Heating Energy Demands and Sustainable Generation Concepts for Agricultural Greenhouses

Lucas Macrae Semple
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Heating Energy Demands and Sustainable Generation Concepts for Agricultural Greenhouses

By

Lucas M. Semple

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada

2017

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Heating Energy Demands and Sustainable Generation
Concepts for Agricultural Greenhouses

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DECLARATION OF PREVIOUS PUBLICATIONS

This thesis includes three original papers that have been previously published/ submitted for publication in peer reviewed journals, as follows:

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ABSTRACT

There is currently a global effort to reduce dependency on carbon-based fuels and move towards more sustainable practices utilizing renewable energy sources. This is in part due to the detrimental effects to the environment and climate change caused by the procurement and combustion of these fuels. Buildings account for a significant portion of global final energy use for heating and cooling purposes. This work focuses on the agricultural greenhouse sector in a cold climate, where significant heating demands are present and are typically met by utilizing significant amounts of natural gas. The heating demand of these structures is examined as well as sustainable generation concepts that have the potential to reduce this dependency on carbon-based fuels. Chapter II investigates the potential of closed greenhouse systems in a cold climate, where active cooling is implemented and the heat removed is stored for later use. It is determined that the annual cooling demand is equal to or greater than the heating demand in each of the cold climates examined and the use of a high-insulating cover material would be most suitable due to the significant reduction in annual heating demand. Chapter III analyses the ability of a large-scale solar collector system to cover a significant portion of the greenhouse heating demand during the summer months. It is determined that a solar collector system with total area of ~575 m² is able to cover 97% of the heating demand during the month of July and approximately 27% of the annual demand of a 0.4 hectare greenhouse. By replacing natural gas CO₂ equivalent emissions are reduced by about 95 tonnes/ year and a payback period of about 10 years is achievable with carbon tax at a rate of $200/ tonne of CO₂ equivalent emissions. Finally, Chapter IV simulates the performance of a large-scale solar collector system with seasonal thermal energy storage (STES), where year-round heat is supplied by the system. High and low-temperature systems are able to cover approximately 64% of the annual heating demand and achieve a system coefficient of performance of about 21.7 and 2.9, respectively. The systems are able to reduce CO₂ equivalent emissions by ~220 tonnes / year and a payback period of about 7 years is achievable with a 70% subsidy and carbon tax at a rate $200/ tonne of CO₂ equivalent emissions.
DEDICATION

I dedicate this work to my beautiful wife who has supported me throughout this endeavour and to my family for their love and confidence.
ACKNOWLEDGEMENTS

I would like to thank my advisors Dr. Rupp Carriveau and Dr. David S-K. Ting for their guidance and support during the preparation of this work. They have been a pleasure to work with and learn from and I hope our relationship continues to grow in the future.
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CHAPTER I

Introduction

1.0 Background

The need for progress towards a low-emission economy is increasingly better understood. To avoid dangerous climate change, greenhouses gas emissions need to stabilize in 5–10 years and approach zero by the second half of the century [1]. Heat supplied to buildings, and especially those in cold climates, is identified as a key user of final energy. Heating energy demands throughout the industrialized world are generally met by combusting a carbon-based fuel such as natural gas, coal, oil, or propane. Combustion of these fuels results in the release to the atmosphere of what are referred to as greenhouse gases; carbon dioxide, methane and nitrous oxide [2]. There are also emissions associated with the procurement of these finite resources and processing into usable forms. Furthermore, these resources are not readily available throughout the world and further emissions are produced during transportation to the end-user. This presents a pressing need to accelerate the development and deployment of advanced clean energy technologies in order to address the global challenges of energy security, climate change and sustainable development [3].

The topic of this work is the agricultural greenhouse sector, with a focus on greenhouses in cold climates. A greenhouse is an enclosed structure, covered with glass or a transparent plastic, which creates a favourable microclimate for crop growth. As the cover materials are designed for maximum light transmission, the insulating properties of a greenhouse structure are far inferior to those of a conventional building. Whether seasonal or year-round harvesting schedules are implemented by a grower, there is a portion of the winter season where crops are present in the greenhouse. As individual operations can easily exceed 20 hectares in plan area and a difference between indoor and outdoor temperatures of up to 40 °C can be experienced, greenhouses in cold climates have significant heating demands. Heating systems typically represent the highest consumption of energy in greenhouses and can account for up to 90% of the total demand [4, 5, 6].

There are several design and operational strategies for energy conservation available to greenhouse operators and these have been well studied and reviewed [7, 8]. Utilizing thermal curtains, a thermal mass on the interior of the greenhouse, adjusting set-point temperatures, and proper placement of heating pipes are examples of conservation techniques. This work aims to look beyond conservation techniques and examine greenhouse systems of the future. The closed greenhouse concept described in Chapter II has been implemented to a limited extent in Europe but offers the possibility to significantly reduce the heating energy demand. With widespread resources throughout the world, solar energy is a low-emission alternative to conventional carbon-based fuels for space heating needs. Chapters III and IV assess the potential of large-scale solar collector systems with and without seasonal thermal energy storage (STES) to cover the summer and year-round heating load.
2.0 Methodology

The work presented herein is in large part based on the operational characteristics of greenhouses in Southwestern Ontario; a region with the highest density of greenhouses in North America. Information has been obtained from published research on greenhouses from international sources and has been supplemented with more detailed information from meetings with regional growers. Energy usage data for heating purposes has been obtained from regional growers in Southwestern Ontario.

The software program TRNSYS, a Transient System Simulation Program, was utilized to simulate the greenhouse microclimate and heating systems. TRNSYS is a complete and extensible simulation environment for the transient simulation of thermal and electrical systems, including multi-zone buildings [9]. Simulation of the greenhouse interior microclimate has been used in conjunction with the obtained energy usage data to determine the heating load profile for a greenhouse. The load profile has then been utilized to assess the performance of solar collector systems with and without seasonal thermal energy storage. Sensitivity analyses have been carried out in each respective section to assess the stability of the model in relation to key input parameters.

References

CHAPTER II
Assessing Heating and Cooling Demands of Closed Greenhouse Systems in a Cold Climate

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1.0 Introduction

A greenhouse is an enclosed structure that creates a favourable micro-climate for crop production. They can produce much higher crop yields with more consistent crop quality than field crops [1]. Energy costs are a major economic factor in greenhouse operations. Heating systems typically represent the highest consumption of energy in greenhouses and can account for up to 90% of the total demand [2,3,4]. Heating is conventionally accomplished by combusting a carbon-based fuel in a boiler and a hydronic heating system is utilized to distribute heat within the greenhouse. During the summer months natural or forced ventilation strategies are implemented to avoid overheating and dehumidify the indoor air. A general schematic of the ‘open’ greenhouse energy flow is shown in Figure 1A.

Indoor air temperature has long been recognized as the most significant factor influencing plant development, while net production is mostly influenced by available solar radiation [5]. Humidity control is another important thermal condition affecting the growth of crops [6]. In an effort to reduce heating demand and fossil-fuel usage, and in turn related emissions from greenhouse operations, optimal design and operation of greenhouses has been thoroughly studied by numerous researchers. Greenhouse cover material properties directly affect short-wave solar radiation transmission to the greenhouse interior and long-wave thermal radiation losses to the sky. Zhang et al [7] compared double and single polyethylene (PE) covering materials to single glass and found double-PE covering materials could result in significant energy savings over single glass. Furthermore, high insulating double-glass covering materials have been observed to reduce annual energy consumption by 25-33% [8]. However, due to the importance of solar radiation on crop production, increased insulating properties that negatively affect transparency have to yield large savings to be economically viable [9]. In addition, improved cover insulating properties lead to higher greenhouse humidity levels and the anticipated decrease in energy use for heating may be countered by a need for more venting for dehumidification purposes. To reduce heat loss during times of low outdoor temperatures, thermal curtains are widely used in greenhouses to retain thermal energy near the plants and prevent radiative heat losses to the outside. Among passive techniques, thermal curtains are one of the most practical and appropriate methods of reducing consumption of heat [10]. Another passive technique, utilizing a sensible or latent thermal energy storage
material on the interior of the greenhouse, has also been investigated by various authors [11,12,13]. Energy conservation potential, by adjusting temperature set-points based on outdoor temperatures and available solar radiation, has also been shown [5]. Energy savings without any reduction in crop yield were found by controlling mean air temperature; reducing the set point during cold outdoor conditions and increasing afterwards when favourable conditions are present. Also, the appropriate placement of heating pipes within the greenhouse has been shown to play an important role in reducing energy consumption and ensuring homogeneous temperature distribution [14,15,16].

Although several design and operational strategies for energy conservation are available to greenhouse operators, they are implemented to varying extents and greenhouses are still heavily dependent on fossil fuels. In an effort towards a sustainable energy supply, researchers in the Netherlands state that simple measures like installing a moveable energy screen in traditional greenhouses or improving existing designs on a small scale are not enough [17]. Based on this, ‘closed’ greenhouse systems have been in development since the late 1990’s to conserve energy [18]. Instead of using ventilation strategies during the summer months to release heat and dehumidify the greenhouse, active cooling and dehumidification systems are used. Excess solar energy collected during the summer months is stored via some form of seasonal thermal energy storage (STES), typically aquifer thermal energy storage (ATES), and re-used in the winter to heat the greenhouse [19]. A general schematic diagram of the closed greenhouse energy flow is shown in Figure 1B. In practice, ‘semi-closed’ systems are most common where the cooling system is designed to meet a base load and peak demands are still met with ventilation strategies. Alternatively, in closed greenhouses without an STES system, heat recovery ventilation can be utilized where the warm greenhouse air being removed can heat the colder incoming air from the outside, reducing the overall demand [20].

Installed systems in the Netherlands with seasonal storage have shown that heating energy savings in the range of 20 to 60% are possible compared to the traditional ‘open’ greenhouse [21,22,23]. As carbon dioxide is injected into the greenhouse to promote crop growth, reduction or elimination of natural ventilation leads to a more consistent and elevated indoor CO₂ concentration by minimizing losses to the outdoor environment. This has shown to increase crop production by 10-20% [22,23]. The above advantages have also been accompanied by significant decreases in pesticide use and water consumption for irrigation. In the Belgian climate, Coomans et al. determined that heat recovery ventilation strategies in a semi-closed greenhouse reduced annual heating demand by up to 28% [20]. They also found it to be most effective during the spring and fall seasons.

In colder climates, winter heating demands are significantly increased and closed greenhouse installations are limited. Experiments in semi-closed greenhouses with heat recovery ventilation in Finland showed a decrease in the summer heating usage by 35-50%, but no significant reductions throughout the rest of the year [24]. Wong et al. assessed the closed greenhouse with seasonal storage for the Canadian climate setting and found that annual greenhouse gas emissions could be reduced by up to 86% [1]. However, the authors stated it was difficult to obtain directly applicable information in Canada in support of the reported study. Yildiz et al. then compared conventional, semi-closed and closed greenhouse systems equipped with air-source heat pumps throughout Canada [25]. They
determined the semi-closed systems provided considerable savings in both energy use and water consumption over the conventional greenhouse. For systems with seasonal storage, an interesting characteristic to consider is the surplus energy ratio (SER). The SER is the annual ratio between excess heat during the summer months and heating demand during the winter months [26]. In Sweden, Vadiee and Martin determined an ideally closed greenhouse has an SER ratio of about three [26]. The same authors also found the most influential factor on payback period of a closed greenhouse system with seasonal storage is whether the system is designed for peak or base load [27].

This paper aims to expand on past analyses of closed greenhouse systems in cold climates. The Canadian landscape has been chosen as it contains approximately 2,400 hectares of greenhouse area [28]. Data obtained from greenhouse operators has shown that in excess of 500,000 cubic metres of natural gas is used annually per hectare for heating purposes. Where past studies have evaluated small-scale greenhouses or have not focused on monthly
heating and cooling data, this paper specifically assesses the monthly demands and surplus energy ratio with varying cover materials for a 0.4 hectare greenhouse. The interior microclimate of the greenhouse is modelled using TRNSYS software and validated with natural gas usage data from a reference greenhouse. The effect of location and cover material on the SER and the potential for heat recovery ventilation is assessed for the most concentrated greenhouse areas in the country.

2.0 Greenhouse Model

The software program TRNSYS, a Transient System Simulation Program, was utilized to simulate the greenhouse microclimate. TRNSYS is a complete and extensible simulation environment for the transient simulation of systems, including multi-zone buildings [29]. To model the reference greenhouse a Type 56 Multi-Zone Building component was used. A 3-dimensional rendering of the greenhouse was created. The structural and thermal properties were assigned utilizing the TRNSYS sub-program TRNBuild. Climate data is fed into the TRNSYS simulation environment by an external weather module. Based on the location, orientation and geometry of the structure, global solar radiation incident on each of the external facades is calculated at each time step by internal modules.

The modelled Venlo-type greenhouse has a plan area of 4,000 m$^2$, gutter height of 5.5 metres (m), 10 bays each with a width of 5 m, and a roof slope of 25$^\circ$. A portion of the greenhouse is shown in Figure 3. The structure was created with a series of lower and upper thermal zones to simulate conditions within and above the crop. The lower zone extends to a height of 3.5 m. The greenhouse exterior was approximately 96% glazed to account for shading from construction elements. The glazing material properties were chosen to represent those of double polyethylene (PE) cover material and an overall average heat transfer coefficient of 3.2 W/ m$^2$·°C was chosen, which is within the range of values reported by others [7]. The coefficient is not constant and is calculated by the TYPE 56 component at each time step based on the outside climate parameters and interior conditions [30].

![Figure 2 – Components of TRNSYS Simulation](image)

Figure 2 – Components of TRNSYS Simulation
2.1 Energy and Mass Balance

The greenhouse micro-climate is a dynamic environment influenced by the outdoor conditions, internal control mechanisms and indoor factors [10]. Energy and mass balance of the greenhouse interior components is essential to appropriately describe the environment. It is typically comprised of five major components: growing medium, floor, crop, greenhouse cover, and indoor air, with the control volume ending at the outdoor ambient air [10,31]. The simulation conducted herein focuses on the final four components listed. The thermal capacity of each lower node has been set to simulate the presence of a crop. Discussions with greenhouse operators revealed crop density is initially very small at the time of planting and can reach up to 10 kg/m² when fully grown. Increasing the thermal capacity of the lower nodes throughout the year was not possible in the structure and a constant crop density of 6 kg/m² has been utilized. The thermal properties of the crop are assumed to be similar to those of water [11]. A sensible energy balance was carried out for the air in each thermal zone considering gains from surfaces of the zone, infiltration, ventilation, coupling air flows with adjacent zones and internal gains. The sensible energy flux can be described as follows [30]:

\[ \dot{Q}_{sens,i} = \dot{Q}_{surf,i} + \dot{Q}_{inf,i} + \dot{Q}_{vent,i} + \dot{Q}_{g,c,i} + \dot{Q}_{cplg,i} \]  

(1)

Where:

- \( \dot{Q}_{sens,i} \) = Sensible Energy Flux of Zone [kJ/hr]
- \( \dot{Q}_{surf,i} \) = Convective Gain from Surfaces
- \( \dot{Q}_{inf,i} \) = Infiltration Gains
- \( \dot{Q}_{vent,i} \) = Ventilation Gains
- \( \dot{Q}_{g,c,i} \) = Internal Convective Gains
- \( \dot{Q}_{cplg,i} \) = Gains from Coupling Air Flows from Adjacent Zones

The energy flux for each particular surface is calculated considering combined convective and radiative energy fluxes. The solar radiation flux is calculated for external surfaces where internal surfaces also include long-wave radiation exchange between internal objects and adjacent walls. Infiltration, ventilation and coupling gains are dependent on user-defined air movement rates and temperature differences between environments. These gains can be defined for each zone by the following:

\[ \dot{Q}_x = \dot{V} \rho C_p (T_x - T_i) \]  

(2)

Where \( x \) represents the particular gain, \( \dot{V} \) is the defined air flow rate, \( \rho \) is the density of air, \( C_p \) is the specific heat capacity of air, and \( T_x \) and \( T_i \) are the temperatures of the incoming air and zone air at the previous time step, respectively. The temperatures of the infiltration and ventilation gains are set to outdoor ambient conditions. Infiltration was set at 0.5 air changes per hour (ACH) and ventilation was set at 60 ACH when active [32,33]. Coupling air flows between lower zones begins at 1 ACH and gradually decreases to simulate the stagnation of horizontal air movement as the crop increases in size, as shown in Figure 3. Internal gains in the model encompass
energy that is convected and radiated from the outside surface of the hot water and steam heating pipes. Indoor air velocity was assumed to be 0.15 m/s based on estimates by others [15,34].

The latent energy flux for each thermal zone is determined by an effective capacitance humidity model. Similar to sensible energy flux, the model considers the latent energy gained or lost by the air in the zone due to infiltration, ventilation, coupling air flows and internal gains. The latent energy flux is calculated at the end of each time step based on the following [30]:

\[
Q_{\text{lat},i} = h_v \left( \dot{m}_{\text{inf},i} (h_a - h_{\text{req},i}) + \dot{m}_{\text{vent},i} (h_{\text{vent}} - h_{\text{req},i}) + W_{g,i} + \sum \dot{m}_{\text{cplg},j} (h_j - h_{i}) - M_{\text{eff},i} (h_{\text{req},i} - h_{i,t-\Delta t}/\Delta t) \right)
\]

Where
- \(Q_{\text{lat},i}\) = Latent Energy Flux of Zone [kJ/hr]
- \(h_v\) = Heat of Vapourization of Water [kJ/kg]
- \(\dot{m}\) = Air Mass Flow Rate [kg/m³]
- \(h\) = Humidity Ratio [kg\,water / kg\,air]
- \(W_{g,i}\) = Internal Humidity Gain [kg\,water/hr]
- \(M_{\text{eff},i}\) = Effective Moisture Capacitance of Zone [kg]
- \(\Delta t\) = Length of Timestep

Subscripts
- \(a\) = Outdoor Ambient
- \(\text{vent}\) = Ventilation
- \(\text{inf}\) = Infiltration
- \(\text{req}\) = Required
- \(\text{cplg}\) = Coupling

It is known that crop evapotranspiration, that is transpiration from the crop leaves and evaporation from the growing medium, plays an important role in the energy balance of the greenhouse microclimate [10,31]. Crop evapotranspiration was simulated in the model via an internal humidity gain. The humidity gain is gradually increased after planting to account for increases in crop size and solar radiation and reaches a maximum of 25 grams of water /hour /m² during the summer months when solar radiation is highest and the crop is nearing maximum height.
2.2 Model Controls

Day and night set point temperatures are set to those of the reference greenhouse. Ventilation is active when the interior temperature exceeds 25 °C or relative humidity exceeds 85%. Thermal curtains are closed when global solar radiation is less than 5 W/m². Both steam and hot water boilers are utilized in the model with boiler efficiency considered to be 75%. The hot water boiler feeds a stratified water storage tank. Steam and hot water piping systems are modelled, with the hot water system located in the lower nodes and the steam system located in the upper nodes. Morning pre-heating was active between 3 and 6 am. The total heat transfer from the hot water and steam piping systems to the interior of the greenhouse was monitored. A high-pressure fogger is used for humidity control and set-points are those of the reference greenhouse.

3.0 Reference Greenhouse

The reference greenhouse chosen for this project is an approximately 8.1 hectare venlo-type greenhouse with double PE cover. The greenhouse is located in Leamington, Ontario and is used for pepper cultivation of various varieties. The heating system consists of both steam and hot water piping systems, with the hot water system located near the floor of the greenhouse and the steam system located near the greenhouse roof. The hot water system is the primary heat source. The steam system is used to remove condensation from the greenhouse cover in the early morning hours and also during times of peak heating demand. Indoor day and night set-point temperatures are typically 23°C and 22°C, respectively. Relative humidity is generally maintained between 75 and 85%. Thermal curtains are utilized and closed at night during the winter months. During the summer months the curtains are not utilized as outdoor ambient temperatures during the night are generally above 15°C and heat retention is not necessary. To avoid large and sudden changes in indoor temperature, the temperature of the greenhouse is raised approximately 1°C / hour in.
the early morning hours to reach the daytime set-point prior to the sun rising. This morning pre-heating ‘activates’ the plants out of the cool night temperatures and takes place throughout the growing season.

Six years of energy usage data from 2009 to 2015 was obtained to validate the model. Natural gas is the primary fuel for heating purposes, however due to shortages during the coldest of winter nights, coal and heavy oil are also used for supplemental heating. The monthly energy usage for heating purposes is shown in Figure 4. The average annual energy usage is approximately 7,900 Gigajoules (GJ) per 0.4 hectares. Planting typically takes place in the first week of January and the crop is terminated in mid-November. The temperature in the greenhouse is held at 5 °C after this time. This is why the heating energy usage for November and December is low in comparison to the decreasing ambient temperatures during these months.

4.0 Results and Discussion

4.1 Reference Greenhouse

The greenhouse simulation was performed over a one-year period beginning on January 1 with time steps equal to 1 hour. Weather data for Detroit, Michigan was utilized due to its close proximity to Southwestern Ontario. The typical meteorological year (TMY2) data set is utilized and represents typical conditions based on data from the 1961-1990 National Solar Radiation Data Base (NSRDB) and is produced by the National Renewable Energy Laboratory (NREL) [35]. The required energy input for both the steam and hot water boiler are calculated and compared to the average monthly energy usage data from the reference greenhouse. The results are shown in Figure 4. As can be seen, the model adequately simulates the reference greenhouse energy usage. The total annual energy demand was about 7,700 GJ for the 0.4 hectare greenhouse, a deviation of about 3% from the reference data.

The monthly heating energy demand and energy removed due to ventilation for the simulated reference greenhouse are shown in Figure 5. The heating energy demand, that is the heat delivered by the hot water and steam piping systems, was approximately 4,700 GJ. The model was also run over a two-year period and energy usage was 0.1% greater in the second year, likely due to initial start-up of the heating system at the beginning of the simulation. The interior greenhouse temperature generally peaked above 30°C on summer days and rose above 40°C on 6 dates; July 3rd, 5th, 6th, 8th, 11th and 12th. Ventilation kept the relative humidity in the greenhouse generally below 85%. Energy removed from the greenhouse due to ventilation was about 4,000 GJ. Based on this, the surplus energy ratio (SER), as defined in equation 4, for the reference ‘open’ greenhouse would be approximately 0.85.

\[
SER = \frac{Annual\ Cooling\ Demand}{Annual\ Heating\ Demand}\quad (4)
\]
4.2 Closed Greenhouse

To simulate the ‘closed’ greenhouse, ventilation was not utilized and the cooling demand was assessed based on a set point temperature of 25°C. An ideally constructed closed greenhouse was considered and infiltration was reduced to 0 ACH. Both sensible energy demand and latent energy demand for humidity control were considered. Results of the simulation showed that the heating demand decreased to approximately 2,800 GJ. The cooling...
demand of the greenhouse increased to approximately 5,300 GJ giving an SER of about 1.9. Additional dehumidification was necessary as the inside relative humidity regularly exceeded 85% during the summer months. This is due to the decreased interior temperature in relation to the open greenhouse and inability to dehumidify via exchange with outdoor air. This occurrence is consistent with observations by others [1,36]. The monthly heating and cooling demands of the closed greenhouse are shown in Figure 6.

By comparing Figures 5 and 6 we can see that no significant decrease in heating demand occurs between the months of May through August. This can be attributed to morning pre-heating of the crop, which occurs throughout the summer months regardless of the interior temperature. Throughout the fall, winter and spring seasons daytime high ambient temperatures are generally lower than the greenhouse set-point temperature. The cooling demand during these seasons is also focused around the daytime hours. Heat recovery ventilation would provide the opportunity to cool and dehumidify the interior air while warming the colder outside air before entering the greenhouse, thus reducing the overall heating demand during these seasons. This would be most effective in March, April, September and October where considerable cooling demands are present. During the summer months the daytime ambient temperature is generally above the indoor set-point and warming of the air before entering the greenhouse is not necessary.

![Figure 6 – Monthly Heating and Cooling Demand for Closed Reference Greenhouse](image)

The greenhouse cover material plays an important role in heating and cooling demands. To assess the effects of different covering materials, the annual energy demands have also been assessed for single and double glass cover materials. For single and double glass overall heat transfer coefficients of 5.7 and 1.4 W/ m²·°C, respectively, were
utilized [37]. The results of this assessment are shown in Figure 7 along with the demands for the reference cover material of 3.2 W/ m²·°C, representative of double PE. The cooling demand increases by approximately 23% for the double glass covering material to 6,600 GJ, while the demand for single glass showed a slight increase to about 5,400 GJ. The heating demand steadily increases with the increase of cover heat transfer coefficient. The SER for U-values of 1.4, 3.2 and 5.7 W/ m²·°C are 3.4, 1.9 and 1.5, respectively.

![Figure 7 – Annual Heating and Cooling Demand for Closed Greenhouse with Differing Cover Materials](image)

### 4.3 Closed Greenhouse in Different Canadian Settings

The three most concentrated greenhouse areas in Canada are Ontario, British Columbia and Quebec. The locations of Montreal, Quebec and Vancouver, British Columbia, both located in the Southern portion of their respective provinces, were chosen as simulation sites. Meteonorm climate data published by Meteotest (www.meteotest.com) was utilized for these locations [35]. Montreal typically has colder winters and comparable summers to Southern Ontario, whereas the climate in Vancouver is much milder for both seasons. The temperature data used in the simulation for each of the locations is shown in Figure 8. The hourly data for Detroit, Michigan is shown. However, the hourly data for the other two locations has been removed for clarity and is represented by a polynomial trend line. Identical controls and set points were utilized for each of the chosen locations.

The annual demands in relation to cover properties are shown in Figure 9. The heating and cooling demands make practical sense in relation to the temperature data. Montreal, with significantly colder winters than the other two locations has an appropriately higher heating demand. Similarly Detroit, representing the Southern Ontario climate,
has the warmest summers and appropriately the largest cooling demand of the three locations. Table 1 presents the annual demands and SER ratios for the various conditions. As can be seen a surplus energy ratio of at least 1 is achieved in all locations. Heat recovery ventilation potential was observed to be similar to that of Southwestern Ontario. The spring and fall seasons offered the greatest potential to significantly reduce the heating demand due to significant ventilation that takes place while outdoor temperatures are below the interior set-point.

It can be seen that for a U-Value of 5.7 W/ m²·°C the cooling load is only slightly less than that for a U-Value of 3.2 W/ m²·°C and is actually higher for the Southwestern Ontario climate. This is attributed to greater solar radiation transmission through the single glass cover material.

![Temperature Data](image-url)
Figure 9 – Closed Greenhouse Annual Heating and Cooling Demands for Differing Locations and Cover Materials

Table 1 - Annual Heating and Cooling Demands for Closed Greenhouse with Differing Locations and Cover Materials (Heating (GJ), Cooling (GJ), SER)

<table>
<thead>
<tr>
<th>Location</th>
<th>Cover U-Value (W/ m²/ °C)</th>
<th>1.4</th>
<th>3.2</th>
<th>5.7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heating / Cooling / SER</td>
<td>Heating / Cooling / SER</td>
<td>Heating / Cooling / SER</td>
<td></td>
</tr>
<tr>
<td>Detroit, MI</td>
<td></td>
<td>1,910/ 6,580/ 3.4</td>
<td>2,850/ 5,340/ 1.9</td>
<td>3,630/ 5,450/ 1.5</td>
</tr>
<tr>
<td>Montreal, QC</td>
<td></td>
<td>2,430/ 6,400/ 2.6</td>
<td>3,590/ 5,150/ 1.4</td>
<td>4,600/ 4,800/ 1.0</td>
</tr>
<tr>
<td>Vancouver, BC</td>
<td></td>
<td>1,940/ 5,970/ 3.1</td>
<td>2,850/ 4,710/ 1.7</td>
<td>3,710/ 4,520/ 1.2</td>
</tr>
</tbody>
</table>

4.4 Discussion

An SER ratio of three for a closed greenhouse has been reported in other studies [23,26]. This is in agreement with the results of this study. The day and night set point temperatures of 23°C and 22°C used herein are suitable for this particular grower. However, lower set-point temperatures may be more representative of a broader range of greenhouse operations. A decrease in the set point temperatures and in turn the heating energy demand would lead to an overall increase in the SER, especially in the cold climates studied here.
In assessing the potential of a closed greenhouse system, an SER of 1 is necessary if the entire heating demand is to be met with heat removed and stored from the summer months. As can be seen it appears this can be achieved at all three locations with any of the cover materials studied. However, in addition to a sufficiently large cooling capacity, a seasonal thermal energy storage system of sufficient capacity must be feasible to fully close the greenhouse. The high-insulating double glass cover material, in addition to offering the largest SER, also significantly decreases the annual heating demand and in turn the necessary storage capacity. The heating energy savings observed with the double glass cover are generally within the range of values reported by others [9]. With a high-insulating cover material and the inability of the closed greenhouse to mix indoor air with outdoor, the greenhouse interior becomes less affected by the outdoor conditions and the environment is more easily controlled. Hence it can be concluded that if a fully closed greenhouse is desirable, a cover material with high-insulating properties should be utilized, provided light transmission is not sacrificed. This is consistent with recommendations for energy efficient greenhouse design [21,38].

As an SER ratio of three provides far more cooling capacity than necessary for a closed greenhouse design, a semi-closed greenhouse would allow the cooling capacity to be technically and economically optimized at a much lower base cooling load. In this case, natural ventilation strategies would be utilized to cover peak cooling loads. The amount to which the greenhouse could be opened is dependent on the efficiency of the cooling, dehumidification and seasonal storage systems.

Reduction in fossil fuel consumption must be weighed against the increase in electricity usage to run circulation pumps, heat pump(s), and humidity control systems [22]. Furthermore, the energy cost savings need to be assessed in relation to capital investment costs while also considering the economic benefits of potential increases in crop production. An overall assessment with these factors can determine if an optimal system lies with seasonal storage or a heat recovery ventilation system.

5.0 Sensitivity Analysis

A sensitivity analysis was carried out on the greenhouse model to determine the relative impact of altering key model parameters. The analysis observed the heating demand for the month of January and the percent change relative to the initial baseline demand. The results are shown in Figure 10. It can be observed that altering the infiltration rate and indoor set-point temperatures showed the greatest change in the monthly demand. As each of these parameters directly affect the required heating demand the results are considered reasonable. The remaining parameters showed small changes to the heating demand. Overall, the analysis gives a satisfactory level of confidence in the stability of the model. It should be noted that changes to certain parameters are not linear and are based on dynamic operational controls of the system. For example, as the infiltration rate decreases the amount of cold outside air naturally entering the building decreases. However, this leads to increased indoor temperatures and humidity and more ventilation is then required, bringing in greater amounts of cold outside air through ventilation.
For the simulation of the greenhouse heating system encompassing the steam and hot water boilers, piping systems, water storage tank and system controls, there were several parameters involved. These parameters were estimated based on conversations with greenhouse operators and available information. It is realized that changes to system parameters can have direct and significant effects on system energy use. Among these, the boiler efficiency parameter directly correlates to the amount of energy required to produce a unit amount of useful heat. Overall system efficiency can be defined as the useful thermal energy delivered to the greenhouse divided by the energy input to the boilers:

$$\eta_{\text{system}} = \frac{\text{Useful Thermal Energy Delivered to Greenhouse}}{\text{Energy Input to Boilers}}$$

Figure 11 presents the monthly system efficiency for the reference greenhouse. It can be seen that efficiency ranges from approximately 66% during the month of January to 48% during the summer months. The decrease in efficiency can be attributed to the lower heating demand during the summer months, which resulted in more on/off operation of the boilers. However, this cannot be confirmed. Furthermore, heating systems vary between growers and this efficiency curve will not be consistent. It is therefore concluded for future work it may be more appropriate to simply assess the required heating demand of the greenhouse at each time step based on the interior set-point temperature, rather than simulating the operation of the entire heating system. The heating demand profile can be compared to the obtained grower energy usage data for comparison.
6.0 Conclusion

This paper provides an assessment of the closed greenhouse system in a cold climate considering different Canadian settings. The interior microclimate of a 0.4 hectare greenhouse has been modelled using TRNSYS software and validated with natural gas usage data from a regional grower. The following conclusions can be made:

1) An SER ratio ranging from 1.5 to 3.4 was observed for the Southwestern Ontario location considering single glass, double polyethylene, and double glass cover materials, respectively. The SER ratio for the locations of Montreal, Quebec and Vancouver, British Columbia was found to range between 1.0 and 3.1. In conclusion, the annual cooling demand is equal to or greater than the heating demand for all locations and a fully closed greenhouse is possible in these cold climate conditions.

2) The use of a high-insulating double glass cover material would likely be most suitable for a closed greenhouse system with seasonal storage. This is due to the significant reduction in annual heating demand and in turn the necessary seasonal storage capacity.

3) Heat recovery ventilation has potential to reduce the heating demand during the fall, winter and spring seasons. This is due to significant ventilation that takes place during these seasons while ambient temperatures are below the interior set-point.

4) A semi-closed greenhouse would allow the cooling capacity to be optimized at a much lower base cooling load. The amount to open the greenhouse, as well as the options of seasonal storage or heat recovery ventilation, are site dependent. The optimal design will need to be assessed considering the reduction in fossil fuel usage, increase in electricity usage to run the active components of the system, as well as the anticipated increase in crop production.
References


CHAPTER III

Potential for Large-Scale Solar Collector System to Offset Carbon-Based Heating in Ontario Greenhouse Sector

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1.0 Background

Climate change and air quality continue to be significant challenges, with wide ranging effects to social, environmental and economic well-being [1]. Extreme weather events continue to have grave consequences for human health and infrastructure. As people’s reliance on infrastructure increases, when it is damaged and destroyed the effects are more widely felt. In Canada, these widespread effects have clearly been seen. The years of 2009 to 2012 saw record-high levels of insured losses from natural disasters, with claims near or above $1 Billion [2]. This was followed by a historic $3.2 Billion in losses in 2013 as a result of flooding in Alberta and Toronto. For comparison, total insured losses averaged $400 Million for the 25-year period between 1983 and 2008.

The need for progress towards a low-emission economy is increasingly better understood. To avoid dangerous climate change, greenhouses gas emissions need to stabilize in 5~10 years and approach zero by the second half of the century [3]. In Ontario, overall provincial emissions reduced by approximately 5.9% between 1990 and 2012, however emissions from transportation and buildings increased by 8% and 2%, respectively, and are currently the most significant contributors to Ontario’s Emissions outside of electricity [4]. Accounting for less than 1 per cent of global emissions, Ontario is still among the largest per capita emitters of greenhouses gases in the world [5].

With over 1,000 hectares of greenhouses as of 2015, building energy demands are a major factor in the Ontario greenhouse sector. For a greenhouse to maintain an adequate indoor temperature throughout the year, space heating demands can account for up to 90% of the total seasonal energy demand [6]. This heating demand is primarily met by natural gas infrastructure throughout the province. With current constraints on the natural gas and electricity grids threatening to impede expansion and Ontario electricity prices continuing to rise, a low-emission innovative energy solution is needed to meet the energy demands of this important sector and contribute to reducing overall greenhouse gas emissions.
2.0 Introduction

The indoor temperature of a greenhouse strongly influences the rate of development, fruit colour, and balance between vegetative growth and fruit development [7]. In Ontario, bell peppers, tomatoes and cucumbers are the main greenhouse production crops and have optimum 24-hour indoor temperatures of generally between 18 and 22 °C. In order to facilitate year-round crop production, agricultural greenhouses have a large heating demand during the winter months. Natural gas fired boilers are utilized in the majority of greenhouses in Ontario and some have the ability to combust heavy oil for supplemental use. During the summer months overheating is controlled by ventilation techniques using vents in the greenhouse cover where indoor air is mixed with outdoor.

A review of available greenhouse heating technologies has been carried out by others [8]. The majority of non-fossil fuel dependent techniques have been installed in relatively small-scale greenhouses. The potential of flat plate solar collectors to improve the indoor temperature of a greenhouse has shown promise provided sufficient solar radiation is available [9,10]. However, one of the barriers to utilizing solar energy for space heating is the misalignment between available solar radiation and building heating demand in the greenhouse sector and elsewhere. This renders a solar collector system unviable without incorporating some form of seasonal thermal energy storage [11]. Interestingly, in addition to the ventilation techniques utilized during the summer months to cool the greenhouse, heat is supplied in the hours prior to sunrise to avoid sharp changes in indoor air temperature between the night and day. The indoor air temperature is recommended to be raised by 1 °C/hour to achieve the indoor daytime set point temperature approximately ½ hour prior to sunrise [7]. After analyzing monthly natural gas usage for twelve growing years from three different greenhouse operators in Ontario, it was observed that over 20% of the total annual natural gas usage occurred between May and September. These are typically the warmest months of the year and receive the highest amount of solar radiation. In addition, the year-round heating demand present in greenhouses is a key factor to maximizing utilization of a large-scale collector system. Based on this, a potential exists for a large-scale solar collector system to offset greenhouse carbon-based heating during the summer months.

Large-scale solar collector systems for space and water heating applications were first installed in Europe in the late 1970’s [12]. As of 2007, approximately 200,000 m² of solar collectors were installed in Europe as part of large-scale systems greater than 500 m² in size. However, this accounted for only 1% of the total installations in Europe at the time with the vast majority being small-scale systems, typically 2-30 m² in size, as part of solar domestic hot water systems. The majority of large-scale systems have been employed in block and district heating networks, however, systems have been utilized elsewhere and have potential in buildings with a large year-round heating demand [13]. Denmark as of 2013, with approximately 386,000 m² of installed solar collectors in large-scale applications, hosts 9 of the 10 largest solar heating plants in Europe [14]. Systems have been designed since the early 2000’s to handle both heating and cooling loads utilizing heat-driven cooling devices. Large-scale solar collector systems have been less prevalent in North America. One large-scale system equipped with seasonal energy storage was commissioned in 2007 in Okotoks, Alberta. After 5 years of operation, the system was able to provide 97% of the space heating needs for a community of 52 houses [15].
Large-scale solar heating systems have two major applications. The first and most common are systems equipped with diurnal (short-term) storage, usually consisting of an insulated steel tank for storing hot water. Systems with short-term storage are generally designed to meet 10–20% of the total annual load [16,17]. The majority of large-scale solar collector systems are designed in this manner and their intent is to cover the summer hot water and space heating load [12]. The second application are systems equipped with long-term or seasonal storage, where solar radiation captured during the summer months can be stored and utilized during the colder months when heating demands are greatest. These systems are usually designed to meet 50–70% of the total annual load. However, initial investment can be double that of a system with short-term storage due to the high initial costs of the seasonal storage component [17].

In this study, a transient simulation is carried out utilizing TRNSYS software to model the indoor greenhouse microclimate and determine the heating demand profile for a greenhouse in Southern Ontario, an area with the highest density of greenhouses in North America. The heating demand profile is validated with actual natural gas usage data from Ontario greenhouses. Finally, a large-scale solar thermal collector system designed to meet the summer heating demand is incorporated and the reduction in natural gas and carbon emissions are explored. An economic assessment of system installation is carried out and the benefits of reducing carbon emissions are discussed in relation to a tax on emissions.

3.0 Greenhouse Model

3.1 Interior Microclimate

The software program TRNSYS, a Transient System Simulation Program, was utilized to simulate the greenhouse microclimate. TRNSYS is a simulation environment for the transient simulation of energy systems and encompasses multi-zone buildings [18]. A 3-dimensional greenhouse rendering was created utilizing a Type 56 Multi-Zone Building component and the TRNSYS sub-program TRNBuild. A venlo-type greenhouse was modelled with a plan area of 0.4 hectares, gutter height of 5.5 metres (m), 10 bays each with a width of 5 m, and a roof slope of approximately 25°. Double-polyethylene cover material, commonly used in Southern Ontario, was utilized with an overall heat transfer coefficient of 3.2 W/m²·°K, which is within the range of values reported by others [19]. A series of lower and upper thermal zones were created within the greenhouse to simulate conditions within and above the crop, as shown in Figure 1. A constant crop density of 6 kg/m² was considered and the thermal properties of the crop are assumed to be similar to those of water.
A schematic layout of the controls involved in the microclimate simulation is shown in Figure 2. Based on recommended growing conditions and discussions with greenhouse operators, the day and night indoor set point temperatures were set at 22°C and 18°C, respectively. In addition, heat is supplied between the hours of 3 and 6 am year-round, regardless of the indoor temperature, to facilitate morning pre-heating prior to sunrise. Infiltration was set at 0.5 air changes per hour (ACH) [21,22]. When the indoor temperature exceeded 25°C or relative humidity exceeded 85%, ventilation through the greenhouse cover vents was activated and set at a rate of 60 ACH [21]. Thermal curtains close when global solar radiation is less than 5 W/m² during the winter months. During the summer months the curtains are not utilized as outdoor ambient temperatures during the night are generally above 15°C and heat retention is not necessary. Indoor air velocity was assumed to be 0.15 m/s based on estimates by others [23,24]. In order to avoid instabilities in the simulation, coupling air flows between lower and upper thermal zones was set at 1 ACH. Similarly, coupling air flows between lower zones was set at 1 ACH at the beginning of the growing season and gradually decreased to simulate the stagnation of horizontal air movement as the crop density increases, as shown in Figure 3. Crop evapotranspiration plays an important role in the energy balance of the greenhouse microclimate [25,26] and was accounted for in the model via an internal humidity gain. It has been assumed that during the summer months when solar radiation is highest and the crop is nearing maximum height, 60% of solar radiation reaching the interior of the greenhouse is converted to latent heat by transpiration [23,27,28]. This value was set at 20 grams of water /hour /m² at night. A high-pressure fogger is used to maintain the indoor relative humidity between 75 and 85%.
3.2 Energy and Mass Balance

Energy and mass balance of the greenhouse interior is typically comprised of five major components: growing medium, floor, crop, greenhouse cover, and indoor air, with the control volume being the outdoor ambient conditions [25,26]. Sensible energy balance is carried out for each thermal zone at each time step considering gains from surfaces of the zone, infiltration, ventilation, coupling air flows with adjacent zones and internal gains. The sensible energy flux can be described as follows [29]:

$$Q_{sens,i} = Q_{surf,i} + Q_{inf,i} + Q_{vent,i} + Q_{g,c,i} + Q_{cplg,I}$$  \(1\)

Where:

- \(Q_{sens,i}\) = Sensible Energy Flux of Zone [kJ/hr]
- \(Q_{surf,i}\) = Convective Gain from Surfaces [kJ/hr]
- \(Q_{inf,i}\) = Infiltration Gains [kJ/hr]
\[ \dot{Q}_{\text{vent},i} = \text{Ventilation Gains [kJ/hr]} \]
\[ \dot{Q}_{\text{g,c},i} = \text{Internal Convective Gains [kJ/hr]} \]
\[ \dot{Q}_{\text{cplg},i} = \text{Gains from Coupling Air Flows from Adjacent Zones [kJ/hr]} \]

Combined convective and radiative energy fluxes are considered in determining the overall energy flux for each particular surface at each time step. Solar radiation flux is calculated for external surfaces while internal surfaces also include radiative exchange between internal objects and adjacent walls. Infiltration, ventilation and coupling gains are dependent on user-defined air movement rates and temperature difference between environments. These gains can be defined by the following:

\[ \dot{Q}_x = \dot{V} \cdot \rho \cdot C_p \cdot (T_x - T_i) \] (2)

Where \( x \) represents the particular gain, \( \dot{V} \) is the defined air flow rate, \( \rho \) is the density of air, \( C_p \) is the specific heat capacity of air, and \( T_x \) and \( T_i \) are the temperatures of the incoming air and zone air at the previous time step, respectively. The temperatures of the infiltration and ventilation gains are set to outdoor ambient conditions.

An effective capacitance humidity model is used to determine the latent energy flux for each thermal zone at each time step. The capacitance of a thermal zone is defined as a factor of the air mass in the zone. The model considers the latent energy gained or lost due to infiltration, ventilation, coupling air flows and internal gains. The latent energy flux is calculated based on the following [29]:

\[ \dot{Q}_{\text{lat},i} = h_v \left[ \dot{m}_{\text{inf},i} (h_a - h_{\text{req},i}) + \dot{m}_{\text{vent}} (h_{\text{vent}} - h_{\text{req},i}) + W_{g,i} + \sum_{\text{surf}} \dot{m}_{\text{cplg}} (h_j - h_i) - M_{\text{eff}} (h_{\text{req},i} - h_{i, t\Delta t}/\Delta t) \right] \] (3)

Where
\[ \dot{Q}_{\text{lat},i} = \text{Latent Energy Flux of Zone [kJ/hr]} \]
\( h_v \) = Heat of Vapourization of Water [kJ/kg]
\( \dot{m} \) = Air Mass Flow Rate [kg/m²]
\( h \) = Humidity Ratio [kg water / kg air]
\( W_{g,i} \) = Internal Humidity Gain [kg water/hr]
\( M_{\text{eff}} \) = Effective Moisture Capacitance of Zone [kg]
\( \Delta t \) = Length of Timestep [hr]

Subscripts
- \( a \) = Outdoor Ambient
- \( \text{vent} \) = Ventilation
- \( \text{inf} \) = Infiltration
- \( \text{req} \) = Required
- \( \text{cplg} \) = Coupling

### 3.3 Heating Energy Demand

Climate data for Windsor, Ontario was utilized and fed into the model by an external weather module. Canadian Weather Year for Energy Calculation (CWEC) climate dataset was utilized (www.climate.weather.gc.ca). Ambient
temperature data is shown in Figure 4. Morning pre-heating occurs in the greenhouse throughout the year, regardless of the indoor temperature, between the hours of 3 and 6 am. Pre-heating demand during these hours was assumed to be 50% of the maximum load. The sensible heating energy demand for specific days of the year is shown in Figure 5. The total annual demand for the greenhouse was determined to be approximately 5,230 GJ or 1310 MJ/ m² (360 kWh/ m²). The maximum load was determined to be approximately 2,880 MJ (800 kW) occurring on January 17th.
Figure 5 – Modelled Greenhouse Heating Energy Demand

3.4 Grower Data

Natural gas usage data for twelve recent growing years from three different greenhouse operations in Southern Ontario was obtained. The greenhouses ranged in size from 5 to 12 hectares, cover consisted of either double polyethylene film or glass and thermal curtains were utilized in all cases. The greenhouses produce bell peppers, cucumbers and tomatoes in various proportions. No artificial lighting strategies were utilized and planting schedules are tailored to match available natural sunlight, with planting typically occurring in January. The annual distribution of energy usage for each greenhouse, with data normalized per 0.4 hectares of greenhouse being heated, is presented in Figure 6.

Approximately 20% of the annual demand occurs during the month of January. Between May and September the demand varies from 3.5 to 6% and these months account for approximately 22% of the annual total. The annual
average from the 12 growing seasons is approximately 6,900 GJ per 0.4 hectares of greenhouse. A crop is typically terminated in mid-November and the indoor temperatures are maintained above freezing until planting again in January. This is why the energy usage in November and December is minimal with respect to the ambient temperatures.

The overall efficiency of a greenhouse heating system can be defined as the useful thermal energy input to the greenhouse divided by the energy input to the heating system. The efficiency is determined by the relative performance of several components, with the main factors being the boiler efficiency, losses from the water storage tank and piping systems, and operational controls. In recent years, natural gas fired boilers have improved efficiency to greater than 90% in some cases. Based on the varying age and differing manufacturers a boiler efficiency of 85% has been considered herein [30]. From this, an overall system efficiency of 75% has been chosen for comparison. Figure 7 presents the monthly sensible heating demand determined from the greenhouse model and the heating demand based on the grower energy usage data and a heating system efficiency of 75%. As can be seen, the monthly data closely correlates over the majority of the year. This serves as validation for the modelled demand profile.

![Figure 6](image_url)

Figure 6 – Energy Usage Data Obtained from Regional Growers
3.5 Solar Collector System

A solar collector system was modelled in the TRNSYS environment with the objective of eliminating boiler energy usage during the summer months. Due to the below freezing conditions present in Ontario during the winter months, an indirect solar thermal system is necessary. In this system an antifreeze solution is used for the collector system and is separated from the water-side of the system by a heat exchanger. The system is comprised of a solar collector field, heat exchanger and short-term water storage tank. A simplified schematic layout of the system is shown in Figure 8. Table B-1 in Appendix B provides a full list of the main TRNSYS components and variables utilized in the simulation. An antifreeze solution, consisting of 50% propylene glycol and 50% water, is circulated through the solar thermal collectors and source side of the heat exchanger. The specific heat capacity of the solution is 3.6 kJ/kg·°C at 40 °C [31]. A TRNSYS Type 91 constant effectiveness heat exchanger, with effectiveness set to 0.8, was utilized. Water is circulated from the bottom of the storage tank through the load side of the heat exchanger and back to the top of the storage tank.

The heating demand profile described in sections 3.3 and 3.4 is fed into the simulation environment using a Type 682 component, which imposes the load on a flow stream at each time step. The simulation was run with time-steps equal to 6 minutes. A water-only piping system was considered for the greenhouse. Energy transfer to the greenhouse interior is dependent on the mass flow rate of water in the system and the inlet and outlet temperatures of the greenhouse piping system. In order to appropriately simulate the heating system, water mass flow rate and temperatures typically seen greenhouse operations are utilized. An outlet water temperature of around 40 °C can be observed in greenhouse heating systems studied by others [10,32] and was confirmed by conversations with greenhouse operators. This maintains an adequate temperature difference and desired heat transfer between the circulating fluid and the interior. The flow rate varied between approximately 15,000 and 34,000 kg/hr and is
calculated at each time step by isolating $m$ in equation 4, where $T_{in}$ is equal to the temperature in the top portion of the storage tank. The load met by the heating system is calculated at each time step based on the following [33]:

$$\dot{Q} = (T_{in} - T_{out})m \cdot C_p$$

Where:

$\dot{Q}$ = Rate at which energy is added to or removed from the flow stream (kJ/hr)

$T_{in}$ = Temperature of liquid arriving at the load (°C)

$T_{out}$ = Temperature of liquid leaving the load (°C)

$m$ = Mass flow rate (kg/hr)

$C_p$ = Specific heat of the liquid (kJ/kg·°C)

The short term water storage tank is a critical part of the solar collector system. In addition to its main purpose of storing thermal energy for use at a later time, thermal stratification of the tank is important [15]. Warm water at the design temperature must be available at the top of the tank to feed the greenhouse piping system and cooler water must be available at the bottom of the tank to absorb energy from the solar collectors. As the temperature at the bottom of the tank increases and becomes closer to the solar collector outlet temperature, the efficiency of the system decreases. An initial tank size of 100 m$^3$ was utilized based on scaling down from a typical tank size utilized for an 8 hectare greenhouse. The tank is separated into five horizontal nodes to model thermal stratification. Each node thermally interacts with adjacent nodes through fluid conduction and fluid movement; either movement due to inlet flow streams or natural mixing due to temperature inversions. As the desired inlet piping temperature and top of tank temperature is between 50 and 60°C, glazed flat-plate solar collectors were chosen due to their suitability for low-temperature applications. These collectors are able to provide useful heat up to about 50 °C above ambient temperature [34].

A differential controller is utilized to control operation of the solar pumps by monitoring the temperature difference between the bottom of the tank and solar collector outlet. It is recommended for indirect systems with a heat exchanger that the ‘off’ set point temperature difference be in the range of 3 to 6 °C and the ‘on’ set point be 5 to 9 °C higher [35]. This maintains thermal stratification in the tank by only running the system when sufficient solar energy is available for harvest and minimizes pump on/off operation. Thus, the solar source and load pumps are turned on when the temperature difference reaches 12 °C and are turned off when this difference drops below 4 °C. The effect of altering these set point temperatures for pump operation is explored in section 4.0.

The flow rate of the solar collector source pump is set at 12.5 kg/hr/m$^2$ and is increased to 25 kg/hr/m$^2$ when the temperature rise across the collector system exceeds 15 °C. The flow rate is again reduced to 12.5 kg/hr/m$^2$ when the temperature rise drops below 10 °C. This is the recommended range of mass flow rate for a solar collector loop [36]. It also allows for a 15°C temperature rise across the solar system to be maintained, enhancing thermal stratification in the storage tank and reducing pump energy use [15]. It has been shown that a more detailed, proportionally variable flow rate approach has a minor effect on overall system performance [37]. The flow rate on the load side of the heat exchanger is also variable and set to achieve the same effective capacitance. Solar collectors
for large-scale systems are aligned in a series-parallel arrangement dependent on a thermal and hydraulic optimization. The system herein utilized 5 collectors in series.

![Figure 8 – Schematic Layout of Solar Collector System](image)

A flat-plate collector used in similar Canadian applications was chosen for the model. The collector parameters were obtained from standard collector performance rating results carried out by the Solar Rating & Certification Corporation (SRCC) [38]. The chosen collector has a gross area of 2.873 m², an optical gains coefficient ($F_R \tau_a$) of 0.768, and a heat loss coefficient ($F_R U_l$) of 4.035 W/m²°C. A detailed description of the flat-plate collector internal structure and operating characteristics can be found elsewhere [34,35]. A Type 1c flat plate collector was utilized in the simulation environment and incident angle modifiers given in the SRCC rating were provided as inputs to the component. The useful heat delivered by a solar collector in steady state operation can be described as [34]:

$$q_{useful} = q_{solar} - q_{loss}$$  \hspace{1cm} (5)  

$$q_{solar} = F_R \tau_a K I_c A_c$$  \hspace{1cm} (6)  

$$q_{loss} = F_R U_l A_c (T_{fluid,in} - T_{ambient})$$  \hspace{1cm} (7)  

Where:

$q_{useful} = \text{Useful Heat Delivered by System (W)}$

$q_{solar} = \text{Optical Radiant Heat Gain (W)}$

$q_{loss} = \text{Thermal Heat Loss (W)}$

$K = \text{Incident Angle Modifier}$

$F_R \tau_a = \text{Optical Gains Coefficient}$

$I_c = \text{Global Insolation (W/m}^2\text{)}$

$A_c = \text{Gross Area of Collectors (m}^2\text{)}$

$F_R U_l = \text{Heat Loss Coefficient (W/m}^2\text{/°C)}$
\[ T_{\text{fluid,in}} = \text{Incoming Fluid Temperature (°C)} \]
\[ T_{\text{ambient}} = \text{Ambient Air Temperature (°C)} \]

The solar collectors were set at a slope from the horizontal equal to the location latitude of approximately 42°, which is generally most appropriate for maximizing annual solar radiation exposure. Table 1 and Figure 9 show the daily average total horizontal radiation and incident radiation for the collector angle. As can be seen the daily horizontal radiation for the summer months varies between 20 and 23 MJ/m². Water piping circulation for morning pre-heating is the primary load that needs to be met during the summer months. The total daily load, considering only morning pre-heating at a load of 1,440 MJ/hr for 4 hours, will be approximately 5,760 MJ. Tank and system losses will be in addition to this, however, it is anticipated they will be minimal during the summer months due to the reasonable ambient temperatures. For initial estimation, assuming a solar collector efficiency of 50%, it was determined a system of about 600 m² would be suitable. A system of 40 parallel branches of 5 collectors in series, for a total area of approximately 575 m², was utilized.

Operating variables of the solar collector system over a 48 hour period for two specific dates are shown in Figure 10. The temperature rise across the solar collectors is maintained around 15 °C as intended. It can be seen that the collector inlet and outlet temperatures follow the ambient temperature during the night. On the day of July 10th where morning pre-heating is the only load present, it can be seen that the tank temperature decreases at 3 am when the heating cycle begins. Where apparently sudden changes are observed in the collector outlet temperature, this can be attributed to the changing flow rate through the solar collectors as the temperature rise across the collectors exceeds 15 °C or drops below 10 °C.

![Figure 9 – Horizontal Solar Radiation for Windsor, Ontario](image-url)
Table 1 – Daily Average Radiation for Windsor, Ontario

<table>
<thead>
<tr>
<th></th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Horizontal Radiation (MJ/m²)</td>
<td>6.1</td>
<td>9.3</td>
<td>13.8</td>
<td>17.6</td>
<td>22.3</td>
<td>23.3</td>
<td>19.6</td>
<td>14.3</td>
<td>10.3</td>
<td>6.6</td>
<td>4.9</td>
<td></td>
</tr>
<tr>
<td>Daily Incident Radiation on Collector @ 42° (MJ/m²)</td>
<td>10.9</td>
<td>14.6</td>
<td>17.7</td>
<td>18.9</td>
<td>21.0</td>
<td>20.5</td>
<td>20.9</td>
<td>19.8</td>
<td>16.9</td>
<td>14.6</td>
<td>11.2</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Figure 10 – Solar Collector System Operating Data (Beginning 12:00pm)
Figure 11 shows the monthly heating supplied by the solar collector system, required auxiliary heating and efficiency of the solar collector system. The system is able to cover approximately 97% of the heating demand during the month of July and about 84% during the months of June and August. The system is able to cover 27% of the annual load. The efficiency of the solar collector system can be defined as the useful heat delivered by the system divided by the total solar radiation incident on the collectors, as follows:

\[ \eta = \frac{q_{\text{useful}}}{I_c A_c} \]  

(8)

The efficiency of the collector system reaches a maximum of 47% during the month of August. Months with lower amounts of solar radiation will see a decrease in efficiency. This is because the amount of hours the circulation pumps are running per day is decreased as it takes longer during the morning hours to reach the required 12 °C temperature difference between the bottom of the storage tank and collector outlet. Furthermore, it can be seen in Figure 10 that the temperature of the bottom of the storage tank is 20 to 25 °C higher in the month of July than in March. Although high amounts of solar radiation are present during the summer months, the high storage tank temperature again increases the required time during the morning hours to reach the required temperature difference. This illustrates the dynamic nature of the collector efficiency.

As covering the summer heating load of a greenhouse is the focus of this study, the collector slope can be tailored to maximize useful energy gain during the summer months. It can be observed in Table 1 that horizontal solar radiation exceeds incident radiation on the collector at 42° slope during the summer months. Figure 12 shows the heating supplied by the collector system with a collector slope approaching horizontal. At a slope of 18° the system is able to cover 100% of the heating demand during the month of July, 90% and 88% of the demand during June and August, respectively. It should be noted that the overall annual amount of heating supplied by the system decreased
by approximately 8% compared to the collectors at a 42° slope. It was found that when the slope continued below 18° the energy supplied during the summer months began to decrease.

![Figure 12 – Heating Supplied by Collector System with Decreasing Collector Slope](image)

**4.0 Sensitivity Analysis**

To assess the relative influence of certain parameters in the model, a sensitivity analysis was carried out. The results of the analysis are shown in Figure 13. Annual heating supplied by the solar collector system was used as a baseline for the analysis and is represented with a value of 0 in the figure. The original and altered value for each parameter investigated is shown on the figure, along with resulting percent change from the baseline value. It can be seen that storage tank size can have a significant impact on system performance if not of sufficient size. Altering the temperature difference for solar pump on/off operation was observed to have a minor impact. This is consistent with comments from others where the parameter has little impact on annual predictions [39]. The analysis showed that the model was relatively stable over the parameters investigated and gives a satisfactory level of confidence in the results obtained.
5.0 Economic Analysis

5.1 Current Economics

Current costs of solar thermal collector systems can range widely based on system design and project location. Costs per square metre of collector area are typically between $125 and $750 [40,41]. Although the above analysis is based on 0.4 hectares of greenhouse, it is anticipated that a greenhouse operator investing in a large scale solar system would size the system to provide sufficient solar heat for several hectares of greenhouse and take advantage of economies of scale to minimize initial cost. Based on this, a conservative cost of $500 per square metre of collector area has been utilized and a 575 m² collector system would have an initial installed cost of approximately $288,000.

Using an electricity cost of $0.06/kWh and the modelled power consumption of the solar collector loop pump and water tank loop pump, annual energy costs were estimated to be about $750. Based on the annual energy usage of 6,900 GJ/0.4 hectares outlined in Section 3.4, if the collector system was to cover 27% of the annual load, this would result in a reduction of 1860 GJ of natural gas. Natural gas prices for greenhouse operators have fluctuated in recent years between $4 and $5/GJ [42]. A reduction in annual usage of 1860 GJ would correlate to savings of approximately $9,300/0.4 hectares/year, based on a natural gas price of $5/GJ. A simple payback period can be calculated for an installed system based on the following:
\[
\frac{\text{Capital Cost (\$)}}{\text{Annual Savings (\$)}} = \frac{\text{Capital Cost}}{\text{Natural Gas Savings – Pump Operation}} = \text{Simple Payback} \quad (9)
\]

The simple payback period based on natural gas prices of $5/GJ would be approximately 34 years.

### 5.2 Carbon Emission Reductions and Carbon Tax

In Canada, the provinces of British Columbia, Alberta, Manitoba, Ontario and Quebec currently have some form of carbon tax, price on carbon, or cap and trade policy in place, with the goal of reducing greenhouse gas emissions. The policies of each province are different and apply to different emissions producers dependent on their annual output. Generally, a carbon tax has been implemented at a rate of $20 / tonne of greenhouse gas emissions and is intended to increase in real terms in the years after implementation [43].

Carbon dioxide is considered one of the major greenhouse gas contributors, along with methane and nitrous oxide [44]. The carbon dioxide equivalency emissions for natural gas burned as a fuel is ~0.05 tonnes CO\(_2\)e / GJ [44]. Considering the solar collector system described herein is able to reduce natural gas usage by approximately 1860 GJ/ year/ 0.4 hectares of greenhouse, this correlates to a reduction of about 95 tonnes of CO\(_2\) equivalent emissions (CO\(_2\)e). With emissions taxed at a rate of $20 / tonne CO\(_2\)e, the additional annual savings from emission reductions would be approximately $1,900/ 0.4 hectares/ year. In this scenario the simple payback period would be reduced to about 28 years. The payback period is reduced to approximately 10 years with emissions taxed at a rate of $200 / tonne CO\(_2\)e.

### 6.0 Discussion

The analysis performed herein has shown that a large-scale solar collector system is able to cover the majority of the summer heating load for an agricultural greenhouse. It is noted that operational controls for a system such as this are very important and directly correlate to system performance. It has been assumed that a typical natural gas fired boiler would be utilized to cover the auxiliary demand and proper integration of the solar collector system is critical. The sensitivity analysis showed that changes to system variables, set point temperatures and flow rates had a relatively minor impact on overall system performance. This gives a good level of confidence in the obtained results.

Appropriate system size is ultimately dependent on the goal of the greenhouse operation. Natural gas usage can be completely eliminated for the months of June through August by increasing the collector area. However, in this scenario there will be excess energy during the month of July that will need to be dealt with. Some form of seasonal energy storage would provide the ability to store this excess heat for use at a later time and cover a greater proportion of the annual heating demand. However, the initial system cost would be significantly increased. This should be the focus of future work.
From the economic analysis it can be seen that the described system is not likely to be considered economically attractive from a greenhouse operator. In addition to the carbon tax some form of government or utility subsidy will be necessary to achieve a payback period of less than 10 years. Should a system be sized for a larger amount of greenhouse area there will likely be capital cost reductions due to economies of scale. Overall, it has been shown that this carbon-free technology has the ability to cover a significant portion of the annual heating demand of an agricultural greenhouse.

### 7.0 Conclusion

This paper analyzes the potential of a large-scale solar collector system with short-term storage to offset carbon-based heating in the Ontario greenhouse sector. A transient model of the greenhouse microclimate and indoor conditioning systems is carried out using TRNSYS software and validated with actual natural gas usage data. The following conclusions can be presented:

1) An array of 200 solar collectors with a total area of 575 m² is able to cover 97% of the heating demand during the month of July and approximately 84% during the months of June and August. The system has the ability to reduce the annual heating energy demand by approximately 27% and by replacing natural gas usage correlates to a reduction in CO₂ equivalent emissions of about 95 tonnes/ year.

2) Reducing the collector slope can maximize useful energy gain during the summer months and heating supplied by the same collector area can increase to 100% during the month of July and 90% during the months of June and August. However, this also resulted in an overall decrease in the annual heating supplied by about 8%.

3) Set-point temperatures for on/off operation of the collector system as well as increased mass flow rates were shown to have a relatively minor impact on overall performance of the system.

4) After considering annual operational costs the system was determined to have a simple payback period of about 34 years considering current natural gas prices. With carbon emissions taxed at a rate of $20/ tonne CO₂e the payback period is reduced to 28 years. At a rate of $200/ tonne CO₂e the payback can be reduced to 10 years.

### References


CHAPTER IV

A Techno-Economic Analysis of Seasonal Thermal Energy Storage for Greenhouse Applications

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1.0 Introduction

There is a pressing need to accelerate the development and deployment of advanced clean energy technologies in order to address the global challenges of energy security, climate change and sustainable development [1]. In 2009 the International Energy Agency (IEA) reported that global energy demand for heat represented 47% of final energy use [1]. With widespread resources throughout the world, solar energy is a low-emission alternative to conventional carbon-based fuels for space heating needs. One of the longstanding barriers to utilizing solar energy for space heating purposes is the obvious misalignment between solar energy supply and consumption [2]. Seasonal thermal energy storage (STES) provides a solution to this mismatch by allowing solar energy harvested during the summer months to be stored and utilized during the winter months when heating demands are greatest. The IEA in its Heating and Cooling Roadmap and the District Heating and Cooling Technology Platform include thermal energy storages as central components in energy efficient systems of the future [3].

An industry that has benefited from solar energy for many years is the agricultural greenhouse industry. A greenhouse is an enclosed structure, which traps short wavelength solar radiation and retains long wavelength thermal radiation to create a favourable micro-climate for higher productivity [4]. In contrast to conventional buildings, greenhouses are designed for maximum solar radiation transmission and can be considered a massive solar collector. As a result, the insulating properties of typical greenhouse cover materials are far inferior to those used in conventional buildings. The necessary interior micro-climate conditions are dependent on the type of crop but generally require an indoor temperature of between 18 and 22 °C. In locations with a moderate climate these indoor temperatures may be achievable with minimal additional energy input for heating purposes. However in regions with a seasonal climate, significant heating energy demands are present during the winter months and can account for up to 90% of the overall greenhouse energy demand [5]. A survey of greenhouse operations from Southwestern Ontario, a region with the highest density of greenhouses in North America, revealed average annual natural gas usage is in excess of 450,000 m³ per hectare.
Several studies have been carried out regarding the potential for solar assisted ground-source heat pump (SAGSHP) systems, as outlined by Mehrpooya et al [6]. In heating dominated buildings utilizing a ground-source system, annual heat extraction exceeding heat injection can lead to a decrease in mean ground temperature over time and decreased system coefficient of performance (COP) [7]. With a solar-assisted system, solar energy harvested is used for ground recharge and increasing the source fluid temperature entering the heat pump. Many studies have been conducted on SAGSHP systems for buildings with promising results [7,8,9,10]. For greenhouses, reviewed studies on similar systems are generally conducted on small-scale greenhouses less than 300 m² in plan area [6,11,12,13] or aim to keep the greenhouse interior temperature above 10–12 °C [11,14]. With increased interior set-point temperatures, a cold climate, and operations commonly exceeding 20 hectares (~200,000 m²) in plan area, annual heating demands are significantly increased. In order to achieve a significant solar fraction in this type of setting, large-scale solar collector plants and seasonal storage are required.

Large-scale solar collector systems connected to local or district heating systems are well developed in Europe. By the end of 2015, 235 large-scale solar thermal systems >350 kWth (500 m² collector area) were in operation in Europe [15]. Most systems are designed to cover the summer hot water and space heating load, amounting to an annual solar fraction of 10-20% [16,17]. A system designed in this manner was discussed in Chapter III. Systems in operation with some form of seasonal thermal storage are typically able to achieve a solar fraction of about 50% [15], although one documented system in Canada has achieved a solar fraction of 100% for a community of 52 houses [18].

The aim of this paper is to assess the required size of a solar collector system with seasonal thermal energy storage to cover a significant fraction of the annual heating demand of a 0.4 hectare greenhouse in a cold climate. The study will compare low and high-temperature storage systems, with and without a heat pump, from a technical and economic perspective. As the interior microclimate of a greenhouse is a delicate balance, the system will be integrated into a typical heating system without altering standard greenhouse construction practices or interior climate controls.

Figure 1 – General View of Proposed System
2.0 Methodology

2.1 Greenhouse Load Profile

A transient simulation of the greenhouse interior microclimate was carried out using TRNSYS software and the sub-program TRNBuild. A 0.4 hectare venlo-type greenhouse was modelled with a gutter height of 5.5 metres (m) and a series of lower and upper thermal zones, to differentiate the areas within and above the crop. Greenhouse cover consisted of double-polyethylene material with a heat transfer coefficient 3.2 W/m$^2\cdot$ºC. Day and night set-point temperatures were 22 and 18ºC, respectively. The set-point increased at a rate of 1 ºC / hour in the hours prior to sunrise for morning ‘pre-heating’ of the crop and to avoid sudden changes in indoor temperature. Infiltration was set at 0.5 air changes per hour (ACH). The model assumed a constant crop density of 6 kg /m$^2$ and that the thermal properties of the crop were similar to those of water. Crop transpiration was included via an internal humidity gain. Lighting strategies to promote year-round production were not considered and a typical season involves crop production from January to mid-November, after which time the set-point temperature was decreased to 5 ºC.

The climate conditions for the most southern region in Canada, Southwestern Ontario, were used in the simulation. Canadian Weather Year for Energy Calculation (CWEC) climate dataset was utilized (www.climate.weather.gc.ca). The province of Ontario accounts for over 50% of the greenhouse space in Canada [19] and Southwestern Ontario in particular is an area with the highest density of greenhouses in North America. The region is generally characterized by hot, humid summers and cold winters. Climatic parameters of temperature, solar radiation, humidity and wind velocity are fed into the TRNSYS simulation environment from an external weather module. Hourly temperature and solar radiation data used in the simulation are shown in Figures 2 and 3, respectively. Winter temperatures reach -20 ºC and temperatures above 30 ºC are common during the summer months. Daily horizontal radiation peaks at ~23 MJ/ m$^2$ during the month of June.
The sensible energy demand for the greenhouse was calculated at each time step considering surface gains, infiltration, air flow within the greenhouse and internal gains. The resulting hourly heating load profile for the 0.4 hectare greenhouse is presented in Figure 4. The peak demand is approximately 2,880 MJ/ hr (~800 kW) occurring in mid-January. Approximately 50% of the annual demand occurs during the months of January through March. Morning pre-heating occurs year-round, regardless of the indoor temperature, and was applied between the hours of 3 and 6 am with a load equal to 50% of the maximum load. The total annual demand for the greenhouse was determined to be approximately 5,230 GJ or 1310 MJ/ m$^2$ (360 kWh/ m$^2$).

Heating fuel usage data from 3 different greenhouse operators over 12 growing seasons from Southwestern Ontario revealed average annual usage is approximately 6,900 GJ/ 0.4 hectares, as presented in Chapter III. Figure 5 presents the monthly sensible heating demand determined from the greenhouse model and the heating demand based on the grower energy usage data, considering an overall heating system efficiency of 75%. As can be seen the monthly data closely correlates over the majority of the year and serves as validation for the modelled demand profile.
2.2 System Components

2.2.1 General

Greenhouse heating is conventionally accomplished by combusting a carbon-based fuel, typically natural gas, in either a hot-water or steam boiler and heat is distributed to the greenhouse interior via a hydronic piping system. Ventilation techniques through the greenhouse cover are utilized to cool the greenhouse during the summer months and for humidity control. The aim of this study is to incorporate the solar collector system and seasonal storage into typical operating controls, meaning greenhouse cooling will still take place via typical ventilation strategies.

In the interior hydronic piping system, water, or steam in some cases, is circulated through the greenhouse and energy is exchanged with the interior by convective and radiative heat transfer. The overall energy transfer to the interior is dependent on the mass flow rate of the system and the temperature drop of the fluid across the hydronic

Figure 4 – Heating Demand Profile from Model

Figure 5 – Monthly Heating Energy Demand
system. In typical greenhouse applications the system is designed for a leaving water temperature from the greenhouse of around 40 °C to maintain an adequate temperature difference and desired heat transfer between the circulating fluid and the interior. This can be observed in greenhouse heating systems studied by others [20,21].

Based on the load profile presented in Figure 4 it can be seen that a system sized for peak load will be greatly oversized for the majority of the year. The systems herein are sized for 25% of the peak load, or about 720 MJ/ hr (~200 kW), which will cover approximately 65% of the annual demand. TRNSYS software is utilized for simulating the greenhouse heating system.

2.2.2 Solar Collector System

Large-scale solar collector fields are designed with a number of flat-plate collectors in a series-parallel arrangement. Flat-plate collectors are utilized due to their suitability for low temperature applications (<100 °C). The useful energy delivered by a solar collector can be defined by [22]:

\[
q_{useful} = q_{solar} - q_{loss} \quad (2)
\]

\[
q_{solar} = F_r \tau a K I_c A_c \quad (3)
\]

\[
q_{loss} = F_r U_l A_c (T_{fluid,in} - T_{ambient}) \quad (4)
\]

Where:

- \( q_{useful} \) = Useful Energy Delivered by System (W)
- \( q_{solar} \) = Optical Radiant Heat Gain (W)
- \( q_{loss} \) = Thermal Heat Loss (W)
- \( K \) = Incident Angle Modifier
- \( F_r \tau a \) = Optical Gains Coefficient
- \( I_c \) = Global Insolation (W/m²)
- \( A_c \) = Gross Area of Collectors (m²)
- \( F_r U_l \) = Heat Loss Coefficient (W/m²/°C)
- \( T_{fluid,in} \) = Incoming Fluid Temperature (°C)
- \( T_{ambient} \) = Ambient Air Temperature (°C)

Solar collector efficiency can generally be defined as the collector useful energy gain divided by the total solar irradiation per gross unit area. Collector parameters were obtained from standard collector performance rating results. The chosen collector has a gross area of 2.873 m², an optical gains coefficient (Fₐτa) of 0.768, and a heat loss coefficient (FₐUₙ) of 4.035 W/m²/°C. The slope of the collectors was set to the location latitude of 42°. A Type 1c flat-plate solar collector was used in the TRNSYS simulation environment.

2.2.3 Borehole Thermal Energy Storage

Sensible thermal energy storage is a simple, relatively mature technology for seasonal energy storage compared to other alternatives, such as latent or chemical thermal storage [2]. The amount of heat stored is dependent on the temperature increase of the storage material and the specific heat of the material. Water, with its favourable
properties and generally widespread availability, is commonly used for short-term thermal storage in tanks. Water is also used in seasonal storage applications in tanks buried underground, pits with an insulated cover, or underground aquifers where geologic conditions are favourable [3]. The ground, soil or rock, underlying a site can also be used for seasonal storage. With soil storage, commonly referred to as borehole thermal energy storage (BTES), a number of vertical boreholes are drilled into the storage medium. The boreholes are used to exchange energy between a heat carrier fluid, which is circulated through pipes within the boreholes, and the storage medium [23]. A BTES system will be used in this study due to its applicability in a generally wide range of geologic conditions and its favourable economics in comparison to tank or pit seasonal storage [3]. The BTES system is modelled in the TRNSYS environment using a Type 557a component, which is based on the model developed by Hellström [23]. The boreholes are assumed to be placed evenly within a cylindrical storage volume. The model considers convective heat transfer within the boreholes and conductive heat transfer in the ground. Based on the temperature difference between the circulating fluid and the storage medium, heat can be injected into or extracted from the medium.

Extraction of energy from the BTES during the winter months for space heating falls into two categories; low and high temperature storage [24]. In general, where ground temperatures exceed 40 ºC direct-use of the fluid exiting the bore field is possible. Where ground temperatures are below 40 ºC a heat pump is required. Although the required heat injection during the summer months is greater with higher design temperature, the operational costs are significantly reduced as a heat pump is not required during operation. The BTES system is modelled with several strings of 6 boreholes in series extending from the centre to the edge of the bore field, as shown in Figure 6. Circulation through the borehole strings is alternated to promote radial stratification within the storage volume, with water circulating from the center to edge during heat injection and in the opposite direction during heat extraction. This promotes lower temperatures near the edge of the bore field to minimize heat losses [25]. Additionally, 0.2 m of insulation is placed over the storage volume with a thermal conductivity equal to 0.15 kJ/hr·m·ºC [26].

The required number, depth and spacing of boreholes are dependent on the geologic conditions of the site. Southwestern Ontario is located within the physiographic region of the Saint Clair Clay Plains, which is essentially an extensive clay plain with minor changes in elevation [27]. Considering a certain proportion of sand, the soil thermal conductivity and heat capacity have been estimated to be 7.2 kJ/hr·m·ºC and 2145 kJ/m³·ºC, respectively [28,29]. It has been assumed that groundwater flow is negligible. Based on ground temperature mapping the mean annual average ground temperature is considered to be 9 ºC [28,30].
2.2.4 System Controls – High-Temperature

A schematic of the investigated high and low temperature systems are shown in Figure 7. Table B-2 in Appendix B provides a full list of the main TRNSYS components and variables utilized in the simulation. The greenhouse heating load profile is fed into the simulation environment using a Type 682 component, which imposes heating and cooling loads onto a flow stream. The load met by the heating system is calculated at each time step based on the following [31]:

\[ \dot{Q} = (T_{\text{in}} - T_{\text{out}}) \dot{m} \cdot C_p \]  

(5)

Where:

\( \dot{Q} \) = Rate at which energy is added to or removed from the flow stream (kJ/hr)
\( T_{\text{in}} \) = Temperature of liquid arriving at the load (°C)
\( T_{\text{out}} \) = Temperature of liquid leaving the load (°C)
\( \dot{m} \) = Mass flow rate (kg/hr)
\( C_p \) = Specific heat of the liquid (kJ / kg·°C)

When a heating load is present, pump P1 is turned on and water is drawn from the upper portion of the short-term storage tank and sent through the greenhouse. The high-temperature system is designed for entering and leaving temperatures from the greenhouse of 50 and 40 °C, respectively, during the winter months. Pump P1 is a variable speed pump and the flow rate is adjusted according to the load and temperature in the upper portion of the short-term storage tank. For the high-temperature system, the flow rate varied between approximately 15,000 and 34,000 kg/hr. It is calculated at each time step by isolating \( \dot{m} \) in equation 5, where \( T_{\text{in}} \) is equal to the temperature in the top portion of the storage tank.
Figure 7 – Schematic Layout of Investigated Systems

A Type 534 vertical storage tank is utilized with a volume of 200 m$^3$. The tank height to diameter ratio is ~1:1 and five horizontal nodes were used to model thermal stratification within the tank. Hot water at the design temperature must be available at the top of the tank to heat the greenhouse and cooler water must be present at the bottom of the tank to feed the collector system. Due to the potential for freezing conditions, a 50% propylene-glycol to water solution is utilized for the solar collector (source) loop with a specific heat capacity of 3.6 kJ/kg·ºC at 40 ºC [32]. On the load side of the heat exchanger, water is drawn from the bottom of the tank and returned to the top. A Type 91 constant effectiveness heat exchanger is utilized between the source and load loops, with efficiency set to 0.8. The solar collector load and source pumps, P3 and P4, respectively, are turned on when the temperature difference between the collector outlet and bottom of the tank reaches 12 ºC and are turned off when the difference becomes less than 4 ºC. This promotes thermal stratification in the storage tank. The flow rate through the solar collectors is set at 12.5 kg/hr·m$^2$ and is increased to 25 kg/hr·m$^2$ if the temperature rise across the solar collectors exceeds 15 ºC. The flow rate on the load side of the heat exchanger is set to achieve the same effective capacitance.

Pump P2 is utilized for the transfer of energy between the storage tank and the BTES system. Heat injection into the bore field occurs when the temperature difference between the upper portion of the tank and the average ground temperature exceeds 7 ºC and no greenhouse heating load is present. Heat extraction from the bore field occurs when the tank temperature drops below 52 ºC and continues until a temperature of 56 ºC is reached. The mass flow rate for the BTES was chosen to be within the range of flow observed in the solar collector loop and greenhouse, and was set at 12.5 kg/hr·m$^2$ of collector area.

2.2.5 System Controls – Low-Temperature

The low-temperature system operates in generally the same structure as the high-temperature system. Storage tank size is reduced to 100 m$^3$. The main difference is that the greenhouse heating loop is a closed system and a heat
pump is utilized to increase the fluid temperature, as shown in Figure 7. The system is designed for entering and leaving temperatures from the greenhouse of 45 and 40 °C, respectively. The coefficient of performance (COP) is an important factor for heat pump operation and can be defined as follows:

$$COP = \frac{Q_{\text{heat}}}{Q_{\text{input}}}$$

(6)

Where:

$$Q_{\text{heat}} = \text{Useful heat delivered (kJ/hr)}$$

$$Q_{\text{input}} = \text{Input energy required (kJ/hr)}$$

As the COP increases, the required energy to run the heat pump decreases for the same amount of provided useful heat. For heat pump selection to meet the design load, four 52.8 kW (15 Ton) water-to-water heat pumps connected in parallel were utilized. The heat pump performance at various flow rates and fluid temperatures was entered into the Type 927 component based on manufacturer results [33]. The source and load side flow rates were set to 2.4 and 3.2 L/min·kW, respectively, as per manufacturer specifications. The number of heat pumps in operation, as well as the load and source flow rates, is set to vary with the heating demand. With an inlet source temperature of 10 °C, the heat pump has a rated coefficient of performance of 3.3 [33].

Solar collector controls were the same as those used for the high-temperature system. Heat extraction from the bore field occurs when the tank temperature drops below 12 °C and continues until a temperature of 16 °C is reached. The mass flow rate for the BTES was chosen to be within the range of flow observed in the solar collector loop and greenhouse. The rate was set at 25 kg/hr·m² of collector area during charging and 50 kg/hr·m² during discharging.

2.2.6 Pump Power

Required power for each of the circulating pumps was estimated based on flow rate and anticipated pressure drop across the respective system. Variable speed pumps were utilized in all cases. At maximum flow conditions for the low and high-temperature systems, respectively, the following were utilized; P1: 12 kW, 10 kW; P2: 8kW; P3: 1.5 Kw; P4: 7.5 kW, 24 kW, P5: 9 kW.

3.0 Results

3.1 System Operation

Simulations were initiated on April 1st and run over a 4 year period to allow the BTES system to reach its operating capacity. 6 minute simulation time steps were utilized. Initial estimates were made for size of the solar collector system and number, depth and spacing of boreholes for the BTES, followed by numerous iterations. Results of these iterations are discussed in Section 3.2. The systems in this section were chosen based on a design heating fraction of 65%. The low and high-temperature systems had 861 m² and 2,009 m² of solar collectors, respectively. A BTES
A system of 120 boreholes to a depth of 30m was determined suitable for both systems. A borehole spacing of 2.5 m was chosen for the high-temperature system, resulting in a soil volume of 19,500 m$^3$, and a spacing of 3 m was chosen for the low-temperature system, resulting in a soil volume of 28,000 m$^3$.

Average ground temperature for both the high and low-temperature systems over the simulation period are shown in Figure 8. In year 4 the average temperature peaks at over 60 °C in mid-September for the high-temperature system. This leads to temperatures at the ground heat exchanger outlet of between 58 and 45 °C over the winter months for replenishing the storage tank. The low-temperature system peaks at a temperature of about 25 °C. The minimum ground temperature is dictated by the return temperature from the load, which is approximately 40°C and 10 °C for the high and low temperature systems, respectively.

![Graph showing average ground temperature for high and low-temperature systems](image)

**Figure 8 – Average Ground Temperature for High and Low-Temperature Systems**

Figure 9 shows the collector and storage tank operating temperatures for a typical day during the summer months. When the solar collector pumps are off the collector inlet and outlet temperatures are equal. As can be seen the desired temperature rise across the solar collectors of 15 °C when in operation is generally achieved. The low-temperature system is able to operate for a longer portion of the day due to the lower storage tank temperature and ability to meet the required temperature difference between the tank and collector outlet. This in turn increases the efficiency of the collector system. After sunset, the temperature decrease in the upper portion of the tank can be seen as the water is circulated through the BTES system for heat injection.

Figure 10 shows the collector and storage tank operating temperatures for a typical day in November. Based on the collector inlet and outlet temperatures, it can be observed that very little solar energy is harvested. The temperature in the upper portion of the storage tank for both systems is observed to increase when the temperature falls below the set-point temperature and is occurring when no solar energy is being harvested. This shows that the controls are working properly as energy is extracted from the BTES system, making hot water available for heating the
greenhouse. The upper tank temperature can also be seen decreasing in the hours prior to sunrise as hot water is extracted for morning pre-heating.

Figure 9 – Collector and Buffer Storage Tank Temperatures – Beginning June 20th at midnight
  a) High-Temperature b) Low-Temperature
Heat supplied to the greenhouse and auxiliary heating required are shown in Figure 11. Collector useful energy gain, energy transfer to the BTES system and BTES losses are presented in Figure 12. Energy injected into the BTES system is shown as a positive value and energy extracted as a negative value. It has been assumed a natural gas fired boiler would supply the required auxiliary heat. The low-temperature system provides a consistent heat supply throughout the winter season with use of the heat pump, which was able to achieve the rated COP of about 3.3. In contrast, heating supplied by the high-temperature system decreases throughout the winter months as the return.
temperature from the bore field decreases, along with the average ground temperature. The high-temperature system is able to supply in excess of 720 MJ/hr heating power at times when the buffer tank temperature exceeds 50 °C, which occurs regularly during the summer and shoulder seasons. This can be seen in the months of October and November where the high-temperature system is able to cover almost the entire heating load. Each of these systems was able to cover approximately 64% of the annual heating demand of the greenhouse. It can be observed in Figure 12 that the high-temperature system has considerably greater losses from the BTES system.

Table 1 shows performance results for both systems during the 4th year of operation. It can be seen that the solar collector efficiency of the low-temperature system far exceeds that of the high-temperature system. This is due to the lower storage tank temperature. The collector efficiency and total electricity consumption of 154 GJ for the high temperature system are in relatively good agreement with performance results from a comparable system [34], where a collector efficiency of 0.34 was reported and annual electricity use was 173 GJ. The solar fraction presented in Table 1 is defined by:

\[
\text{Solar Fraction} = \frac{\text{Heating Supplied} \times \text{Total Annual Demand (GJ)} - \text{Electricity Use (GJ)}}{\text{Total Annual Demand (GJ)}}
\]

![Figure 11 – Heating Supplied and Required Auxiliary Heat](image)

- a) High-Temperature
- b) Low-Temperature

<table>
<thead>
<tr>
<th>Collector Area (m²)</th>
<th>High-Temperature</th>
<th>Low-Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,009 m²</td>
<td>2,009 m²</td>
<td>861 m²</td>
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<tr>
<td>BTES Volume (m³)</td>
<td>19,500 m³</td>
<td>28,000 m³</td>
</tr>
<tr>
<td>Heating Supplied (%)</td>
<td>0.64%</td>
<td>0.64%</td>
</tr>
<tr>
<td>(\text{COP}_{\text{system}})</td>
<td>21.7</td>
<td>2.9</td>
</tr>
<tr>
<td>Electricity Use (GJ)</td>
<td>154 GJ</td>
<td>1,179 GJ</td>
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<tr>
<td>Solar Collector Efficiency (%)</td>
<td>0.38%</td>
<td>0.58%</td>
</tr>
<tr>
<td>BTES Efficiency (%)</td>
<td>0.32%</td>
<td>0.71%</td>
</tr>
<tr>
<td>Solar Fraction (%)</td>
<td>0.70%</td>
<td>0.41%</td>
</tr>
</tbody>
</table>
Figure 12 – Monthly Energy Transfer between System Components

a) High-Temperature b) Low-Temperature

3.2 BTES Performance

Results of the iterative process to obtain a suitable number of boreholes are shown in Figure 13. Overall system coefficient of performance is presented for the high-temperature system whereas heat pump average coefficient of performance during the month of January is presented for the low-temperature system. A decrease in the COP can be observed with increasing number of boreholes for the high-temperature system. This is due to lower ground temperatures as the injected energy is spread over a larger area, reducing the ability to extract energy from the BTES system. In contrast, the heat pump coefficient of performance during the month of January increases with the number of boreholes for the low-temperature system. A series of 120 boreholes was determined to be an optimum...
value for the low-temperature system and was also selected for the high-temperature system for comparison purposes.

![Graph](image1.png)

**Figure 13** – System Performance with Varying Number of Boreholes

b) High-Temperature b) Low-Temperature

An important consideration in a BTES system is the ratio of storage volume to surface area, which directly correlates to losses from the system. The efficiency of a seasonal storage system can be determined by the ratio of annual heat injected to heat extracted. For the high-temperature system during the 4\textsuperscript{th} year of operation, approximately 1,430 GJ of heat was injected and approximately 460 GJ was extracted, resulting in a BTES efficiency of about 32\%. This value is in good agreement with performance results from an operating BTES system of similar size [34], where an efficiency of 0.36 was reported. BTES efficiency for borehole depths of 30, 40 and 50 m were investigated for the high-temperature system and are shown in Figure 14. As can be seen an increase in
depth considering the same storage surface area lead to a decrease in efficiency. Although shallower boreholes are possible, a depth of 30m was chosen as a good balance between depth and required number of boreholes.

Figure 15 shows the effect of varying solar collector area on BTES efficiency for the low-temperature system dimensions. It can be observed that the efficiency for the low-temperature system is far superior to that of the high-temperature system. This is due to the lower temperature difference between the storage volume and the surrounding ground, which reduces heat loss. It should be noted that a suitable collector area and BTES dimensions are not based solely on BTES performance, but on a balance between this, heating demand and system cost.

![Figure 14 – BTES Efficiency, High-Temperature System](image)

![Figure 15 – BTES Efficiency, Low-Temperature System](image)
3.3 Levelized Cost of Electricity

A good measure for comparison of overall system performance is the Levelized Cost of Electricity (LCOE). For the systems studied herein, the LCOE can be defined as:

\[
LCOE = \frac{\text{Total Cost over Lifetime of System}}{\text{Total Energy Delivered over Lifetime of System}}
\]

\[
\text{Total Cost over Lifetime of System} = C_C + \sum_{t=1}^{n} \left( C_{Mt} + C_{Ot} \right) \frac{1}{(1+r)^t}
\]

\[
\text{Total Energy Delivered over Lifetime of System} = \sum_{t=1}^{n} \left( E_t \right) \frac{1}{(1+r)^t}
\]

Where:
- \( n \) = Lifetime of System (Years)
- \( r \) = Discount Rate (%)
- \( C_C \) = Capital Cost ($)
- \( C_{Mt} \) = Maintenance Cost in Year \( t \) ($)
- \( C_{Ot} \) = Operational Cost in Year \( t \) ($)
- \( E_t \) = Energy Delivered in Year \( t \) (GJ)

A cost of $500/m\textsuperscript{2} installed solar collector has been utilized [35,36]. Borehole drilling and installation costs have been estimated at $125/m [35] and a heat pump cost of $710/kW has been utilized [37]. The lifetime of the system has been taken as 25 years with a discount rate of 5%. An electricity rate of $16.6/GJ ($0.06/kWh) has been utilized with an annual increase of 3%. Maintenance costs were assumed to be 1% of the capital cost per year.

The estimated capital cost, annual costs during the first year of operation, and LCOE are presented in Table 2. The larger sized high-temperature system requires more capital but much lower operational costs. Overall, the low-temperature system results in a lower LCOE by approximately 10%. It can be seen that maintenance also plays a significant role in annual costs for both systems. With maintenance costs reduced to 0.5% of the capital cost per year, the LCOE for the high and low-temperature systems was reduced to 34.0 and 31.3 $/GJ, respectively. It should be noted that cost for auxiliary heating has not been included.

<table>
<thead>
<tr>
<th>Table 2 – Estimated System Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High-Temperature</strong></td>
</tr>
<tr>
<td>Solar Collectors ($)</td>
</tr>
<tr>
<td>Bore Field ($)</td>
</tr>
<tr>
<td>Heat Pump ($)</td>
</tr>
<tr>
<td><strong>Total Capital Cost ($)</strong></td>
</tr>
<tr>
<td>Annual Operating ($)</td>
</tr>
<tr>
<td>Annual Maintenance ($)</td>
</tr>
<tr>
<td><strong>Total Annual Cost ($)</strong></td>
</tr>
<tr>
<td>LCOE ($/GJ)</td>
</tr>
</tbody>
</table>
As mentioned previously, optimal system sizing is based on both system performance and economic evaluation. The systems described above were each able to meet approximately 64% of the annual demand. Figure 16 presents the percentage of annual heating demand covered and LCOE for differing solar collector areas. For each of these cases the other system parameters have been held constant. It can be seen that a minimum LCOE for the high-temperature system coincides with the chosen collector area. However, for the low-temperature system the minimum LCOE occurs at a smaller collector area of 718 m². This results in an LCOE of 32.0 $/GJ, a reduction of about 3% from the base case, and the system is able to cover approximately 62% of the annual demand.

Figure 16 – Percentage of Heating Covered and Levelized Cost of Electricity (LCOE) with Varying Collector Areas
a) High-Temperature b) Low-Temperature
3.4 Sensitivity Analysis

A sensitivity analysis was carried out on both the low and high-temperature systems to assess the stability of the model and relative influence of key parameters. Annual heating supplied by the system was used as a baseline. Figure 17 shows the results of the analysis. It can be observed that no parameter caused a change of greater than 2% in the annual heating supplied by the system. The high-temperature system showed greater variability where parameters of the borehole thermal energy storage system were altered. Changing the borehole spacing, soil heat capacity and insulation thickness resulted in absolute changes to the annual heating demand in the range of 0.7 to 1.7%. Altering the same parameters for the low-temperature system resulted in changes in the range of only 0.1 to 0.2%. This should be expected as the mean ground temperature is increased much more significantly in the high-temperature system. The importance of an appropriately sized short-term storage tank is also revealed by the analysis, where a decreased tank size for the high-temperature system resulted in a decrease of about 1.8%. Overall, the model is observed to be stable over the parameters investigated and gives a satisfactory level of confidence in the results.

![Sensitivity Analysis](image)

Figure 17 – Sensitivity Analysis – Annual Heating Supplied by System (% Change from Baseline)

4.0 Discussion

There are many factors to take into consideration when assessing large-scale solar systems with seasonal thermal storage. Aside from economic considerations, there is a great difference in overall system coefficient of performance for the two systems. The high-temperature system requires minimal operational energy and is able to achieve a system COP of 21.7. The low-temperature system, on the other hand, is only able to achieve a system COP of 2.9.
Although this is greatly improved performance from a typical natural gas fired boiler, the energy burden has been moved from natural gas to electricity. In an effort to deploy clean energy technologies and minimize the use of carbon-based fuels, the overall environmental gain in terms of carbon emission reductions is then based on the electricity production methods in the region where the project is to be deployed.

In Ontario, electricity production is 99% free of smog and greenhouse gas emissions [38]. This is in large part due to the coal power generation phase-out that was completed in 2014. In 2015, the province produced 280,933 TJ (78,037 GWh) of electricity and 537,737 tonnes of CO$_2$ equivalent (CO$_{2e}$) emissions [38]. Emissions per unit of electricity produced can then be calculated at 0.0019 tonnes CO$_{2e}$/GJ. Considering the systems presented in Section 3.1, the low and high-temperature systems would produce approximately 2.2 and 0.3 tonnes of CO$_{2e}$ emissions /

The payback period for the described systems is highly dependent on the price of natural gas. Considering natural gas at a price of ~$5/GJ the annual cost would be about $34,500 / 0.4 hectares. Considering only energy costs for the low and high-temperature systems presented in Section 3.1, annual savings equate to approximately $2,400 and $19,500, respectively, including auxiliary heating using natural gas. Figures 18 through 20 present the simple payback period for both systems with varying natural gas price, carbon tax, and capital cost subsidy from government and/or energy provider. Ultimately, it will be a combination of these factors that lead to an economically viable installation. To achieve a payback period of less than 7 years, a 70% subsidy and carbon tax at ~$200/Tonne of CO$_{2e}$ emissions would be required, with natural gas at a price of $5/GJ. With a natural gas price at $10/GJ, a 7 year payback period could be achieved with a 50% subsidy and carbon tax at ~$200/Tonne of CO$_{2e}$ emissions. It should be noted that the subsidy portion could also encompass capital costs less than those estimated herein.

The systems described in this paper were sized for a 0.4 hectare greenhouse operation. It is likely that an operator installing such a system would be interested in heating a much larger greenhouse area and further cost reductions could be realized due to economies of scale. This should be the focus of future research. Furthermore, there are many different system designs that could be viable aside from those presented herein. Greater optimization of system controls to increase thermal stratification in the storage tank and radial stratification in the BTES would improve system performance.
Figure 18 – Simple Payback Period with varying Carbon Tax (Natural Gas @ $5/GJ)

Figure 19 – Simple Payback Period with varying Natural Gas Cost (Carbon Tax @ $60/Tonne $CO_{2e}$)

Figure 20 – Simple Payback Period with varying Capital Cost Subsidy (Natural Gas @ $5/GJ, Carbon Tax @ $60/Tonne $CO_{2e}$)
5.0 Conclusion

A techno-economic assessment has been presented for the design of large-scale solar collector systems with seasonal thermal energy storage for greenhouse applications. Both low and high-temperature systems have been explored for a 0.4 hectare greenhouse located in Southwestern Ontario, Canada. The following conclusions can be drawn:

1) High and low-temperature systems consisting of 2,009 and 861 m² solar collector area, respectively, were able to cover 64% of the annual heating demand of a greenhouse. An economic optimum for the low-temperature system was determined to lie with a smaller system covering approximately 62% of the annual demand. The LCOE for the low and high-temperature systems was determined to be ~$32/GJ and ~$36/GJ, respectively.

2) Solar collector and BTES efficiency for the low-temperature system were significantly higher than that of the high-temperature system, attributed to lower operating temperatures.

3) Overall system COP for the high and low-temperature systems was 21.7 and 2.9, respectively. The difference can be attributed to heat pump electricity use in the low-temperature system.

4) Heat pump operation provided a more consistent heating supply throughout the winter season, whereas the high-temperature supply decreased throughout the winter due to decreasing ground temperatures as heat was extracted.

5) Compared to a typical natural gas fired boiler, the systems described herein can reduce CO₂e emissions by ~220 Tonnes / 0.4 hectares / Year. A payback period of ~7 years is achievable with a 70% subsidy and carbon tax at $200/Tonne of CO₂e emissions.

References


CHAPTER V

Conclusions and Recommendations

1.0 Summary and Conclusions

The need to reduce dependency on fossil fuels for heating purposes in the agricultural greenhouse sector and move towards a more sustainable energy supply is imminently necessary. The work presented herein has examined the potential of closed greenhouse systems and large-scale solar collector systems to reduce this dependency.

The closed greenhouse system was presented in Chapter II. In this system, natural ventilation for cooling and dehumidification purposes is replaced with active systems and the thermal energy recovered can be stored for later use. This leads to an overall reduction in the annual energy usage for heating purposes, as well as providing the potential for improved crop productivity. It was determined that the annual cooling demand is equal to or greater than the heating demand in each of the cold climates examined and a fully closed greenhouse is possible. The use of a high-insulating double glass cover material would likely be most suitable for a closed greenhouse system due to the significant reduction in annual heating demand and in turn the necessary seasonal storage capacity. It was also determined that heat recovery ventilation techniques have potential to reduce the heating demand during the fall, winter and spring seasons. A semi-closed greenhouse would allow the cooling capacity to be optimized at a much lower base cooling load.

Chapter III assessed the potential of a large-scale solar collector system to cover the summer heating demand of a 0.4 hectare greenhouse. In order to avoid sudden changes in indoor temperature and ‘wake’ the crop, morning pre-heating is utilized in greenhouses in the hours prior to sunrise year-round, regardless of the indoor temperature. This results in over 20% of the annual heating demand occurring during the months of May through September. It was determined that an array of 200 solar collectors with a total area of 575 m$^2$ is able to cover 97% of the heating demand during the month of July and approximately 84% during the months of June and August. The system has the ability to reduce the annual heating energy demand by approximately 27% and by replacing natural gas usage correlates to a reduction in CO$_2$ equivalent emissions of about 95 tonnes/ year. The useful energy harvested by the collector system can be maximized during the summer months by decreasing the slope of the collectors. After considering annual operational costs, the system was determined to have a simple payback period of about 34 years considering natural gas at a price of $5/GJ. With a carbon tax at a rate of $200/ tonne of CO$_2$ equivalent emissions, the payback can be reduced to 10 years.

Chapter IV simulated the performance of a large-scale solar collector system with seasonal thermal energy storage (STES). STES provides a solution to the mismatch between solar energy supply during the summer months and heating demand during the winter months. Both high and low-temperature storage systems were examined and their performance was compared. High and low-temperature systems consisting of 2,009 and 861 m$^2$ solar collector
area, respectively, were able to cover 64% of the annual heating demand of a 0.4 hectare greenhouse. The optimum levelized cost of electricity (LCOE) for the high and low-temperature systems was determined to be ~$36/GJ and ~$32/GJ, respectively. The efficiency of both the solar collector system and borehole thermal energy storage (BTES) system were significantly higher for the low-temperature system, attributed to the lower operating temperatures. Overall system COP for the low and high-temperature systems was determined to be 2.9 and 21.7, respectively. The difference can be attributed to heat pump electricity use in the low-temperature system. Compared to a typical natural gas fired boiler, the described systems can reduce CO₂ equivalent emissions by ~220 Tonnes / 0.4 hectares / Year. A payback period of ~7 years is achievable with a 70% subsidy and carbon tax at $200/Tonne of CO₂e emissions.

2.0 Recommendations

The analyses and results presented herein are built on past research in the area and are meant to provide a stepping stone for future researchers. Ultimately, it will be a combination of factors that contribute to reducing the heating energy demand of greenhouses in a cold climate and the dependency on carbon-based fuels.

The greenhouse heating demand is affected by many factors. Greenhouse cover material, age, maintenance practices, crop and sub-crop type, operational controls and weather all affect the heating demand and will vary annually. Thus, it is recommended that future work focus on the design of sustainable heating systems, their integration into existing operations, and the economic framework that will best promote their utilization. It was shown in both Chapters III and IV that in order for a carbon tax to legitimately assist in making such systems economically viable, the tax needs to be in the range of ~$200/ tonne CO₂e emissions.

Although the closed greenhouse system has the potential to significantly reduce heating demands, it constitutes a fundamental change in the way greenhouses are operated. Obtaining an annual crop yield that is consistent in both quantity and quality is of paramount importance to any greenhouse operation. It was observed throughout the research for this work that operational preferences vary between growers and are generally based on what has been done in past years and previous generations. Implementing active systems for cooling and dehumidification, as proposed in the closed greenhouse system, presents a significant change from typical practices and are not likely to be readily accepted by greenhouse operators. This has been observed over the past decade in the Netherlands where some dismiss the idea as being too far-fetched. Nonetheless, some aspects of the concept, such as high-insulating cover materials, present a straightforward way to reduce the demand without significant changes to the accepted operational methods. Future work should further assess the challenge of overheating during the summer months while using a high-insulating cover material.

An economic optimum for a large-scale solar system likely lies with a combination of the systems presented herein. A suitable system is dependent on the specific goals of the operator; whether they are cost minimization, maximizing the solar fraction or simply implementing a system that is carbon-free. Calculating the levelized cost of
electricity for the 575 m² collector system presented in Chapter III, covering the summer heating load, in the manner described in Chapter IV reveals a value of about $17.2/ GJ. This is approximately half of the $32-36/ GJ determined for the seasonal storage systems in Chapter IV. However, without some form of seasonal storage the solar collector system will only be able to cover significant portions of the demand during the summer months. If a pilot project were to be implemented, a reasonable starting point would be a system without seasonal storage that could be expanded at a later time. This is due to the reasonably attractive payback period in comparison to the seasonal storage systems and much more straightforward operational controls. The practical knowledge gained from the installation would be very useful prior to incorporating the seasonal storage technology.

It is anticipated that more attractive economic evaluations of the systems can be discovered when larger greenhouses are investigated, as economies of scale will play a larger role. This should be the focus of future work. Furthermore, more detailed optimization of the systems described herein should be carried out as well as exploring different system architecture and components. The low-temperature system described in Chapter IV could be realized with heat pumps connected in series to further increase the inlet water temperature to the greenhouse. A system involving a bypass to avoid the heat pumps could be useful during the summer months to take advantage of the higher short-term tank temperatures. Furthermore, different solar collector technology, such as evacuated tube collectors, should be explored for their suitability in the greenhouse environment.
APPENDIX A

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Chapter II: Assessing Heating and Cooling Demands of Closed Greenhouse Systems in a Cold Climate

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## Component Variables Utilized in TRNSYS Simulations

Table B-1 - Chapter III – Potential for Large-Scale Solar Collector System to Offset Carbon-Based Heating in Ontario Greenhouse Sector - TRNSYS Component Variables

<table>
<thead>
<tr>
<th>Component Name / TRNSYS Type</th>
<th>Variable</th>
<th>Value</th>
<th>Unit</th>
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</table>
VITA AUCTORIS

NAME: Lucas M. Semple

PLACE OF BIRTH: Windsor, ON

YEAR OF BIRTH: 1987

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