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Energy, environmental and economic assessment of electricity savings from the operation of green roofs in urban office buildings of a warm Mediterranean region

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ABSTRACT

Green roofs are an important technique to efficiently mitigate adverse environmental impacts of buildings. This study focuses both on energy conservation and sustainability related aspects of two alternative green roof solutions applied to a typical urban office building in representative climatic areas of Cyprus in the Eastern Mediterranean. Simulations regarding the buildings' energy demand were conducted using EnergyPlus software. Based on these results and using an in-house developed algorithm, the primary energy consumption for each alternative solution was computed, assuming variable refrigerant flow air-to-brine heat pump as heating and cooling system, coupled with a calculation of the associated emissions of carbon dioxide, nitrogen oxides and sulphur dioxide. The analysis shows a reduction in primary energy consumption up to 25% in heating and up to 20% in cooling operation, thanks to the use of green roofs, and a corresponding reduction in emissions. The economic viability of the proposed green roof solutions was also examined, taking into consideration both monetary and environmental costs. The results show that the green roof solutions increase the lifetime cost up to 40,000 €, however they can lead to additional environmental and economic benefits which are hard to quantify.

1. Introduction

It is widely evident that the most prosperous societies worldwide are those whose service sector exhibits a strong and growing contribution to national economic output. Such a strong growth, however, inevitably increases the sector's ecological footprint. In the European Union, for example, final energy consumption has followed a declining path in the last years. This trend is mainly due to the reduction of final energy consumption in the sectors of industrial production, transportation, and households. On the contrary, the service sector has followed a different path: its energy consumption has risen by approximately 5.7% during the same period (EEA, 2015).

Among others, the application of green roof technology on the rooftops of commercial buildings is one of the promoted solutions to mitigate the relevant energy, environmental and climate impacts (Ascione, 2017; Viola, 2017). In principle, a green roof is the roof of a building that it is partially or completely covered with vegetation and a growing medium (such as soil or gravel). It can be applied either as a retrofit of the existing building's envelope or at the construction phase of new buildings, affecting not only the building's energy and environmental performance but also the microclimate of the surroundings (Aflaki et al., 2017; Skelhorn et al., 2016; Vacek et al., 2017).

In this paper we analyze the energy aspects of green roof technology in Cyprus, a semi-arid island located in the Eastern Mediterranean. Following the EU-wide trend, the commercial and public service sector is responsible for a substantial portion of total energy consumption of Cyprus, with a share of more than 14%, which is slightly lower than that of the residential and clearly higher than that of the industry sector (IEA, 2014). Since most of the commercial buildings are placed in the four major cities of Cyprus (Paphos, Limassol, Larnaca, and Nicosia), it is essential to focus any

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analysis on the increasing energy use of this sector in urban areas. In general, cities are responsible for 70% of anthropogenic carbon dioxide (CO_2) emissions and a surge in air pollution, turning them into not only a basic perpetrator but also an immediate victim of climate change (Rigter et al., 2016).

A considerable research effort has been devoted to analyzing the energy, environmental and economic aspects of green roofs. In China, for example, Yang et al. (2015) analyzed air conditioning electricity consumption and temperature recordings of various roof structures (including vegetated, clay and ceramic coatings) of a commercial building in Guangzhou. Two different studies were conducted in Hong Kong. The first one (Chan and Chow, 2013a) investigated both the energy performance and the cost payback period of a green roof system under distinct forthcoming climatic conditions, while the second one (Chan and Chow, 2013b) updated the Overall Thermal Transfer Value (OTTV), which is a method of calculating possible building envelope's heat gains, with a set of correction factors, in order to be applicable in the cases of planted rooftops.

In the US, alternative methods were employed to evaluate the energy performance of green roofs. Moody and Sailor (2013), developed the ratio of Heating, Ventilation and Air-Conditioning (HVAC) energy consumption for a building with a traditional roof to that of a building of with a planted roof, called Dynamic Benefit of Green Roofs (DBGR), while Yaghoobian and Srebric (2015) simulated different case studies using the Department of Energy (DOE) commercial reference building models Moreover, in the UK, green and cool roof renovating technologies were examined in contrast to the application of traditional insulation in a classic office building located in Central London (Virk et al., 2015).

Regarding the Mediterranean region, where similar climatic conditions prevail, recent studies have attempted to evaluate the impact of this technological solution through various approaches. Indicatively, based on experimental and numerical analysis, green roofs can lead to the reduction of energy both entering the building during heating days and exiting the building during cooling days, with the lack of increased insulation being in favor of the overall energy performance (Bevilacqua et al., 2016; Silva et al., 2016). In addition, Costanzo et al. (2016) and Karachaliou et al. (2016) showed that the Urban Heat Island (UHI) effect can be mitigated efficiently with the implementation of green roof technology. Finally, regarding shallow green roofs, Bevilacqua et al. (2015) found that the spatial factor constitutes an important determinant in terms of overall thermal performance and vegetative arrangement.

Adding to the analyses of previous studies that were mentioned above, in this paper we explore the potential benefits of green roofs not only on energy conservation but also on other sustainability aspects. The analysis focuses on a typical reference office building in Cyprus under various building thermal insulation (BTI) scenarios. We carefully select native plants and the corresponding conservative irrigation regimes, and consider ways to exploit recycled urban resources (rubber crumbs and waste compost). We examine the economic viability of the proposed green roof alternatives using a comprehensive approach that accounts not only for the possible monetary benefits from energy savings, but also for the economic benefits of a reduced environmental impact, in terms of avoided costs of emissions of Carbon Dioxide (CO_2), Sulphur Dioxide (SO_2), and Nitrogen Oxides (NO_x). Although based on an individual case study, our findings can be expanded in order to estimate the effects of such a technology on a wider urban scale, which can lead to useful policy recommendations for the broader adoption of green roof systems.

2. Methodology

2.1. Building features

The determination of the geographical and morphological characteristics of the typical office building in Cyprus was based on a detailed analysis of the current typology of this country's building stock. The relevant information has been mainly obtained from the Statistical Service of Cyprus (CYSTAT, 2015) and has been enhanced through contacts with planning and construction engineers as well as site visits.

The service sector's buildings constitute approximately 34% of the existing building stock, with stores and offices accounting for more than half of them (CYSTAT, 2015). They are primarily located in the city areas, and their height varies depending on the type of urban zone they fall into. On average, they are developed in 4 stories above ground floor, which is usually formed as an open pillared space. The covered surface rarely exceeds 1500 m^2, and their typological characteristics include expanded areas of transparent structural elements and the absence of balconies.

Based on the aforementioned description, a new typical office building has been designed from scratch, in accordance with common design and construction practices in Cyprus, in order to be considered representative of this specific category's building stock. It is a four-story building that incorporates a pilotis[1] in the ground floor and has a rectangular 365 m^2 floor plan, identically repeated in all stories. The building has two independent free sides, the south and west ones, while the north and east ones are in direct contact with adjacent properties and accommodate both the supporting and communal areas. The office rooms are spread across the free sides of the building, while the common areas, storage and server room, and the conference room are located in the blind ones and in the core of it. The three-dimensional representation of the office building is presented in Fig. 1.

The load bearing structure and the masonry are made of reinforced concrete and perforated bricks, respectively. In some of the examined cases, extruded polystyrene is used as a thermal insulation layer. It is applied on the outer side of the vertical structural elements and the ceiling above the pilotis. The heat insulation thickness values derive from the relevant requirements for the maximum thermal transmittance (U-value) of the current regulation (MECIT, 2015a) and are presented in Table 1.

As shown in Fig. 1, windows are allocated along the south -main- and west sides of the building and occupy 35%–40% of their surface, whereas the north and east sides are made exclusively out of opaque elements, in accordance with common design and construction practices in Cyprus. Windows bear an aluminum frame with thermal break and a thermal transmittance (U_f-value) equal to 2.98 W/(m^2K) and double glaze with thermal transmittance (U_g-value) equal to 2.8 W/(m^2K). It is worth noticing that for the above given values the external openings can meet the legislative provisions of the minimum energy efficiency requirements with regard to Decree 359/2015 (MECIT, 2015a).

2.2. Climatic and geographical features

Cyprus' geographical position is Latitude 35° North, Longitude 33° East, and its climate is determined by strong Mediterranean characteristics (MOA, 2016). Based on the Köppen-Geiger Climate Classification (KGCC) and the respective high resolution Google Earth maps (Kottek et al., 2006; Rubel et al., 2017), Cyprus is divided

[1] Pilotis are columns or similar structural elements that support a building above ground.