Integration of Organic Waste Recycling and Greenhouse Agriculture

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Abstract

The objective of this paper is to determine the potential for using organic waste to operate greenhouses in Canada. TRNSYS was used to perform annual energy simulations of a 4,000 m^2 greenhouse. Results indicate that 9.1 million wet tonnes/yr organic waste could be used to operate 1.12 million m² of new greenhouse agriculture area while producing 1,072 GWh/yr and 2,070 GWh/yr of exportable electrical and thermal energy, respectively. This research addresses the imminent problems of food and energy security, while at the same time offering promising solutions to the urgent issues of climate change and local food production.

Keywords: recycling, organic waste, biogas, energy, greenhouse, food security

Résumé

Cet article a pour but de déterminer le potentiel d'utilisation des déchets organiques pour opérer des serres au Canada. TRNSYS a été utilisé pour effectuer des simulations de consommation énergétiques annuelles d'une serre de 4000 m^2. Les résultats indiquent que 9,1 millions de tonnes/an de déchets organiques peuvent être utilisés pour opérer 1,12 millions de m² de surface pour la serriculture tout en produisant 1072 GWh/an et 2070 GWh/an d'énergie électrique et thermique exportable, respectivement. Cette recherche porte sur les problèmes imminents de la sécurité alimentaire et de l'énergie, tout en offrant des solutions prometteuses pour les questions urgentes liées au changement climatique et à l'agriculture locale.

Mots clés : recyclage, déchets organiques, biogaz, énergie, serre, sécurité alimentaire

1. Introduction

Concerns around waste management are growing, led by a lack of available landfill sites, the increasing costs of disposal, and the environmental degradation produced by current practices. Organic waste, consisting mainly of municipal wastes (food scraps and yard waste), farming wastes (livestock manure and agriculture residues) and sewage sludge, is the largest contributor to the waste stream, and must therefore be at the centre of strategies for waste reduction, reuse and recycling. Biological treatment using anaerobic digestion (i.e. the breakdown of organic waste by bacteria in the absence of oxygen), followed by composting, has been shown to be an effective way to recycle organic waste. With the Canadian government's objective of increasing the rate of recycled organic waste from approximately 20% today, we are thus presented with a unique opportunity to rethink the design of Organic Waste Recycling (OWR) facilities before they are built [1].

Ideally, OWR facilities should be designed to treat both municipal and farming organic waste streams together. This method, known as co-digestion, carries numerous advantages: 1) we gain great economies of scale compared to treating the wastes separately; 2) the energy production and operational stability of the biological process is improved; and 3) high-quality fertilizer suitable for greenhouse agriculture can be produced, allowing for essential nutrients such as phosphorus, nitrogen and potassium to be recycled. Farming wastes, in particular livestock manures, significantly contribute to environmental degradation. Yet despite this, OWR facilities today are generally designed to treat municipal waste separately from farming waste, and there are currently no plans for the combined treatment of both streams.

Co-digestion facilities can also be combined with greenhouses to integrate waste management and agricultural goals. This carries immense promise owing to several benefits: 1) the energy and fertilizer produced by the OWR facility can be used to operate a greenhouse, thereby saving resources; 2) great economies of scale can be achieved in the purchase of the greenhouses' mechanical and HVAC equipment; and 3) greater efficiency is gained in the material and energy flow between the greenhouse and OWR facility. Today, there are only a few examples where greenhouses are combined with OWR. The Swiss biogas company Kompogas has built one such facility, where tomatoes are grown inside an adjacent greenhouse using energy and fertilizer from the OWR process [2].

Figure 1 shows how OWR outputs satisfy all the requirements for operating the greenhouse. The greenhouse's organic waste is treated by the OWR facility, which can be achieved most efficiently with the greenhouse located on-site. By converting approximately 50% of the waste's volatile solids into energy in the form of biogas, the anaerobic digestion process reduces the volume of the organic waste by about 30% [3]. The produced biogas can be burned in a CHP engine to produce electricity, heat, carbon dioxide and water. Carbon dioxide can be supplemented to the greenhouse to accelerate crop growth and improve crop quality. The residual organic waste, or digestate, is then composted at thermophilic temperature to obtain a pathogen-free compost fertilizer.

This research aims to identify optimal methods for combining greenhouses with co-digestion facilities and to determine the potential for building such facilities in Canada. The energy produced from the organic waste would be entirely used to operate the OWR process and the integrated greenhouses during peak winter design conditions. It is assumed that all of the produced biogas would be combusted in a CHP engine, and that the electricity and thermal energy not used by the greenhouses would be exported to the grid and used for district heating.

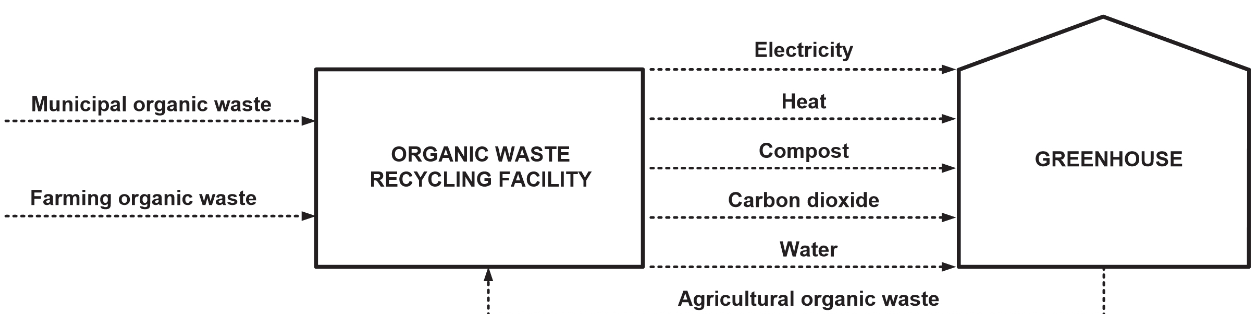

Figure 1. Integration of OWR and greenhouse agriculture.

2. Organic waste inventory and outputs

An important design consideration is the mixture of organic wastes that would produce a high-quality compost fertilizer suitable for greenhouse agriculture. A feedstock mixture consisting of 75% municipal organic waste (food scraps and yard waste) and 25% livestock manure would provide a fertilizer with the adequate carbon and macronutrient content [4]. The analysis assumes that all of the available municipal organic waste would be treated by these facilities, and that a portion of the total livestock manure would be co-digested in order to obtain the desired mixture. Table 1 shows the amount of municipal organic waste generated per province, $M_{municipal}$ [5]. Based on this, the amount of livestock manure, M_{manure}, required for the co-digestion mix is:

$$M_{manure} = \frac{M_{municipal}}{1 - f_{manure}} - M_{municipal} \quad (1)$$

where f_{manure} is the fraction of manure in the mix (25%) [4].

The methane production rate from organic waste, $V_{methane}$, is determined using:

$$V_{methane} = f_{dry} \cdot f_{solids} \cdot S_{degraded} \cdot Y_{methane} \cdot \left(M_{municipal} + M_{manure}\right) \quad (2)$$

where f_{dry} is dryness of the waste (27%), f_{solids} is the solids:minerals ratio (90:10), $S_{destroyed}$ is the anaerobic degradation efficiency (50%) and $Y_{methane}$ is the theoretical yield of methane (0.5 Nm^3 methane per kg of dry organic solids degraded obtained by stoichiometry, $C_5H_7NO_2$ (average elemental formula for biomass) + 3 H_2O → 2.5 CH_4 + 2.5 CO_2 + NH_3, i.e. 0.35 kg CH_4 or 0.5 Nm^3 CH_4/kg dry organic solid degraded).

The amount of compost produced is assumed to be 40% of the input organic waste [6].

Table 1 shows the amount of organic waste (in wet tonnes) treated by co-digestion and the methane and compost production for each province. The co-digestion of 9.1 million wet tonnes/yr of organic waste in Canada would produce 546.8 million m^3/yr of methane and 3.6 million tonnes/yr of compost.

Table 1. Inventory of wastes, energy and fertilizer production

Provinces	Percent of total waste generation	Food scraps and yard waste (tonnes/yr)	Livestock manure (tonnes/yr)	Total organic waste (tonnes/yr)	Methane production (m^3/yr)	Compost production (tonnes/yr)
Maritimes	5%	312,322	104,107	416,429	24,985,760	166,572
Quebec	27%	1,819,837	606,612	2,426,449	145,586,960	970,580
Ontario	37%	2,503,665	834,555	3,338,220	200,293,200	1,335,288
Manitoba	4%	274,010	91,337	365,347	21,920,800	146,139
Saskatchewan	4%	290,047	96,682	386,729	23,203,760	154,692
Alberta	12%	846,993	282,331	1,129,324	67,759,440	451,730
British Columbia	12%	788,787	262,929	1,051,716	63,102,960	420,686
Total	**100%**	**6,835,661**	**2,278,554**	**9,114,215**	**546,852,880**	**3,645,686**

The electrical and thermal power (Q_{elec} and $Q_{thermal}$) produced by the combustion of methane in a CHP engine is given by:

$$Q_{elec} = V_{methane} \cdot HV_{methane} \cdot \eta_{elec} \tag{3}$$

$$Q_{thermal} = V_{methane} \cdot HV_{methane} \cdot \eta_{thermal} \tag{4}$$

where, $HV_{methane}$ is the median heating value of methane, 37 MJ/m³, and η_{elec} is the electrical efficiency (35%) and $\eta_{thermal}$ is the thermal efficiency (45%) of the CHP engine, based on the performance reported by manufacturers [7].

The electrical and thermal power consumed by the OWR facility is assumed to be 5% and 10% of the biogas production, respectively [8]. The exportable power available for operating greenhouses, Q_{elec_export} and $Q_{thermal\_export}$, is determined by subtracting the power produced from the power consumed by the OWR facility. Table 2 shows how OWR in Canada could produce 192,481 kW and 224,561 kW of electrical and thermal power, respectively, that could be used to operate the greenhouses.

Table 2. Electrical and thermal power production and use by the OWR facility

Provinces	Peak electrical power production [kW]	Peak thermal power production [kW]	Peak electrical power use [kW]	Peak thermal power use [kW]	Exportable electrical power [kW]	Exportable thermal power [kW]
Maritimes	10,260	13,192	1,466	2,931	8,794	10,260
Quebec	59,784	76,865	8,541	17,081	51,244	59,784
Ontario	82,249	105,748	11,750	23,500	70,499	82,249
Manitoba	9,002	11,573	1,286	2,572	7,716	9,002
Saskatchewan	9,528	12,251	1,361	2,722	8,167	9,528
Alberta	27,825	35,775	3,975	7,950	23,850	27,825
British Columbia	25,913	33,316	3,702	7,404	22,211	25,913
Total	**224,561**	**288,721**	**32,080**	**64,160**	**192,481**	**224,561**

3. Greenhouse details

This section covers the design, modeling and control of the greenhouse that would be integrated with the OWR facility. The greenhouses would operate using the available energy from the organic waste recycling process. In order to calculate the potential greenhouse area, its peak electrical and thermal energy requirements must first be determined.

3.1 Greenhouse design

Figure 2 illustrates the 4,000 m² greenhouse that was selected for the analysis. The envelope consists of air-filled double-glazing (72.6% solar transmittance at normal incidence angle; the thermal conductance found using the program Windows 7.3 is U=2.91 W/m²·°C for the walls and U=3.45 W/m²·°C for the roof) with 10% framing (U=4 W/m²·°C). There is a 0.8 m high wall around the greenhouse perimeter composed of concrete 0.15 m thick with rigid insulation (U=1 W/m²·°C) on the exterior. The floor consists of a concrete slab 0.1 m thick.

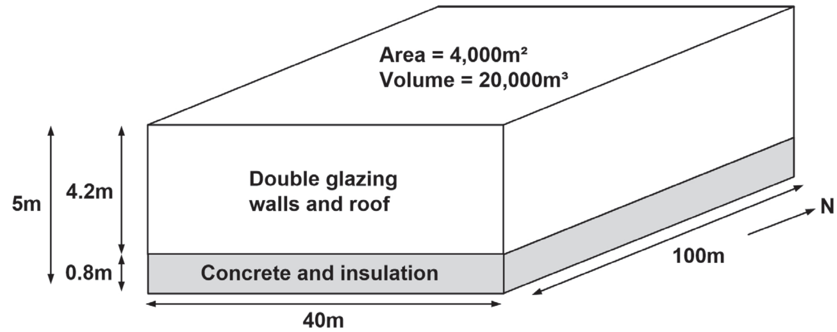

Figure 2. Greenhouse geometry and dimensions.

3.2 Greenhouse energy modeling

TRNSYS 17.2 is the simulation environment used for the transient simulation of the greenhouse. Type 56 was originally developed to model multizone buildings and is used here with certain assumptions to create the greenhouse energy model. The flat roof greenhouse geometry was created in Sketchup and imported into TRNSYS in order to provide detailed radiation calculations using view factor matrices. The walls are modelled according to the transfer function relationships defined from surface to surface [9]. Longwave radiation was calculated using the Gebhart model [10]. The energy balance for an arbitrary building geometry is detailed in the TRNSYS 17 manual [11]. Figure 3 illustrates the energy transfer mechanisms considered in the greenhouse model.

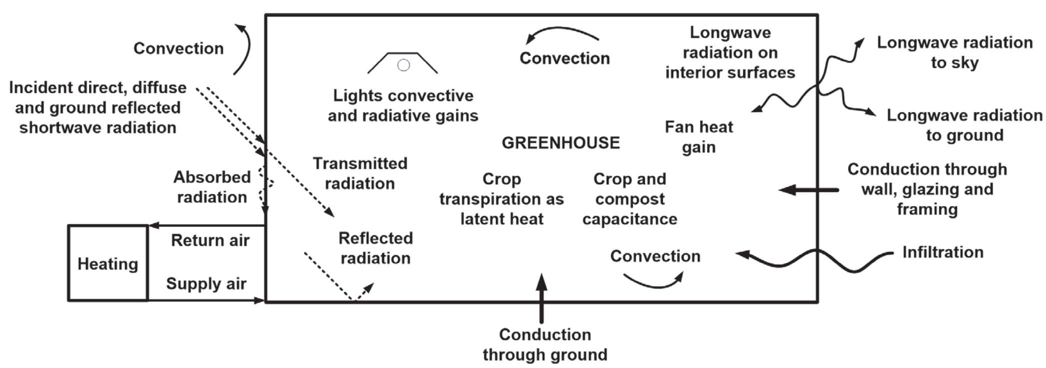

Figure 3. Energy transfer mechanisms considered for the greenhouse model.

The greenhouse energy balance is given by the following equation:

$$Q = Q_{surface,j} + Q_{\inf} + Q_{vent} + Q_{gain} + Q_{blind} + Q_{latent} \tag{5}$$

where

$Q_{surface,j}$ is the convective gain from all the interior surfaces j, defined by:

$$Q_{surface,j} = h_{i,j} \cdot A_j \cdot \left(T_j - T_{air}\right) \tag{6}$$

where $h_{i,j}$ is the interior convective heat transfer coefficients, A_j is the interior surface areas, T_j is interior surface temperatures, and T_{air} is the greenhouse air temperature. The energy balance on the interior surfaces considers convection to the exterior air, longwave radiation to the ground and the sky, conduction through the greenhouse envelope, longwave radiation exchange between the greenhouse internal surfaces, and absorbed shortwave radiation. Calculation of detailed heat transfer to the ground is achieved by discretising it into control volumes using type 1244.

The interior convective heat transfer coefficients are calculated using [11]:

$$h_{i,j} = a \cdot (T_j - T_{air})^b \tag{7}$$

where the coefficients a and b depend on the inclination of the surface and the direction of the heat flow. The exterior convective heat transfer coefficients are calculated by [12]:

$$h_{o,j} = 5.7 + 3.8 \cdot V_{wind} \tag{8}$$

where V_{wind} is the wind speed.

Q_{inf} is the infiltration gain, calculated by type 571, and defined by:

$$Q_{\inf} = m_{\inf} \cdot c_p \cdot (T_{ext} - T_{air}) \tag{9}$$

where c_p is the specific heat of air and T_{ext} is the exterior air temperature. m_{inf} is the infiltration mass flow rate, calculated using the following equation:

$$m_{\inf} = \rho \cdot V \cdot \left(K_1 + K_2 \cdot \left|T_{ext} - T_{air}\right| + K_3 \cdot V_{wind}\right) \tag{10}$$

where ρ is the air density, V is the greenhouse volume and K_1, K_2 and K_3 are empirical constants based on ASHRAE for medium constructions [13].

Q_{vent} is the ventilation gains, given by:

$$Q_{vent} = m_{vent} \cdot c_p \cdot \left(T_{\sup ply} - T_{air}\right) \tag{11}$$

where m_{vent} is the ventilation mass flow rate, and T_{supply} is the ventilation air supply temperature.

Q_{gain} are the internal heat gains (fan heat and convective fraction of artificial lighting).

Q_{blind} is the absorbed solar radiation on the internal blinds that is directly transferred as a convective gain to the greenhouse air.

Q_{latent} is the latent heat transfer to the greenhouse air defined by the following energy balance:

$$Q_{latent} = h_v \cdot \left(m_{\inf} \cdot (\omega_o - \omega_{air}) + m_{vent} \cdot (\omega_o - \omega_{air}) + W_{irrig}\right) \tag{12}$$

where h_v is the heat of vaporization of water, ω_o is the humidity ratio of the exterior air, ω_{air} is the humidity ratio of the greenhouse air, and W_{irrig} is the rate of irrigation water to the plants.

The thermal energy, $Q_{thermal}$, required to heat the ventilation air to the desired supply temperature is:

$$Q_{thermal} = m_{vent} \cdot c_p \cdot \left(T_{return} - T_{\sup ply}\right) \tag{13}$$

where T_{return} is the temperature of the mixed return and fresh exterior airstreams.

3.3 Greenhouse climate control

Exterior air is delivered to the greenhouse in order to regulate temperature and humidity. Figure 4 provides details on the greenhouse climate control strategies. The ventilation system design consists of under-channel ducted air distribution which has been proven to increase ventilation efficiency by delivering fresh air directly to the plants [14]. This technique uses blowers to push conditioned air through flexible plastic ducts positioned beneath suspended growth channels. Ventilation air is supplied by a fan (20 W/m^2) at a rate of 120 kg/hr/m² and at a heating setpoint temperature of 18°C, with between 5-100% consisting of fresh exterior air, depending on the exterior environmental conditions [15]. When the exterior air temperature is above 18°C, the supply air is 100% exterior air, whereas when the exterior air temperature is below 0°C and there is no sun, the supply air consists of its minimum value of 5% exterior air. For exterior air temperatures between 0-18°C, the ventilation rate is calculated using linear algorithms based on the exterior temperature and horizontal solar radiation. A heat exchanger (type 760) is used to transfer heat from the exhaust air stream to the exterior air stream. A sensible heat transfer efficiency of 75% is assumed.

Thermal screens are used to reduce night heat loss. The movable screens increase the thermal resistance of the greenhouse envelope by 0.125 m²·°C/W and is activated during the night when the ambient air temperature is below 5°C. Blinds are used to reduce overheating inside the greenhouse. Two movable blinds of 50% and 75% transmittance are activated when the ambient air temperature is above 10°C and the total horizontal irradiance is above 400 W/m² and 600 W/m², respectively.

Artificial lighting is provided by high-pressure sodium lights with an intensity of 150 W/m². The lights are on for 16 hr/day (5am-9pm) from December to February, and for 12 hr/day from October to November and March to April (lights are off during hours of peak solar radiation from 12pm-4pm). The lights are off from May to September. It is assumed that 10% of the light's energy is convected to the air node and 90% is emitted as radiation. The latent heat due to evapotranspiration is assumed to be equal to the rate of irrigation water supplied to the plants, which ranges from 0.04-0.4 kg/hr/m² depending on the level of solar radiation [16].

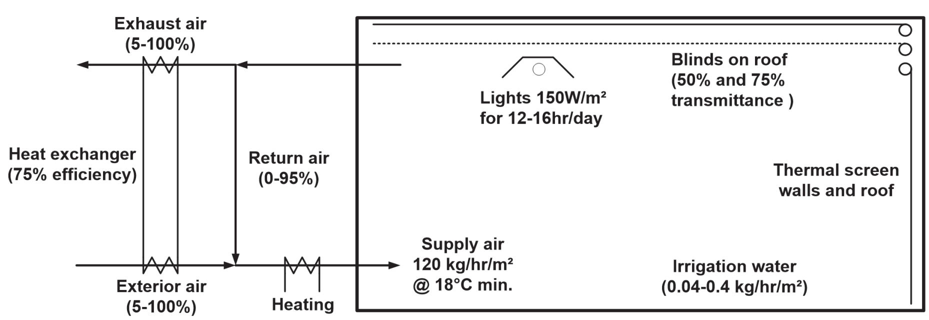

Figure 4. Greenhouse climate control details.

4. Results

4.1 Greenhouse climate during peak design conditions

Energy simulations were performed for both a warm sunny day and a cold winter day in order to verify that the greenhouse temperature is maintained within a suitable range for crop production. Hottel's clear sky model was used to calculate the incident solar radiation on the greenhouse surfaces [17]. An exterior relative humidity of 90% and a wind speed of 0.5 m/s and 10 m/s were selected for the summer and winter days, respectively. Figure 5 shows the results for the daily variation in greenhouse air temperature and the defined peak exterior air temperatures and total horizontal solar radiation levels. The minimum and maximum greenhouse air temperature is found to be 15°C and 43°C for the winter and summer design day, respectively. The peak summer greenhouse air temperature is too high for most plants. However, the analysis did not consider the effect of cooling the greenhouse, which can be achieved using excess heat from the CHP engine to drive an absorption chiller.

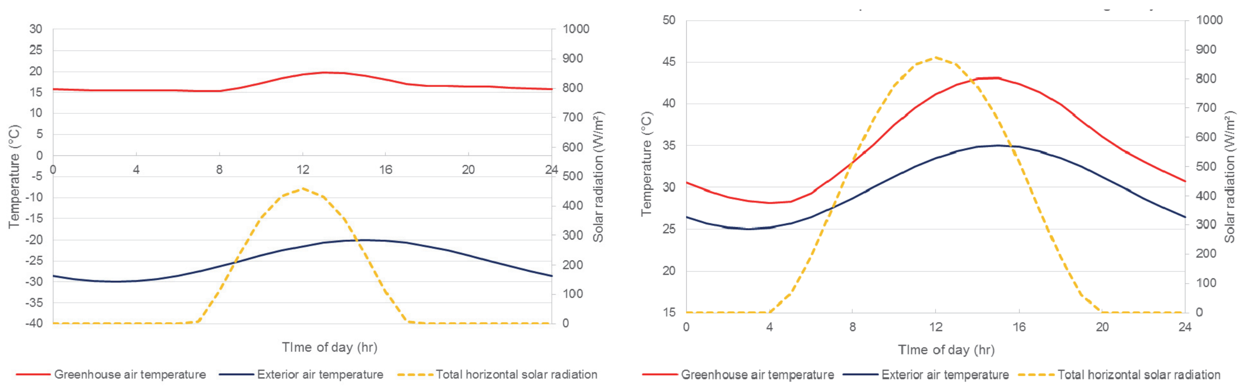

Figure 5. Daily greenhouse temperature during peak winter (left) and summer (right) design conditions.

4.2 New greenhouse agriculture area and net energy production

The new greenhouse agriculture area that could be operated from the organic waste's energy is determined by assuming that either all of the electrical or thermal power produced would be consumed by the greenhouse during the peak winter design condition. Based on the energy model for the 4,000 m² greenhouse, the peak electrical and thermal power demand during the winter design day ($Q_{elec\_m^2}$ and $Q_{thermal\_m^2}$) is 0.17 and 0.20 kW/m², respectively. The greenhouse area that could be operated with the energy from the organic waste is dictated by either its electrical or thermal power demand and is calculated using the following equation:

$$A_{GH} = \min\left[\frac{Q_{elec\_export}}{Q_{elec\_m^2}}, \frac{Q_{thermal\_export}}{Q_{thermal\_m^2}}\right] \quad (14)$$

Electrical and thermal energy will be available to export to the grid, except during peak winter conditions. In order to determine the amount of energy that could be exported, annual energy simulations for the greenhouse using typical meteorological year data is required. The energy consumed by the greenhouse would vary across Canada, and a representative city for each province was therefore selected for the energy simulations. For each hour of simulation, the electrical and thermal power required to operate the greenhouse area in each province

(Q_{GH_elec} and $Q_{GH\_thermal}$) is recorded. The net electrical and thermal energy available for export (E_{elec_net} and $E_{thermal\_net}$) is given by:

$$E_{elec\_net} = \sum_{t=0}^{8760} \Delta t \cdot \left(Q_{elec\_export} - Q_{GH\_elec}\right) \quad (15)$$

$$E_{thermal\_net} = \sum_{t=0}^{8760} \Delta t \cdot \left(Q_{thermal\_export} - Q_{GH\_thermal}\right) \quad (16)$$

Table 3 shows that 1.12 million m^2 of new greenhouse agriculture area could be operated with the energy produced by the selected organic waste in Canada. The net electrical energy that could be exported to the grid is 1,072 GWh/yr, and the thermal energy available for district heating would be 2,070 GWh/yr.

Table 3. New greenhouse area and net energy production

Provinces and representative city for energy simulations	New greenhouse agriculture area (m^2)	Net electrical energy production (GWh/yr)	Net thermal energy production (GWh/yr)
Maritimes (Halifax)	51,301	49	96
Quebec (Montreal)	298,920	285	551
Ontario (Toronto)	411,244	393	766
Manitoba (Winnipeg)	45,008	43	79
Saskatchewan (Saskatoon)	47,642	45	84
Alberta (Edmonton)	139,124	133	252
British Columbia (Vancouver)	129,564	124	242
Total	**1,122,803**	**1,072**	**2,070**

5. Conclusion

This paper presented a design for the optimal recycling and reuse of organic waste for greenhouse agriculture, while energy modeling and simulations highlight the untapped potential of implementing such technologies across Canada. The co-digestion of municipal organic waste (food scraps and yard waste) and livestock manure would provide energy, carbon dioxide, water and high-quality compost suitable for greenhouse agriculture. The results show that 1.12 million m^2 of new greenhouse agriculture area could be operated in Canada with the energy produced by the recycling of 9.1 million tonnes/yr of organic wastes. In addition, 1072 GWh/yr of electrical energy could be exported to the grid, and 2070 GWh/yr of thermal energy would become available for district heating.

This research addresses the imminent problems of food and energy security, while at the same time offering a promising solution to addressing the urgent issues of climate change and local food production. The remainder of Canada's organic wastes that are not considered in this study may be anaerobically co-digested in a similar fashion to reduce human impact on the environment and provide stable and renewable energy infrastructure. The concept of integrating OWR and food production remains a widely unexplored topic, and it is hoped that other researchers and developers will be inspired by this work to advance the science further.

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8. Biography

James Bambara obtained a B.Sc. and M.A.Sc. in the Building Engineering Program at Concordia University. He is currently pursuing doctoral studies in the Building Engineering Program at Concordia University. His doctoral research is aimed at developing an integrated and closed-loop organic waste recycling and renewable energy production system to operate greenhouses, with the ultimate goal of enhancing sustainable food and energy security while reducing the environmental damage caused by current waste management practices.

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 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.