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Air-conditioning energy consumption due to green roofs with different building thermal insulation

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HIGHLIGHTS

- Green roof & control plots assess cooling effect of building thermal insulation (BTI).
- Air-conditioning energy use under green roofs monitored by precision energy logger.
- Simple green roof with BTI expectedly imposes less cooling load than without BTI.
- Complex green roof with BTI imposes anomalously more cooling load than without BTI.
- Green-roof and building heat sink effects jointly induce thermal insulation breaching.

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ABSTRACT

On hot days, green roofs could reduce heat flux into indoor space and air-conditioning energy use. Most thermal-benefit studies estimate energy saving based on temperature measurements. A field experiment on the roofs of two residential buildings in subtropical Hong Kong was designed to measure air-conditioning electricity consumption in relation to three factors: (1) building thermal insulation (BTI): omitted at Block 1 and installed at Block 2; (2) green-roof type: each block had a bare (Control) and two extensive green-roof plots, namely simple Sedum and more complex herbaceous Peanut vegetation; and (3) three summer weather scenarios: sunny, cloudy, and rainy. Air-conditioning electricity consumption of six vacant apartments below the experimental plots was monitored by precision energy loggers. Under all weather conditions, the unshielded Control imposes high cooling load at Block 1, but BTI at Block 2 cuts heat ingress. Sedum reduces more energy consumption than Control at both blocks, with Block 2 better than Block 1. The best effect occurs on sunny day, followed by cloudy and rainy. Sedum roof with BTI enhances thermal benefit. Without BTI, Sedum roof consumes more energy, hence the simple green roof cannot substitute BTI function. Under three weather scenarios, Peanut uses more electricity at Block 2 than Block 1, indicating the joint operation of green-roof heat-sink effect (GHE) and building heat-sink effect (BHE) at Block 2. Thicker substrate with higher moisture-holding capacity generates GHE. Added BTI material layers create BHE, with thermal resistance reduced by moisture penetration and elevated temperature. Their joint effect has raised thermal mass and thermal capacity. A rather steep thermal gradient is formed to induce thermal-insulation breaching to push heat into indoor space. At Block 1, Peanut roof can partly compensate for omission of BTI. At Block 2, however, Peanut coupled with BTI can synergistically increase cooling load. The findings can inform policies and design of green roof and associated BTI in cities with hot summer.

1. Introduction

Green roof studies cover thermal and associated energy consumption of indoor space. Buildings consume a large proportion of the energy used by cities, mainly for HVAC (heating, ventilation, and air-conditioning). Municipal authorities are taking actions to retrofit existing buildings and regulate new-building design to improve energy efficiency. The roof is the most important part of a building envelope for lowering energy consumption [1]. Raising roof mass structure and insulation can suppress and delay heat ingress into interior space and reduce its diurnal temperature amplitude [2].

In many cities, the overwhelming artificial cover has raised absorptivity for solar radiation and thermal capacity. Heat dissipation by ground longwave radiation is hindered by more cloud cover

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and higher particulate concentration in the lower atmosphere. Inadequate green and blue (water bodies) covers in compact urban areas can raise the Bowen ratio, and subdue natural cooling by evapotranspiration. The accumulated heat has to be released from the urban fabric mainly by convection. However, dense packing of buildings and road limits ventilation and sensible heat dispersal by convection. As cities get hotter, they consume more energy to meet HVAC and human-comfort requirements [3]. Meanwhile, cities are expanding and intensifying, with more humans and machines generating more heat to accentuate the urban heat island (UHI) effect [4,5]. The superimposition of global warming further aggravates temperature rise in cities [6].

In many cities, buildings consume the bulk of the energy, of which air-conditioning tends to take a large share [7]. Under the joint impacts of climate change, urban heat island (UHI) effect, rising cost of energy, and environmental impacts of conventional energy generation, most countries are attempting to improve energy efficiency and reduce energy use [8,9]. It has been predicted by various modeling studies that air-conditioning energy demand will rise significantly in the near future as a response to rising temperature especially in cities [10,11]. Rising affluence and expectation will also increase air-conditioner installation and utilization. Increasing air-conditioner use can aggravate the air-pollution problem [12]. One way to achieve energy saving is to equip buildings, particularly their envelopes, with installations or coatings to reduce solar energy intake [13]. Various innovative countermeasures could be adopted with the help of regulation through enforcement of building codes or voluntary compliance [14].

Enlightened city governments have developed enabling policies and measures to tackle climate-change challenges, making them climate-resilient and climate-proofed [15,16]. Urban green spaces (UGS) or urban green infrastructure (UGI) in general in built-up areas can bring natural cooling and contribute to climate adaptation [17,18]. In well-vegetated areas, solar energy can be converted from the consumptive mode of warming to the productive mode of cooling [19,20], and reduce air-conditioning energy consumption [21]. In compact areas, the chance of inserting UGS is slim. The building envelopes including bare rooftops and facades provide alternative greening sites [22,23]. They offer a potential resource to ameliorate the UHI effect. The efficacy of green roofs in fulfilling this role could be optimized by in-depth research.

Green roofs can bring energy saving in different ways. For individual buildings, passive cooling can suppress downward heat flux into top-floor indoor area to reduce air-conditioning electricity consumption. Intake of cooler air by air-conditioning units placed on or near green roofs can reduce energy required to cool to the desired temperature [24]. For a building with large central air-conditioning machines installed on rooftop, this benefit could be shared by all floors. At the city scale, widespread green-roof installation can reduce summer temperature to reduce air-conditioning energy consumption [25,26]. In dry climate that demands irrigation, the total cost of installing and maintaining green roofs could be judged against energy savings [27].

Energy saving of green roof is more significant in cities with a hot summer [28–30]. In the tropics, high summer temperature often exceeds the normal human-comfort threshold. Green roofs can bring notable passive cooling benefits to both outdoor and indoor environment [31–33]. Temperate-latitude cities can also benefit in summer from green-roof cooling. As artificial heating of indoor space is seldom practiced in the tropics, retention of indoor warmth in winter is mainly relevant to areas outside the tropics [30,34]. It is helpful to understand the magnitude, characteristics and factors of air-conditioning energy conservation due to green roofs. Most studies estimate energy saving from temperature measurements [35], calculated heat flux patterns [36,37], or modeling computation [38]. No study has attempted to monitor directly energy consumption of indoor space under green roofs. The lack of directly measured energy data denotes a knowledge gap that may hamper understanding of this pertinent aspect of green-roof science.

Thermal resistance of building thermal insulation (BTI) varies greatly between buildings. Older structures often follow superseded standards that are less efficient. Green-roof retrofitting on buildings with differential BTI could usher different indoor thermal benefits. Some recent studies imply that buildings with poor BTI could benefit more from green-roof installation [20,39]. This is based on the assumption that a roof cooled by vegetation could create a thermal gradient to draw heat upwards from indoor space. Other studies find that green roofs cannot compensate for omission of BTI [40]. This apparent contradiction could be clarified by additional research.

A controlled field-experimental study has been designed to tackle the above uncertainty, aiming at five objectives: (1) to develop methods to monitor directly air-conditioning energy consumption in relation to green-roof thermal benefit; (2) to test the effect of green roofs on two buildings respectively without and with BTI on air-conditioning energy consumption; (3) to test the above effect in relation to two extensive green-roof with different plant growth form and photosynthesis–transpiration physiology; (4) to evaluate the above effects in relation to three tropical summer weather scenarios, namely sunny, cloudy and rainy; and (5) to assess the monetary value of energy savings.

2. Study area and methods

2.1. Study area

The study was conducted in humid-tropical Hong Kong situated at the southern coast of China at latitude 22°N and longitude 114°E. The climate is largely regulated by the Asian monsoon system with hot-humid summer characterized by high temperature often exceeding 30 °C in daytime and frequent heavy rainfalls. The warm period extending from May to September coincides with the rainy season, shedding about 2300 mm per annum. Winter is relatively short and mild with temperature seldom falling below 10 °C. The city has experienced a warming trend characterized by rising average annual temperature, and increasing occurrence of hot days (maximum exceeding 33 °C in daytime) and hot nights (minimum stays above 28 °C in nighttime) [41]. Some 63% of the total energy use in Hong Kong is consumed by buildings, with air-conditioning taking the largest share [42,43]. The poor thermal insulation of many buildings contributes to wasteful use of air-conditioning energy [44]. The community is finding ways to reduce energy use of buildings.

2.2. Experimental design and green roof installation

The experiment requires two sites without and with BTI, which was achieved at a new public housing estate in a new town in Hong Kong. The rooftops of two high-rise residential buildings with the same layout were chosen (Fig. 1). At Block 1, BTI layers were omitted to denote poor thermal insulation. At Block 2, the full complement of BTI was installed to denote good thermal insulation. The BTI design and materials are widely adopted in Hong Kong, with the thermal insulation laid above the waterproof membrane (Fig. 2).

At each block, three experimental plots were demarcated based on the layout of three domestic flats lying underneath (Fig. 1). The flats were kept vacant throughout the experimental period to minimize human impacts and provide uniform treatment to all units. The building design required minor adaptation to minimize the