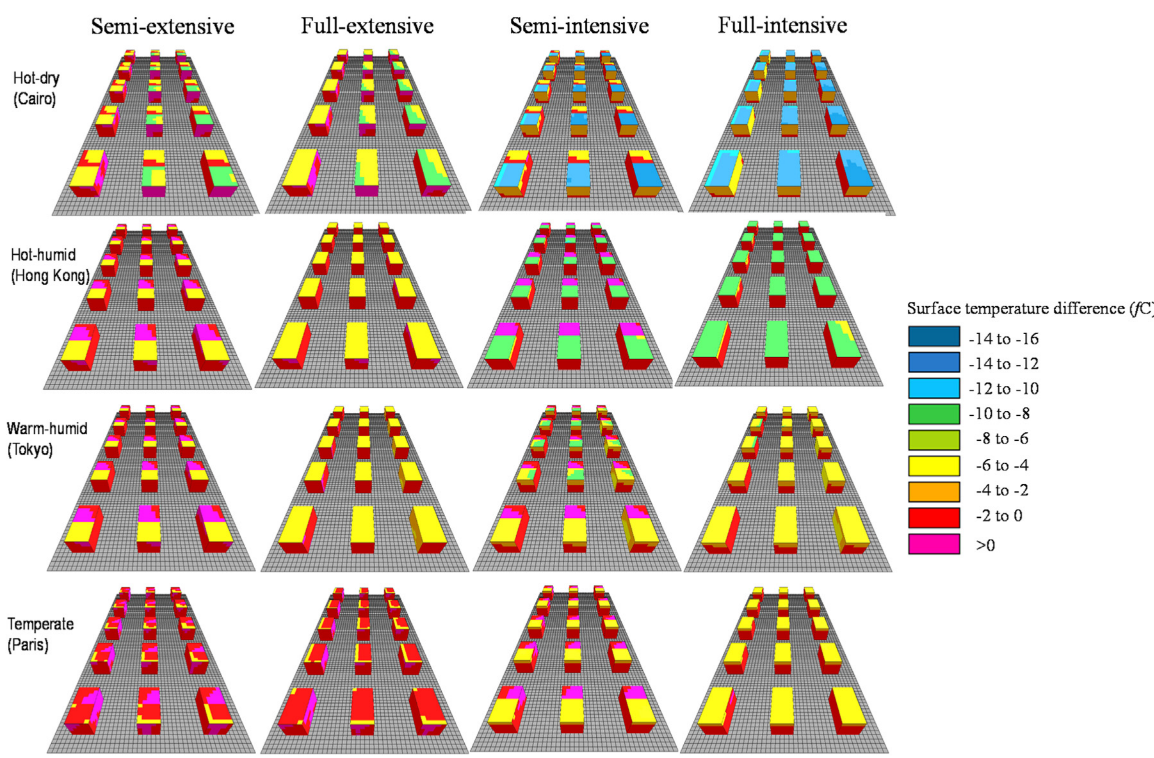

Fig. 7. Effect of green-roof types on roof surface temperature under difference climate at 12:00 noon. This plot is for low urban density and almost similar for High and medium densities.

and thereby provide thermal insulation to the building. Moreover, the degree of surface temperature reduction by the green-roof increases with the increased solar intensity, as higher reduction was observed during day time. At nighttime, the surface temperature difference is not significant, not more than 4 °C was observed in any case based on our simulation results.

These results are compatible with those of previous experimental studies: An empirical study by Tam et al. [12] showed that green-roof is capable of providing thermal insulation effects in hot-humid climates. Experiment studies by Karachaliou et al. [19] and Foustalieraki et al. [53] in Athens showed that green-roof can lower the surface temperature up to 15 °C and 21.9 °C, respectively. Wong et al. [54] found maximum temperature reduction of 30 °C by green-roof in Singapore. Also, a reduction of ~5–10 °C was found in La Rochelle, France, [55]. Therefore, these results echo the exterior surface temperature reduction by green-roofs under different climates, although the magnitude also varies among climates.

3.3. Effect of green-roof on indoor air temperature

The indoor air temperature difference (with and without green-roof) of the top floor of each building has been compared for daytime (using 15:00 h data, period of maximum temperature) and nighttime (using 0:00 h data) to identify the thermal impact of the

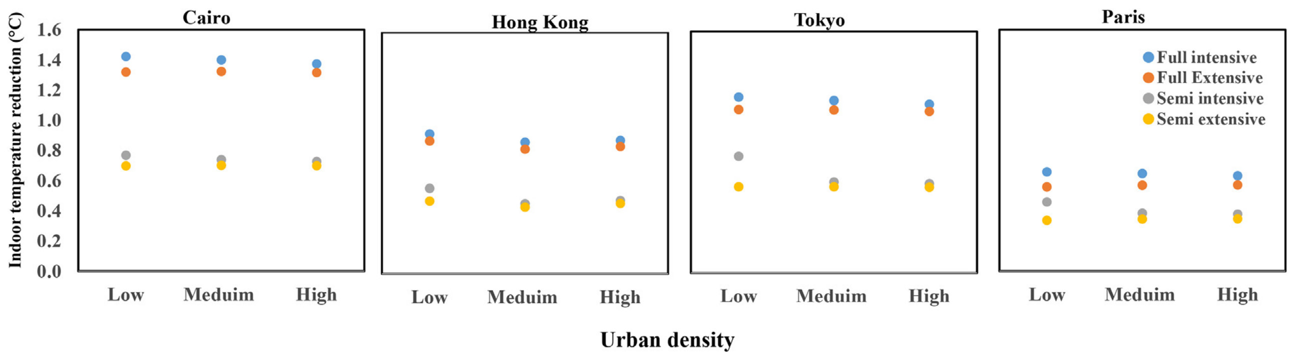

Fig. 8. Indoor temperature reduction under different green-roof types, climates and urban densities.

green-roof. The top floor for low, medium and high 'density' buildings correspond 4th, 12th and 24th floor, respectively. The cooling effect during the daytime under different climates and urban densities is shown in Fig. 8. Comparatively, full-intensive green-roof has the highest ability to decrease indoor air temperature, whereas semi-extensive had the least impact. The effect of urban density is not significant as shown in Fig. 8. The maximum temperature decrease of 1.4 °C was observed in Hot-dry climate of Cairo with full-intensive green-roof. The minimum temperature decrease of 0.3 °C was noted in temperate Paris with semi-extensive green-roof.

At nighttime, the negligible effect of green-roof types on indoor air temperature at was observed (Figure not shown). For all the considered cases, the maximum decrease was found with full-intensive green-roof in Cairo, which is 0.3 °C. On the other hand, in Paris, slightly increase of ~0.1 °C was observed. It is should mentioned that the outdoor air temperature of Paris at this time was 22.6 °C, 22.2 °C and 21.6 °C for low, medium and high urban density, respectively. This value is lesser than the building cooling set point which is 25 °C and could thereby influence the operative indoor air temperature.

In general, our results further reveal the potential of green-roof in reduce the indoor air temperature. The effect is higher in hot climates during the day time. The degree of temperature decrease may depend upon climate condition as well as the properties of green-roof. For instance an experiment study by Yu et al. [18] in Shanghai showed that indoor air temperature at night is about 2.5 °C higher for green-roof than conventional roof. Another experiment by Karachaliou et al. [19] in Athens showed with green-roof indoor temperature decreases up to 0.7 °C. These results shows that green-roof is effective in providing thermal benefits (courtesy of the insulation provided by the substrate and greenery) to the building and able to reduce indoor air temperature as well.

3.4. Electricity peak reduction by green-roofs

The effect of green-roof on electricity peak reduction has been determined by comparing the cooling electricity consumption with and without different green-roof on the hottest day of each studied climate under different urban densities as depicted in Fig. 9. As expected during the hotter daytime period, buildings with green-roof resulted in cooling peak reduction due to solar radiation blockage and insulation effect created by the greenery and its sub-layers. Apparently, the cooling peak reduction decreases with increasing urban density, regardless of the climate (or city). It should be noted that building envelope coverage of green-roof is 20% for a low density building, whereas it is only 5% for a high density building. These results are compatible with the indoor temperature reduction, where full-intensive green-roof being the most effective type and semi-extensive green-roof being the least. The maximum electricity peak reduction with full-intensive green-roof was found in Cairo with 5.2%, 1.7% and 0.8% respectively for low, medium and high urban densities. The highest electricity peak reduction for semi-extensive green-roof found as 2% in Cairo for low urban density and its 0.3% for Paris, which is the least. Interestingly, semi-intensive shows higher electricity peak reduction than full-extensive in all climates signifying the need to prioritize high leaf density and vertical green coverage than lower leaf density with high spatial coverage. Our results agree with Silva et. al [13], which shows both intensive and extensive green-roof are capable of providing energy benefits in hotter outdoor conditions, as the former is more effective. Furthermore, Berardi [27][27] showed that green-roof are capable of reducing building energy demand by 3% with full-extensive type.

Overall, Cairo showed the highest electricity peak reduction and Paris showed the least. The order of effectiveness follows this: hot-dry (Cairo), hot (Warm)-humid, Hong Kong/Tokyo and temperate

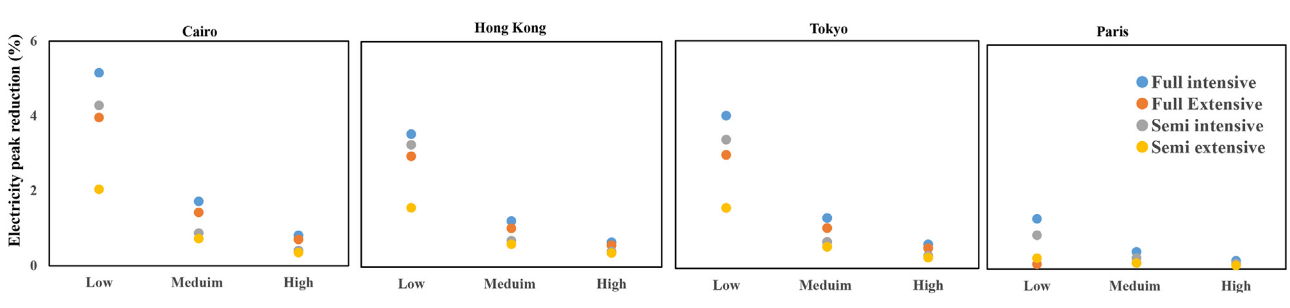

Fig. 9. Electricity peak reduction by green-roofs on the hottest day (Cairo – 7th July, Hong Kong – 1 st July, Tokyo – 3rd July, Paris – 2nd July) under different climates and urban densities.

(Paris). Electricity peak reduction is more promising with intensive than extensive green-roof.

4. Conclusion

This study has employed an integrated modelling approach using EnergyPlus and ENVI-met in studying temperature and electricity peak reduction by green-roof under different climates and urban densities. Our results show that relative humidity and solar intensity are key parameters which determines the evaporating cooling potential of green-roofs. In hot/warm-humid climate, green-roofs are less efficient for outdoor cooling and electricity demand reduction unlike in the hot-dry climate while the least efficiency was observed in the temperate climate characterized by low solar intensity and humidity. The order of efficiency of green-roof types is full-intensive, semi-intensive, full-extensive and semi-extensive for outdoor cooling and indoor energy use reduction, suggesting the need to emphasis higher vertical (with high leaf density) than horizontal plant coverage for these purposes. On the other hand, the order of efficiency for indoor daytime temperature reduction is full-intensive, full-extensive, semi-intensive and semi-extensive. Therefore, the intent of green-roof installation should be a determining factor for the type and spatial extent to be implemented. While full-intensive green-roofs are beneficial in any case, they seem not realistic as rooftop are used for other purposes such installation of utility gadget and rainwater harvesting, we therefore recommend semi-intensive to builders, architects and urban planners even though the magnitude of benefits will be reduced coupled with higher cost of installation and maintenance.

However, our findings are not all inclusive and should be applied with findings of related studies (all cited in the bibliography and others). For instance, other greenery configuration parameters were not tested which may influence the magnitude of our results. Previous studies [7,27] have shown that increase in leaf density could lead to higher green-roof cooling effect. Our study also assumed a well-watered greenery, lower water content will reduce its evaporative cooling capacity [56]. In dry climate as Cairo, it is important to have efficient irrigation system for continual benefit from green-roof, a low-cost means to achieve this the use of harvested rainwater as irrigation source as suggested by An et al. [30]. Furthermore, soil thickness impacts the energy use reduction i.e. the higher the soil depth, the lower the downward heat flux and consequently energy use [27]. Also, different plant species could produce different magnitude of climate and energy saving as observed by Jim [57] who shows that sedum than peanut plant for both temperature and energy use reduction. Lastly, roof surface only account for 20% of total urban surfaces therefore greenery of the other 80% is advocated for result-driven heat island, heat stress mitigation and energy use reduction.

Appendix A.

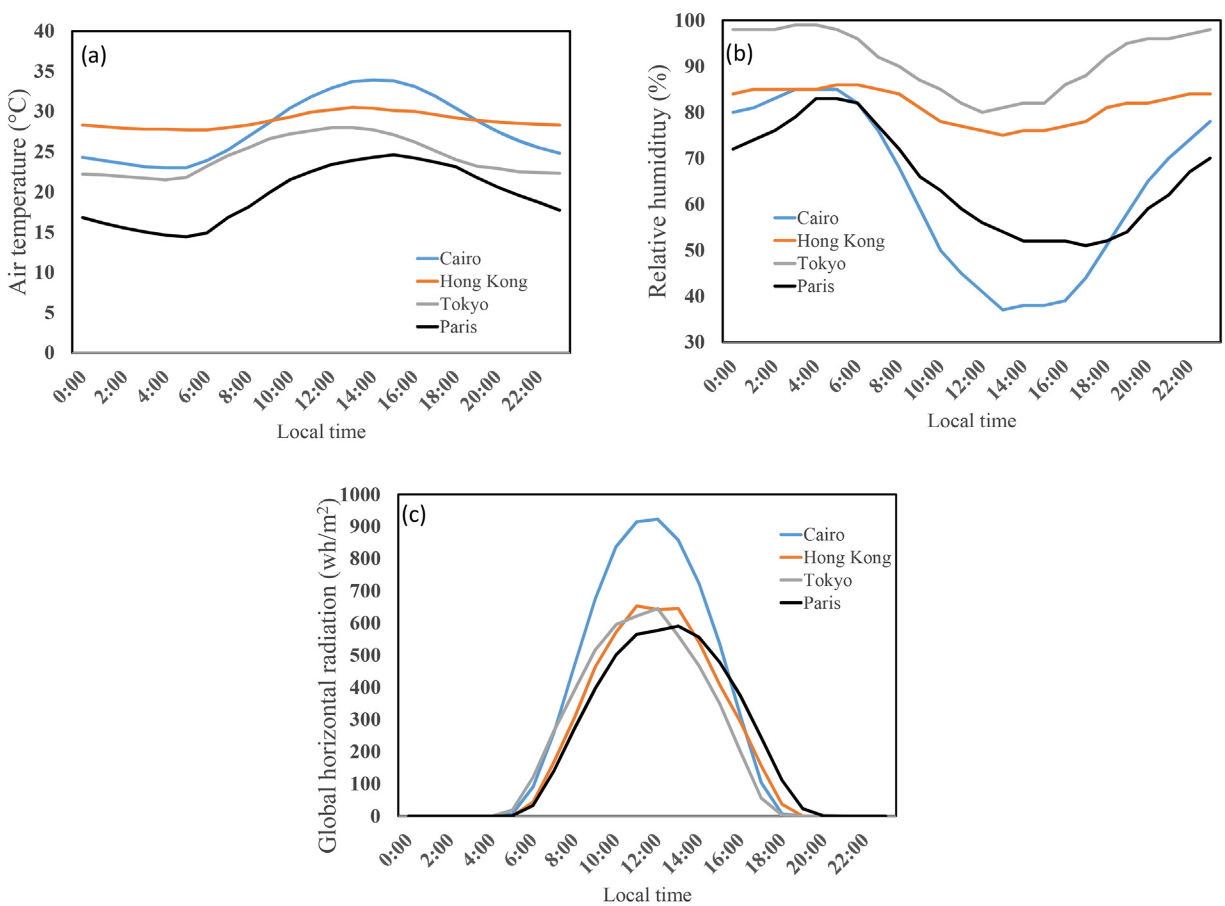

Fig. A1. Hourly variation of (a) air temperature (b) Relative humidity and (c) Global radiation in different climate (source: EnergyPlus's EPW database).

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