Evaluation of the Potential of Attached Solariums and Rooftop Greenhouses in Quebec

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Abstract

The addition of a solarium to a house or a rooftop greenhouse on an existing building may provide many benefits: they can provide heat to the buildingand adequate conditions for growing vegetables whileoffering additional floor area. The objective of this paper is to evaluate the energy potential of retrofitted solariums and greenhouses for the province of Québec. A total of eight case studies have been simulated using EnergyPlus. Results indicate that solariums could collectfrom 27.6kWh/m^2 to 144.1 kWh/$m^2$of net useful heat per floor areaof solarium while rooftop greenhouses could reach net zero heating consumption or even generate moderate surplus heat.

Keywords: solar energy, potential, solarium, sunspace, greenhouse

Résumé

L'ajout d'un solarium à une maison ou d'une serre sur le toit d'un bâtiment existant peut offrir de nombreux avantages : ils peuvent fournir de la chaleur au bâtiment adjacent et des conditions adéquates pour la culture des légumes ainsi qu'une surface de plancher supplémentaire. Cet article a pour but d'évaluer le potentiel énergétique de l'intégration de solariums et de serres à des bâtiments existants au Québec. Huit scénarios ont été simulés à l'aide du logiciel EnergyPlus.Les résultats indiquent qu'un solarium pourrait recueillir une chaleur nette utile variant entre 27,6 et 144,1 kWh/m^2 de surface de plancher de solarium, tandis qu'une serre installée sur un toit pourrait atteindre une consommation énergétique nette zéro pour le chauffage ou même générer un léger surplus de chaleur.

Mots clés : énergie solaire, potentiel, solarium, véranda, serre

1. Introduction

Building-integrated solariums and greenhouses can provide many benefits: they can be used as solar collectors, they provide adequate conditions for growing plants and they offer additional living space for the occupants. Some jurisdictions recognized the energy saving potential of attached sunspaces and awarded grants to conduct demonstration projects.

For instance, the US Department of Energy awarded a grant in 1981 to add an experimental sunspace to an existing house in Delaware which reduced the heating needs of the house by 40% and the domestic hot water load by 30%[1]. A decade later in Glasgow, UK, the CEC Energy Demonstration Program launched the Solar Energy Demonstration Project that undertook the retrofit of 36 apartment dwellings by adding a glazed veranda and a glazed conservatory/utility extension[2]. The effect of these two buffer spaces is estimated to reduce the mean heating consumption by 31%.

Typical greenhouses, used to extend the cultivation season, are usually stand-alone structures located in the suburbs. With growing cities and increased reliance on imported vegetables, urban agriculture is a rising trend which is trying to bring closer farmers and consumers. The city of Montreal carried out in 2012 a public consultation about the state of urban agriculture on its territory. The first commercial rooftop greenhouses appeared in Montreal [3]and New York city [4]in 2011. These structures can be thermally linked with their host building and contribute to reduce their heating loads.

Asunspace can,under some circumstances, provide excess energy for heating an adjacent building. However, their performance is highly dependent on their design and operation characteristics [5]. As pointed out by Kesik and Simpson, regardless of their designs, solariums conditioned with the same set points as a house require more annual space heating per unit of floor area than a house [6]. Therefore, it is essential for an energy efficient solarium to minimize heating requirements and allow wider temperature fluctuations than in a normally conditioned room.

The goal of this paper is to assess the energy saving potential of retrofitted solariums and rooftop greenhouses in the province of Québec, Canada. Simulations during the heating season are conducted using the building simulation software EnergyPlus[7]. Six different case studies of houses with attached solariums have been considered. Solariums with different sizes, orientations and envelope qualities have been studied. Two rooftop greenhouses case studies with different floor area and various levels of envelope performance have been considered.

2. Methodology

An approach similar to the one presented by Pelland and Poissant in [8] for the evaluation of the potential of building-integrated photovoltaics in Canada is followed. Existing single detached and single attached residential buildings and commercial buildings with a floor area greater that 929 m^2 are deemed good candidates for the retrofit of solarium/greenhouse for this study. Simulations are carried out during the heating season (from October $1^{st}$to April 28^{th}) using EnergyPlus. All case studies have been simulated using Canadian Weather for Energy Calculations (CWEC) files for Montreal.

2.1 Residential buildings

Table 1 presents the number of dwellings and total floor area of single detached and attached buildings in the province of Quebec. According to the Survey of Household Energy Use [9], the average number of storeys of residential buildings in Québec is 1.37. The total ground floor area is simply calculated as the total floor area divided by the average number of storeys.Apartment buildings were excluded from this study due to the lack of data characterizing their average number of storeys.

Housing type	Nb of dwellings [10]	Total floor area(km^2) [10]	Total ground floor area (km^2)
Single detached	1 644 500	215,3	157,2
Single attached	298 500	35,6	26,0

Table 1.Number of dwellings, total floor area and ground floor area of residential buildings in Québec in 2010.

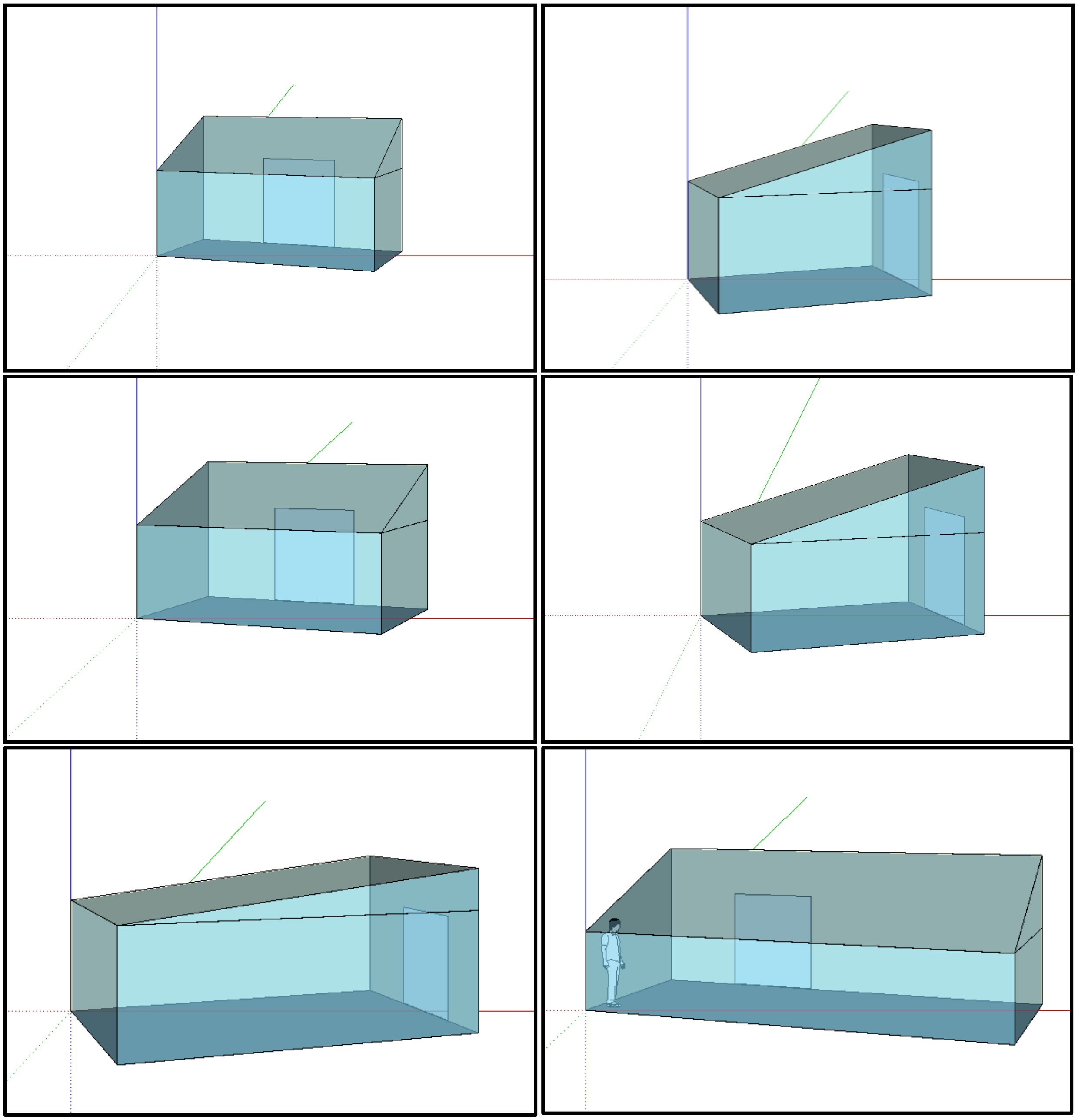

Image 1: Solarium designs – floor area and orientation – 12m^2 20°W (upper left), 12m^2 70°W (upper right), 15m^{2}20°W (centre left), 15m^2 70°W (centre right), 30m^2 20°W (lower left) 30m^2, 70°W (lower right) (green axis is due north)

The average total area and ground floor area of a single detached building are equal to 130.9 m^2 and 95.6 m^{2}respectively while the average total area and ground floor area for a single attached building are 119.2 m^2 and 87.1m^2. The average construction year of a single detached and attached building is 1978 and 1986 respectively. In 2010, the average total energy consumption of residential buildings is 220 kWh/m^2 from which 139 kWh/m^2 is used for space heating [10].

Three different solarium sizes have been modelled: 12 m^2, 15 m^2 and 30 m^2. All solariums are retrofitted adjacent to the backyard wall of an existing house. Two back wall orientations are considered: 20°W and 70°W. One shading element parallel to the back wall with a height and width of 7 m by 8 m is located 10 meters away from the back wall, centred. This shading element represents typical shading by neighbouring houses in urban locations. The four solarium designs investigated in this study are depicted in Figure 1 where the solid green axis is pointing north. Their geometrical parameters are indicated in Table 2. All solariums have a maximum height of 3 m and a glazed sliding door 1.8 m wide connecting to the house. Solarium façades with orientation between -90° to +90° (0° being south) are glazed while others are opaque and insulated. The selected heat balance algorithm is conduction transfer functions with a time step of 15 minutes.

Solarium design	Common wall length (m)	Width (m)	Roof angle	South wall height (m)
12 m^2, 20°W	5	2.4	25°	1.88
12 m^2, 70°W	3	4	15°	1.93
15 m^2, 20°W	5	3	25°	1.85
15 m^2, 70°W	3.4	4.4	15°	1.82
30 m^2, 20°W	8.33	3.6	25°	1.54
30 m^2, 70°W	4.5	6.66	6.6°	2.23

Table 2.Solariums geometrical parameters.

Two different solariumenvelopes have been investigated: a conventional and an upgraded envelope. The conventional solarium is constructed with regular double glazing with argon and low emissivity coating. The airtightness is moderate with a constant infiltration of 0.5 air changes per hour (ACH). The floor is made of 200 mm of exposed concrete with R5 (RSI 0.88) insulation beneath. The upgraded solarium is equipped with improved windows, with a low iron outer pane and a slightly reduced emissivity of the inner pane. An interior low emissivity shade is deployed at night when the outdoor temperature is below 20°C to further reduce heat losses. The infiltration rate is reduced to 0.1 ACH and the insulation below the concrete slab is increased to R10 (RSI 1.76).In both cases, the adjacent house is assumed to have a constant temperature of 20°C. The heating set point inside the solarium is 10°C. The heating needs along with the excess heat inside the solarium when the temperature exceeds 28°C are presented in the next section.

Conventional	Upgraded
Conventional double glazing with argon and low e	Improved double glazing with argon and low e
Constant infiltration at 0.5 ACH	Constant infiltration at 0.1 ACH
R5 insulation below the 200 mm concrete floor	R10 insulation below the 200 mm concrete floor
	Low emissivity shade deployed at night

Table 3.Solarium design characteristics.

2.2 Commercial buildings

The total floor area and estimated ground floor area for commercial and institutional buildings in Québec are presented in Table 4. As indicated in the Commercial and Institutional Building Energy Use Survey[11], the average number of storeys of commercial and institutional buildings is equal to 2.70. Consequently, the total ground floor area is estimated by dividing the total floor area by the average number of storey.

As presented in [11], the total floor area of commercial and institutional buildings greater than 929 m^2 was 63.6 km^2 in 2000, or 89.4% of the total floor area. Using this proportion and the more recent data presented in the 2008 Commercial & Institutional Consumption of Energy Survey[12], the total floor area of buildings greater than 929 m^2 is estimated to 161.7 km^2.

Building size	Total floor area(km^2)	Total ground floor area (km^2)
All	180.8 [12]	67.0
>929 m^2	161.7	59.9

Table 4.Total floor area and ground floor area of commercial and institutional buildings in Québec in 2008.

The average year of construction of commercial and institutional buildings in Québec is 1961 [11]. In 2010, the average energy intensity was 462 kWh/m^2 from which 171 kWh/m^2 is consumed for space heating [10], which is even higher than for residential buildings.

Buildings with ground floor areas of 2,000m^2 and 10,000m^2have been modelled. Since roofs are often used for mechanical systems, a retrofit rooftop greenhouse covering only 70% of the roof is considered. Only one orientation at 20° west is simulated. Both are symmetrical multispan greenhouses with roof angles of 30°,wall height of 2.5 m and a span width of 5m. The 1,400 m^2 greenhouse has seven spans while the larger 7,000m^2 greenhouse has 16 spans, which are both depicted in Figure 2.The smaller and larger greenhouses have dimensions 40 m by 35 m and 87.5 m by 80 m respectively.

Three different greenhouse envelope designs have been considered. The conventional greenhouse design is constructed with a single pane clear glass and an interior shade with low emissivity, deployed at night. All façades/roof sections are glazed. There is a constant infiltration of 0.5 ACH and a mechanical ventilation of 5 ACH with 80% heat recovery from 9am to 4pm for humidity control during the entire heating season. The upgraded greenhouse design is equipped with high performance low iron/low emissivity/argon double-glazing. The infiltration is reduced to 0.1 ACH and the ventilation schedule remains identical. The north glazed wall is replaced with an insulated and thermally massive north wall and 100mm of concrete is added on the floor. The high performance greenhouse design is like the previous design but with high solar gain triple glazing on the north roof sections and east/west walls. The building underneath is assumed to have a constant temperature of 20°C. The heating setpoint inside the greenhouse was set at 15°C and the excess heat above 25°C was compiled.

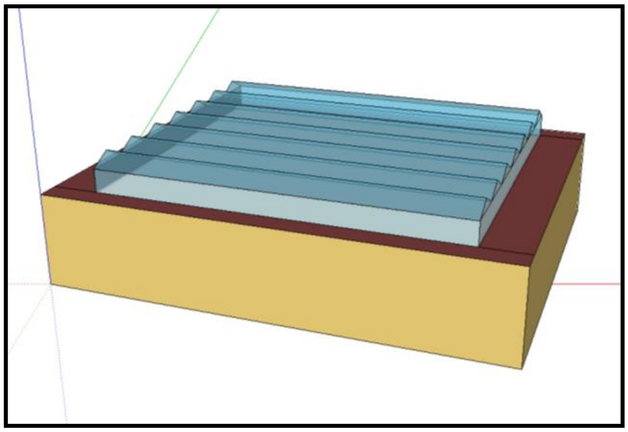
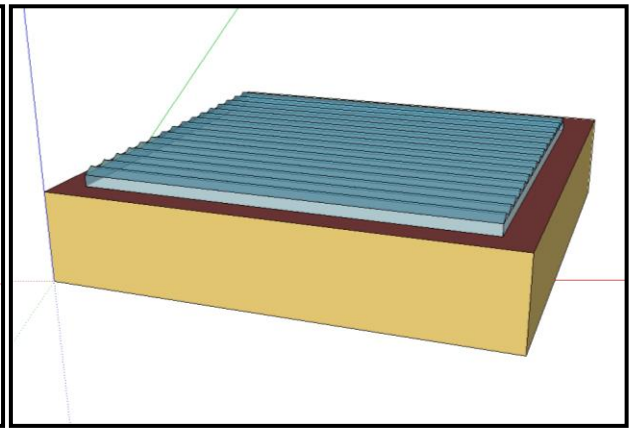

Image 2: Rooftop greenhouse designs – 1,400 m^2, 20°W (left) - 7,000 m^2, 20°W (right)

Conventional	Upgraded	High performance
Fully glazed	North wall replaced with an insulated and massive north wall	North wall replaced with an insulated and massive north wall
Single glass	Improved double glazing with argon and low e	Improved double glazing on south and triple on other orientations
Interior shade with low emissivity	Interior shade with low emissivity	Interior shade with low emissivity
Constant infiltration at 0.5 ACH	Constant infiltration at 0.1 ACH	Constant infiltration at 0.1 ACH
	100 mm of concrete on floor	100 mm of concrete on floor

Table 5.Solarium design characteristics.

3. Results and discussion

3.1 Attached solariums

The heating needs, excess heat and net energy balance of the four cases studied are presented in Table 6. It can be seen that even conventional solariums can supply more useful heat than their heating needs with a net energy balance of 28-75 kWh/m^{2}of solarium floor area. Upgraded solariums are twice as efficient and can generate a net energy balance of 118-144 kWh/m^2.

It is interesting to compare the energy potential of solariums per floor area of 28-144 kWh/m^2 with the useful solar energy generated by water-based solar thermal panels in Montreal, which is between 150-610 kWh/m^2, depending on the size of the system[13].Although less efficient per unit area, a solarium provides not only heat but also additional living/growing space. However, the wide variation of the energy performance of solariums indicate that careful design and high quality materials must be selected in order to build a high performance solarium with the capability of supplying significant amount of heat to a house.

Considering an average single detached house in Quebec with a total floor area of 130.9 m^2 which undertakes the addition of an upgraded solarium, the heating consumption could be reduced by 1,612-4,092 kWh, depending on the size and design of the solarium. This would reduce the average 139 kWh/m^2 heating load down to 108-127kWh/m^2, a 9% to 23% reduction.

Design type	Conventional			Upgraded		
Solarium size and orientation	Heating needs (kWh/m^2)	Excess heat (kWh/m^2)	Net energy balance (kWh/m^2)	Heating needs (kWh/m^2)	Excess heat (kWh/m^2)	Net energy balance (kWh/m^2)
12 m^2, 20°W	33.2	108.4	75.3	15.7	158.3	142.6
12 m^2, 70°W	32.9	100.2	67.3	13.3	147.5	134.3
15 m^2, 20°W	36.9	94.3	57.5	10.3	154.5	144.1
15 m^2, 70°W	31.0	86.4	55.4	11.5	131.3	119.8
30 m^2, 20°W	29.5	82.0	52.5	5.5	141.9	136.4
30 m^2, 70°W	37.2	64.8	27.6	5.2	123.0	117.8

Table 6.Heating needs, excess heat and net energy balance of four solariums designs during the heating period.

If 1% of all attached and detached houses in Quebec would undertake an upgraded solarium retrofit, 31.3-79.5GWhof solar heat could be generated.

3.2 Rooftop greenhouses

The heating needs, excess heat and net energy balance of the two rooftop greenhouses studied are presented in Table 7. Large rooftop greenhouses, used for the commercial production of vegetables, must have a thermally controlled indoor climate to support satisfactory crop growth. A heating set point of 15°C has been chosen for these simulations and the excess heat was compiled for temperatures above 25°C.It can be seen that conventional single glazed greenhouses exhibit heating needs that far exceed the excess heat that can be collected with a net energy balance ranging from -298 to -321 kWh/m^2.

By increasing the airtightness, adding interior thermal mass and switching to high quality double glazing, upgraded greenhouses can become fairly close to being net zero regarding their heating consumption. In other words, upgraded greenhouses have the potential to supply enough heat to adjacent buildings to compensate for their own heating consumption throughout the year.

The thermal performance of greenhouses can be further improved by converting north, east and west glazing to high solar heat gain low emissivity triple glass. Doing so allow generating a positive net energy balance of about 30 kWh/m^2. At this point, adding a second thermal screen could be more cost effective that selecting triple glazing and would limit weight. This practice of using two thermal screens, common in some European countries like The Netherlands, has not been modeled in this case due to the inability of EnergyPlus to simulate two interior shading devices.

Covering 1% of the ground floor area of commercial and institutional buildings with a floor area greater than 929 m^2 with rooftop greenhouses on 70% of the roof area would create 0.42 km^2 of urban cultivation area, enough to provide vegetables for about 300,000 persons. By careful design and operation, it is possible to build greenhouses with a net zero heating demand in a climate like Montreal.

Design type	Conventional			Upgraded			High performance		
Solarium size and orientation	Heating needs (kWh/m^2)	Excess heat (kWh/m^2)	Net energy balance (kWh/m^2)	Heating needs (kWh/m^2)	Excess heat (kWh/m^2)	Net energy balance (kWh/m^2)	Heating needs (kWh/m^2)	Excess heat (kWh/m^2)	Net energy balance (kWh/m^2)
1,400 m^2, 20°W	344.6	23.2	-321.4	73.2	70.4	-2.8	47.5	77.1	29.6
7,000 m^2, 20°W	320.4	22.2	-298.2	66.3	67.3	1.0	43.2	73.9	30.7

Table 7.Heating needs, excess heat and net energy balance of two rooftop greenhouse designs during the heating period.

3.2 Discussion

It is important to keep in mind that the performance of solariums and greenhouses is highly dependent on their design and operation. This is the reason why, throughout this work, a range of performances was presented. The designs have been chosen simply based on experience and have not been optimized. It is possible to design solariums and greenhouses that would have a higher performance than what is presented in this study. On the other hand, it is also possible to design and operate solariums and greenhouses in a way that they would never reach a net zero heat balance and could even become high heat consumers.

In this study, all excess heat during the heating season has been considered useful. Considering the low insulation levels and high heating requirements of the existing building stock, it seems reasonable to assume that all excess heat would be welcome at all times in adjacent buildings. However, for new buildings with a better envelope, this might not be the case and a more detailed study considering the interactions between a solarium and a housewould be required.

An *Ideal Loads Air System* has been selected for these simulations, which means that a 100% efficient HVAC system was assumed. Heating and cooling set points were entered in the *Thermostat* module. The ideal load assumption is realistic in the case of solariums heated with electric baseboards, but large greenhouses are likely to be equipped with a central combustion heating system where in this case the actual efficiency of the heating system should be taken into account. The total cooling energy for a given cooling set point was interpreted in this study as the excess heat available for heating adjacent buildings during the heating season.

For the solarium models, the distribution of the solar radiation on interior surfaces is modelled by projecting the sun's ray on interior surfaces, as described in details in [14] for the *Full Interior and Exterior* option. However, for the greenhouse models, all beam solar radiation is assumed to fall on the floor, as described in [14]according to the *Full Exterior* option. This assumption appears reasonable in this case, given the large surface of the floor compared to that of the walls.

4. Conclusion

This paper presents an analysis of the energy saving potential of attached solariums and rooftop greenhouses in the province of Québec. Various realistic situations have been considered. A total of eighteen case studies have been simulated with the EnergyPlusbuilding simulation software. Six different solarium designs with different sizes and orientation have been considered. Two rooftop greenhouse models with different sizes have also been simulated.

For all cases, different building envelopes have been analysed. Results indicate that the investigated solariumsexhibit a net energy balance of 28-144 kWh/m^{2}of solarium floor area. Retrofitting an upgraded solarium to an average house would reduce its heating consumption by 1,612-4,092 kWh, depending on the size of the solarium, which corresponds to a 9% to 23% reduction. Retrofitting an upgraded solarium to 1% of all single detached and attached houses in Québec would save 31.3-79.5 GWh annually.

Conventional greenhouses experience heating needs that far exceed their potential excess heat contribution. However, with improved air tightness, thermal load levelling and high quality double glass, net zero heating can be achieved. Surplus heat of up to 31 kWh/m^2 of greenhouse floor area can be collected when using high performance triple glazing on the northern, eastern and western orientations. Covering 1% of large commercial and institutional buildings in Quebec with rooftop greenhouses could provide enough vegetables to feed 300,000 people without increasing the total energy consumption of the province.

5. References

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6. Acknowledgements

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7. Biography

Diane Bastien obtained a B.Sc. in physics from the University of Montreal. She is currently a PhD Candidate in Building Engineering at Concordia University. She is specialized in renewable energies, especially in the integration of solar energy in buildings. Her doctoral research project is to develop a methodology for enhancing solar energy utilization in building-integrated solariums and greenhouses.

Dr. Andreas K. Athienitis is the Scientific Director of the NSERC Smart Net-zero Energy Buildings Strategic Research Network (2011-2016) and the founding Director of the NSERC Solar Buildings Research Network (2005-2010). He holds a Concordia University Research Chair, Tier I in Integration of Solar Energy Systems into Buildings. He obtained a B.Sc. in Mechanical Engineering (1981) from the University of New Brunswick and a Ph.D. in Mechanical Engineering from the University of Waterloo (1985).His research interests are in solar energy engineering, energy efficiency, modeling, optimization and control of building thermal systems, building-integrated photovoltaics and daylighting.