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Research article

A life cycle inventory analysis of wood pellets for greenhouse heating: a case study at Macdonald campus of McGill University¹

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Abstract: Wood pellets are one of the most promising alternatives to fossil fuel in Canada. Using wood pellets for heating allows saving on heating source expenses as compared to fossil fuels. Moreover, direct carbon emissions from wood pellets are regarded as carbon neutral since regrowth of vegetation captures and stores carbon that already exists in the atmosphere. Using wood pellets as a heating fuel for greenhouse vegetable production is expected to result in less greenhouse gas emissions than fossil fuels. Increasing the domestic consumption of wood pellets for greenhouse heating in Canada would reduce the environmental impact of energy consumption. This study investigates the potential of using wood pellets as an alternative fuel for commercial greenhouses in Quebec. This study applied a life-cycle analysis to demonstrate the energy flows and environmental consequences of using wood pellets for greenhouse vegetable production. The results found that greenhouse gas emissions from wood pellets are lower than natural gas in greenhouse operations.

Keywords: life-cycle-analysis; wood pellets; greenhouse gas emissions; greenhouse vegetable production; renewable energy

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1. Introduction

Wood pellets, produced from wood residues from sawmills and other wood product-manufacturers, are a renewable energy source that can be used for greenhouse heating. Wood pellets are inexpensive due to the low cost of its input material [1]. In contrast to directly using sawdust and other wood wastes as fuel, wood pellets have the advantage of a lower moisture content (4–7%) and a relatively higher density, which allows for easier transportation, storage, and higher combustion efficiency [2]. A relative complete combustion of wood pellets would lead to the reduction of harmful particulate emissions as compared to the direct combustion of wood wastes. Combustion of wood can generate ambient pollutions containing polycyclic aromatic hydrocarbons (PAHs). Scientists measured the existence of PAHs in wood ash and found that the majority of hazardous elements, including PAHs, remained in the ash [3,4]. This would suggest that only small amounts of PAHs were released to the atmosphere. Moreover, carbon emissions from the combustion of wood pellets are considered to be carbon neutral since the regrowth of vegetation captures and stores carbon that already exists in the present atmosphere [3,4]. Consequently, wood pellets as a fuel is regarded as having less GHG (greenhouse gas) emissions than other conventional fuels.

There are approximately 42 wood pellet production plants in Canada as of 2015, of which 65% of the pellet production capacity is in British Columbia and the remaining 35% is in Quebec, Ontario, and the other provinces. The total wood pellet production capacity of Canada in 2015 was about 4.4Mt, an increase of 34% since 2012. Canada produces at 65% of its capacity, meeting 20% of world demand [5]. Compared to Western Canada, Eastern Canada's wood pellet production capacity is smaller in scale and accounts for only 10% of the Canadian wood pellet production. Quebec is one of the largest producers in Eastern Canada. Currently, domestic use of wood pellets is mainly for residential heating. Canada presently exports 70%–75% of its wood pellets to other countries, with its major trading partners being the EU, followed by the USA, and Japan. Domestic wood pellet consumption has remained flat for decades, approximately 200,000 tonnes annually.

For greenhouse operations, heating accounts for a large share of total costs (approximately 30%) [6]. Currently, fossil fuels, such as heating oil and natural gas, are the most commonly utilized fuels for commercial greenhouses. These fuels result in higher heating costs and prominent environmental impacts [7,8]. Since 2000, the price of fossil fuels has increased sharply, leading to an increased interest in finding alternative fuel sources [9]. Climate change has become one of the biggest challenges countries face in the process of economic development. Fossil fuels contribute greatly to GHG emissions [10]. Countries are taking initiatives to set reduction goals to combat climate change. Canada signed onto the Copenhagen Accord in 2009 and committed to reduce its GHG emissions to 17% below 2005 levels by 2020. At the Paris climate conference (COP21) in 2015, Canada has further pledged its target to cut emissions by 30% from 2005 levels by 2030 [11]. One way to avoid the volatile fossil fuel market and to meet environmental targets is to replace fossil fuels by renewable energies.

This study assesses the GHG reductions from using wood pellets as an alternative fuel for greenhouse vegetable production taking the Macdonald campus greenhouse as a case study. Several life-cycle analysis studies have been conducted for wood pellets in British Columbia, with few studies having been undertaken for Eastern Canada. To the best of our knowledge, no comprehensive

literature on life-cycle analysis of greenhouse heating using wood pellets is available for Quebec.

A brief literature review is presented in section 2, with the objectives of this study. Section 3 describes the methods and data sources. Section 4 provides the results of the study. Section 5 concludes the paper.

2. Literature Reviews

With an increasing concern for global warming and the implementation of the Kyoto protocol, renewable energy has drawn interests to replace fossil fuels to reduce GHG emissions. Wood pellets, produced using sawdust, are considered to have less GHG emissions as an energy source. Pa [12] established the BC wood pellet life cycle inventory from production to its transportation to Europe. and assessed the GHG emissions from using wood pellets for district heating in BC. The study found that one tonne of BC pellets exported to Rotterdam emitted 295 kg of CO₂eq, of which 35% occurred during transportation. If wood pellets were used domestically, 1 GJ of wood pellets in BC would generate 7.93 kg of CO₂eq, which was half the emissions if were exported to Europe. Magelli et al. [13] assessed the environmental impact of wood pellet production in BC and their transportation from BC to Europe using streamlined life cycle analysis (LCA). The study found that 7.2 GJ of energy was consumed for 1 tonne of wood pellets from its production to shipment to Europe. This represented up to 39% of the total energy content of the wood pellets. The total fossil fuel content for BC wood pellets was 19% when wood residuals were used for the wood pellet drying process. Raymer [14] compared the GHG emissions from different kind of wood energies using LCA in a micro-level data study. The results indicated that combustion of 1 tonne of wood pellets caused 59 kg of CO₂eq. The study also concluded that the wood pellets emitted 5% of the GHG emissions a comparable amount of oil would generate. Ghafghazi et al. [15] applied the LCA approach to investigate the impact of renewable energy sources for district heating in BC. They estimated that the global warming effect of renewable energy was at least 200 kg CO₂eq less than natural gas. This study also found that the major source of emissions was from the production process of wood pellets. Chau et al. [16] evaluated the feasibility of using wood biomass to heat an average sized greenhouse in BC. The study concluded that it was economically feasible to replace the existing natural gas boiler system with biomass boilers to provide 40% of the heating requirement for a medium and large sized greenhouse if the natural gas price went up by 3% per year, given a 25 year lifespan. McKenney et al. [17] explored the economic feasibility of using biomass from short-rotation willow plantations as an energy source for greenhouse heating in Southern Ontario. They argued that taking a 21 years lifespan, it was not economically feasible for greenhouse producers currently using natural gas to convert to biomass. This was mainly due to the fact that natural gas prices at the time were at their lowest level over the previous five-years. The conclusion of this study reflected that policy incentives were needed for greenhouse producers to adopt biomass heating systems over current natural gas heating systems. Policy incentives such as subsidies or allowing farmers to sell carbon credits to industrial sectors could be used. Many studies on greenhouse operations either compared the energy requirement for greenhouse heating, or estimated the costs for greenhouse operation, however, very few expand their work to investigate both energy and operating costs.

This study investigates the environmental impacts of using Quebec wood pellets as a heating

source for vegetable production in greenhouse operations. A LCA was conducted to estimate the total energy requirements and GHG emissions for greenhouse vegetable production operation that used wood pellets. To undertake this study, a greenhouse on the Macdonald Campus of McGill University was converted to burn wood pellets. Wood pellets are compared to electricity and natural gas for greenhouse heating. The study also investigates the sensitivity of wood pellet heating requirements to changes in thermal, combustion efficiency, and temperature settings in the greenhouse.

3. Materials and Methods

3.1. System boundary for wood pellets

Information concerning wood pellets in this study is based on wood pellets produced in Quebec. Pellet production technologies are quite standard in Quebec and are similar to BC and the USA. The process of wood pellet production and transportation are illustrated in Figure 1. Trees are harvested from the forests and transported to sawmill. Wood residues from sawmill, including sawdust and shaving, are transported to pellet plants, where the pellet densification takes place. Wood pellets are then packed and sold to consumers.

A LCA was undertaken to estimate the energy requirements and GHG emissions from 1 tonne of Quebec wood pellets. The LCA is a cradle to grave analysis that assesses the energy requirement and environmental impacts from the extraction of the raw material till the end use and deposit of the products [18]. The incentive to explore alternative energy sources, such as wood pellets, for greenhouse heating is to reduce the environmental impacts from greenhouse vegetable production. A LCA can estimate these impacts and the degree of sustainability of wood pellets compared to fossil fuels.

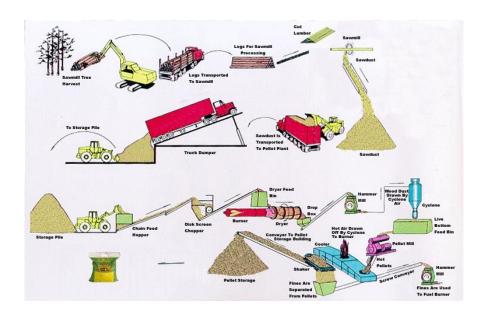


Figure 1. Production of wood pellets in Quebec. Source: Energex [19].

The system boundary was defined based on ISO 14044 series recommendations [20]. The

boundary was set from harvesting of logs, to the processing in sawmills, densification of wood pellets, and finally the combustion of the wood pellets in the Macdonald greenhouse (Figure 2). Energy requirements for the manufacturing process and transportation associated with the wood pellet production and consumption were included and computed in the LCA. Finally, GHG emissions associated with the total energy usage were estimated for the environmental impact evaluation. Energy required to harvest 1 m³ of logs in Eastern Canada forests and to process them in a sawmill plant was estimated using information provided by Natural Resources Canada [21]. The energy required to harvest and haul 1 m³ of logs from the forest to a sawmill was 294 MJ. This included 146.87 MJ from the use of diesel fuel for harvesting, 0.15 MJ from electricity, and 147.12 MJ from the use of diesel fuel for hauling. Total CO₂eq emitted from the wood harvesting is 21 kg CO₂eq per m³. The average distance from the forest to a sawmill was estimated to be 111 km for this study. During the sawmilling operation, 6% of the wood is converted into sawdust. It is assumed that 6% of the total energy used for wood harvesting and the sawmill operation is used to produce sawdust. This assumption is consistent with EPA guidelines [18] that energy usage and emissions for a co-product can be allocated by weight. It was estimated that the average distance from sawmill to a pellet plant was 100 km. In the pellet plant, sawdust is dried and pelletized. It was estimated that, on average, 7.5 tonnes of sawdust would be used to produce 5 tonnes of wood pellets. The ratio between raw material and final product is 1.5. Natural gas or sawdust is widely used for sawdust drying in Canada. If using sawdust, 10% of the sawdust would be used as fuel to dry the rest of sawdust. Mani [22] estimated the energy consumption for pellet densification by using either sawdust or natural gas. In this study sawdust was used for pellet densification since all interviewed factories used sawdust as the energy source for pellet densification. The final product is placed in 40-pound sacks, whereas 80% of Canadian pellets are shipped in bulk. It was estimated that the transportation distance from the pellet plant to the Macdonald greenhouse was 200 km. For greenhouse heating, the average furnace combustion and thermal efficiency is 92.5% and 81.2% and was assumed for wood pellets respectively. Appendix I provides more detail on the energy inventories from wood harvesting to the wood pellet plant operation and the assumptions to establish the life-cycle energy inventory of wood pellets.

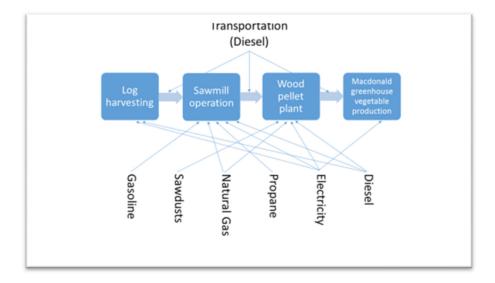


Figure 2. System boundary for wood pellets.

3.2. Macdonald greenhouse vegetable production

The greenhouses on the Macdonald campus were used to study the impacts of using wood pellets, natural gas, and electricity. The greenhouses were of the same dimensions and were covered with double layer polyethylene. The dimensions (length \times width \times height in meters) for the greenhouses were $29.25 \times 5.49 \times 2.745$. For carbon dioxide (CO₂) enrichment, a propane burner was installed inside the greenhouse and it was connected to a propane tank outside of the greenhouse. 400W light bulbs were used as the supplemental lighting and powered by electricity. An exhaust fan was installed in each greenhouse for ventilation. The greenhouses were originally constructed with electricity as their heating source. For the purpose of this study, one of the greenhouses was modified to use wood pellets as its heating source. A wood pellet furnace (SBI Caddy Alterna) was installed in the greenhouse.

Common greenhouse practice in Quebec is to produce four types of vegetables, i.e. tomatoes, peppers, cucumbers, and lettuces. It is assumed in this study that one type of vegetable grows in the greenhouse at a time, for one year. The energy requirements to support the heating to produce greenhouse vegetables were estimated. Three heating sources, i.e. wood pellets, natural gas, and electricity, are made comparable in this study because they were set to heat up the same greenhouse with same vegetable production type and temperature requirement for one year. The optimum greenhouse practice for each type of vegetable was assumed to be implemented [23]. This includes the optimum temperature settings for each plant according to its growth stage, controlled CO₂ level in the greenhouse, ventilation and lighting schedules according to temperature, season, and solar radiation rate. It is assumed that the lighting schedule and ventilation settings are identical across these four vegetables. Details of the greenhouse operation settings in this study can be found in Appendix II. On average, one square meter of greenhouse is expected to produce on average 48.25 kg of tomatoes, or 13.65 kg of cucumbers, 18.7 kg of peppers, or 163 heads of lettuces in Quebec. The production varies by plant species and scheduling.

Using wood pellets for greenhouse vegetable production provides the baseline for this paper. The other two scenarios, using electricity and natural gas for greenhouse vegetable production were estimated accordingly. Comparisons among these three scenarios would give readers a clear picture on how choice of heating fuel affects energy consumption, GHG emissions, and operating costs for greenhouse vegetable production. The question of whether wood pellets would provide avoided GHG emissions as compared to natural gas will be answered.

3.3. Electricity as the heating energy source

Electricity is not commonly used for greenhouse heating due to its high costs. However, according to greenhouse statistics, 7.5% of greenhouses used electricity for heating energy in Quebec. Electricity for heating is considered to be clean. Its environmental impact depends upon how the electricity is generated and what is the combination of fuel sources used for electricity generation. Run-of-river power plants tend to have lower environmental impacts, especially in terms of GHG emissions. Reservoirs have higher GHG emissions. Electricity generated from coal has the highest environmental impact [24].

In Quebec, over 90% of the electricity is from hydropower. Therefore, the environmental impact from electricity used for greenhouse heating is expected to be low. In this study, it was assumed that the domestic and agriculture rate, called "D rate", offered by Hydro-Quebec was used to estimate the costs. Despite the relatively low cost of electricity in Quebec, it is still not the lowest cost heating source. Using electricity for commercial greenhouse heating may reduce the GHG emissions, however. The operating costs from using electricity for greenhouse heating is high. GHG emissions from electricity in Quebec were weighted by the composition of power generation sources [25]. Emission factors for different power plants were from Tremblay et al. [26]. It was estimated from this study that the emission factor from electricity generation in Quebec was 36.993 g CO₂eq/kWh. It was assumed that there is a 100% energy convergence from electricity to heating.

3.4. Natural Gas as the heating source

The common fuel used in commercial greenhouses in Quebec and British Columbia is natural gas. The system boundary for using natural gas for greenhouse vegetable production was set at the extraction of natural gas to the combustion of natural gas in the greenhouse. It was expected that the total GHG emissions from wood pellets would be lower than those of natural gas for the same greenhouse operation. Life cycle emission factors for natural gas were estimated by the EPA [27] with a value of 72.3 kg CO₂eq/MMBtu.

Natural gas was assumed to be the heating source for the greenhouse in this scenario, leaving the other variables unchanged from the baseline. The natural gas price has fluctuated widely over the last ten years [28]. As a result, this exposes the greenhouse industry to risk in terms of costs. In addition, increasing concerns about GHG emissions from fossil fuel use also motivates greenhouse operators to find alternative energy sources. In this scenario the combustion efficiency for natural gas is assumed at 92.5% [16].

3.5. Combustion and thermal efficiency of wood pellets and furnace

Sensitivity tests were conducted on the wood pellet heated greenhouse. Combustion efficiency determines the air emissions from wood pellet combustion. Higher combustion efficiency leads to lower wood pellet consumption for the same energy requirement. The combustion efficiency for this furnace was tested to be between 90% and 95%. A sensitivity analysis was undertaken on combustion efficiency by varying the efficiency from 90% and 95%. Thermal efficiency estimates the rate of energy content in the wood pellets converted to heating energy. Moisture content in the wood pellets affects the thermal efficiency. The premium wood pellets used at the Macdonald greenhouse have a low moisture content of 4%. Thermal efficiency of the wood pellets used at the Macdonald greenhouse was 81.2%. Thermal efficiency of wood pellets varies greatly with the quality of the wood pellets, moisture content, as well as the furnace quality. Thermal efficiency for pellets can range from 65% to 85%. The thermal efficiency was changed by 5% over the range of 65% to 85. Temperature settings inside the greenhouse directly affect the energy requirement to heat the greenhouse [23]. The baseline scenario takes the average temperature for all stages. The energy requirement changes by setting the temperature at the lower or upper bounds and these two limits were investigated respectively.

4. Results and Discussion

Total energy requirements and GHG emissions for greenhouse heating were estimated using a life cycle analysis for scenarios considered in this study. Operating costs associated with the greenhouse were also estimated.

4.1. Wood pellet production

The total energy requirement to produce 1 tonne of wood pellets and delivered to the Macdonald campus was 15.34 GJ, while the low heating value for 1 tonne of wood pellet is 19.39 GJ. Table 1 provides the estimated amount of total energy used by fuel type. The energy requirement includes the energy used in tree harvesting, sawmill operation, pellet operation, and transportation of wood pellets.

Table 1. Total energy use to produce 1 tonne of wood pellets from log harvesting to their delivery to the Macdonald campus.

	Diesel	Propane	Electricity	Natural gas	Sawdust
Energy unit (MJ)	5309	8.56	6414.07	0.41	3608.86

Table 2. Energy requirement and GHG emissions using wood pellets for greenhouse tomato production.

	Energy	Energy	CO ₂	CH ₄	N ₂ O	CO ₂ equivalent
	(kWh)	(MJ)	(kg)	(kg)	(kg)	(kg)
Greenhouse operation						
Heating (Wood pellets)	205,804.47	740,836.83				5,145.11
Lighting	39,219.06	141,177.34				1,450.83
Ventilation	570.32	2,052.98				21.10
Electricity (Furnace)	5,991.84	21,568.90				221.66
Wood pellets production						
Diesel	9,108.59	32,788.29	2,257.37	0.11	0.34	2,364.85
Propane	79.76	287.10	16.98	0	0.001	17.3629
Electricity	59,743.50	215,059.40				2,210.09
Natural Gas	3.79	13.66	0.68	0	0	0.69
Gasoline	34.19	123.09	8.13	0	0	8.39
Sawdust	33,614.59	121,002.84	6,386.26	0.34	0.13	6,434.99
Wood pellets transportation						
Diesel	11,209.23	40,349.99	2,777.98	0.14	0.42	2,910.24
Total	365,379.34	1,315,260.40				20,785.32
Fossil Fuel emission						15,640.21

Table 3. Energy requirement and GHG emissions using wood pellets for pepper greenhouse heating.

	Energy	Energy	CO_2	CH_4	N_2O	CO ₂ equivalent
	(kW h)	(MJ)	(kg)	(kg)	(kg)	(kg)
Greenhouse operation						
Heating (Wood pellets)	214,376.73	771,694.48				5,359.42
Lighting	39,219.06	141,177.34				1,450.83
Ventilation	570.32	2,052.98				21.10
Electricity by Furnace	5,361.88	19,301.21				198.35
Wood pellets production						
Diesel	9,487.98	34,154.01	2,351.40	0.12	0.35	2,463.36
Propane	83.08	299.06	17.69	0.00	0.00	18.09
Electricity	62,231.96	224,017.15				2,302.15
Natural Gas	3.95	14.23	0.71	0.00	0.00	0.71
Gasoline	35.62	128.21	8.47	0.00	0.00	8.74
Sawdust	35,014.72	126,042.90	6,652.26	0.35	0.14	6,703.03
Wood pellets Transportation						
Diesel	11,676.12	42,030.66	2,893.68	0.14	0.43	3,031.46
Total	378,061.41	1,360,912.21				21,557.23
Fossil Fuel emissions						16,197.79

4.2. Baseline scenario: using wood pellets for greenhouse heating

The energy flows and GHG emissions associated with each greenhouse vegetable production is calculated in a greenhouse with the dimensions of $29.25 \times 5.49 \times 2.745$ meters that is used for greenhouse production for a year. Four vegetables were included in the analysis of greenhouse production at the Macdonald greenhouse. Planting schedule and optimum temperature differed by plant. Consequently, the energy required for the greenhouse differs across the four vegetables. The results indicate that cucumbers and peppers required more energy for heating than tomatoes and lettuces. The energy required for lighting and ventilation was the same, which were 39,219.06 and 570.32 kWh per year respectively, across the four vegetables.

Table 4. Energy requirement and GHG emissions using wood pellets for Cucumber greenhouse heating.

	Energy	Energy	CO_2	CH_4	N_2O	CO ₂ equivalent
	(Kw h)	(MJ)	(kg)	(kg)	(kg)	(kg)
Greenhouse operation						
Heating (Wood pellets)	226,354.14	814,809.72				5,658.85
Lighting	39,219.06	141,177.34				1,450.83
Ventilation	570.32	2,052.98				21.10
Electricity by Furnace	5,300.32	19,079.61				196.07
Wood pellets production						
Diesel	10,018.06	36,062.22	689.71	0.03	0.10	2,600.99
Propane	87.72	315.77	5.19	0.00	0.00	19.10
Electricity	65,708.92	236,533.18				2,430.77
Natural Gas	4.17	15.02	0.21	0.00	0.00	0.75
Gasoline	37.61	135.38	2.48	0.00	0.00	9.23
Sawdust	36,971.02	133,085.03	1,951.25	0.35	0.14	7,077.54
Wood pellets transportation						
Diesel	12,328.47	44,378.95	848.78	0.14	0.43	3,200.83
Total	396,599.83	1,427,645.19				22,666.05
Fossil Fuel emissions			·			17,007.2

Table 5. Energy requirement and GHG emissions using wood pellets for Lettuce greenhouse heating.

	Energy	Energy	CO_2	$\mathrm{CH_4}$	N_2O	CO ₂ equivalent
	(Kw h)	(MJ)	(kg)	(kg)	(kg)	(kg)
Greenhouse operation						
Heating (Wood pellets)	152,210.16	547,912.75				3,805.25
Lighting	39,219.06	141,177.34				1,450.83
Ventilation	570.32	2,052.98				21.10
Electricity by Furnace	3,901.54	14,044.41				144.33
Wood pellets production						
Diesel	6,736.59	24,249.77	1,669.52	0.08	0.25	1,749.01
Propane	58.99	212.33	12.56	0.00	0.00	12.84
Electricity	44,185.47	159,054.98				1,634.55
Natural Gas	2.81	10.10	0.50	0.00	0.00	0.51
Gasoline	25.29	91.03	6.01	0.00	0.00	6.20
Sawdust	24,860.89	89,492.04	4,723.19	0.25	0.10	4,759.24
Wood Pellets Transportation						
Diesel	54.87	29,842.30	2,054.55	0.10	0.31	2,152.37
Total	271,771.11	978,297.73				15,736.24
Fossil Fuel emissions						11,930.99

Using wood pellets as the heating fuel for a greenhouse, cucumber production consumes the most wood pellet energy, i.e. 814,809.72 MJ per year. This is followed by pepper, tomato, and lettuces production, with 771,694.48 MJ, 740,836.83 MJ, and 547,912.75 MJ per year respectively. The ranking of wood pellet energy required for heating is determined by the optimal temperature requirements by vegetables. Greenhouse cucumber requires the highest level of heating, followed by pepper, tomato, and lettuce.

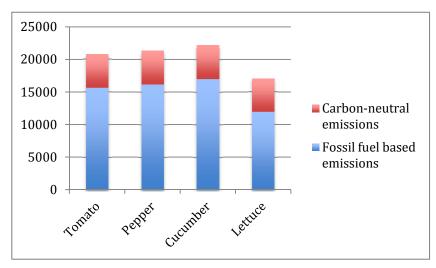


Figure 3. Fossil fuels and carbon neutral CO_2 equivalent emissions by greenhouse vegetable type (kg).

GHG emissions from the combustion of wood pellets followed the same ranking as the wood pellet energy input for the four vegetable productions. GHG emissions from the direct combustion of wood pellets was 5,658.85 kg, 5,359.42 kg, 5,145.11 kg, and 3805.25 kg of CO₂eq respectively for cucumber, pepper, tomato, and lettuce productions. The GHG emissions from the direct combustion of wood pellets is considered to be carbon neutral, since the combustion of wood pellets releases GHGs that were earlier sequestrated in the wood and had already presented in the atmosphere. Therefore, these emissions are not fossil fuel based. GHG emissions associated with the life-cycle of wood pellets from wood harvesting to their transportation to the Macdonald campus contains fossil fuel based emissions. They were estimated to be 17,007.2 kg, 16,197.79 kg, 15,640.21 kg, and 11,930.99 kg for cucumber, pepper, tomato, and lettuce respectively. The total GHG emissions from the life cycle of wood pellets, regardless of the energy sources are 22,666.05 kg, 21,557.23 kg, 20,785.32 kg, and 15,736.24 kg of CO₂eq respectively for cucumber, pepper, tomato, and lettuce. However, direct combustions of wood pellets, and combustion of sawdust for wood pellet production can be considered as carbon neutral. Therefore, the carbon footprint of wood pellets can be further reduced (Figure 3).

Normally, heating costs dominate the operating costs for greenhouse production. Among the four vegetables, i.e. cucumber, pepper, tomato, and lettuce, the operating costs are \$10,873.14, \$9,790.61, \$10,030.72, and \$7,640.55 respectively. Costs to produce tomatoes are higher than peppers, which is reversed to the heating requirement ranking. This is because tomato seeds cost approximately 6 times that of pepper seeds. For all four vegetable productions, heating source (wood pellets) and electricity (for ventilation and supplemental lighting) take the first and second largest share of total operating

costs. Seeds cost varies greatly by types of vegetable grown in the greenhouse. For the same area of greenhouse, cucumber seeds cost the highest, followed by tomato seeds, pepper seeds, and lettuce seeds (Table 7).

4.2.1. CO₂ enrichment

The Macdonald greenhouse uses propane as its source of CO₂ enrichment. The CO₂ requirement for each plant does not differ by much, from 8,189,613 to 8,196,762 liters. Lettuce requires the most CO₂ on a yearly basis reflecting its relatively higher requirement for CO₂ concentration for photosynthesis (Table 6).

	CO ₂ requirement (liter)	Propane (liter)
Tomato	8,189,613.08	8,189.61
Pepper	8,189,613.08	8,189.61
Lettuce	8,196,762.73	8,196.76
Cucumber	8,195,332.80	8,189.61

Table 6. CO₂ enrichment by vegetable.

4.2.2. Greenhouse operating costs

The operating cost for a greenhouse by plant type differed due to heating costs. The pellet furnace and propane burner maintenance costs were assumed to be constant, with values of \$75 and \$150 respectively. Propane was used for CO₂ enrichment and the costs for propane did not differ much by plant type, at approximately \$330. This includes the propane fuel cost of 67 cents per liter and \$125 delivery charge (Table 7).

	Tomato	Pepper	Cucumber	Lettuce
Wood Pellets	6,858.28	7,143.94	7,362.62	5,072.29
Maintenance	225.00	225.00	225.00	225.00
Propane	330.50	330.50	330.60	330.50
Electricity	2,018.95	1,991.17	1,988.46	1,926.77
Seeds	598	100	786	86
Total	10,030.72	9790.61	10,873.14	7,640.55

Table 7. Greenhouse operation costs by vegetable (CAD).

4.3. Scenario 2: Electricity as the greenhouse heating source

This scenario estimates the energy requirements and total GHG emissions associated with using electricity as the heating source for the greenhouse operation. Table 8 provides the results by vegetable type. It was assumed that thermal efficiency was 100% for electrical heating and other variables

remained the same as the baseline. The energy requirement for the greenhouse operation was lower with electricity than wood pellets. On site use of electricity was assumed to have zero emissions. When using electricity as the heating source, GHG emissions from the greenhouse operation were much lower than using wood pellets for each vegetable. The total emissions from electricity used for greenhouse tomatoes, peppers, cucumbers, and lettuce production were estimated to be 7,190.30 kg, 7,428.48 kg, 7,753.14 kg, and 5,701.16 kg CO₂eq respectively. Similar to the baseline results, greenhouse cucumber production generates the most GHG emissions among the four vegetables, due to its higher heating requirement amongst the four vegetable greenhouse productions.

	Heating (Electricity)	Total energy	CO ₂ equivalent	Operating costs
	(MJ)	(MJ)	(kg)	(CAN)
Tomato	556,442.54	699,672.85	7,190.30	10,820.94
Pepper	579,619.72	722,850.04	7,428.48	11,163.47
Cucumber	611,211.43	754,441.74	7,753.14	11,630.37
Lettuce	411,537.27	554,767.58	5,701.16	8,679.39

Table 8. Greenhouse heating by electricity.

In this scenario it was assumed that the cost of electricity for the greenhouse operation was set at the "D" rate, which cost 5.32 cents per kWh⁴. Greenhouse cucumber production costs the most among four greenhouses. Operating costs for greenhouse tomato production is higher than the pepper production due to a higher seeds cost, while lettuce production had the lowest cost among the four vegetables due to lower electricity consumption.

4.4. Scenario 3: Natural gas as the greenhouse heating source

Natural gas is a commonly used heating source for greenhouse production in Quebec and British Columbia. On average, total CO₂eq emissions using natural gas were higher than that for wood pellets. However, the operating costs associated with natural gas were estimated to be lower than wood pellets. Natural gas consumption in terms of energy units for tomato, pepper, cucumber, and lettuce cultivation were estimated to be 601,559.50 MJ, 626,615.92 MJ, 645,796.35 MJ, and 444,905.15 MJ respectively. Differences in energy requirements were because the temperature setting for each vegetable is different. Moreover, GHG emissions were dependent on fuel consumption. The highest GHG emissions were from cucumber cultivation, at 24,960.11 kg of CO₂eq, with the highest operating costs at \$8,259.59. Taking greenhouse cucumber production as an example, Figure 4 compares the total life cycle GHG emissions by varying heating fuel. Natural gas heating carries the highest environmental burden, followed by wood pellets. Using electricity as a heating source results in the lowest GHG emissions due to the composition of electricity generation in Quebec. The same trend is observed for the other vegetables.

In this study the greenhouse that used natural gas for heating used propane for CO₂ enrichment. It is also possible, thought uncommon for commercial greenhouses, that an external filter can be installed on the chimney of the natural gas burner to clean the exhausted gas. The aim of this step is to use the

exhaust gases from natural gas combustion for CO₂ enrichment. If this technology can be matured, the costs of greenhouse operation would be reduced further, and the GHG emissions from natural gas combustion would reduce.

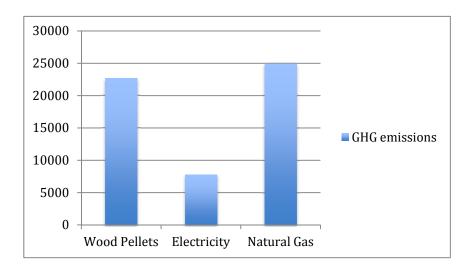


Figure 4. Total GHG emissions from cucumber production by heating sources (kg CO₂eq.)

The costs of greenhouse operations using natural gas are lower than those when wood pellets or electricity are used. This result contradicts Chau et al. [16] results. The main reason for the difference is the difference in prices of heating in BC and QC⁵. Economies of scale due to the larger size of the BC wood pellet processing sector could result in lower costs for the wood pellets. Also, the difference in provincial taxes could affect the price of wood pellets. The other reason that may cause the difference in the price of wood pellets may be the quality of wood pellets. In our study premium wood pellets were used for greenhouse heating, which have the highest price and are of the best quality. The wood pellets considered by Chau et al. [16] may not be of premium quality and therefore costs less.

Table 9. Greenhouse heating using natural gas by vegetable type.

	Heating (natural gas)	Total energy	CO2 equivalent	Operating costs
	(MJ)	(MJ)	(kg)	(CAN)
Tomato	601,559.50	766,371.89	23,390.19	7,946.08
Pepper	626,615.92	789,160.46	24,268.32	7,665.24
Cucumber	645,796.35	808,119.27	24,960.11	8,259.59
Lettuce	444,905.15	602,192.46	17,662.77	5,899.30

4.5. Sensitivity tests

4.5.1. Combustion Efficiency

Lower combustion efficiency would require greater wood pellet consumption, while higher combustion efficiency would require lower wood pellet consumption to meet the same energy demand in greenhouse. Increasing the combustion efficiency from 90% to 95% resulted in a savings in wood pellet combustion by 4.6%, 4.6%, 6.2%, and 4.4% for tomato, pepper, cucumber, and lettuce greenhouse respectively. Increasing combustion efficiency had the greatest impact on the most energy intensive greenhouse vegetable production, i.e. cucumbers. The change in energy requirement for

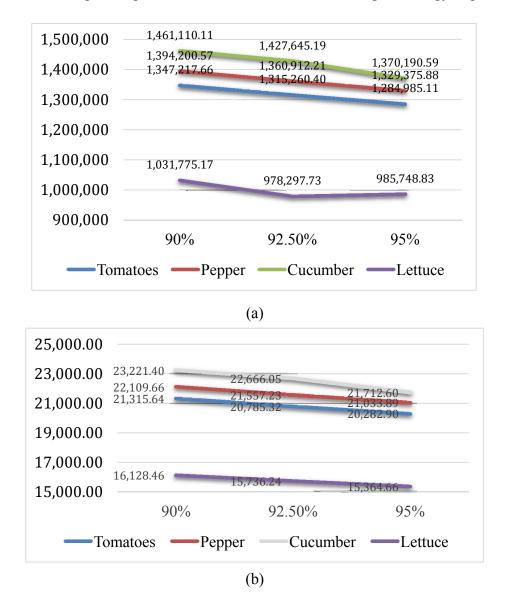


Figure 5. Sensitivity test on the combustion efficiency of wood pellets. (a) Combustion efficiency impact on energy use by vegetable (MJ); (b) Combustion efficiency impact on GHG emissions by vegetable (kg CO₂eq).

greenhouse lettuce was the lowest. A 5% increase in combustion efficiency would lead to a 4.8% decrease in GHG emissions for tomato, 4.8% for pepper, 6.5% for cucumber, and 4.7% for lettuce. The impact on costs from combustion efficiency changes was due to the changes in pellet combustion. An increase in combustion efficiency of 5% would reduce the costs by 3.6% to 5% for the four greenhouse vegetable operations, which was generally smaller than the change in combustion efficiency (Figure 5).

4.5.2. Thermal Efficiency

Thermal efficiency is the conversion rate of energy from the fuel to heating energy. Similar to combustion efficiency, an increase in thermal efficiency would lead to a reduction in fuel consumption and GHG emissions, thus the costs would be lower as well.

For greenhouse tomato production, an increase in thermal efficiency from 65%-70% would reduce wood pellet consumption in terms of energy units by 6.4%, GHG emissions by 6.6%, and costs by 5.5%. It was also observed that the marginal decrease in energy, GHG emissions and costs would diminish with increased thermal efficiency. For greenhouse pepper production, the energy and GHG emissions results from an increase in thermal efficiency were similar to greenhouse tomato production. A change of 5% in thermal efficiency on average would reduce the energy, GHG emissions, and costs by 6.4%, 6.6% and 5.5% respectively. Greenhouse cucumber production requires the highest energy consumption among the four vegetables investigated. The reduction in energy requirement by an increase in thermal efficiency from 65% to 70% and from 70% to 75% was 6.4% and 6.0% respectively. Similarly, total GHG emissions reduction corresponding to these changes were 6.7% and 6.2% respectively. Reduction in cost were 5.6% for an increase in thermal efficiency of 65% to 70%, and 5.1% for an increase of 70%-75%. Changes in energy and GHG emissions from greenhouse lettuce production follows the same trend as the other vegetables. If thermal efficiency increases from 65% to 70%, the energy, GHG emissions, and costs would decrease by 6.2%, 6.5%, and 5% respectively. With an increase in thermal efficiency, the rate of decrease in these variables diminishes (Figure 6).

4.5.3. Temperature requirements

Like thermal and combustion efficiency of wood pellets, the temperature setting in a greenhouse directly affects energy consumption. Temperature setting has direct impact on the heating requirements for greenhouse production. When choosing the lower bound temperature for the greenhouse, it resulted in a decrease of 2%, 2% and 1.8% in energy requirement, GHG emissions, and costs. When the upper bounds were set for the greenhouse temperature, energy input, GHG emissions and costs would increase above the baseline by 4%, 4%, and 3%. Overall, in most cases, lower temperature means lower yields and slower growth. Such a relationship is clear for lettuce, i.e. that a cooler temperature usually means that lettuce requires a longer time to grow. However, for tomatoes, cucumbers, and peppers, the relationship between yields and temperature is rather more complicated. The temperature affects not only fruit growth and ripening but also pollination and fruit set.

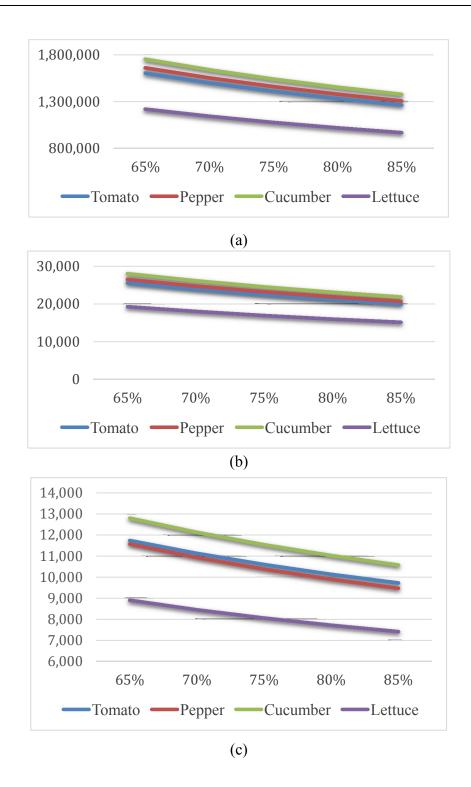


Figure 6. Sensitivity tests on thermal efficiency. (a) Thermal efficiency impact on energy requirement by vegetable (MJ); (b) Thermal efficiency impact on GHG emissions by vegetable (kg CO₂eq); (c) Thermal efficiency impact on operating costs by vegetable (CAD).

Comparing the baseline with the other scenarios, the GHG emissions from natural gas for greenhouse heating was higher than wood pellets. However, with the current price of natural gas and wood pellets in Quebec, natural gas is a lower cost heating fuel than wood pellets. As a result, at least

in the short term, it is less costly for greenhouse operators in Quebec to use natural gas for greenhouse heating. However, depending on natural gas as the heating fuel may expose the greenhouse industry to the risk of price fluctuations. Large price fluctuations have occurred in the price of natural gas in the last ten years. In 2006, the price of natural gas spiked to an average price of 44.86 cents per m³ as compared to its current price of 25 cents per m³ in Quebec [27]. In comparison, the supply of wood pellets is comparatively stable and it is a renewable resource.

The direct GHG emissions from the combustion of wood pellets are considered to be "carbon neutral". Natural gas has a much higher environmental impact than the combustion of wood pellets. Greenhouse operators may be asked to provide abatement for the reduction of GHG emissions from the combustion of natural gas. In this study, the abatement costs for using natural gas was not included in the costs estimation. It is also possible that when abatement costs were added to the greenhouse operation, the costs between using wood pellets and natural gas for heating would reverse.

Comparing electrical heating with heating using wood pellets, it was found that GHG emissions were higher when using wood pellets. This is due to the fact that 90% of the electricity in Quebec was generated by hydropower. The sensitivity study indicates that when the combustion and thermal efficiency for wood pellets was increased to 92.5% and 81.2% respectively, the total operating costs at the Macdonald greenhouse for using wood pellets was lower than using electricity even if the price of electricity in Quebec is among the lowest in Canada. Natural gas remains the lowest in costs at current prices. To investigate this issue, it was estimated that to generate 1 kWh of heat for the greenhouse, it costs 5.32 cents for electricity, and 4. 43 cents for wood pellets. Increasing the thermal and combustion efficiency for wood pellets combustion would reduce the costs of generating 1 kWh of heat with wood pellets even more. For example, when the thermal and combustion efficiency were assumed to be 85% and 95% at the Macdonald greenhouse, the costs for wood pellets was reduced to 4.12 cents per kWh heat.

This study specifically estimated the energy required and GHG emissions from the life cycle of wood pellets. The GHG emissions were estimated to be 288 kgCO₂eq per tonne of wood pellet production, with an equivalence of 14.89 kgCO₂eq/GJ. This result is consistent with Sjølie and Solberg's [28] study that wood pellets life cycle GHG emissions varies between 113–482 kgCO₂eq/tonne, and their estimates resulted in the emissions to be 236 kg CO₂eq/tonne in Norway. The emissions computed from this study also coincides with Murphy et al. [29] simulation. Murphy et al. [29] computed a 2.3–17.1 kgCO₂eq/GJ emissions from the Irish wood pellets. Magelli [13] estimated the life cycle GHG emissions of BC wood pellets transported to Europe, and found the emissions to be 29 kg and 39 kg CO₂eq/GJ if using sawdust or natural gas for drying respectively. As can be concluded from the results of this study and others, the domestic use of wood pellets as energy source in Canada has the advantage of reducing GHG emissions. Overall, comparing GHG emissions from 1 tonne of wood pellets from eastern Canada to other studies about the life cycle of EU wood pellets, Canadian wood pellets have the advantages of lower level of GHG emissions intensity.

5. Conclusion

This study investigated the energy consumption, GHG emissions, and greenhouse costs for the greenhouse at the Macdonald campus of McGill University. Tomato, pepper, cucumber, and lettuce are commonly grown vegetables in greenhouse in Quebec. It was assumed one vegetable (tomato, pepper, cucumber, and lettuce) grew in the greenhouse at a time for a year. All weather parameters were assumed for the Montreal climate.

Three fuels, i.e. wood pellets, electricity, and natural gas, were compared as sources for heating a greenhouse. To investigate the total GHG emissions for the greenhouse operation by fuel type across vegetables, a life cycle analysis was undertaken. The system boundary for these three fuels were all set at the extraction of the raw material to the end use of the fuel, e.g. for wood pellets this was from the harvesting of the logs to the combustion of the wood pellets at the Macdonald greenhouse.

Greenhouse cucumber production required the greatest amount of energy for heating. This was because the optimum temperature for cucumber growing was higher than the other greenhouse vegetables. Since heating is the major source of costs in a greenhouse operation, cucumber greenhouse operation costs were the highest. For all scenarios, it was found that greenhouse cucumber production costs the most, followed by tomato, pepper, and lettuce production.

The general trend from the estimation is that using wood pellets for heating a greenhouse costs less than electricity. An increase in thermal and combustion efficiency would lead to a lower operating costs for all vegetable productions. The life cycle GHG emissions from wood pellets are higher than using electricity in Quebec due to the methods of electricity generation. Even though electricity costs are much lower in Quebec than the other provinces, the costs difference between wood pellets and electricity is still large in Quebec. If comparing electricity heating and wood pellet heating in other provinces in Canada, an even greater gap in operating costs is expected. Electricity generated from Hydro-Quebec is "clean", since 90% of the electricity is from hydropower. With a different combination of electrical power generations, GHG emissions would increase. However, it was assumed that there was no emission from the direct use of electricity.

The results indicate that using natural gas for greenhouse heating costs less than using wood pellets. However, the life cycle GHG emissions from natural gas were higher than for wood pellets. It is important to take into account that in this study, abatement costs was not included. Since natural gas generates more GHG emissions, abatement costs would be higher. An investigation into the abatement costs for natural gas heated greenhouses would provide a better comparison between the fuel sources. It could be possible that if abatement costs were included in the analysis, then the cost difference would be reversed. In Quebec, the price of natural gas was at its lowest in five years, while in Canada, the average price of natural gas in 2012 was at its lowest in 14 years. The price of natural gas has fluctuated greatly in the past decade, from a high of 44.86 cents per m³ in 2006 in Quebec and 31.99 cents per m³ in 2007 in Canada. The price of natural gas dropped to 25 cents per m³ in Quebec and 12.85 cents per m³ in Canada in 2012 [27]. The heating costs using natural gas would be larger than wood pellets when the price of natural gas exceeds 38.75 cents per m³. This trend is expected in the next decade. Moreover, the increased concern with environmental issues, such as global warming, would be beneficial for wood pellets because their GHG emissions from combustion are considered to be carbon neutral.

The temperature requirements during the growing stage of greenhouse vegetable will have an impact on the energy requirements, GHG emissions, and cost. A lower temperature inside the greenhouse required less energy, thus the total GHG emissions and costs are also less. It is expected that increased the thermal and combustion efficiencies of the wood pellet furnace would lower the energy requirement, total GHG emissions and costs. This however, is dependent on the technology developments of the wood pellets furnace design.

Currently in Quebec, the majority of greenhouses are heated by natural gas. Undertaking this analysis on a commercial operation would give more insights into the advantages and disadvantages of using wood pellets for heating. If the Canadian wood pellet industry experiences economies of scales, an expansion of production capacity would enhance the competitiveness of Canadian wood pellets as an alternative fuel, hence encouraging the domestic application of wood pellets as a renewable energy to reduce GHG emissions.

Conflict of Interest

All authors declare no conflicts of interest in this paper.

Appendix I. Energy requirement for wood pellets production from tree harvesting to pellet plant

1. Tree Harvesting

In both Eastern and Western Canada, wood harvesting is dominated by mechanical systems, where 99% of the harvesting activity is conducted by mechanical methods. In this study, energy and GHG emissions from wood harvesting in Quebec was estimated using the average value for Eastern Canada [22]. The compositions of tree species in Eastern Canada are as follow: spruce 54%, pine 21%, fir 14%, and other type of trees 11%. The average wood density of forests was estimated by the tree composition to be 383 kg/m³. Energy sources for harvesting 1 m³ of logs in Eastern Canada was estimated by Natural Resources Canada and is given in Table 1 [21].

Table 1. Energy use for harvesting 1 m³ of wood in Eastern Canada.

Fuel type	Unit	Energy use
Diesel fuel (harvesting)	L	3.2900
Electricity	kWh	0.0296
Diesel fuel (hauling)	L	3.3000

Source: Natural Resources Canada [21]

2. Sawmill Operation

During the sawmilling operation, 6% of wood is converted into sawdust. It is assumed that 6% of the total energy used for wood harvesting and the sawmill operation is used to produce sawdust. For a sawmill, the energy used for lumber production was estimated and listed in Table 2.

Table 2. Energy use for 1 m³ of lumber processing in sawmill in Canada.

Fuel Type	Physical unit	Energy unit (MJ)
Electricity	70.83 kWh	358.73
Liquid propane gas	0.19 L	5.71
Diesel	2.57 L	114.82
Natural gas	6.09 L	257.24
Gasoline	0.06 L	2.51

Source: Natural Resources Canada [21], L: liters.

3. Pellet Plant Operation

In a pellet plant, sawdust is dried and pelletized. It was estimated that, on average, 7.5 tonnes of sawdust can produce 5 tonnes of wood pellets. The ratio between raw material and final product is 1.5. Natural gas or sawdust is widely used for sawdust drying in Canada. If using sawdust, 10% of the sawdust is used as fuel to dry the rest of sawdust. Mani's [22] estimation for the energy requirement to produce wood pellets was used for this study (Table 3). The final product is placed in 40-pound sacks, whereas 80% of Canadian pellets are shipped in bulk. The average transportation distance from the pellet plant to the end user was 200 km by distribution of pellet plants in Quebec.

Table 3. Energy use to produce 1 tonne of wood pellet in a pellet plant.

	Electricity	Wet sawdust for drying	Diesel Energy	Transportation from plant to consumer
Energy unit (MJ)	404	3168	206	318

Appendix II. Greenhouse Operation

As for common greenhouse practice in Quebec, four types of vegetables are produced in greenhouses, i.e. tomatoes, peppers, cucumbers, and lettuces. In this study it was assumed that only one type of vegetable grows in the greenhouse at a time, for one year. The energy requirements and GHGs emissions from the greenhouse operation differs by the vegetable grown.

The optimum greenhouse practice for each type of vegetable was assumed to be implemented [23]. This includes the optimum temperature settings for each plant according to its growing stages, controlled CO₂ level in the greenhouse, ventilation and lighting schedules according

to temperature, season, and solar radiation rate. It is assumed that the lighting schedule and ventilation settings are identical across these four vegetables. Greenhouse temperature and CO₂ levels are set separately according to the vegetable grown.

1. Heating Energy Requirements for Greenhouse Vegetable Production

The greenhouse vegetable growing schedule and temperature differs by plant type and geographic locations of the greenhouse. In Quebec, the cultivation of tomatoes and peppers adopt the long-season crop practice, while cucumbers and lettuce follow a multiple planting practice. Planting schedule and temperature setting by plant type was based on common practice in Quebec (Table 1).

Seeding and **Beginning** Vegetable **Plant Raising Full Harvesting Transplanting** Germination Harvesting Night Day Night Night Day Night Day Night Day Day 19-21 19-21 19 19 Tomato 25 25 24 24 20 - 2217 - 29Pepper 25 25 21 - 2320 - 2124 21 21 - 2418 - 2121-2317 - 18Cucumber 27 - 2827 - 2824 21 23 - 2523 - 2523 21 23 17 - 21Lettuce 16-21 16 - 2116 - 2116-21 15 - 1813 - 1815 - 1815 - 1813 - 1813 - 18

Table 1. Temperature setting by vegetable (degrees Celsius (°C)).

Source: Wees [33] and Ministry of Agriculture, Ontario [23]

Tomatoes are the most common greenhouse vegetable in Canada [31]. In 2011, sales of tomatoes reached \$496 million, which represented a 4% increase since 2010. Tomato cultivation is found to be the most profitable, amongst all greenhouse vegetable production [34]. A long-season crop practice is adopted for greenhouse tomato production. Cultivation of greenhouse peppers follows a similar schedule as tomato in Quebec (personal communication with Dr. Wees, McGill University, Canada). Compared to tomatoes and peppers, cucumber plants grow rapidly [23]. Depending on light and growing conditions, marketable fruits can be produced in 8–12 weeks following seeding. A three-crop production cycle is selected for cucumber production since the three-crop production cycle maintains high fruit quality and market share [23]. Greenhouse lettuce grows year-round [33]. A new batch is seeded every 8–10 weeks depended on the time of the year. Lettuce requires relatively cooler temperatures compared to other greenhouse vegetables.

According to the outside and inside temperature of greenhouse, the dimensions of the greenhouse, energy requirement for greenhouse heating can be estimated using heat loss methods [33]: Heating requirement= Total heat loss

$$= U * S * (T_{inside} - T_{outside}) + 0.5 V * N * (T_{inside} - T_{outside})$$

$$(1)$$

where, U is the heat transfer coefficient determined by the covering material. In this study, the U value for double layer polyethylene is at 4 W/m^2 °C. S is the total exposed surface of the greenhouse with the unit of m². T_{inside} and $T_{outside}$ represent the temperature inside and outside the greenhouse.

T_{inside} can be determined by the temperature setting by stage, while T_{outside} was estimated using the average monthly temperature in Montreal. Constant number 0.5 represents the heat content of the air. V is the greenhouse volume in m³. N is the number of air exchanges per hour set to be constant at 1. Equation (1) estimates the greenhouse heating requirement per hour. The total annual heating requirement is then estimated using equation (1) to multiply the number of heating hours per year.

2. Supplemental Light

Sunlight is not always sufficient for plant growth due to changes in the weather conditions. It is standard that greenhouses utilize supplemental light to support plants use CO₂ for photosynthesis. For plants to survive, the minimum light intensity is 3 W/m². However, the optimum light intensity is 400–500 W/m² for most of the plants. Supplemental light intensity typically ranges from 10–40 W/m² [33]. In this study, high-pressure sodium (HPS) bulbs are utilized for supplemental lighting. Each bulb is 400 W of power and the output efficiency for these bulbs is 25–26%. In this study the output efficiency of the bulb is 25%. With the knowledge of supplemental light intensity and the size of greenhouse, the number of bulbs required for the greenhouse was estimated to be 28 bulbs with power of 400 Watts each. The total electricity used per year can be estimated using the following information: the bulb power, supplemental lighting schedule by month, number of days per month, and number of bulbs in the greenhouse.

3. Ventilation

Ventilation is required for greenhouse operations for cooling, bringing in more CO₂ from outdoors, and controlling the relative humidity [33]. Ventilation can occur through opening vents in the roof and sidewalls of greenhouse. The advantage of natural ventilation is that the operation costs are lower. However, natural ventilation is inadequate in hot weather, especially when there is no wind. As a result, mechanical ventilation is required in greenhouses. The greenhouse was installed with a single speed belt driven fan for ventilation. Its air movement capacity is 535 m³/minute. The motor power is 0.746 kW. The energy usage (electricity) for the fan operation is estimated by using daily temperature data from Environment Canada and the solar radiation rate. It is assumed that the exhaust fan turns on when the outside temperature is above 21 Degree Celsius, and shuts down below 21 degree. When the temperature lies between 0 to 21 degree, the exhaust fan also turns on when the solar radiation rate is greater than 146 μmol/(m² *sec). If the temperature is below 0 degree, the exhaust fan turns on when the solar radiation rate is above 440 μmol/ (m² *sec).

4. Carbon Dioxide Enrichment

Concentration level of CO_2 requirement inside the greenhouse differs by vegetable type (Table 2). However, the length of CO_2 enrichment per day depends on the number of hours of sunlight during the day as well as the outside temperature. CO_2 is added to the greenhouse only during daytime, when the plants use the CO_2 for photosynthesis. During the summer time, the number of hour decreases since the ventilation in summer time dilutes the CO_2 concentration to atmosphere levels.

Table 2. Carbon Dioxide level by vegetable.

Vegetable	Desired CO ₂ level (PPM)	
Tomato	1000	
Pepper	1000	
Cucumber	1000-1500	
Lettuce	1200	

Source: Wees [33]

CO₂ enrichment in these greenhouses was obtained through the combustion of propane. A small propane burner was installed inside the greenhouse and was attached to a propane tank outside the greenhouse. Total propane requirement for one year of CO₂ enrichment was estimated. To do this, the CO₂ requirement per hour was calculated according to the following equation [33]:

$$CO_2$$
 add to the greenhouse $(E) = CO_2$ used by $crop + CO_2$ lost by exfiltration (2)

where

$$CO_2$$
 used by $crop = S \times Plant$ usage rate of $CO_2/(hour*m^2)$ (3)

$$CO_2$$
 lost by exfiltration = $V \times N \times 0.000001 \times (Desired CO_2 \ level - 350ppm)$ (4)

S is the greenhouse floor area in m²; V is the greenhouse volume in m³, and N is the number of air changes per hours, which is set to be 1 for this study.

The calculated amount of CO_2 to be added to the S m^2 of greenhouse area (E) represents the number of liters of CO_2 required for enrichment per hour. The total CO_2 enrichment per month can be estimated with:

Total
$$CO_2$$
 requirement per year= $E \times C_i \times M_i$ (5)

where C_i is the number of hours of CO_2 enrichment per day; and M_i represents the number of days per month. Subscript "i" denotes the month of the year. Total CO_2 enrichment per year was then estimated by adding up the CO_2 consumption for each month.

Propane was used as the source for CO₂ enrichment. One liter of propane can provide 1000 liters of CO₂ [33]. Assuming complete combustion and negligible CO₂ leakage from the propane burner, the propane consumption per year for CO₂ enrichment was calculated.

Appendix III. Emission Factor by power plant type

	Reservoir	Run-of-river	Nuclear	Natural gas
g CO ₂ eq/kWh	15	4	8	650

Source: Tremblay et al. [26]

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