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Building-integrated rooftop greenhouses: An energy and environmental assessment in the mediterranean context

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HIGHLIGHTS

- iRTG incorporates urban agriculture into and improves energy efficiency in buildings.
- iRTG concept recycles low-grade, waste thermal energy for growing vegetables.
- iRTG is an adaptable concept to promotes food security through urban agriculture.
- Indoor building climate affects iRTG more than outdoor climatic conditions.
- iRTG achieved annual CO_2 and cost savings of 113.8 kg CO_2 (eq)/m^2/yr and 19.63 €/m^2/yr.

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ABSTRACT

A sustainable and secure food supply within a low-carbon and resilient infrastructure is encapsulated in several of The United Nations' 17 sustainable development goals. The integration of urban agriculture in buildings can offer improved efficiencies; in recognition of this, the first south European example of a fully integrated rooftop greenhouse (iRTG) was designed and incorporated into the ICTA-ICP building by the Autonomous University of Barcelona. This design seeks to interchange heat, CO_2 and rainwater between the building and its rooftop greenhouse. Average air temperatures for 2015 in the iRTG were 16.5 °C (winter) and 25.79 °C (summer), making the iRTG an ideal growing environment. Using detailed thermophysical fabric properties, 2015 site-specific weather data, exact control strategies and dynamic soil temperatures, the iRTG was modelled in EnergyPlus to assess the performance of an equivalent 'free-standing' greenhouse. The validated result shows that the thermal interchange between the iRTG and the ICTA-ICP building has considerable moderating effects on the iRTG's indoor climate; since average hourly temperatures in an equivalent freestanding greenhouse would have been 4.1 °C colder in winter and 4.4 °C warmer in summer under the 2015 climatic conditions. The simulation results demonstrate that the iRTG case study recycled 43.78 MWh of thermal energy (or 341.93 kWh/m^2/yr) from the main building in 2015. Assuming 100% energy conversion efficiency, compared to freestanding greenhouses heated with oil, gas or biomass systems, the iRTG delivered an equivalent carbon savings of 113.8, 82.4 or 5.5 kg CO_2(eq)/m^2/yr, respectively, and economic savings of 19.63, 15.88 or 17.33 €/m^2/yr, respectively. Under similar climatic conditions, this symbiosis between buildings and urban agriculture makes an iRTG an

Abbreviations: ICTA-ICP, Institute of Environmental Science and Technology (ICTA) and Catalan Institute of Paleontology (ICP); iRTG, integrated rooftop greenhouse; RTG, rooftop greenhouse; UA, urban agriculture.

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efficient resource-management model and supports the promotion of a new typology or concept of buildings with a nexus or symbiosis between energy efficiency and food production.

1. Introduction

Buildings account for approximately half of the world's primary energy consumption [1–3], and agriculture and food production are reported to consume between 13 and 15% of total energy in developed countries [4–6]. Greenhouses are one of the most energy-demanding components of the agricultural industry [7–9] because ideal climatic conditions are created by closely controlling internal temperature and humidity levels for satisfactory plant growth in central and northern Europe.

While the decarbonisations of these two sectors require different solutions, an interesting possibility exists with an urban agriculture concept in which additional efficiencies can be derived from the integration of buildings and food production. A rooftop greenhouse (RTG), whereby soil-free farming methods such as hydroponics or aeroponics [10–12] may be integrated into a building, is an example. Although considerable amounts of non-renewable energy are conventionally used to operate greenhouses in central Europe, an integrated method could help decarbonise greenhouse-based food production and promote more efficient and sustainable greenhouse heating [13,14]. Empirical data are missing in this area, and this has formed the foundation of this work: full annual results are presented for the operational characteristics of the world's first case of a fully-integrated rooftop greenhouse for scientific research. Within this article, ICTA-ICP refers to the entire building under study; the integrated rooftop greenhouse (iRTG) is used to refer to the rooftop greenhouse.

The objective of this paper is, therefore, (a) to report the measured annual data that outlines the symbiosis between the iRTG and the building in energy terms and (b) using computer simulation, to quantify the heating energy that iRTG has passively and actively recycled from the ICTA-ICP. The reduced environmental impact resulting from this integration is then calculated using kg $CO_2(eq)/m^2/yr$ as the index. In doing so, the advantages offered by the iRTG concept relative to a conventional freestanding greenhouse are highlighted. While reporting the first scientific case for support on the application and feasibility of an iRTG; the findings also redefine a unique typology or concept of building design that can have a nexus or symbiosis between energy efficiency and food production worldwide as a strategy in support of food security and green urbanism. While seeking to offer an original perspective on the theme of integration of greenhouses in buildings and demonstrating the viability of this concept, this work also highlights the need for further research in the adaptation of iRTG concept under various urban energy and operational systems and climatic conditions around the world.

1.1. Global urbanisation and the food challenge

The United Nations, in its 2010 perspective, noted that more people live in urban settings than in rural areas. The projection of this trend is that world urbanisation will increase from 50% in 2009 to 69% in 2050 [15]. A total of 75% of the EU population currently lives in cities, a percentage that is expected to rise to 80% by 2020 [16]. This high concentration of people in cities has major socio-economic ramifications, and food production and its supply and security requires closer examination [17].

According to figures provided by the Food and Agriculture Organization of the United Nations (FAO), almost a billion people suffer from malnutrition, and four hundred million are chronically undernourished [18]. Conversely, urbanisation has generated a two-pronged nutritional burden: nutritional deficiencies and the emergence of over-nutrition among vulnerable groups in urban areas [19]. In recognition of this, the concept of urban agriculture (UA) seeks to offer innovative solutions to ensure the environmental and economic sustainability of food supplies within urban contexts and also to promote food of high nutritional quality.

Urban agriculture ranges from entirely commercialised agricultural facilities to production at the household level [20] and usually complements rural agriculture [21]. Urban agriculture is a historical reality in developing countries [22,23], where even today 800 million people are engaged in urban agriculture, producing 15–20% of the world's food [24]. It is believed that 10–20% of the nutritional needs of families living in urban areas in developing countries are met by the consumption of fruits and vegetables from urban agriculture [21].

Because of its adaptability to any built environment and typology, urban agriculture's benefits encompass economic, social and environmental elements [25]. In urban areas of relatively high residential density with mixed land use and limited access to green spaces for food production, rooftop greenhouses (RTGs) can provide the opportunity for cities to produce high-nutrient food with maximum efficiency, minimising production and transport costs and optimising space use in a built environment where buildings can foster food production.

1.2. Conventional greenhouses

Greenhouses, regardless of their degrees of complexity, attempt to provide ideal conditions for adequate plant growth throughout the year [26,27]. The principal regulated parameters are light, temperature, humidity and air quality [28–30]. The origin of the greenhouse goes back to ancient times. They were popular during 15th to 18th centuries in France, England and the Netherlands, but their use for commercial production began only in the mid-19th century, increasing after 1945 [26] and culminating in today's widespread deployment in Europe. More specifically, the estimate for the European Mediterranean region is >200,000 ha of in-use greenhouses in 2006 and 1,950,000 ha by 2010. Spain had 53,842 ha during 2005, and in 2009, Almería possessed a total of 27,000 ha [31].

Specifically, the Mediterranean area ecosystems have the characteristics of several regions in the world, such as southern Chile, California, the European Mediterranean basin, Cape Province in South Africa, and southwest Australia [32,33]. In the European Mediterranean basin, the development of Mediterranean horticulture was reshaped by the energy crisis in the 1970s, when low-cost plastics and local materials were used to build the first generation of widely deployed greenhouses. A basic Mediterranean greenhouse is characterised by large inner volumes within a low-cost structure (i.e., low-cost polyethylene roof and walls), total transparency, natural ventilation, no heating, limited use of climate control systems, and stability with respect to wind and thermal screens [34,35]. The seasonal operational regime of Mediterranean greenhouses seeks the maximisation of solar irradiation and the minimisation of thermal energy loss (autumn and winter), as well as the reduction of excess temperatures in spring and summer [36–38]. High temperatures and high solar radiation can affect