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Experimental evaluation and energy modeling of a greenhouse concept with semi-transparent photovoltaics

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Abstract

The use of semi-transparent photovoltaics (STPV) as a greenhouse cladding material can serve to transmit daylight while providing some shading and solar electricity generation. This paper experimentally validates an energy model of a greenhouse concept employing STPV. The model is then used to compare the energy performance of a full-scale greenhouse and a vertical farm concept, with both employing STPV. Simulation results for Montreal indicate that the vertical farm generates 49% less solar electricity and consumes up to 31% less heating than the greenhouse, whereas their cooling energy demand is approximately equal. This research evaluates promising design concepts for year-round urban agriculture and renewable energy generation.

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Keywords: urban/local agriculture; rooftop greenhouse; vertical farm; leafy green crop production, solar energy; semi-transparent photovoltaics

1. Introduction

According to the most frequently cited statistical estimate of production-to-consumption distances in the United States, food travels on average 2400 km from the farm to the consumer [1]. For certain foods, therefore, local production can significantly lower emissions and waste. Leafy greens such as spinach and kale are good candidates for local food production, both because they perish quickly and because significant nutrient value is lost during transportation. Therefore, research is needed to identify and analyze designs capable of efficiently growing these crops within the urban environment.

Leafy greens can be produced in stand-alone greenhouses/vertical farms or by using greenhouses that are integrated into building roofs and façades in new or retrofit applications. The commercial viability of urban rooftop greenhouse agriculture was demonstrated by Lufa Farms in Montreal, Canada [2]. Despommier explains how creating vertical farms in urban centers is a potential solution to food safety and security [3].

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Leafy greens can be damaged by excessive heat and sunlight, and therefore shading is generally provided. Semi-transparent photovoltaics (STPV) can be used as a building cladding material that transmits a fraction of daylight while providing shading and solar electricity generation [4]. One study performed annual simulations to compare the energy consumption of a greenhouse with and without STPV, and found that heating and cooling can be reduced by 11% and 30%, respectively [5]. Moreover, greenhouse design for space-efficient leafy greens production can be achieved by stacking the growth channels and using energy-efficient grow lights such as light-emitting diodes (LEDs) [6].

Recently, climate control of greenhouses has been improved by using the closed concept which conditions and recirculates the air (temperature, humidity and carbon dioxide levels) within the greenhouse space. One study summarizing the Dutch experience with closed greenhouses reported that it is possible to increase yields by 20%, reduce energy use by 30%, consume 50% less water, and lower pesticide use by 80% [7].

This study presents the testing of a greenhouse concept employing STPV cladding in a solar simulator - environmental chamber laboratory. The experimental results are used to validate a TRNSYS energy model of the greenhouse. In a second part, a simulation study is performed to compare the solar energy generation and thermal energy consumption of a conventional greenhouse and a vertical farm concept employing STPV. The vertical farm carries the advantage of using less space and will likely consume less energy for heating in winter. However, a vertical construction will have less roof area and hence it is expected that less solar energy generation would result.

2. Experimental greenhouse

2.1. Experimental details

The Concordia University solar simulator - environmental chamber (SSEC) laboratory is an indoor research facility designed to emulate outdoor weather conditions in order to provide a fully controlled and monitored environment for research, development and testing of solar energy applications and advanced building envelopes. A 4.65 m^2 experimental greenhouse (2.37 m x 1.96 m x 2.03 m) was built (Fig. 1a). Six 58 Watt STPV modules (45% polycrystalline solar cells, 50% glass and 5% aluminum framing) are used to cover one of the walls. The transmittance (τ) of the glazing is 77% and the thermal conductance is U=233 $W/m^2/K$. The walls and roof are made of 4 mm polypropylene painted black with U=11.4 $W/m^2/K$. The floor is made of 4 mm polypropylene over 19 mm plywood. The greenhouse is placed inside the environmental chamber which is maintained at a constant air temperature of 5°C (Fig. 1b). The solar simulator lampfield is configured to provide shortwave radiation with an average irradiance of 1038 W/m^2 on the STPV wall with a distribution uniformity of 86%. Two fans mix the air within the greenhouse.

a) b)

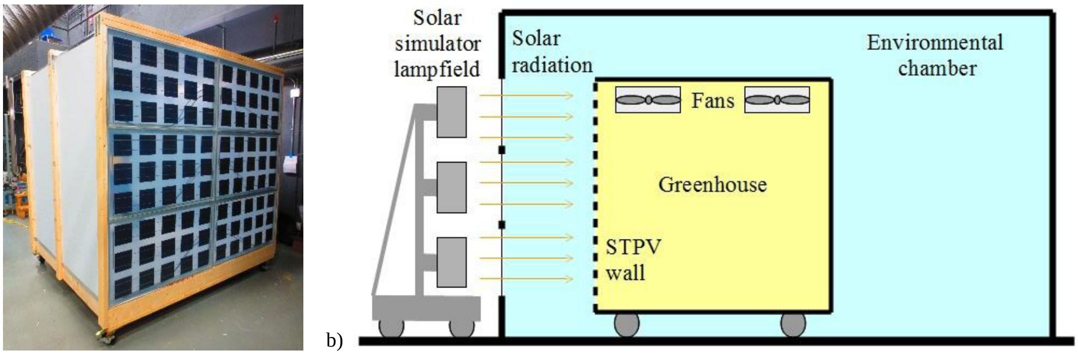

Fig. 1. (a) Photo of the exterior of the experimental greenhouse; (b) Experimental setup inside the SSEC laboratory.