Solar Powered Root-Zone Heating for Seed Germination

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Abstract

A solar-powered heating system is presented, with the goal of providing sufficient heat to the root-zone of germinating plants during late winter and early spring. The system is designed as an alternative to the current heating methods which incorporate the use of energy-intensive heating fans. The newly proposed method of heating aims to eliminate some of the inefficiencies that currently result from using heating fans. The proposed design uses electric heating cables supplied by solar power to create an optimal germination environment. The root-zone heating system is described and tested through multiscale modeling and experimental implementation.

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List of Abbreviations

AC	Alternating Current
BOS	Balance of System
CAD	Canadian Dollars
CRCE	Canadian Renewable Conservation Expense
DC	Direct Current
DHI	Direct Horizontal Irradiance
DNI	Diffuse Normal Irradiance
DOE	United States Department of Energy
ESH	Equivalent Sun Hours
LCD	Liquid-crystal Display
LED	Light-emitting Diode
NEC	National Electrical Code
NREL	National Renewable Energy Lab
PEX	Crosslinked Polyethylene
PV	Photovoltaic
RoHS	Restriction of Hazardous Substance
SAM	System Advisor Model
SIMEB	Simulation Énergétique des Bâtiments
USD	United States Dollars

1. Introduction

At the Horticultural Centre on Macdonald Campus of McGill University, produce is grown and sold to the student and local community. The Horticultural Centre also offers work-study programs and internships for students interested in agricultural production. The Horticultural Centre's season begins in late March when Michael Bleho, manager of the Centre, begins seeding his onion crop. Planting begins in seed trays held in the Horticultural Centre building, where traditional heating ensures an adequate germination temperature. When the onions have germinated, Mr. Bleho moves the seed trays into the greenhouse to continue growth. There, they are heated by four electric fans which supply hot air to the greenhouse. These fans are an inefficient heating technique, as they work to heat the full volume of the greenhouse. This strains energy costs of the greenhouse, and does not necessarily provide targeted heating to the seed trays which need it most. As a result, Mr. Bleho requested that Bioresource Engineering students design a system which heats the greenhouse more efficiently and sustainably, bringing total costs of production down and allowing him to begin the growing season earlier in the greenhouse. This eliminates the need to transport trays from the Horticultural Centre to the greenhouse, and ensures good growth of crops.

The section of the greenhouse which this project concerns is the front half of the building, measuring a length of 14 meters. This section features a centre galvanized-steel table of dimensions of approximately 1100 cm x 250 cm, upon which seed trays are placed. The seed trays in use are made from thermoformed polypropylene, and are standard across the horticultural industry (Greenhouse Megastore). Currently, the greenhouse uses two ceiling fans and two floor fans to ensure proper temperature within the building. The fans work at night to keep germinating plants warm, while sunlight provides heat during the day. The design team will work with Mr. Bleho to replace these fans with a root-zone heating system, aided by advice from members of the Department of Bioresource Engineering and related industries.

1.1. Vision Statement

To design and implement an efficient solar powered root-zone heating system, capable of maintaining optimal seed germination temperatures in the Northern Hemisphere.

2. Literature Review

2.1. Onion Seed Germination

Onions, or *Allium cepa*, are planted from seed or from partly grown bulbs. The Macdonald Campus Horticultural Centre plants their onion crop from seed. Onions are a perennial crop which consist of a root system, bulb, and tubular leaves (Block, 2010). Onions are a monocotyledon plant, whose "primary root is protected by a sheath … which pushes its way out of the seed first" (DuPont, 2012). Onions undergo epigeal germination, in which the cotyledon grows above the soil surface. As can be seen in Figure C1, the radicle initially grows above the soil, and later penetrates the surface to begin growing as part of the root system (Kumar). As the cotyledon grows, it turns green and begins to develop a plumule, which will become a leaf (Kumar). Onion germination is inhibited by light, and therefore requires a steady source of heat during the night. At the Macdonald Campus Horticultural Centre, sunlight ensures adequate temperature during the day; the heating system is required mainly at night, and is critical for onion growth.

The Macdonald Campus Horticultural Centre begins seeding its onion crop in late March, when temperatures outside hover around 0°C. Though onions are generally a hardy crop, there are several considerations which must be accounted for when ensuring that the seeds will germinate successfully. The two main parameters which must be met for germination of any plants are temperature and moisture content.

Temperature affects germination success in three main ways. Unless seeds are germinated, they will deteriorate at a steady pace, and will eventually lose viability. The rate of deterioration is dependent on temperature. Most seeds are initially dormant, and lose dormancy when they are ready to germinate; this also occurs at a temperature-dependent rate (Roberts, 19880. Finally, once seeds have lost dormancy, the "rate of germination … shows a positive linear relation between the base temperature (at which and below which the rate is zero) and the optimum temperature (at which the rate is maximal)" (Roberts, 1988). These relationships clearly define the need for adequate temperature to ensure successful germination. DuPont (2012) states that seeds subjected to any temperatures above or below germination temperature ranges can either harm the seeds, or cause them to enter a dormant period, delaying germination. Furthermore, if seeds are subjected to minimum or below-minimum germination temperatures, effects are felt on the time to germination, the percent of seeds germinated, and the rate of growth after germination (Brown et al, 2015). In fact, studies on the effect of temperature on days until germination have shown that temperatures within the germination range will lead to successful germination within 5 days, while temperatures five degrees above or below the germination range can add over 10 days to the average germination time (Brown et al, 2015).

To best provide for onion seed germination, seeds should be kept between a range of 10 - 35°C. The specific optimum temperature for germination is around 24°C. If kept around this temperature, onion seeds will germinate in four days, a very efficient germination time (Brown et al, 2015). If onions are to be transplanted outside, the seedlings should be 'hardened-off' to prepare for the change in conditions. The hardening-off process requires a fluctuation in temperature between night and day, in order to prepare the seedlings for the fluctuation that will occur in the field. Therefore, a week before plants are to be transplanted to the field, temperatures should be reduced (DuPont, 2012). The optimal temperature range for this stage of growth in the daytime is between 15 to 18°C, while in the nighttime it is between 13 to 15°C (Brown et al, 2015).

Moisture content is also an important parameter for plant germination. Seeds take up water from the soil through direct contact; "as this soil dries, moisture is replaced by capillary action from nearby soil pores, helping facilitate germination" (Brown et al, 2015). In order to create a beneficial germination environment, soil moisture must be maintained at all parts of the growing unit. Soil moisture content is also related to temperature, as soil temperature will affect the availability of water to the plant. In a study conducted in a greenhouse, it was found that maximum temperatures decreased with an increasing soil moisture content, while minimum temperatures increased (Al-Kayssi et al, 1990). "The mere absorption of a given amount of heat by soil," the study states, "does not necessarily assure a rapid rise in temperature" (Al-Kayssi et al, 1990). From the results presented, soil moisture content can be seen to have a beneficial effect on capacity of the soil to hold heat. At night, this effect is even more pronounced (Al-Kayssi et al, 1990). Additionally, increased soil moisture content provides protection to the plant's root-zone by lowering the fluctuation between daytime and nighttime temperatures (Al-Kayssi et al, 1990). Although fluctuation is important during hardening-off, it can be harmful during germination. Providing optimal moisture to the soil will allow germinating seeds to grow more uniformly, reducing risk of crop loss.

There are three main phases of water uptake during germination, during which moisture content is critical for success. The first phase is characterized by a rapid increase of water content. This occurs as soon as the seeds are sowed, and occurs very quickly for small seeds such as onions (Finch-Savage et al, 1992). Following this phase, the seeds enter a relatively stagnant phase of water imbibition, as very little water is absorbed. The length of this phase is determined by the availability of water in soil (Finch-Savage et al, 1992). This phase ends as the radicle begins to grow, and the seed enters phase three, in which water content increases steadily. For onion seeds, this transition step is the most water-sensitive moment. After the seed has entered phase three, and the radicle has begun to grow, moisture content becomes a secondary parameter, while temperature becomes the major influence. Therefore, the step into phase three is the rate-limiting step, which "may control the progress toward seedling emergence" (Finch-Savage et al, 1992). If soil does not hold moisture of a quantity above base water potential, germination progress will stop. Thus, it is critical that at the end of phase two, onion seeds are provided with enough moisture to sustain entry into phase three, and greenhouses must ensure that heating practices do not negatively affect soil moisture content.

2.2. Root-zone Heating

A plant's root zone often exists at a different temperature than the air surrounding it, due to heat transfer and the effect of moisture on the soil. This inconsistency in temperature can lead to yield losses, described in a study where root-zone temperatures resulted in delayed emergence time of seedlings (Wang, 2013). Low root-zone temperatures can also affect water uptake by the plant, leading to potential yield losses even following germination (Wang, 2013). Root-zone temperature is critical to plant growth because the roots help regulate physiological processes within the plant. Wang (2013) states that root-zone temperature can adjust "the rate of physiological processes, such as water and minerals uptake, leaf growth, and metabolite concentrations." In tomatoes, a high root-zone temperature contributed to water uptake, increased enzymatic activity, and nutrient transport (Wang, 2013).

The current design of the Macdonald Horticultural Centre Greenhouse uses fans which heat the ambient air of the greenhouse. This design is often prohibitively expensive, and does not ensure that a uniform supply of heat will be delivered to the germinating plants. Innovative root-zone heating systems allow heat to be focused on the soil of germinating plants, lowering total energy costs and ensuring that all plants receive uniform heat. In a study conducted in a glass greenhouse, bench-top root-zone heating saved half the energy that a more traditional system used (Sachs et al, 1992). Temperatures stayed warm around the surface of the bench, while in other areas of the greenhouse, temperatures were around 5°C lower (Sachs et al, 1992). Temperatures in pots on heated benches ranged between 5 - 10°C higher than in a more traditional heating design (Sachs et al, 1992).

The Macdonald Campus Horticultural Centre greenhouse is a polyethylene sheet greenhouse, with a perforated bench for planting. Polyethylene greenhouses have been shown to have lower ambient air temperatures, due to the properties of polyethylene as a heat-transferring material. Polyethylene is mostly transparent, leading to high amounts of radiation from objects in the room (Bowman, 1972). Additionally, the inner surface of a polyethylene greenhouse has a lower temperature than the same inner surface of a glass greenhouse, leading to heat loss from radiation by the pots in the greenhouse (Bowman, 1972). Through calculations performed in the Macdonald Campus Horticultural Centre, the thermal efficiency of the polyethylene greenhouse is around 1.86%. This is the thermal efficiency without any additional heat sources. Heat is exchanged by convection, radiation, and evaporation in a greenhouse, as air around the pots, surfaces, and moist soil moves. Therefore, the importance of air circulation must not be understated. Root-zone heating enables free air movements above the pots, ensuring that heat will be distributed to all plant zones.

At night, the temperature of the surface of a pot has been found to be between the average ambient air temperature and the surface temperature of the greenhouse. As previously stated, the surface of the greenhouse can have a very low temperature, due to high heat loss. Therefore, it is especially prudent to examine augmented heating systems in polyethylene greenhouses, which will suffer heat losses in the night throughout the season. Using root-zone heating will ensure that the perforated bench will maintain a steady warm temperature for plant success, and will "optimize conditions [for propagation] and speed the rate of plant growth" (Brown et al, 2015).

Temperatures at the surface of greenhouse planting structures are also affected by the cover placed over them. The majority of heat lost in a greenhouse is lost through the roof of a greenhouse, especially in polyethylene greenhouses (Hartmann et al, 2014). Because the temperature of the surface of the greenhouse is significantly colder than the temperature at pot surface, heat loss occurs at a large rate from the pot to the roof of the greenhouse (Hartmann et al, 2014). To reduce these losses, covers can be placed between the roof of the greenhouse and the propagation table. The main technique used to reduce these heat losses is known as a thermal curtain. A thermal curtain is a piece of material placed "between the crop and the propagation house roof and walls" (Hartmann et al, 2014). The curtains serve a purpose in all seasons - during the winter, they reduce heat losses and therefore can reduce the cost of heating the greenhouse, while during the summer, they can reduce heat stress on plants and decrease the amount of cooling needed (Hartmann et al, 2014). Through the use of innovative thermal curtains, root-zone heating systems can be made highly efficient and can reduce crop losses.

2.3. Daytime Warming and Nighttime Cooling

When the sun rises in the early morning, sunlight warms the ground of the earth, and the ground warms the air in contact with it mainly by thermal conduction (Ahrens, 2012). This warming process only occurs within a few centimeters of the ground because the air is a relatively poor heat conductor that cannot conduct much heat. As the sun rises higher and higher in the sky during the day, more and more energy is being emitted on the ground. This effect then makes the air in contact with the ground even warmer than the early morning.

In late afternoon or early evening, the earth's surface and air above start to give up more energy than they receive; therefore, they begin to cool, in a process called radiational cooling. This is because both the ground and air above the ground cool by radiating infrared energy that they have gained from the sun (Ahren, 2012). The ground, a much better radiator than air, is capable of cooling more quickly. As a consequence, usually shortly after sunset, the earth's surface is slightly cooler than the air directly above it, and this nighttime cooling begins. This radiational cooling phenomenon must be considered in this project because of the temperature drop at nighttime, when the system is still operational.

2.4. Heat and Mass Transfer

An analysis of the heat and mass transfer of the root-zone heating system can be done to gain a better understanding of the mechanisms at work.

Joseph Fourier, a French mathematical physicist, developed an analytical theory of heat in 1978, called Fourier's law of heat conduction (Fourier, 1878). The governing equation generates an analytical solution of heat transfer and the solution is relatively accurate in macroscale solids for engineering design. Thermal energy is conducted in solids by two individual modes: lattice vibration and transport by free electrons (Bergman and Incropera, 2011). A comparatively large number of free electrons move about in the lattice structure of good electrical conductors. The free electrons can carry thermal energy from a higher-temperature region to a lower-temperature region, in the same way that they transport electric charge. Moreover, energy may be transmitted as vibrational energy in the lattice structure of the material. Thermal conductivity, a key parameter in Fourier's law, quantitatively describes the lattice vibration and the motion of free electrons.

In contrast to conduction heat transfer, convection emphasizes heat transfer in fluids. A classical convection scenario describes a hot plate of metal which cools faster when placed in front of a fan than when exposed to steady air. This scenario is defined by Newton's law of cooling, which involves the convection heat-transfer coefficient. The coefficient is also known as the film conductance, and is often determined experimentally for complex systems. Analytical relations might analyze the problem of heat transfer in fully developed laminar tube flow. For instance, the Navier-Stokes equation makes use of dynamic viscosity and density of fluids to simulate the flow velocity (Temam, 2001). However, empirical correlations are often of greatest practical utility for design and engineering objectives, due to the occurrence of undeveloped laminar flow, turbulent-flow systems, and flow systems with large temperature gradients. A simple empirical correlation proposed by Sieder and Tate (1936) is a great example of evaluating laminar heat transfer in tubes. Moreover, decades of research have shown that there exists a velocity and temperature jump at fluid-solid boundaries (Shu et al., 2017), which calls for potential design on the addition of a solid boundary in a fluid or mostly fluid system.

Heat may also be transferred through a perfect vacuum and the mechanism in this scenario is electromagnetic radiation. Thermal radiation is defined when electromagnetic radiation propagates because of a temperature gradient (Bergman and Incropera, 2011). The propagation of thermal radiation occurs in the form of discrete quanta, and the Stefan-Boltzmann law describes the total energy emitted as proportional to absolute temperature to the fourth power.

Mass transfer is scale dependent. On a macroscopic level, mass transfer is usually treated with respect to fluid mechanics. However, there exists a mass transfer on a microscopic level as a result of diffusion from regions of higher concentration to regions of lower concentration. The physical mechanism of diffusion also involves collisions between molecules, and the diffusion rates rely on the molecular velocity (Bergman and Incropera, 2011). Consequently, a dependence of the diffusion coefficient on temperature occurs, since the temperature represents the average molecular speed on a microscopic scale. When the mass diffusion results from a temperature gradient in a system, it is defined as thermal diffusion. The aforementioned two effects are termed coupled phenomena and may be treated by the methods of irreversible thermodynamics.

3. Design Approach

3.1. Design Criteria

Design criteria were established through consultation with the client, Mr. Bleho, as well as through discussion with mentors, advisors, and technicians. The following four design criteria were established.

Functionality. Of utmost importance was the function of the system. The proposed design must reach the optimal germination temperature without the addition of another heating system, such as electric fans.

Safety. The proposed design must pose no risks to the safety of the users, staff, or owners of the Horticultural Centre. Each element of the system must be carefully designed to minimize any risk of danger. The overall system must be discussed with the relevant facilities management staff, to ensure that it meets all safety codes and engineering standards.

Low Maintenance Requirements. The system must require minimal maintenance on the part of any Horticultural Centre staff. Apart from snow removal from the solar panels when necessary, the system should not require intervention by the Horticultural Centre staff to ensure its operation. The heating system should be self-sustaining, in that it does not need to be turned on at any point; it remains operational throughout the growing season. The system should also use parts which can be replaced at a reasonable and justifiable cost.

Ease of Operation and Reliability. The system must be easy to operate and understand. Mr. Bleho and the staff and students of the Horticultural Centre should be able to understand the process of the designed system.

3.2. Design Parameters

After the design criteria were established, design parameters were defined. The following conditions must be met in order to achieve the innovative goals of this project, and serve to define the scope and objectives of the design.

Root-zone Heating. The project aims to address the problem of providing adequate propagation temperatures through root-zone heating. Through bench-top heating cables, augmented by a heating membrane, heat will be provided directly to the soil in which seeds begin to germinate. The cables will be in direct contact with the polypropylene seed trays, providing point-source heat at contact and radiative heat through the heating membrane. The temperature reached by the root-zone heating system should be within the range of 18 - 21°C. These temperatures will ensure germination conditions are met within the soil. The temperatures provided here are optimized for onion growth, as onions are the first crop grown in the season; however, the system should also be adjustable for other crop requirements.

Additionally, the system will provide an innovative system to combat heat loss. The Mini-Greenhouse will provide a cover between the propagation bench surface and the roof of the greenhouse. This zone is the primary zone of heat loss in a greenhouse; therefore, the addition of a Mini-Greenhouse will reduce heat losses in the system. Any heat not absorbed by the soil and germinating plants will be trapped by the Mini-Greenhouse, and returned to the soil. The Mini-Greenhouse will allow the root-zone of plants to remain at a steady warm temperature, even when the outside air temperature, and by definition the surface of the greenhouse, fall to temperatures below freezing.

Sustainability. The use of solar energy aims to reduce the overall ecological footprint of the Macdonald Campus Horticultural Centre. Solar energy is a renewable and non-polluting form of energy, which is a more sustainable alternative to coal, fossil fuels, or even hydroelectric energy. Relying on solar to meet the energy demands for the majority of the growing season will reduce the conventional energy needed in the greenhouse. Additionally, the use of solar power to heat a root-zone system will reduce the total amount of energy used in the greenhouse, as it heats only the critical root plane of the greenhouse, rather than the full air volume. The use of solar energy will contribute to the overall reduced carbon footprint of the campus, making it a leader in innovative uses of renewable energy.

3.3. Alternative Designs

Several alternative designs were examined as options for the root-zone heating system. The technique of root-zone heating has been used in varying ways in greenhouses for many years.

Each alternative design was analysed as a potential system for the Horticultural Centre greenhouse.

Heat Propagation Bench.

A commonly-used technique in small scale heating systems is the heat propagation bench. In a heat propagation bench, sand is used as an insulating medium. An 18-centimeter-deep raised bed is constructed and lined with a heavy-duty plastic liner, to ensure that no leakage occurs. The raised bed is then filled with sand. Heating cables or water pipes are placed in the sand to create heat. Heating cables provide heat directly to the sand, which will transmit it to the root zone (Fluck, 1992). Water pipes will circulate hot water through the system, and have the added benefit of providing moisture to the sand through water vapour. For both water pipes and heating cables, the heating elements should be placed eight to 10 centimeters below the surface of the sand (DuPont, 2017). The system is then covered by a plastic sheet, upon which seed trays can be placed. The sand acts as a radiative heating system, providing heat generated by the heating elements to the root zone of growing plants.

Heat propagation benches hold an inherent higher risk than other systems, due to the number of components and materials required. The risk of contamination of elements is greatly increased. Additionally, the system poses a risk of greater inconvenience to the client and users. The system would not allow for water drainage, a main concern of the client. Mr. Bleho was also concerned that the system would create an unnecessary mess in the greenhouse. Additionally, a heat propagation bench would require more maintenance by the greenhouse staff. Heat propagation benches carry an inherent risk of material failure, as many components are required. Overall, the heat propagation bench was established to be unsuitable for the Horticultural Centre system.

Hydro-radiant Heating.

Two separate hydro-radiant heating systems were examined. Hydro-radiant heating systems utilize a hot water heater and heat exchanger to allow hot water to flow through pipes. The hot water radiates heat from the pipes to the root-zone of plants. This system uses crosslinked polyethylene (PEX) piping, which is resistant to deterioration from heat and other climatic factors. PEX piping cannot be directly attached to a water heater; thus an additional length of metal pipe must be used for the first section. The hydro-radiant heating systems can also be installed directly into a pre-existing hot water system (BioTherm).

The first system examined is an ‘on-bench’ hydro-radiant system. In this system, hot water pipes are placed flush to the surface of the propagation bench, either above or below the table. Hot water passes through the piping system, and pots or seed trays are placed directly on the benches. The hot water radiates heat to the trays, providing the system with enough heat to sustain growth (BioTherm). The second system examined is the ‘under-bench’ hydro-radiant system. In this system, two larger pipes are placed at a distance above the ground of the greenhouse and below the propagation table. These pipes then radiate heat up to the bench (BioTherm).

Both of these systems could be used with a solar thermal collector. A solar thermal collector absorbs and concentrates sunlight to heat a fluid. In cold climates, the fluid passing through a solar collector is usually a glycol-water mix, to ensure that the fluid does not freeze in sub-zero temperatures. Once the heat transfer fluid is heated, it is passed to the water tank, where a heat exchanger transfers the heat carried by the fluid to water. The resulting hot water can be transferred to an on-bench or under-bench system.

Upon close examination of this system, it was determined that the hydro-radiant system was an over-complication of the necessary elements for the Horticultural Centre greenhouse. The available hot water tank posed a problem, as it was too tall for the greenhouse to comfortably fit. The eventual placement of the hot water tank would have caused accessibility problems for the staff of the greenhouse. Additionally, it was determined that the hydro-radiant system would cause unnecessary maintenance strain on the greenhouse staff. This was due to the need for yearly drainage of the whole system, as well as the maintenance and infrastructure needed to ensure that no bacteria were affecting the water quality. The temperature required to maintain good water quality in the heating tank was far above that needed for the system, leading to a high required temperature drop in the water flowing into radiant pipes. It was also found that the solar collector available for this project was not very efficient, making its installation cost much higher than its eventual profit. The additional cost of a heat exchanger, glycol mix, and pumps were deemed to be insurmountable and unnecessary costs. Therefore, this system was not chosen.

Electric Heating Elements.

The use of heating cables was also examined. In this system, heat-generating electric cables are placed directly on the surface of the propagation bench. They can also be placed on a heating membrane, which allows heat to radiate throughout the propagation table. Through point-source heat and radiative heat, these cables provide heat to the seed trays above them. Because the cables themselves are the heating element, they require very little maintenance after being plugged in. The temperature produced can be regulated using a programmable thermostat, allowing them to be used for more than one crop and throughout the beginning of the growing season.

Additionally, soil heating cables can be used with a solar photovoltaic (PV) cell, a solar energy system which can be used to much greater efficiency in the winter than solar thermal collectors. Most PV cells are made from crystalline silicon, which allows electrons to be excited and flow to generate electricity (SolarGreen, 2018). The energy generated can be transferred to power electric heating cables. PV solar arrays have a life expectancy of up to 25 years and do not require large amounts of maintenance (U.S. Department of Energy, 2016).

3.4. Design Selection

After deliberation among the team and with the client, the decision was made to use electric heating cables and a solar photovoltaic cell as the root-zone heating system. This system was chosen because of its efficiency, reliability, and negligible necessary maintenance. The electric cables were found to be highly efficient, affordable, and easily accessible. Upon testing the selected heating cables, the decision was made to add a heating membrane to the system. This augmented the point-source nature of the heating cables by adding a radiative heating effect, ensuring that uniform quantities of heat are being provided to all plants, regardless of location. The heating membrane is to be placed on the perforated propagation table, and drainage holes are to be drilled at equal spacing, to ensure that no standing water from irrigation remains in the root zone for an extended period of time. The cables are placed within the heating membrane, and seed trays are placed directly on top of the heating cables. This layout can be seen in Figure A1, in which the greenhouse is shown with the root-zone system on the propagation bench. The decision was also made to use a solar photovoltaic cell, as its efficiency during the winter was more reliable than a solar thermal collector. The solar PV cell will be grid tied, and a solar inverter will be used to convert the energy generated into usable electricity.

4. Design Implementation

In order to meet the heating requirements of the greenhouse, the design consists of two primary components: the heating cables and heating membrane. To minimize electricity consumption required to heat the cables, the design also incorporates the use of photovoltaic solar energy through a panel set-up connected to the grid. To facilitate understanding of the design, it is helpful to first discuss the current set up of the Horticultural Centre hoop greenhouse.

4.1. Description of the Hoop Greenhouse

The Horticultural Centre's hoop greenhouse is made of semi-circular metal frames that are covered by two layers of polyethylene sheets, commonly referred to as poly film (Hinsley, 2012). The benefits to using poly film include its lightweight nature, requiring minimal support infrastructure, and that it is also permeable to both carbon dioxide and oxygen, allowing for the necessary air exchange required by plants. A double layer of poly film can also reduce heat losses by as much as 30-40% in the winter as compared to glass. Although it reduces light transmittance by 15%, it helps scatter the sun's rays so that they can reach plants from multiple directions and at multiple locations within the hoop greenhouse (Washington State Extension).

Figure C2 shows the precise location of the Macdonald Campus hoop greenhouse of interest. The greenhouse is positioned 6 meters from another similar hoop greenhouse, also operated by the Horticultural Centre.

4.2. Heating Cables

Selected for this design are the EasyHeat De-icing cables in both 240 ft (73 m) and 100 ft (30 m) lengths, both operating at 5 Watts per foot, and compatible with a standard 120 Volt outlet. When selecting the ideal heating cables for this design, several attributes of each cable had to be evaluated, those being, durability, safety and load, heat generation, and capital cost.

Durability. The selected cables are traditionally used on rooftops to melt snow and are made to withstand brutal outdoor winter conditions. The cables are therefore more than capable of handling the stresses of the lifting and dropping of trays they recieve when in the greenhouse. The only potential durability issue with the cables is the risk of rust damage. For economical reasons, rust resistant cables could not be purchased; thus, the design was engineered to use a membrane to protect the cables from rust, among other purposes, as explained in the next section.

Safety and load. To ensure that running electric cables throughout the wet environment of the greenhouse is safe, it is key that the cables are installed by a certified professional, and that they are water resistant throughout the product's lifetime. As mentioned earlier, the cables are traditionally used outdoors during the winter to melt snow, and have no problem handling exposure to water. Furthermore, all cables are installed by a certified electrician who encases the plugins with a metal shield to ensure any wildlife (mice etc.) that might be in the greenhouse is unable to damage the cables. As for the load, the greenhouse is only safely able to support plugins at a 15 Amp load. Thus as a margin of safety and to prevent outages, the maximum load any plugin possess is 12 Amps, leaving a conservative 3 Amps for fluctuation.

Heat generation. The main purpose of the cables is to generate enough heat to maintain optimal seed germination temperatures in the greenhouse. Throughout experimentation, it was determined that the cables not only generate enough heat, but the spacing between the cables is vital to heat generation. Designing for the appropriate quantity of cables and spacing of cables was done through experimentation. Prior to experimentation, the initial spacing between the cables was set at 3.5 inches (8.88 cm), as seen in Figure A2; however, the experiment was conducted with 2.5 inches (6.35 cm) of spacing between the cables, as the prior estimate was deemed too hopeful. As seen in Figure A3 a 2.5 inch (6.35 cm) spacing was chosen, resulting in the use of five 240ft (73 m) and one 100ft (30 m) cable. Any additional cables can be used to insulate other parts of the greenhouse, or for other tasks around the McGill Horticultural Centre. Further explanation into the exact heat generation and temperature differences caused by the heating cables is explained in section 5.2.1.

Finally, the cables are relatively inexpensive compared to their competitors, and fit well into the budget allowing for more financial flexibility without sacrificing design effectiveness. Finances are vital to the stakeholders of this project and finding innovates ways to utilize cost effective products is key to the design's success.

4.3. Heating Membrane

The Schluter heating membrane is a flat polyethylene membrane with octogonal extrusions of 1 inch (2.54 cm) width, each spaced 0.5 inches (1.27 cm) from each other. The membrane is of polyethylene composition and the underside of the membrane has a protective felt layer. This specific membrane was selected based on several attributes such as, versatility, durability, heat distribution properties, insulation, and waterproofing.

In this design, the Schluter heating membrane is responsible for covering approximately 292 ft^2 (27.12 m^2) of galvanized steel table. For this, both a versatile and durable membrane is required. To fit to the table dimensions [436in (11.07 m) x 96in (2.43 m)], the membrane is cut to remove excess dimensions; the Schluter heating membrane allows for this customization. Additionally, the lifetime of the product is important. All of the design hardware has a lifetime of 10 or more years, and correspondingly the durable design of the Schluter membrane is able to endure constant use without the user having to fear damage. It is this versatility and durability that is required of any membrane considered for this design.

Distributing the heat generated by the cables is vital to the consistency and effectiveness of this design. The heating cables generate a very point-source heat, which does not radiate very well. The Schluter heating membrane is traditionally used for heating cables running underneath heated bathroom floors, and does not conduct heat, but directs it upwards. This is perfect for this design, as it is key that all the heat generated by the cables is focused upwards and distributed throughout the trays above. Additionally, the felt protective layer, along with the membrane itself, greatly reduces the impact of the cold steel table on the above trays. The membrane insulates the bottom side of the heating set up, preventing the cold steel from having a negative impact on the heating of the trays. This is a vital parameter of the design.

Additionally, although the cables themselves are waterproof, to some degree the table is not. The galvanized steel table shows several signs of rusting. This emphasizes another benefit of the Schluter heating membrane. The cables are not rust proof and being exposed to rust could potentially damage the lifetime of the design. The heating membrane has a protective felt layer, and is relatively thick polyethylene, thus protecting the cables from any potential rust exposure. Likewise, the membrane somewhat protects the table from water exposure as well.

The above physical and chemical attributes, along with the structural ability of holding the cables tightly in place, are key to why the Schluter membrane was chosen for this design. The final attribute leading to the choice of the Schluter membrane is the financial aspect. As discussed in section 6.4, the membrane is reasonably priced and fits into the proposed budget.

4.4. Solar Photovoltaic System: Overview

In general, a solar photovoltaic system is comprised of a few key components: photovoltaic modules, an inverter to output alternating current (AC), a battery to store direct current (DC), and a charge controller that regulates the flow of charge to a battery to prevent overcharging or discharging. These basic components are displayed in Figure C3 a). The system used for this design project to meet the energy demands of the heating cables is a batteryless grid-tied solar system, similar to that detailed in Figure C3 b) but without the charge controller and battery which are often used to store excess electricity produced. The details of this system and justifications for the design selections are discussed in the following sections.

In addition to the components in Figure C3, a mounting structure is required to position the solar panels in the appropriate orientation towards the sun. Cables are also needed to connect the panels, and Y-branch multi-contact solar connectors (Sino Voltaics, 2015) are included to allow for expansion of the solar energy system and to incorporate additional solar panels in series. It can be seen in Table C2 in the appendix that the Y MC4 connectors, with a 4 mm diameter contact pin, are compatible with the selected photovoltaic modules used in this design which are detailed in the following sections. In addition, it is important to select cables that are sufficient in thickness to be able to minimize resistive losses. All these components that are required to make up the solar energy system are referred to as the Balance of System (BOS) (Jager et al, 2014).

For clarity of discussion and reference to the design elements it is useful to define the scales of reference to a solar system: the solar cells make up photovoltaic modules, which in turn make up photovoltaic panels. Multiple panels can be connected in series to form an array. A clear depiction of this concept is displayed in Figure C4. The following sections discuss the essential elements and considerations for designing a solar energy system.

Partial shading and bypass diodes. The performance of PV modules can be hindered by shading which can occur due to the presence of nearby trees or falling leaves. In a system of series-connected solar cells, shading of one cell reduces the current flowing through it significantly and thus limits the current of the overall module. To overcome this large impact of shading on the overall system, bypass diodes are integrated into the photovoltaic modules. Bypass diodes are connected in parallel to solar cells or panels to provide an alternative path for current to flow in the event that a cell is shaded. In this way, the module can continue to output power but at a reduced voltage (Electronics Tutorials, 2018).

Battery. The solar system design will not include a battery for several reasons. First and foremost, a battery increases the installation costs and technical requirements needed for the system to operate. Furthermore, because power outages are relatively infrequent at the Horticultural Centre, as compared to areas with poor electrical infrastructure, a battery is not necessary for accepted levels of continued and uninterrupted power supply. Finally, on the rare occasion that the power does go out, it is assumed that the heated soil will be able to sustain adequate temperatures for a few minutes until the power is up again and the heating cables are once again functioning (Home Power).

Grid-Connected vs. Off-grid Photovoltaic Systems. In general, grid-connected or grid-tied systems can be cheaper and simpler to install as they do not require a battery to store energy. Other benefits of using a grid-tied system include that it does not require as many components as an off-grid system, such as the charge controller (Home Power). The connection of the grid-tie inverter, which outputs alternating current, to the grid allows the system to essentially use the grid as a virtual battery (Energy Informative, 2013). Due to the large variation in power output of the solar system depending on seasonal and meteorological changes, more or less electricity is often generated than can be consumed by the load at a given time. In this case it may be helpful to purchase and sell back energy to the utility company. Net metering is a service provided by utilities that allows energy generating companies, such as Hydro-Québec in Quebec, Canada, to purchase any excess energy generated by residential energy systems. This requires that the power meters used in the residential system be compatible with net metering. The specifications of the net metering agreements provided to the Horticultural Center of Macdonald Campus are elaborated on in Section 4.6.3.

Location and Orientation. In the Northern Hemisphere, between the latitudes of 23 and 90, photovoltaic cells are oriented at an azimuth angle of 180° or towards the south (Bas, 2011). The general rule of thumb for the angle of tilt is to orient the panels at an angle equal to the latitude of the location, measured from the horizontal (Lighting Research Center, 2006). In considering the appropriate location of the solar panels, it is recommended that the panels be situated north or north-east of the greenhouses portrayed in Figure C2 to meet the space requirements of the panel layout as well as minimize shadowing due to nearby building or objects.

4.5. Solar Photovoltaic System: Component Specifications

The modules and inverter selected for the solar system design are produced by SunPower. SunPower has been ranked as one of the top competitors, alongside LG and Panasonic, in the solar panel manufacturing industry based on their efficiency, price and 25-year warranty. Furthermore, SunPower is commonly considered the best solar manufacturer on the market due to its efficiencies of 22% and higher (Energy Sage, 2018). For this reason, SunPower photovoltaic modules and inverters are used in the analysis to provide the Horticultural Center with the best value per cost of solar energy.

4.5.1. Photovoltaic Module Selection

The photovoltaic module selected for the solar energy analysis is the SunPower X21-345. Each module consists of 96 mono-crystalline Maxeon™ Gen III solar cells, which are most commonly connected in series to minimize resistive losses. The connection of the cells in series can be confirmed by comparing the short circuit current, I_{sc}, of the overall module in Table C1 to that of the individual Maxeon™ cells, which are of similar magnitude. In addition, the overall voltage of the module of 68.2 V is approximately 96 times that of the open circuit voltage of each cell which ranges from 0.713 to 0.730 V, presented in Table C3, depending on the performance mode.

The Maxeon™ Gen III solar cells, also produced by SunPower, are composed of silicon wafers and have been shown to produce 25-35% more power compared to conventional silicon cells. Benefits to using these cells also include that they are corrosion and crack resistant and are eco-friendly due to being lead-free and compliant to the Restriction of Hazardous Substance (RoHS) regulations (SunPower Corp, 2017). A diagram and technical specifications of the Maxeon™ Gen III solar cells are included in Tables C3 and C4 and Figure C5.

The X21-345 module has a peak rated power of 345 W_p and an average rated efficiency of 21.5% (SunPower Corp., 01-2017). Further technical, operational, and mechanical specifications of the SunPower X21-345 are summarized in Tables C1 and C2 in the appendix, and will be referred to in the following analysis. The rated parameters in Table C1 of the SunPower module are determined under Standard Test Conditions (STC) of 25ºC, an irradiance of 1000 W m^{-2}, also referred to as one equivalent sun, and an air mass (AM), or thickness of the air at the equator, of 1.5G (Jager et al, 2014).

The difference in efficiencies of the Maxeon™ Gen III cells and that of the overall module, of 23% (SunPower Corp., 2017) and 21.5% on average, respectively, are due to resistive losses in the connections between cells. Two different efficiencies are often used in describing the performance of modules: aperture area efficiency and module efficiency. The aperture area refers to the area that is active in receiving solar rays and generating electricity, that is, the area covered by cells. In contrast, the module efficiency accounts for both the aperture area and the dead areas on the module which do not generate electricity. For this reason, the aperture area efficiency of a module is larger than that of the module efficiency.

The fill factor is another term that is used to describe the change in solar cell performance. It is computed as shown in Eq (1) by comparing the maximum power (MP) output generated by a cell to the rated or theoretical power.

$$\mathrm{FF} = \frac{P_{max}}{P_{theoretical}} = \frac{I_{MP} * V_{MP}}{I_{SC} * V_{OC}} \quad (1)$$

(National Instruments, 2017)

Where FF is the Fill Factor and I_{sc} and V_{oc} are the short circuit current and open circuit voltage respectively.

4.5.2. Inverter Selection

The grid-tie inverter selected for the design is the SPR-5000x. An illustration of the front panel features is included in the appendix in Figure C6. The inverter consists of a wiring/disconnect box which is used to make AC, DC, and ground connections and is standard for all North American inverter models. In addition, a DC/AC disconnect switch is included which meets the United States' National Electrical Code (NEC) Section 690 requirements for disconnects (SunPower Corp., 2007). This functions as a safety switch which monitors electrical flow and disconnects when a fluctuation, disturbance or dangerous peak is detected in the electrical current (Marshall Wolf Automation, 2017). The front panel of the SPR-5000x also consists of an LCD display screen, LED indicators, and 5 mounting slots.

4.6. Solar Photovoltaic System: Design Specifications

There are two paradigms that may be used to design photovoltaic systems. First, a system may be designed such that the power generated and the load consumed by the appliances, in this case the heating cables, are identical. In the second approach, the design is scaled according to economic returns. The following design methodology uses a mix of these two approaches by first determining the load requirements and solar system energy output independent of one another. It then compares the two values to ensure that the solar system operating throughout the year at least meets, if not exceeds, the demands of the heating cables operating for the months of March and April as required by the Horticultural Center.

4.6.1. Determining Operational Time and Total Load Requirements

The solar system is designed to meet the load requirements of the heating cables. Based on the experimental results presented in Section 5.2.1, it is determined that the heating cables will operate mostly during the night for approximately 12 hours a day. The heating cables will be used throughout the months of March and April, as indicated by the client Mr. Bleho, for a total of 61 days out of the year.

The total load requirements are determined based on five 240-foot and one 100-foot heating cable. With a load rating of 5 W per foot, this gives a total load requirement of

$$[(5 \times 240 \text{ ft}) + 100 \text{ ft}] \times 5 \text{ W ft}^{-1} = 6500 \text{ W} \quad (2)$$

Operating for 12 hours a day: 6500 W * 12 hours day^{-1} = 78 kWh day^{-1}

The daily load of 78 kWh is supplied to the heating cables through alternating current at 120 V. It is important to point out that the electricity generated through the inverter and that received by the cables are not the same. Rather, the electricity generation by the solar power system is considered to indirectly offset the load requirements of the heating cables, and feeds the grid throughout the year whether or not the heating cables are in operation.

The solar system is designed such that it operates throughout the entire year when solar radiation is available for energy generation. The energy consumed by the cables however is only consumed for 61 days. This gives a total annual load requirement of

$$78 \text{ kWh day}^{-1} * 61 \text{ days per year} = 4758 \text{ kWh per year} \quad (3)$$

The power output of the solar system will be computed in the following section independent of the load requirement, assuming full operation throughout the year.

4.6.2. Determining the Number of Photovoltaic Modules and Solar Array

According to the Simulation Énergétique des Bâtiments (SIMEB), Ste-Anne-de-Bellevue received approximately 1205 kWh m^{-2} of total solar radiation on a horizontal surface, or global irradiance (University of Oregon, 2002), in the year 2017 (SIMEB). The average annual solar irradiation can be expressed in terms of annual equivalent sun hours (ESH) by dividing global irradiance by 1 equivalent sun, or 1000 W m^{-2} as follows

$$\frac{1205\ kWh\ m^{-2}}{1\ kW\ m^{-2}} = 1205\ h \quad (4)$$

This equates to 1205 hours per 365 days or 3.3 equivalent sun hours per day.

To account for energy losses through system components such as the inverter, the capacity of the solar panels is estimated with a 17% energy loss, or a DC to AC ratio of 1.20 (Jager et al, 2014). Considering both daily equivalent sun hours and system energy losses, the annual power output per each SunPower X21-345 module, with a peak power rating of 345 W, is as follows

$$(345 \text{ W} * 1205 \text{ h}) / 1.2 = 346.44 \text{ kWh} \quad (5)$$

To meet the total load demand of 4758 kWh per year, at least 13.73 modules are required to be installed. For ease of design, 15 modules will be used for a total installed capacity of

$$346.44 \text{ kWh} * 15 \text{ modules} = 5196.6 \text{ kWh} \quad (6)$$

The 15 modules will be set up in three parallel strings, and each string will consist of five modules connected in series. A setup of three strings connected to the SPR-5000x inverter and grounded is included in Figure C7. This setup of modules will give the following inputs to the inverter, which are calculated using the rated open circuit voltage and short circuit currents of the SunPower X21-345 as presented in Table C1.

$$\text{Total voltage} = \text{Number of modules in series per string x } V_{OC} \quad (7)$$
$$= 5 \text{ x } 68.2 \text{ V} = 341 \text{ V}$$
$$\text{Total current} = \text{Number of parallel strings x } I_{SC} \quad (8)$$
$$= 3 \text{ x } 6.39 \text{ A} = 19.17 \text{ A}$$

These fall below the inverter's rated input parameters of an absolute maximum array open circuit voltage and short circuit current of 600 Vdc and 24 Adc, respectively (SunPower Corp., 2007).

4.6.3. Net metering for the Horticultural Centre of Macdonald Campus

The Horticultural Centre is currently billed by Hydro-Québec at Rate G for its energy demands, making it eligible for the net metering service if the total energy produces is less than 50 kW (HydroQuebec). With an installed capacity of 5175 W according to the previously described design, the Horticultural Centre could sell back any unconsumed energy for a profit.

The total installed capacity of the solar system is calculated as 5196.6 kWh in Eq (6). Since the heating cables required a total of 4758 kWh for the 61 days of operation there remains an excess of 5196.6 kWh - 4758 kWh = 438.6 kWh which can be sold back to Hydro-Québec for kWh credits. In doing so, when the Horticultural Centre requires power, it will first spend kWh credits before beginning to purchase power. Another way of describing this is to say that Hydro-Québec purchases the excess power generated at the retail price of $0.0971/kWh. This is incorporated into the financial analysis in Section 6.4.

4.7. Energy Modeling

The above design process was performed via calculations to size the solar system to meet the energy demands of the heating cables. Another approach to size the solar system is to use an energy modeling software.

The energy modeling software used is a free software provided by the National Renewable Energy Lab (NREL) of the US Department of Energy (DOE) called System Advisor Model (SAM). The inputs to the SAM analysis include the weather data from the location of interest along with the technical specifications of the modules and inverter used.

The data input used in the SAM analysis varies slightly from that used in the calculations in the previous section. Primarily, the weather data used is from Montreal, Quebec as opposed to Ste-Anne-de-Bellevue due to completeness of data available online. The simulation estimates annual solar equivalent sun hours of 1251 hours as opposed to the 1205 hours estimated above. It is therefore expected that that the energy yield simulated through SAM using 15 photovoltaic modules will be larger than that calculated in Eq (6).

The orientation of the panels was selected by experimenting with a variation of azimuth angles and tilt angles. It was found that changing the azimuth angle from 180° only decreases the energy output and therefore the azimuth angle is kept at 180°, orienting the solar modules towards the south. For tilt angle, although the general rule of thumb states that solar panels should be oriented according to the latitude of the location, in this case a tilt of 45°, it was found that a 35° title angle produces the maximum energy output and is thus used.

Results of the SAM analysis using the SunPower X21-345 modules and SPR-5000x inverter yield a total annual energy production of 6472 kWh, for a total module area of 24.5 m^2. As expected, the modeled energy generation is greater than the 5196.6 kWh calculated in Eq (6). The energy yield is 1251 kWh per kW of installed capacity, with a performance ratio of 0.83 and capacity factor of 14.3%. The performance ratio is the ratio of DC to AC yield, and the capacity factor is the ratio of actual power output to the theoretical power output if the system had operated at nominal power for the entire year (Vashishtha, 2012).

The peak energy production occurs during the month of July with a monthly DC energy output of 806.146 kWh and AC energy output of 758.322 kWh. The monthly AC and DC energy outputs are summarized in Table C6 in the Appendix. Figure C8 displays the average direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI), by month. The DNI describes the direct radiation received by the solar panels, as opposed to rays which are reflected off of or transmitted through other objects (Homer Energy). The DHI describes the solar radiation received by a horizontal surface after it has been scattered by the atmosphere (PVPerformance Modeling Collaborative). For further depiction of the system losses, a diagram has been included in Figure C9 in the appendix.

5. Models and Experiments

5.1. Multiscale Modeling

To systematically simulate the heating system in the greenhouse, a multiscale model is proposed in this section. Arranged into two parts, it begins with a macroscale model that simulates the buoyancy-driven heat convection inside the Mini-Greenhouse and the outer greenhouse. The significance of the heating cables and the Mini-Greenhouse is investigated by making a comparison of corresponding thermal efficiencies. Compared with a thermal efficiency of 1.86% in conventional greenhouses, the proposed system with heating cables and the Mini-Greenhouse reaches a maximum of 14.60% thermal efficiency. The second part then focuses on the heat conduction of the soil including thermal contacts between the plastic tray and the soil. A three-dimensional transient heat conduction model is proposed to visualize how the heat from the heating cables propagates through the soil. The temperature of the germination environment is also evaluated to be from 16.74°C to 18.22°C under fairly cold weathers (typically late February and early March in Montreal, Quebec).

5.1.1. Macroscale: Buoyancy-Driven Heat Convection in Greenhouse

The objective of a macroscale model in this project is to evaluate the effectiveness of the two innovative designs, the heating cables and the Mini-Greenhouse. This goal can be achieved by modeling the thermal circulation based on natural heat convection and laminar flow. The governing equations are the Navier-Stokes equation and the heat balance from the first law of thermodynamics, as expressed in Eq (9) and Eq (10).

$$\rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla \bar{p} + \mu \nabla^2 \mathbf{u} + \frac{1}{3}\mu \nabla (\nabla \cdot \mathbf{u}) + \rho \mathbf{g} \tag{9}$$

$$\rho c_p \mathbf{u} \cdot \nabla T - \nabla \cdot (k \nabla T) = 0 \tag{10}$$

ρ, u, p, μ, g, c_p, T, and k are the density, the flow velocity, the pressure, the dynamic viscosity, the gravity, the heat capacity at constant pressure, the temperature, and the thermal conductivity, respectively. The thermal properties of air are used under 288.15 Kelvin, as listed in the Table I below.

Table I. Thermal properties of Air at 288. 15 Kelvin

Density	1.225 kg m-3
Dynamic Viscosity	1.789e-5 N s m-2
Thermal Conductivity	0.02537 W m-1 K-1
Heat Capacity at Constant Pressure	1005 J kg-1 K-1

There are two separate finite-element models designed here, in order to make comparisons of the generated heat circulations. As can be seen in Figure B1, one is a 2-dimensional cross-sectional model with the heating cables assumed as a hot plate, and another is a 2-dimensional cross-sectional model with both the heating cables and the Mini-Greenhouse simplified as a hot plate and an insulated inner layer, respectively. The dimensions of the geometry is the same as the actual scale, with a 6-metre width a 3-metre height of the greenhouse; the seeding table and the Mini-Greenhouse are also modeled in scale. In terms of boundary conditions, an average temperature of weather, ground, and heating cables are selected in this simulation. Since the objective is to demonstrate the effectiveness of the heating cables and the Mini-Greenhouse, there is no demand to input temperature values with a wide range as long as the values are consistent. For both models, the outer layer of the greenhouse is set up as a boundary condition at $T_{outside} = -10°C$ and the ground at $T_{ground} = -5°C$. The Mini-Greenhouse, on the other hand, is modeled as a solid boundary with no-slip condition, which means the fluid has zero velocity relative to the boundary. The hot plate that represents the heating cables remains temperature at $T_{cable} = 30°C$.

With regard to the thermal circulation generated inside the greenhouse, it is obvious to see the difference between the two models from Figure B1. The presence of the Mini-Greenhouse greatly tunes the rising heat down and then minimizes the volume of the thermal circulation. This decrease in volume has shown a reasonable amount of increase in temperature and thermal efficiency. The maximum thermal efficiency, $\eta_{th,max}$ can be estimated based on the Carnot's Theorem and the second law of thermodynamics (Moran, 2018), as written in Eq (11).

$$\eta_{th,max} = 1 - \frac{T_{min}}{T_{max}} \tag{11}$$

T_{min} and T_{max} are the minimum and the maximum temperatures in Kelvin, respectively. In the first model with the heating cables only, the temperature distributes from -10°C to 29.84°C at the steady state. The complete system in the second model offers a temperature range from -10°C to 38.97°C. As discussed in the literature review, Mr. Bleho's greenhouse only has a thermal efficiency at roughly 1.86%. The addition of the two innovative designs, the heating cables and the Mini-Greenhouse, is then capable of obtaining a maximum thermal efficiency of 15.05%. Although the presence of the Mini-Greenhouse only raises the maximum thermal efficiency from 13.15% to 15.05%, its effectiveness in terms of the economical aspect is remarkable. Moreover, the Mini-Greenhouse provides a more stable temperature fluctuation due to the decrease in the volume of the generated heat circulation. The result also brings the potential of planting onions and germinating the seeds in winter. However, an accurate germination environment has not yet been estimated, which calls for a microscale model in the next section.

5.1.2. Microscale: Transient Heat Conduction in Soil

The objective of a transient heat conduction model in soil is to visualize the heat propagation in the soil with the plastic tray, and then to examine the temperature of the seeding environment in the designed system. In this scale, heating cables, seed trays and soil are the main components of the simulation and the size of the model can be reduced due to the periodicity of the geometry. Thus, a 10-by-20 seed tray with soil scales down to a unit tray with soil.

In order to visualize the transient heat propagating through the soil, a three-dimensional model of the soil is simulated by utilizing the finite-element method. The geometry is made up of the periodic unit tray, containing polystyrene as the outer layer and soil inside. The hollow structure at the bottom of the tray is also modeled in the actual scale. The thermal properties of the two materials are listed in the Table II below and the soil properties are selected based on the homogenization with forty percent relative density.

Table II. Thermal Properties of Polystyrene and Homogenized Soil

	Polystyrene	Homogenized Soil
Density	920 g cm^{-3}	1330 g cm^{-3}
Thermal Conductivity	0.085 W m-1 K-1	0.25 W m-1 K-1
Heat Capacity at Constant Pressure	1450 J kg-1 K-1	1926 J kg-1 K-1

Due to the presence of the two materials, thermal contacts between the polystyrene and the homogenized soil need to be taken into account. A resistance analogy of the thermal contacts in a unit tray is then developed, as shown in Figure B2. The heat source quantified as T_{hot} can propagate either from the plastic tray or the soil. If the heat goes from the plastic first, then it may move to the soil after passing over the thermal contact. In the end, the plastic and the soil at the top of the tray expose to the ambient temperature, denoted as T_{cold} here.

A finite-element simulation of the transient heat conduction in the unit tray with thermal contacts between the polystyrene and the homogenized soil is proposed, as demonstrated in Figure B3. The governing equation is based on the transient Fourier heat conduction written in Eq (12), coupled with the Cooper-Mikic-Yovanovich correlation model (Yovanovich, 2015) for the thermal contacts.

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = q_v \quad (12)$$

q_v is the volumetric heat source and the thermal properties of the polystyrene and homogenized soil are listed in the Table II above. The model is initially at an ambient temperature $T = -1°C,\ at\ t = 0\ s$, and is thermally disturbed from a stationary state $\frac{\partial T(x,y,z,t)}{\partial t} = 0°C,\ at\ t = 0\ s$. In the absence of heat source inside the model, the bottom layer of the soil and the polystyrene is raised to the average temperature of the heating cables $T = 40°C,\ at\ z = 0\ cm$. The top layer of the soil and the polystyrene surfaces, on the other hand, is exposed to the environment of the Mini-Greenhouse ($T = -5°C,\ at\ z = 40\ cm$). All the boundary conditions are selected based on the average weathers of February and March in Montreal, Quebec.

In Figure B3, a three-dimensional transient heat conduction model is shown in two types of plots. Figure B3(a-c) is a standard temperature distribution graph and it is clear to see how the heat propages from the bottom of the plastic tray to the top of the soil surface. The heat goes almost uniformly throughout the time and the vertical centerline of the homogenized soil seems to possess a higher temperature than the surroundings. This can be explained by the different paths that heat propagates as discussed in the resistance analogy before. Figure B3(d-e) is an isothermal contour graph that demonstrates the spatial distribution of the heat and the direction of the heating process.

The average depth of onion seeds in the soil is roughly 2.5 centimeters below the surface. In order to evaluate the germination environment, a two-dimensional cut plane is defined, 2.5 centimeters below the top surface of the soil, and a temperature distribution graph over time is then plotted, as shown in Figure B4. In this scenario, a fairly cold environment is being simulated as the boundary conditions to examine if the system is capable of germinating onion seeds in the cold weather, for instance the average weather of February and March in Montreal, Quebec. The soil reaches its thermal equilibrium after roughly 4-hours of cable heating in Figure B4 and offers a germination environment from 16.74°C to 18.22°C. It is worth emphasizing that this temperature range is established under a relatively cold environment, which means the range on average days will be warmer during the growing season. Nonetheless, the cable heating system still performs well in terms of the temperature offered for the onion seeds.

5.2. Experiments and Statistical Analysis

5.2.1. Experimental Testing and Design

In order to test the viability of the design, a small-scale experiment was designed. In this experiment, two parameters were tested. The main parameter tested was soil temperature, which was measured using six thermocouples and an Agilent Data Logger. The experimental design also allowed for testing of various configurations of heating cables. Therefore, three separate treatments were tested, to better understand the heat produced by each configuration.

The first thermocouple was used to test ambient temperature. It was placed on a table away from the rest of the experiment, so as to ensure that it would not affected by the heating cables. The second thermocouple was placed just above the heating cables and mat, and served to test the amount of pure heat created by the design. Following this, four thermocouples were used to test three configurations of heating cables, and one control seed tray. Two treatments were proposed: one in which the heating cables were spaced one unit apart, and two configurations in which the cables were spaced two units apart. As can be seen in Figure A4, the far right of the heating mat was dedicated to single-spaced cables. This configuration was tested to better understand whether single- or double-spaced cables would produce a different amount of heat, and whether one configuration would be more beneficial to the design. This was tested using the third thermocouple.

The fourth and fifth thermocouples were used to test two separate double-spaced cable configurations. The first was a simple configuration, in which each length of cable was placed two units away from the previous; this was the fourth thermocouple. The fifth thermocouple was placed on a double-spaced cable system as well; however, in this configurations, holes were drilled every two units to ensure drainage. Mr. Bleho asked that this design be water-permeable, as he uses a spray technique to irrigate the plants. As the bench is perforated, this does not cause problems with regards to standing water; however, with the addition of a heating membrane, Mr. Bleho was concerned that the plants would become oversaturated if the heating membrane did not drain efficiently. Therefore, holes were drilled at every two unit spaces, in order to ensure that water would not remain the root-zone of plants for an extended period of time. The fifth thermocouple was set up in order to test whether the addition of drainage holes affected the heat transferred to soil. The sixth thermocouple was set up as a control, placed on the perforated seeding table without any additional heating.

Four seed trays were filled with soil of the same variety which Mr. Bleho uses in the greenhouse. Holes were drilled into one section of the heating mat for water drainage, using an electric drill. The cables were tamped down with a hammer, to ensure that they fit snugly into the heating mat. Three seed trays were placed on the heating mat - one on each configuration of cables - and the fourth seed tray was placed on the table. Following this, the soil in each seed tray was watered, to simulate irrigated conditions. A probe, attached to a thermocouple, was inserted into a cell in each tray. Each probe was propped up, so that it would be elevated to around two centimeters above the cables. This simulates the depth of each seed, which is around 2.5 centimeters above the cable surface.

The thermocouples were connected to an Agilent Data Logger. Scans were taken every half hour for 15 days. Due to malfunctioning probes, thermocouples one, two, and three were replaced on the third day. All data was collected in degrees Celsius. Data points were evaluated as they related to the threshold for nighttime onion germination, which was set at 20°C.

The first and third thermocouple were found to have temperatures far outside of the expected range. The first, which measured ambient air temperature, was expected to exhibit temperatures around or up to 5°C above or below the control seed tray. However, it consistently showed temperatures up to 15°C higher than the control during the night. It is hypothesized that this is due to the electrical fans, which Mr. Bleho turned on as they were necessary for growth of plants being seeded in the greenhouse. Additionally, it was expected that the seed tray in the single-spaced configuration would be warmer than the seed trays in double-spaced configurations. In testing, it was found that the single-spaced configuration consistently delivered temperatures below that of the double-spaced configuration. It is believed this is due to a mechanical or human error.

The control thermocouple reported temperatures as expected. During the day, the control seed tray was heated by sunlight, and aided by the electric heating fans. The average temperature of the control was around 20°C. At night, the control tray displayed an average temperature of 7°C, with low temperatures recorded down to 1.9°C. As described previously, the nighttime temperature for onion germination must remain uniform at 20°C, with a fluctuation of 5°C tolerable. The temperatures reported from the control seed tray describe the necessity of a root-zone heating system. Without additional heat, the seed trays and soil cannot sustain onion germination temperatures.

Thermocouples five and six, which both had double-spaced cables with and without drainage holes, respectively, corroborated the need for root-zone heating. There was no significant difference between the reported temperatures for the two double-spaced configurations; therefore, the addition of drilled holes for adequate drainage does not create a potential loss of heat to the system. The configuration with double-spaced cables and drainage holes reported an average daytime heat of 40°C. This result is higher than expected, and illustrates the need for a thermostat, in order to regulate the function of the cables. Due to the impact of the sun's heat on the greenhouse, the cables will not be needed during the day for the majority of the growing season. At this time, a thermostat will switch the cables off, to be turned on again at night when temperatures begin to drop. At night, thermocouple five exhibited an average temperature of 23°C, with fluctuations of 5°C above and below the average, as seen in Figure B5. The temperatures produced under this configuration are precisely in the range for onion germination. The experimental test under these conditions corroborated the need for and success of root-zone heating in extending the growing season, as temperatures were raised from below-zero winter conditions to conditions favourable for seed germination.

5.2.2. Statistical Analysis

An Analysis of Variance (ANOVA) is performed in this experiment. ANOVA is used because the treatment (heating cables or no heating cables) is a qualitative factor while the temperature is a quantitative variable. The following hypotheses are tested for temperature of the two treatments.

- ❑ H_{null} : There is no significant difference of the temperature between heating cables and no heating cables.
- ❑ H_{alpha} : There is a significant difference of the temperature between heating cables and no heating cables (with the alpha value of 0.01).

Table III. Summary of Two Treatments

Treatments	Count	Sum	Average	Variance
Temperature (Heating Cables)	40	1187.8274	29.6957	66.2057
Temperature (No Heating Cables)	40	455.1033	11.3776	62.4674

Table IV. ANOVA Analysis

Source of Variation	SS	df	MS	F	P-value	Fcrit
Between Treatments	6711.06	1	6711.06	104.31	4.92e-16	6.97
Within Treatments	5018.25	78	64.34			

Total	11729.31	79				

Since 104.31>6.97, the null hypothesis is rejected and this represents that there is a significant difference between the temperature with heating cables and without heating cables. This statistical result has matched with the observations and the data plot from the experiment in Figure B5.

6. Design Evaluation

6.1. Environmental Impact

The addition of a solar-powered root-zone heating system to the Macdonald Campus Horticultural Centre will provide a tangible impact on the sustainability of the campus. Through the use of innovative materials and a solar energy system, the campus will benefit and add to the overall environmental impact of the surrounding area.

A solar-energy system will ensure the use of renewable and sustainable energy in all greenhouse production. Solar energy has been shown to be one of the least polluting forms of energy, making it an ideal source of energy for an environmentally-conscious campus. A study by Myhrvold and Caldeira (2012) illustrates that solar photovoltaic energy generation has among the lowest impacts on temperature change caused by energy generation (Figure C10), an important indicator of the carbon footprint of energy sources. Solar energy is a truly renewable source of energy, and can be used around the world. The use of a photovoltaic array ensures that no chemical or waste residues will affect the site, guaranteeing the health of the surrounding ecosystem. Additionally, the system proposed for this project will not require a high amount of maintenance. This makes it a favourable system for the Horticultural Centre, as it allows the greenhouse to be sustainably powered without creating additional work for staff.

The design also improves the overall energy efficiency of the system. By heating only one plane of the greenhouse, rather than the complete air volume, the design minimizes the need for an excess of energy. The Mini-Greenhouse also serves to reduce the total amount of energy required, by protecting against heat loss from the surface of seed trays to the roof of the greenhouse. By optimizing the distance between the plants and the nearest surface, the system provides a secure zone of air movement, ensuring good air circulation among the plants while conserving heat. This will reduce the overall amount of energy needed to heat the greenhouse, providing another aspect of sustainability to the system.

Plant health will also be a key benefactor from this system. Root-zone heating provides a uniform supply of heat to the most critical area of the plants. By eliminating the need for electric fans, the design guarantees that each plant will receive the right amount of heat, regardless of location within the greenhouse. Through the use of a root-zone system with a thermostat, different plants can be provided with different thresholds of heat, as is suitable for their particular germination needs. Additionally, innovations to the system will ensure that plant health is a priority and guarantee in this design. The addition of a membrane will ensure uniform heat distribution to plants, guaranteeing a healthy crop yield, and will mitigate any potential contamination from rust on the seeding tables.

6.2. Social Impact

The social impact of this design cannot be understated. The primary beneficiary of the design will be the Macdonald Campus Horticultural Centre, which will see not only an increase in the sustainability of their production, but an increase in total crop yield and revenue from sales. The system is designed to require minimal maintenance on the part of greenhouse staff, creating an efficient and productive system for crop growth.

In 2018, Mr. Bleho moved his onion crop into the greenhouse on March 21st. Using the estimation of 61 days of growth before transplanting into the field, Mr. Bleho will be able to transplant his crop in the middle of May. Through use of this system, Mr. Bleho will begin seeding his onion crop at the end of February and beginning of March. This will enable him to transplant the crop into the field as early as mid-April. The root-zone heating system will provide an efficient and successful germination and growth environment, even during the cold month of March. After transplanting, onions will take around 90 days until they are ready to harvest. By starting the crop earlier in the spring, Mr. Bleho will be able to transplant earlier in the season, making space for an additional onion crop or other plants to begin. The transplanted onion crop after use of the root-zone heating system will be ready to be harvested as early as the 20th of July, while a traditional heating system would only allow harvest in mid-August. Additionally, this system allows Mr. Bleho to begin other crops earlier. In the 2018 growing season, he is planning to move a crop of peppers into the greenhouse in mid-April. With the addition of the root-zone heating system, this can be done as early as mid-March, increasing the total yield and making room for more crops in the greenhouse.

The additional benefit of sustained uniform growth will reduce yield losses, further augmenting total crop yield. Currently, the greenhouse supports 150 trays of around 200 onions each. This produces, on average, 30000 onions per growing season. However, this yield is subject to losses, due to uneven distribution of heat, difficulties during transplanting, and other external factors. Losses due to uneven heat distribution by the current electric fan system have been calculated to be 2% of the total yield. This constitutes a loss of 600 onions; as the Horticultural Centre sells onions for $0.75, this creates a loss of $450 per growing season. By distributing heat through a uniform root-zone heating system, the Horticultural Centre will be able to virtually eliminate the 2% onion loss due to the electric fan system. This will create an additional $450 in revenue from reduced yield losses alone; this does not account for the revenue produced by additional crop growth in the greenhouse.

The additional length of the growing season will create an additional revenue for the Horticultural Centre. The Horticultural Centre provides farm baskets to students and citizens on campus and in Ste. Anne de Bellevue throughout the summer and fall semester. By adding a month to the growing season, this design allows yields to increase, leading to increased revenue for the Horticultural Centre. This design ensures that very little maintenance will be required. The solar panels will need to be cleaned of remaining snow in the early spring; however, this is not a difficult task and will not have to be performed often. After the heating cables and membranes are installed, the system requires no maintenance, as it is self-regulating through a thermostat. Mr. Bleho and his greenhouse staff will be able to use the greenhouse in the same manner as they currently do, with the added benefit of a longer growing season and increased revenue.

It is of utmost importance that the design is accessible to users. In order to fulfill this parameter, the seeding table must be fully accessible to any staff or students wishing to use or work in the greenhouse. The system itself must be easy to use and understand, must require little to no maintenance, and must deliver efficient and successful results without creating additional work for greenhouse staff. Each element of the system has undergone innovative design to ensure that these parameters are met.

The heating cables will be slotted into the heating mat through the use of metal connectors. They will also be tamped into place upon installation. These processes ensure that the heating cables will not pop out of the membrane spacing when seed trays are removed. Each cable length connecting to an outlet will be laid flush to the ground of the greenhouse and tamped into the ground, to ensure that no tripping hazards arise. Each ‘plugin’ of a length of cable to an outlet will be encased in waterproof material, which will ensure that there is no risk of water interacting with the electrified cable connection. Additionally, the Mini-Greenhouse cover will be easily retractable, allowing even one person to efficiently set up the propagation environment. Finally, the solar energy system will be grid-tied, ensuring that even on days with low solar radiation, energy is reaching the germinating plants. This system is optimized to reduce crop losses while maintaining an easy-to-use system for greenhouse staff.

6.3. Risk Factor Matrix

To quantify the inherent risks in any system, the United States Department of Energy has created a framework for a risk factor matrix. In this framework, risk factors are evaluated at ranks from one to three; one being the least likely and least dangerous risk, while three is the most likely and dangerous. The framework defines contributors and mitigation procedures to ensure that all risks are equally evaluated, and that appropriate measures are taken to ensure the full functionality of the system.

Table V. Risk Factor Matrix

Risk Factor	Risk Rank	Risk Contributors	Mitigation Procedure
Physical tripping hazard from cable system	2	- High human activity around the cables	- Cables installed flush to the ground of the greenhouse - Worker training
Rust damage to cables	1	- Galvanized steel table susceptible to rusting - High water activity around tables due to irrigation - Cables are not optimized for rust resistance	- Addition of heating membrane removes contact between cables and table
Temperature of plants too high	3	- Excessive heat supplied from heating system - Mini-Greenhouse traps excessive amounts of heat	- Thermostat controlling temperature of cables - Removable Mini-Greenhouse cover
Electricity created by solar panels not enough to support the greenhouse	3	- Low incoming solar radiation - Snow cover on solar panels	- Grid-tied solar energy system to provide backup heating
Burns from overheating	1	- Human error	- Worker training
Seed tray deterioration from heat	1	- Material failure from high point-source heat	- Temperature control - Worker training
Soil moisture content prohibitively low due to heating	2	- High point-source temperatures	- Uniform regular irrigation - Temperature controls
Oversaturation of root zone by excess of standing water	2	- Daily irrigation - Solid heating membrane	- Drainage holes at frequent intervals

There are two major risks to be evaluated in this system. The first relates to the solar photovoltaic array. There is a risk, especially during the beginning of March, that the solar photovoltaic array will not produce enough electricity to fully support the heating system. The main cause of this risk is snow cover on the panels. In March, the Montreal area receives around nine days of snowfall, totalling 36 centimeters of snow (Current Results, 2018). Though the solar panels are placed at an angle, which will aid snow removal, some snow may still accumulate on the solar array. This will require manual maintenance in the form of snow removal. Though this is not a time-intensive task, it will need to be performed, as without snow removal, there is a risk that the solar array will stop providing electricity to the system. The number of 'sun days' that Montreal receives in March is another cause of this risk. On average, Montreal receives 26 sunny days in the month of March (Current Results, 2018); however, this number can fluctuate greatly. This can also affect the amount of electricity produced by the system, leading to possible crop losses from lack of heating.

This risk will be mitigated by having a grid-tied solar energy system. By ensuring a back-up system through the Hydro-Quebec electric grid, crops in the greenhouse will never be without heat. When necessary, an inverter will be able to make the switch from solar energy to hydroelectric energy. The solar grid-tie inverter is "designed to automatically shut down once sensing a loss of supply from the utility" (Agarwal, 2017). Grid-tied inverters take direct current energy, created by electrons in a solar cell, and converts it into alternating current, which can be used in household and greenhouse systems (SolarGreen, 2018). The grid-tie inverter will ensure that no crop losses occur due to a lack of solar-powered electricity supplied to the heating cables.

The second major risk faced by this system is the temperature produced by the cables. There is a risk that the temperature produced by the heating cables will exceed the required temperature for seed germination. In the experiment conducted to test the design, the cables frequently produced temperatures up to 40°C during the day, and up to 26°C at night. While the nighttime temperatures are tolerable for onion crops, they are not recommended. Daytime temperatures with the heating system are not tolerable for onion growth or germination. Therefore, the system must be designed to switch off when soil temperature is warmed by the sun to a point that is sufficient for germination. The system is designed to work with a thermostat, which will switch the cables off when the sufficient temperature is reached. Using this, the plants will never be subjected to a temperature which could be harmful to germination success and subsequent plant growth.

6.4. Financial Analysis

This design is engineered and implemented closely adhering to fiscal limitations. Ensuring the economic viability of this project is vital to its success and without economic justification the design would not have been accepted by the client. The following is an in-depth analysis of all monetary attributes of this design divided into four major economic subsections: *Capital Investment and Budgeting, Taxation and Government Incentives, Economic Returns and Benefits, Cost-Benefit Results.*

[All following monetary dollar values include applicable taxes and are in Canadian Dollars (CAD). Values which were converted from United States Dollars (USD) were converted at a rate of **1.00 CAD: 0.79 USD** (TSX).]

6.4.1. Capital Investments and Budgeting

This section is further divided into two subsections, *Greenhouse Heating System* and *Solar Power Supply*. This is done because the Greenhouse Heating System has been paid for by the Sustainability Projects Fund and is being implemented using Hydro Quebec as a power source. Meanwhile, the client is determining the details on whether he would like the solar powered aspect of this design implemented.

6.4.1.1. Greenhouse Heating System

The total initial investment for the heating system, as of its completion in April of 2018, is **$6,070.41**; made by the Sustainability Projects Fund (SPF). This is a summation of two parts, an initially approved project budget of $5,797, of which $2,348.86 was spent, and a revised budget amendment of $3,722, this bringing the total working capital to $6,070.41.

Although the total investment for the development and implication of this design is $6070.41, the actual cost of the final design is only $3,722. The team previously facilitating this project spent $2,348.76 on a hot water tank, which upon review was deemed unfit for the job and is not used in the final, and implemented, design. Although this is a considerable loss of capital, it is important to note that the supplier of the hot water tank is willing to take it back in exchange for a refund of half its cost. This development cost of $2,348.76 results in the difference between stakeholder investment and design cost. The actual cost of having this system implemented in the McGill Horticultural Centre greenhouse is **$3,722**, this includes all materials and labour. All that remains outside this budget is the power supply which, as mentioned above, is covered in the next section. The following is the two budget approvals for this design, this being the current stakeholder investment.

Table VI. Materials and Supplies Capital Expenditures

Materials and Supplies (1)	**Unit Cost (1)**	
Hot Water Tank (Solcan)	$2,348.86	
SUBTOTAL (1)	**$2,348.86**	
Materials and Supplies (2)	**Unit Cost (2)**	
Easyheat Heating Cables (73m)	$656	
Easyheat Heating Cables (30m)	$367	
UV Resistant Twist Ties	$49	
Plastic Mini-Greenhouse Sheet	$12	
Electrician Costs	$1,600	
Misc. Electrical Supplies*	$200	
Schluter Heating Membrane	$838	
SUBTOTAL (2)	**$3,722**	
	TOTAL	**$6,070.86**

*This includes thermometers, and YMC4 Connectors and other cables required to connect the solar photovoltaic modules.

The **SUBTOTAL (2), $3,722**, is the actual initial cost of the heating system and will be used as the initial cost for all applicable calculations. Cost analysis will be done on a 10-year time frame, as all above hardware has a lifetime of 10 or more years; thus replacement and maintenance costs are not relevant.

6.4.1.2. Solar Power Supply

Optimally, the above heating system is powered with SPR-X21-345 SunPower solar panels. With this power system in place the design functions completely independent of HydroQuebec; generating considerable annual savings which will be discussed in the coming *Economic Savings and Benefits* section. The initial cost of the solar power supply is $11,938. This includes installation, all electrical hardware, and applicable setup for this specific design. The following is a cost breakdown of the Solar Power Supply for this design, with all installation included.

Table VII. Power Supply Capital Expenditure

Unit	Unit Cost
X21-345 SunPower Solar Module (15)	$11,385
SPR-5000x SunPower Solar Inverter	$553
TOTAL	**$11,938**

The total initial cost of the design including the solar power supply, before any tax refunds, is **$15,660**.

6.4.2. Taxation and Government Incentives

The Quebec government offers two financial incentive programs and one regulatory program that support the use of solar energy in Quebec. Additionally, the Macdonald Campus Horticultural Centre qualifies as a business, and can benefit from federal incentive programs as well. Of the two financial incentive programs, only one applies to this design.

The RenoVert Tax Credit is a refundable tax credit that applies to all eco-friendly energy expenses and correlates to a 20% tax return on all appropriate expenses that exceed $2,500 with a maximum tax credit of $10,000. This credit is only valid if all solar panels are installed to CAN/CSA-C61215-08 standards, which all applied solar installation adheres to. For this design, the tax credit results in a saving of:
RENOVERT TAX CREDIT: $2,387.60

Canadian Renewable and Conservation Expense (CRCE) is a federal incentive program which allows up to 50% of start-up depreciable renewable energy capital cost to qualify for inclusion as Class 43.1 or 43.2 taxation. In simpler terms, this program gives corporate tax benefits to anyone implementing or developing a renewable energy project. In accordance to the Technical *Guide to Class 43.1 and 43.2, 2013 Edition*, the proposed solar design qualifies for Class 43.1 and the corresponding Claiming Capital Cost Allowance (CCA) of 30% applied annual on all depreciable project assets. Almost all equipment utilized in the solar power supply falls under Section 2.7 *Photovoltaic Electrical Generation Equipment* and Section 2.3 *Active Solar Heating Equipment and Ground-Source Heat Pump Systems* of the CRCE, making all the solar power supply expenses CRCE eligible under Section 2.0 *Qualifying Systems and Equipment*. In summary, 50% of the capital costs of the assets are subject to Class 43.1 taxation, resulting in a

30% tax refund on applicable items. This tax refund only applies on 50% of the initial cost, thus it can be simplified to a 15% refund on the total cost, as oppose to a 30% refund on half the cost.

Table VIII. CRCE Taxation Refunds

Unit	Tax Class	Tax Refund	Unit Cost	Refund Amount
X21-345 SunPower Solar Panel (15)	43.1	15%	$11,385	$1,707.75
SPR-5000x SunPower Solar Inverter	43.1	15%	$553	$82.95
TOTAL	**-**	**-**	**$11,938**	**$1,790.70**

6.4.3. Economic Returns and Benefits

To evaluate the monetary returns of this design, operating costs prior to the implementation of this design must be addressed. Previously, the McGill Horticultural Centre utilized four 4.8kW heating fans to warm the greenhouse. Due to the low efficiency of these fans, the seeds were started for several weeks inside the Horticultural Centre building. This added a labour-intensive process early in the season, and added several days' worth of labour in moving each seed tray into the greenhouse when temperatures increased. This incurs three annual costs: the labour cost of the greenhouse staff moving the seeds daily, the crop yield losses from damage during the moving process, and the running electricity cost of the four fans.

Labour costs. The process of moving the seeds indoors throughout the initial weeks of seeding is labour intensive and costly for the Macdonald Campus Horticultural Centre. With labour amounting to $13.75 an hour:
LABOUR EXPENSE: $770.00

Crop loss. The previous system caused an annual crop loss of 2%. This is a result of both the process of moving the trays throughout the initial seeding weeks, as well as the uneven heat distribution caused by the heating fans. Both issues are resolved with the implementation of the solar powered heating system. This 2% loss results in an annual loss of 600 onions, at $0.75 per onion this yields an annual loss of:
PRODUCT YIELD LOSS: $450

Electricity cost. The previous system ran four 4.8kW electric heating fans. The design eliminates the need for these fans. The Horticultural Centre classifies as 'Rate G' regarding Hydro Quebec billing and pays the corresponding $0.0971 kW/h. With a running time of 12

hours a day, 61 days a year, the annual electrical costs are:
ELECTRICAL COSTS: $1364.69

Benefits. In addition to the elimination of the above costs, the solar power supply for this design is grid tied; meaning that all excess power generated is returned to the province of Quebec. The province of Quebec has policy in place that pays all users who feed renewable energy into the grid, the payment is at the same rate that the user is charged at, in this case the 'G rate'. This design generates on average 438.6 kWh per year of excess energy, at $0.0971 kW/h:
GRID POWER PAYMENTS: $42.58

Finally, the above calculations regarding tax return savings based on the CRCE and RenoVert government initiatives can be quantified as economic returns. This results in the following economic return on the initial investment.

RENOVERT TAX CREDIT: $2,387.60
CRCE TAX CREDIT: $1790.70
TOTAL TAXATION RETURNS: $4178.30

With the expenses eliminated and the appropriate taxation applied, the total monetary savings are as follows:

Table IX. Total Project Savings

EXPENSE	SAVING	SAVING INTERVAL
Labour	$770.00	Yearly
Product Loss	$450.00	Yearly
Electricity	$1,364.69	Yearly
Grid Power	$42.58	Yearly
Taxation Returns	$4,178.30	Exclusively Year 1
YEARLY SUBTOTAL	**$2,627.27**	Yearly
FIRST YEAR SUBTOTAL	**$6,805.57**	Exclusively Year 1

6.4.4. Cost-Benefit Results

To ensure the fiscal validity of any project three key cost-benefit calculations must be computed: the net present value, discounted payback period, and the internal rate of return. Without the results of these three calculations the monetary projections of a design are not adequately examined, and the project cannot be deemed worthwhile. Below, net present value, discounted payback period, and internal rate of return are computed and briefly analysed.

All calculations are done over a 10-year term using a cost of capital of 9%. This is a conservative cost of capital, as running a more ambitious cost of capital would inflate results.

$$NPV = \frac{B_0 - C_0}{(1+i)^0} + \frac{B_1 - C_1}{(1+i)^1} + \ldots + \frac{B_n - C_n}{(1+i)^n}$$

NPV = $8,006.49 (>>0, thus this project is deemed very lucrative over a 10-year period)

DPP = 3.37 years (This indicates that all costs will be recovered in 3.37 years)

IIR = 26.95% (normally anything above the cost of capital, 9% in this case, is deemed acceptable. This IIR is *very* high, once again confirming the fiscal success of this design.)

As all three of the critical criteria for financial validity indicate, this design yields promising cost-benefit results, and is completely valid from a monetary standpoint.

7. Conclusion

The proposed design delivers an efficient and sustainably-powered root-zone heating system to the Macdonald Campus Horticultural Centre greenhouse. In doing so, the system enables the Horticultural Centre to extend its growing season by at least a month, leading to higher yields and increased monetary revenues. Through the innovative use of heating cables, membranes, and heat transfer calculations, the system minimizes yield losses due to insufficient heating and ensures that plant health and plant growth remain the top priority for the greenhouse.

The designed system makes use of electric heating cables and heating membranes. The cables, placed in the membrane, act as point sources of heat to the seed trays sitting above them. The heating membrane distributes the heat uniformly across each tray; together, these elements ensure that each germinating seed receives an adequate, but not excessive, amount of heat. By targeting the root-zone of each plant, the system allows each plant to germinate successfully and quickly. The nature of the root-zone heating system also decreases total energy costs of the greenhouse, as it only requires one plane of the greenhouse to be heated, rather than the total air volume. By decreasing yield losses, adding time to the growing season, and reducing the total energy needed, this system proves to be an efficient and successful technique for seed germination in cold climates. The experimental and simulation results have both demonstrated the success of this proposed system.

The system also makes use of a solar photovoltaic cell. The energy generated from the solar energy array serves to power the electric heating system. An inverter will convert the direct current energy generated by the solar panels into alternating current, able to be used in the greenhouse. To ensure that no heat losses occur on cloudy days or as a result of snow cover, the system will be grid-tied. The addition of solar power to the system contributes to the overall sustainability of the design, making the Macdonald Campus Horticultural Centre a leader in its field in use of renewable energy.

Moving forward, the system will be fully implemented in the month of April. In the coming growing season, it will be fully functional and autonomous. In implementing the design, McGill facilities management will be consulted to ensure the full safety and functionality of the design. Mr. Bleho and the greenhouse staff will be trained on best practices regarding the root-zone heating system and the solar energy system, guaranteeing that the system will be functional and effective into next year as a new growing season commences. This innovative design, incorporating renewable energy and targeted plant growth techniques, provides a benefit to both the Horticultural Centre and the sustainability of the campus itself, and serves as an example to the campus of sustainable horticultural practices.

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Appendices

Appendix A: 2D and 3D Technical Drawings

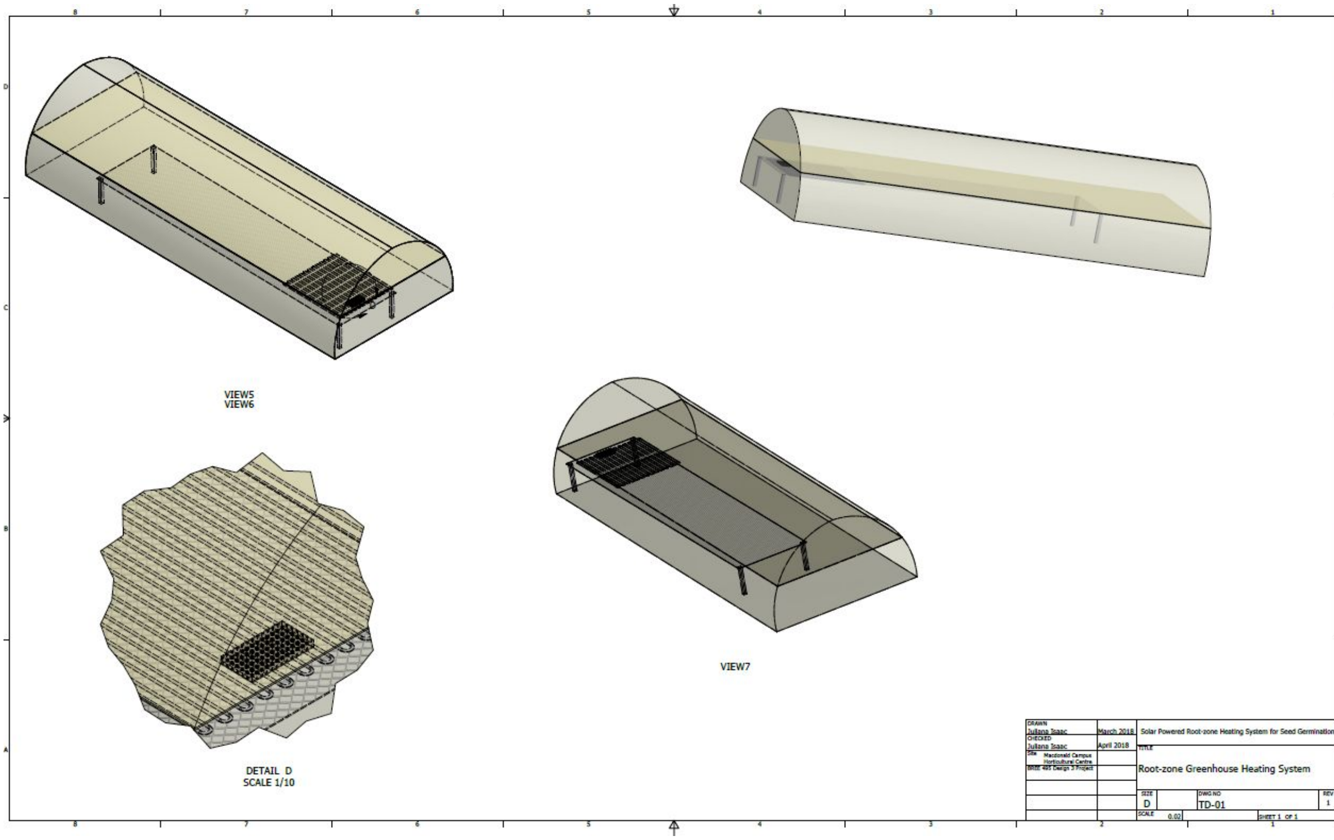

Figure A1. Root-zone Greenhouse Heating System. Isometric and detail views of the root-zone heating system. In the detail drawing, cables can be seen as they rest on the heating membrane, with a seed tray placed on the cables and the Mini-Greenhouse cover above.

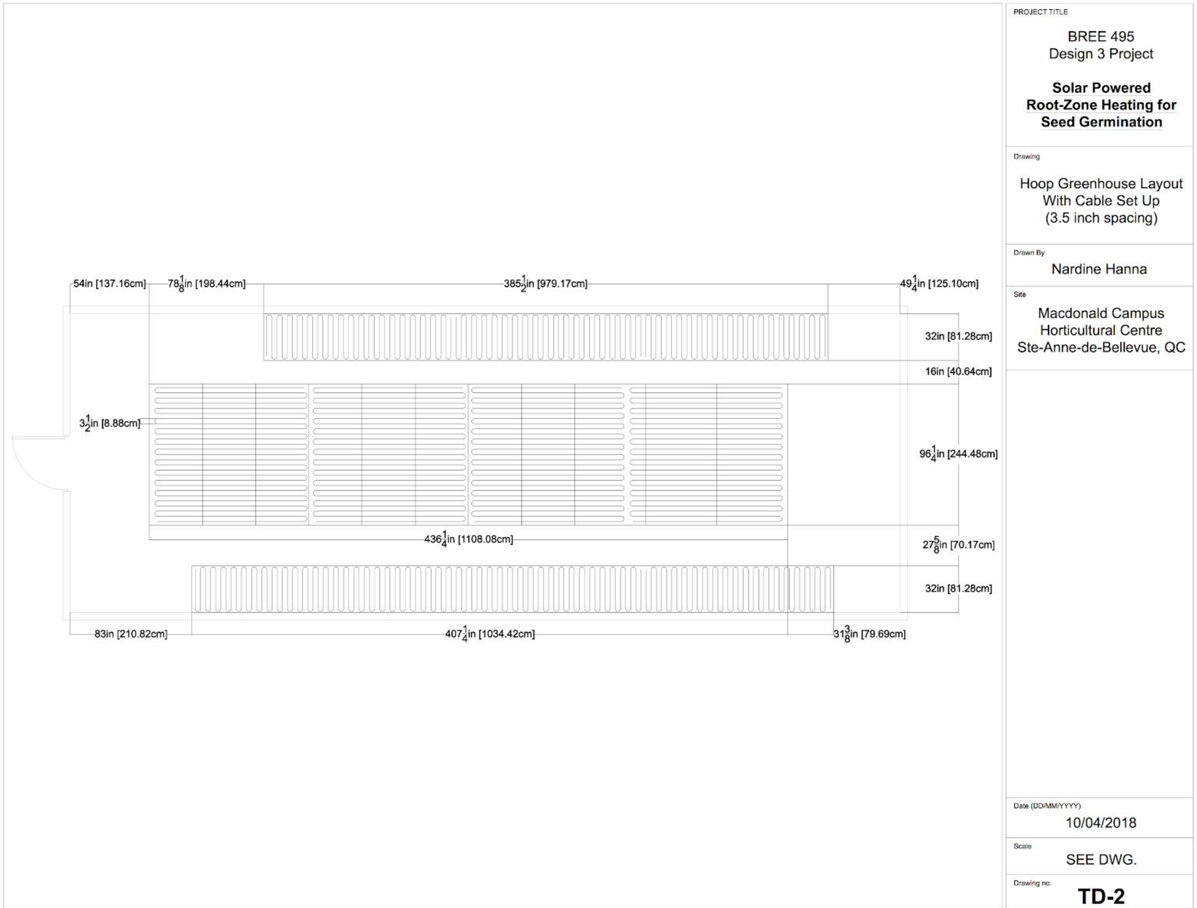

Figure A2. Hoop Greenhouse Layout with Cable Setup (3.5 inch spacing). Technical drawing of the Hoop Greenhouse with a layout of heating cables at a 3.5 inch (8.88 cm) spacing. The heat cables are placed on the Centre table as well as the side tables.

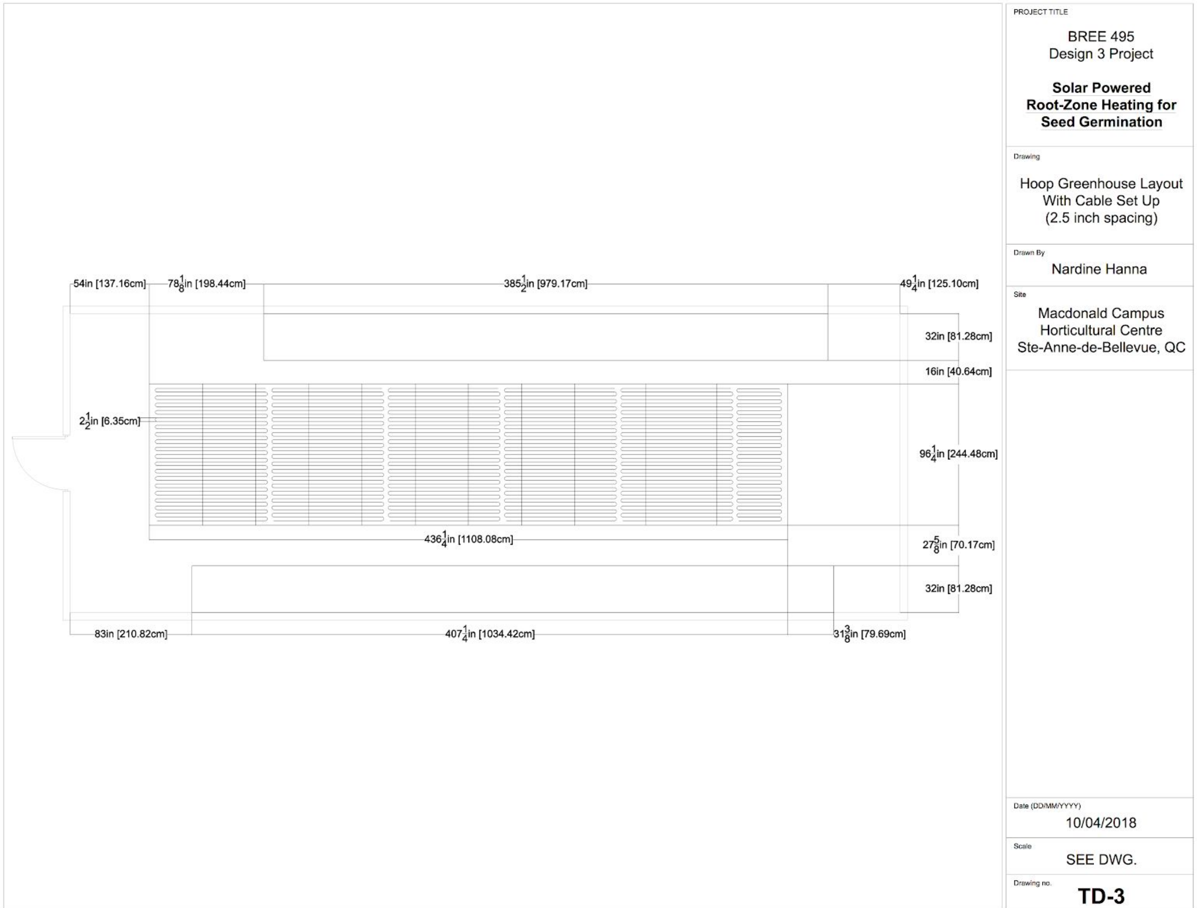

Figure A3. Hoop Greenhouse Layout with Cable Setup (2.5 inch spacing). Technical drawing of the Hoop Greenhouse with a layout of heating cables at a reduced spacing of 2.5 inches (8.88 cm). The heating cables are only placed on the Centre table due to budgeting constraints. This is the layout of the design that is in the process of being implemented for the Horticultural Centre.

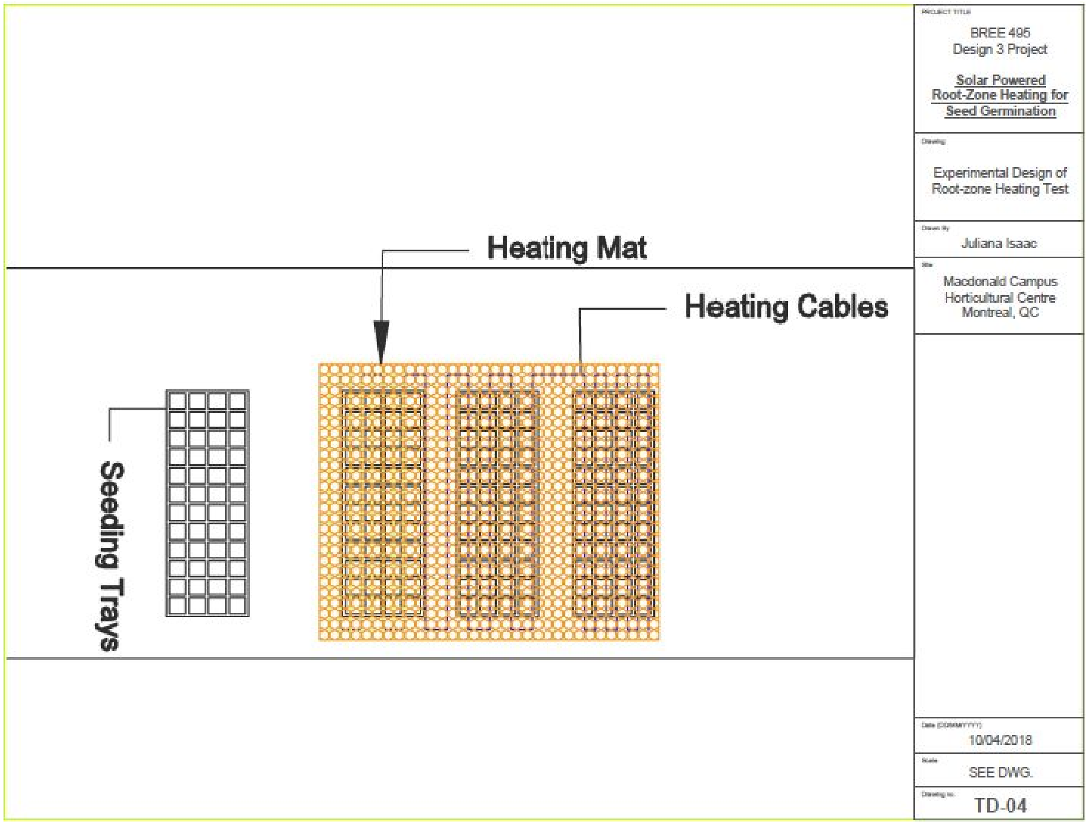

Figure A4. Experimental Design of Root-zone Heating Test. Two-dimensional drawing the experimental set-up. Heating mat, three cable configurations, and seed trays are pictured.

Appendix B: Simulation Graphs

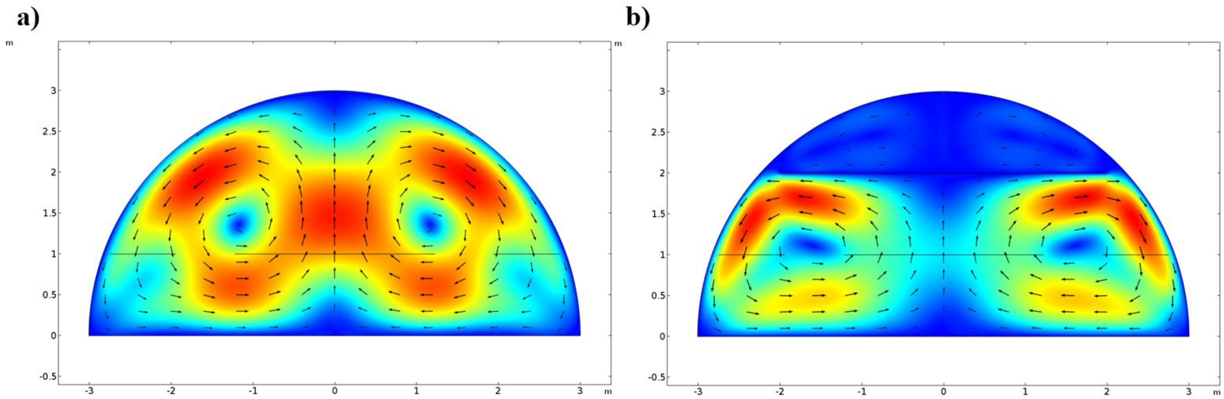

Figure B1. Finite-element simulations of heat convection at steady state. Finite-element simulations of two-dimensional buoyancy-driven heat convection at steady state: a) the heating cables only; and b) the heating cables and the Mini-Greenhouse.

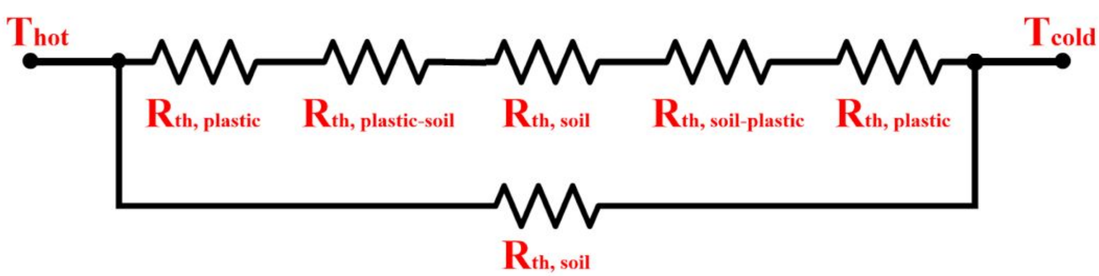

Figure B2. Resistance analogy of heat propagation. A resistance analogy of heat propagation from the bottom of the plastic tray, denoted as T_{hot}, to the top of the soil surface, denoted as T_{cold}.

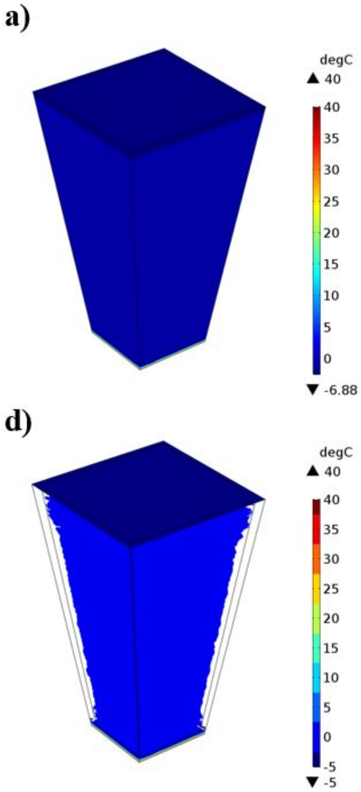

Figure B3. Finite-element simulations of three-dimensional transient heat conduction. Finite-element simulations of three-dimensional transient heat conduction with the thermal contacts. a) temperature distribution plot at 0s; b) temperature distribution plot at 600s; c) temperature distribution plot at 3600s; d) isothermal contour map at 0s; e) isothermal contour map at 600s; and f) isothermal contour map at 3600s.

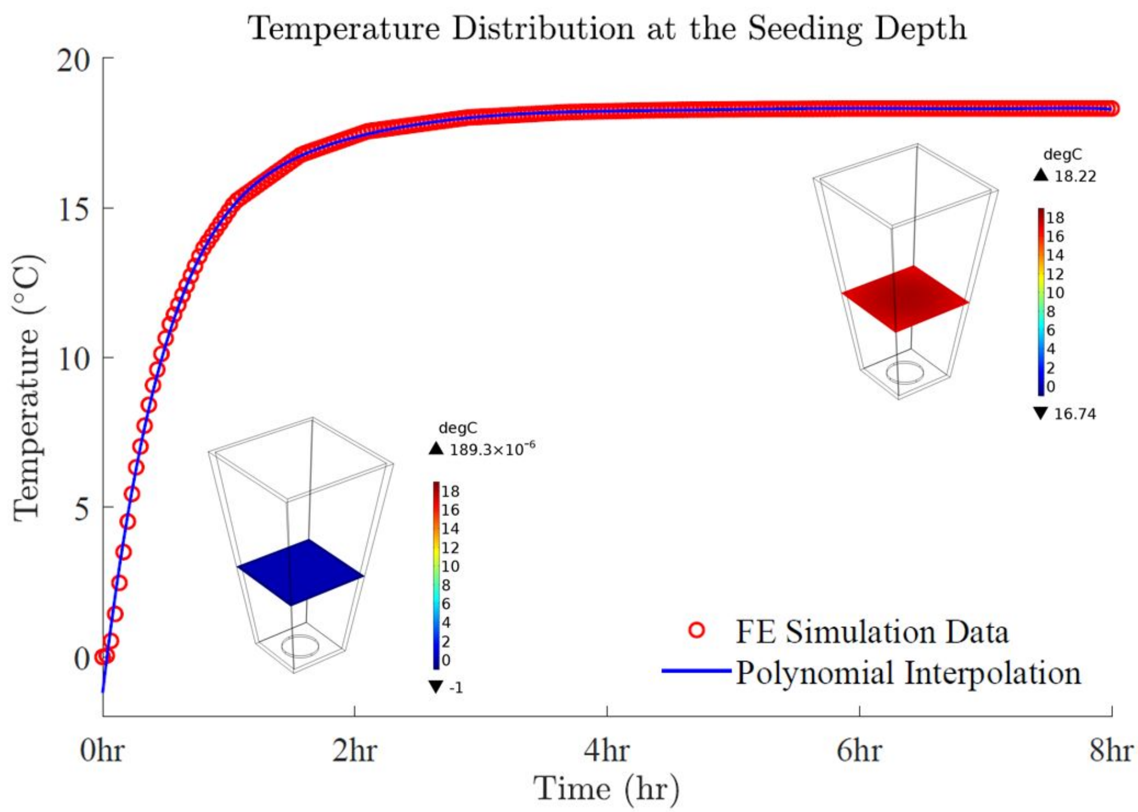

Figure B4. Temperature distribution at seeding depth under cold environment. Temperature distribution at the seeding depth over eight hours under a fairly cold environment, with two subplots of 2-dimensional cut-plane evaluations.

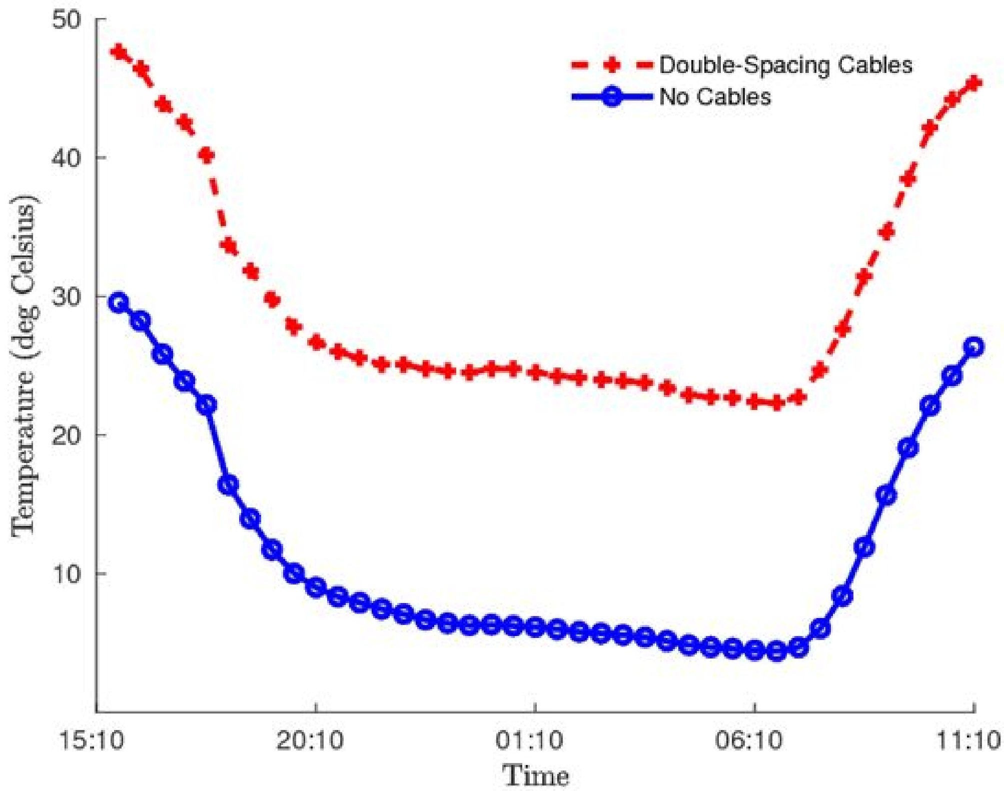

Figure B5. Results of the experimental test. The blue curves describe the control seed tray, which during the night hovered around 3 - 5°C, while the red curve describes the soil temperatures in the double-spaced cable configuration. The average nighttime temperature in this configuration is around 23 - 25°C.

Appendix C: Additional Figures and Tables

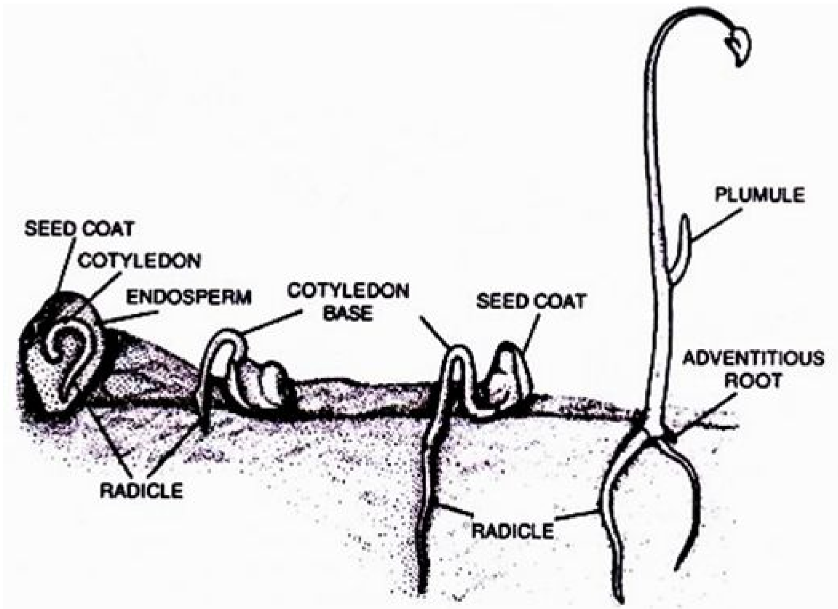

Fig. 4.8. Successive stages in the germination of albuminous seed of onion.

Figure C1. Illustration of onion seed epigeal germination. Kumar, S. (n.d.). *Seed Germination Types (With Diagram)*. Retrieved from Biology Discussion: http://www.biologydiscussion.com/seed/germination/seed-germination-types-with-diagram/15789

Figure C2. Satellite image of the Hoop Greenhouses. Google Maps image of the Hoop Greenhouses with location details included. The greenhouse of interest is the one located to the north.

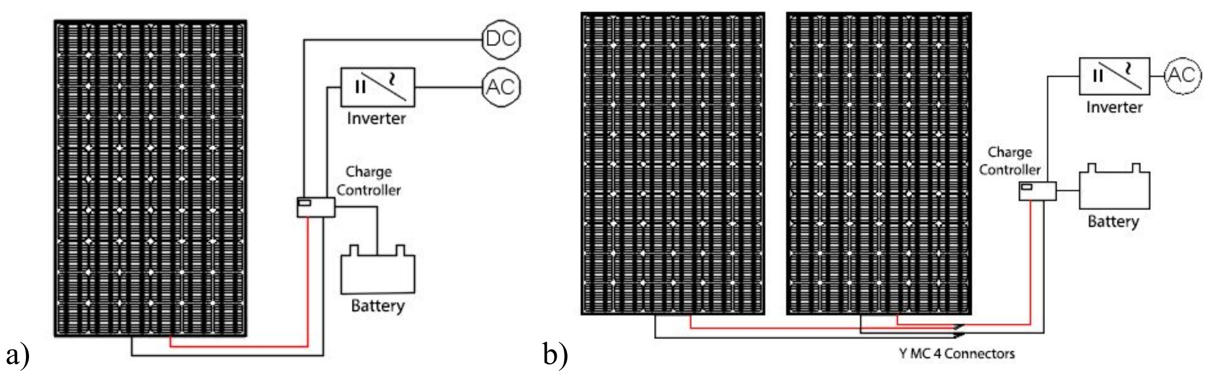

Figure C3. Photovoltaic panels set up to output direct or alternating current. a) Photovoltaic panels set up in general systems to output direct or alternating current. b) Photovoltaic panels set up to output alternating current and which include both a charge controller and battery. The figures are adapted from the (Jager et al, 2014). Red represents the positive contacts of the system and black the negative contacts.

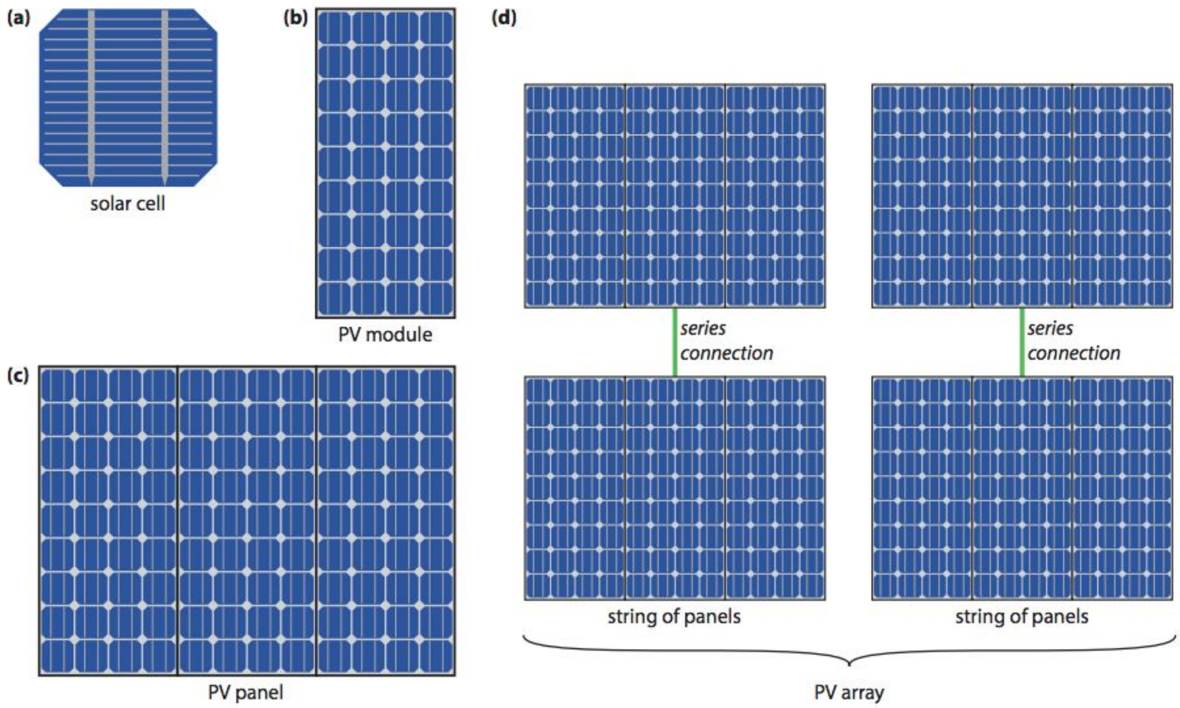

Figure C4. a) A solar cell, b) A PV module, c) a solar panel, and d) a PV array. This figure is taken directly from Jager et al., 2014.

Table C1. Electrical specifications of the SunPower X21-345

Technology	c-Si
Rated power P_{mpp} (W_p)	345
Rated current I_{mpp} (A)	6.02
Rated voltage V_{mpp} (V)	57.3
Short circuit current I_{SC} (A)	6.39
Open circuit voltage V_{OC} (V)	68.2
Average Panel Efficiency (%)	21.5
Dimensions (m x m)	1.56 x 1.05
Maximum warranty on P_{mpp} (years)	25

Table C1 is adapted from material originally presented in Jager et al., 2014.

Table C2. Operating Condition and Mechanical Data for the SunPower X21-345

Temperature	-40ºC to +85ºC
Impact Resistance	25 mm diameter hail at 23 m/s
Appearance	Class A+
Solar Cells	96 Monocrystalline Maxeon Gen III
Tempered Glass	High Transmission Tempered Anti-Reflective
Junction Box	IP-65 Rated
Connectors	MC4 Compatible
Frame	Class 1 black anodized, highest AAMA Rating
Weight	41 lbs (18.6 kg)

Table C2 is taken directly from the SunPower X21-345 Manual (SunPower Corp, 2017).

Table C3. Electrical Characteristics of a typical Maxeon Gen III Cell At Standard Test Conditions (STC)

	Cell Bin	Pmpp (Wp)	Eff. (%)	Vmpp	Impp	V_{OC}	I_{SC}
Ultra Peak Performance	Me1	3.72	24.3	0.632	5.89	0.730	6.18
Ultra Premium Performance	Le1	3.62	23.7	0.621	5.84	0.721	6.15
Ultra High Performance	Ke1	3.54	23.1	0.612	5.79	0.713	6.11

Electrical Parameters are nominal values.
Temp. Coefficient in SunPower Panels: Voltage: -1.74 mV/°C, Current: 2.9 mA/°C, Power: -0.29%/°C

Table C4. Physical Characteristics of the Maxeon™ Gen III Solar Cells

Wafer	Monocrystalline silicon
Design	All back contact
Front	Uniform, black antireflection coating
Back	Tin-coated, copper metal grid
Cell Area	Approximately 153 cm^2
Cell Weight	Approximately 6.5 grams
Cell Thickness	150 µm ± 30 µm

Table C4 is taken directly from Maxeon™ Gen III Solar Cells Manual (SunPower Corp, 2017).

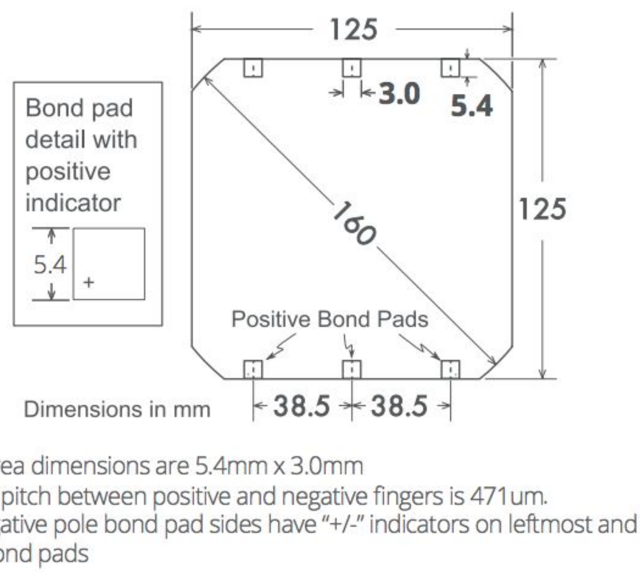

Figure C5. Technical specifications of the Maxeon™ Gen III Solar Cells. Taken directly from Maxeon™ Gen III Solar Cells Manual (SunPower Corp, 2017).

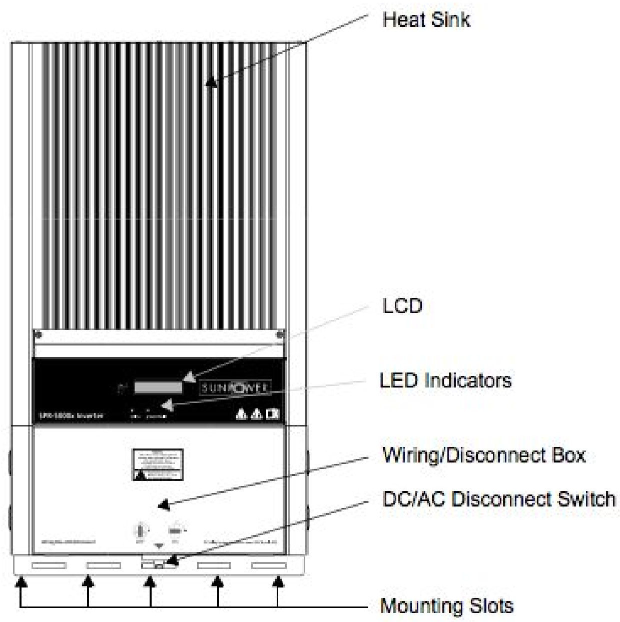

Figure C6. Front Panel features of the SunPower SPR-5000x Solar Inverter (SunPower Corp., 2007).

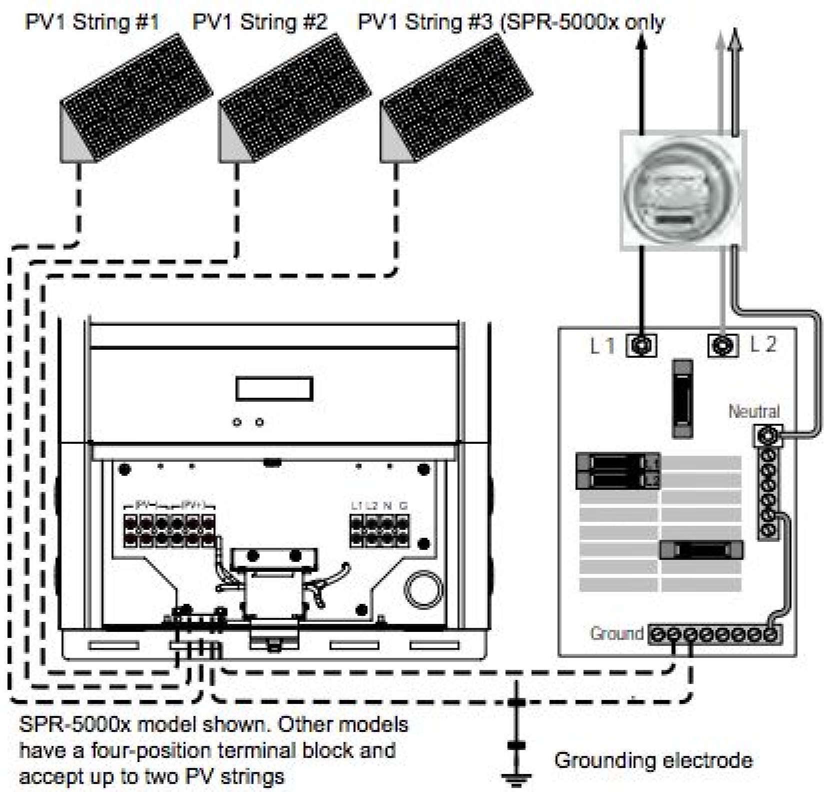

Figure C7. Connection to Inverter and Grounding Diagram. Three strings of photovoltaic modules are connected to the SPR-5000x Solar Inverter. The inverter is grounded via connection to a breaker and the power output is monitored by the meter (SunPower Corp., 2007).

Table C5. DC and AC Energy Outputs per Month

Time stamp	PV array DC energy (kWh/mo)	System AC energy (kWh/mo)	POA irradiance total nominal (kWh/mo)
Jan	454.8	426.177	2224.75
Feb	520.67	488.513	2555.2
Mar	631.26	592.514	3206.18
Apr	654.397	613.387	3480.81
May	701.332	658.548	3850.63
Jun	722.334	678.538	4038.71
Jul	806.146	758.322	4551.82
Aug	667.079	626.651	3764.06
Sep	662.192	622.302	3610.4
Oct	507.854	476.359	2683.97
Nov	270.208	250.921	1394.26
Dec	300.117	279.65	1481.24

The above values are based on a 15 module solar energy system including the SunPower X21-345 module and SPR-5000x inverter.

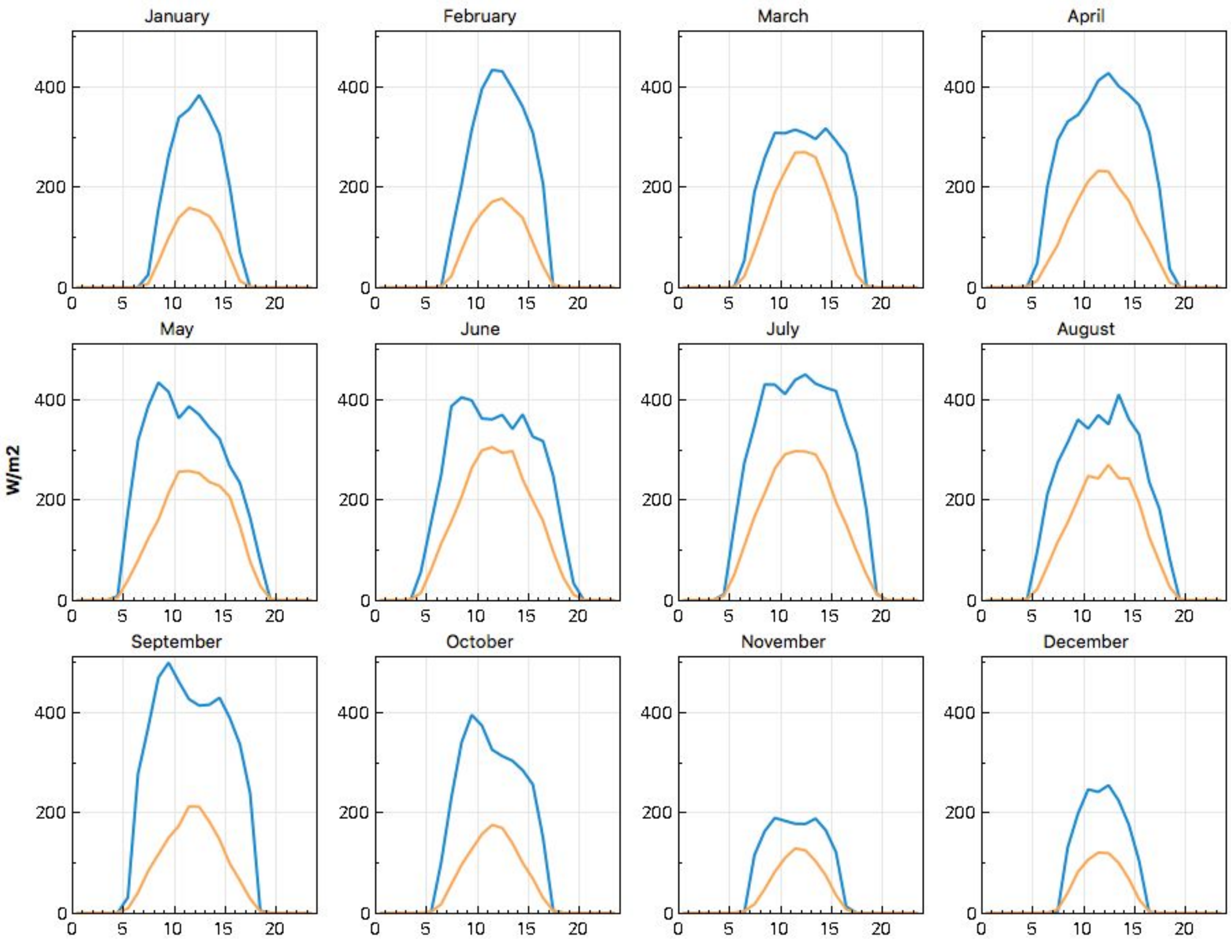

Figure C8. Average direct normal irradiance (DNI) in blue and diffuse horizontal irradiance (DHI) in orange in W m^{-2} by month.

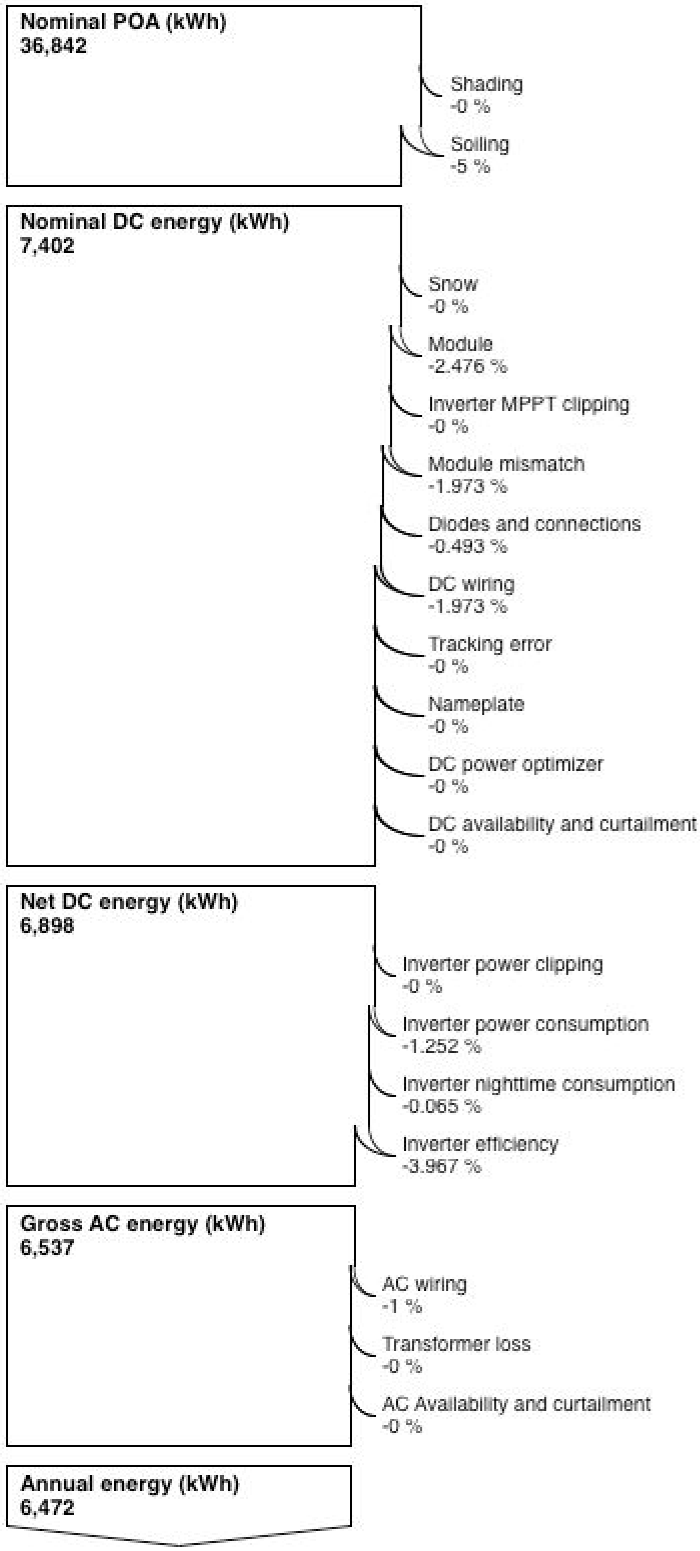

Figure C9. Losses due to various sources in the design solar energy system. The term POA stands for Plane of Array and refers to the energy output of the photovoltaic cells that constitute the modules which form the arrays.

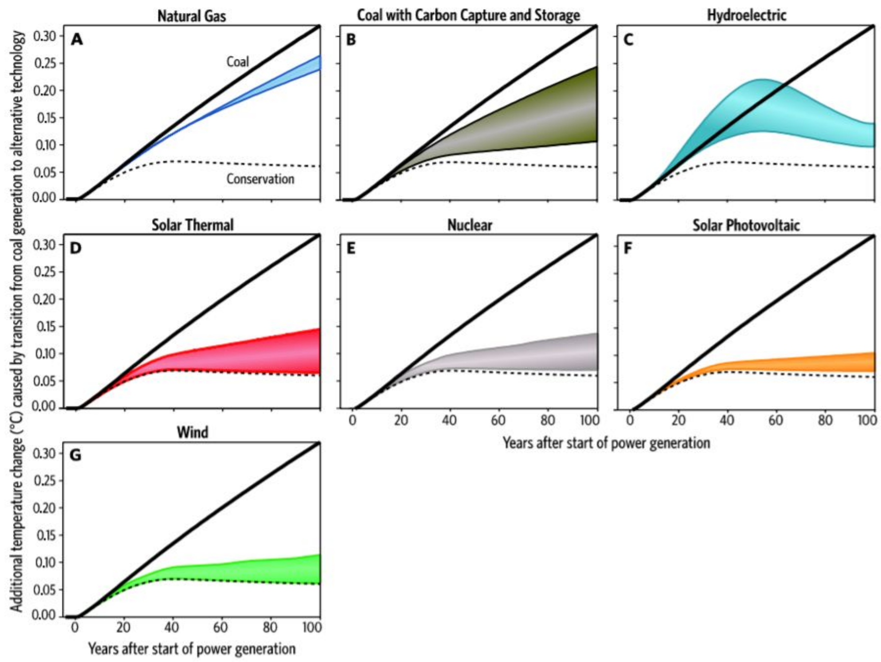

Figure C10. Increase in temperature caused by transition to various energy sources. Image from 'Greenhouse gases, climate change and the transition from coal to low-carbon electricity' by Myhrvold and Caldeira, showing the increase in temperature caused by transition to various energy sources.