Capstone Project Report:

Thermoelectric generator on wood stoves powers system

for growing produce in northern food-scarce regions

Presented to:

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BREE 495: Engineering Design 3

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Abstract:

The global energy crisis has highlighted our need for a departure from current energy practices. This has informed our preliminary design of an alternative space heating system incorporating a thermosiphon utilizing solar power and a hydronic radiant floor. After encountering multiple challenges in terms of meeting the design goals and criteria, a new system is proposed to address vegetable scarcity and general food insecurity in northern regions of Canada, with a particular focus on low-income and indigenous households. The design consists of a thermoelectric generator converting a gradient in thermal energy from wood stoves into electrical energy to power a system providing light to herb and vegetable plants, equipped with light-emitting diodes held by a 3D-printed structure and a soil moisture sensor. A life cycle analysis, cost analysis and payback period evaluation as well as failure modes and effects analysis were performed to characterize the system. The final design yields a payback period of approximately 20 months. Opportunities to improve the system's acceptability and performance are proposed, such as the incorporation of a capacitor, a quieter fan as well as the use of a program capable of alternating between the LED lights and the moisture sensor.

Keywords: global energy crisis, vegetable scarcity, food insecurity, northern regions, thermoelectric generator, LED lights, 3D-printed structure, soil moisture sensor

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1.0 INTRODUCTION

1.1 Summary of preliminary design and findings

The primary focus of the preliminary design process was to identify the largest sources of energy consumption within Canadian residences and explore ways to reduce this consumption in light of the global energy crisis. From this initial focus, it was found that 63% of residential energy use in Canadian homes is typically used for space heating and cooling and that the majority of Canadian homes are being heated by non-renewable technologies, primarily natural gas or oil-powered systems (Natural Resources Canada, 2016). This seemingly presented a large opportunity for a reduction in non-renewable energy use if some portion of the heating could be replaced by a renewable energy system, such as solar energy. The design problem was then further specified to the Thunder Bay Ontario region due to a high number of Heating Degree Days combined with relatively high energy prices compared to other provinces; the combination of a high heating requirement and high costs of heating presented an opportunity for both environmental and economic incentives to developing a design that could reduce non-renewable heating loads (*Electricity Prices in Canada (Updated 2021)*, 2020, *Heating Degree Days (18°C) - Annual Data for Thunder Bay*, n.d.).

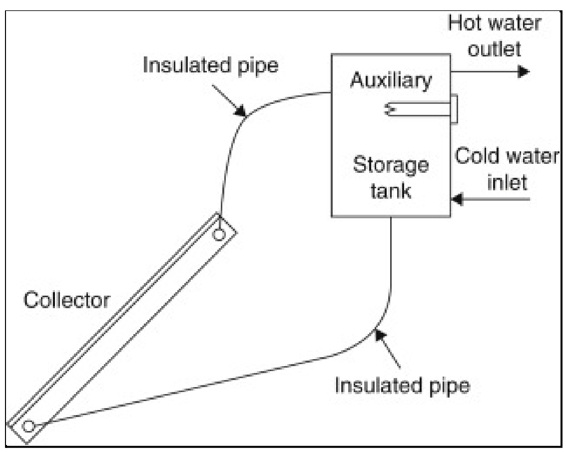

Figure 1. A thermosiphon system (Kalogirou, 2014)

An initial design was proposed which consisted of a thermosiphon connected to a hydronic radiant heat flooring system. Thermosiphons make use of natural convection to passively circulate a working fluid, either water that will be used directly once heated or another working fluid that will transfer heat to the water while absorbing solar energy. The collector consists of a series of tubes that absorb solar radiation. As the working fluid is heating, it becomes less dense and rises to the top of the collector, through an insulated pipe into a storage tank where hot water can be drawn out of an outlet (Kalogirou, 2014). The basic components of a thermosiphon system can be seen in Figure 1.

The first iteration of the design consisted of a thermosiphon system connected with a hydronic radiant heat flooring system to dissipate the heat. Hydronic radiant flooring works by embedding tubes carrying heated water into the flooring, as the heated water circulates it heats objects in contact with the floor directly. This can result in lower energy demands to reach the same level of thermal comfort when compared with forced air systems where the entire room must be heated in order to transfer heat to its occupants (Sattari & Farhanieh, 2006).

A large number of improvements and adjustments were made to the design including the selection of evacuated tube solar collectors in the thermosiphon system to increase collection efficiency, the use of propylene glycol as a working fluid to avoid freezing and ensure continuous circulation and selection of ideal tubing materials using a pugh chart. Even with efficiency improvements, preliminary calculations showed the need for the addition of more components including two pumps, a heat exchanger and a supplementary heating system. The final design is illustrated in Figure 2.

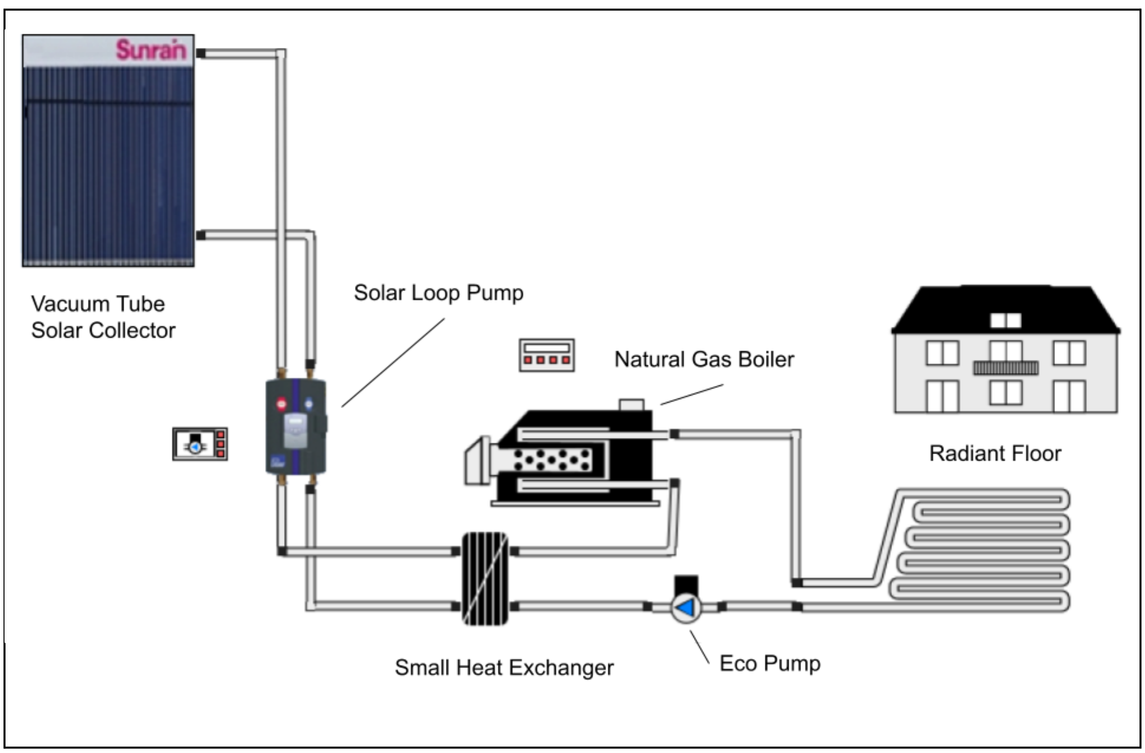

Figure 2. Previous final design and its components

This system was modelled using Polysun, a simulation tool that was developed at the Technical University of Rapperswil in Switzerland that can be used to model complex energy systems that involve both renewable and traditional energy sources (*Polysun – Energiesysteme Präzise Simulieren Und Effizient Planen › POLYSUN*, n.d.). Modelling with this software showed that depending on the insulation and efficiency standards of the home, the system would be able to provide between 32.8% and 89% of heating requirements annually. This indicated that even in cases where homes reached very high standards for insulation and efficiency, a backup heating source would be required. A natural gas boiler was selected due to compatibility with the system and relatively low costs of installation and operation compared to other systems. Unfortunately, the necessary addition of this secondary and non-renewable heating source resulted in increased losses in the system and ultimately an unsatisfactory performance in terms of energy consumption required to power both pumps and the boiler; the system was only able to outperform conventional heating systems in terms of energy use when very high standards of insulation and efficiency were met within the home. Further analysis of the cost of materials and installation showed that there was no economic incentive for the implementation of this system since so payback period could occur in most cases and even in cases where energy savings occurred, the payback period would be much too long to be considered by most consumers.

In addition to the challenges stated in terms of economic and environmental viability, there remained other significant improvements that would be required in order for the system to be viable. Necessary improvements would include the addition of a temperature regulation system, the addition of an air handling system to ensure air quality since no air exchanges occur during the heating process and air exchanges are normally regulated by the heating and cooling system and a mechanism to prevent overheating in summer months when requirements lower but solar radiation increases. In light of the existing problems as well as the remaining requirements, it was ultimately decided that due to the complexity of the design challenge and the inability of the design to meet the identified goals and objectives, it was necessary to reassess the original design challenge and formulate a new design.

1.2 Evolution of design challenge

The preliminary design presented many unforeseen challenges and issues, as developed above. This can be allocated to the large scope of the design, which incorporated many innovative technologies to increase energy efficiency and reach the design goals.

The assimilation of various non-conventional technologies within the same design increases the total costs of the design, which is exacerbated by the inaccessibility of the target area. This would be acceptable if the costs of conventional grid energy in Canada were more expensive. Indeed, the cost of electricity in Canada is one of the lowest worldwide, even in its most expensive provinces, due to the availability of many natural resources capable of producing energy such as water and oil (GlobalPetrolPrices, n.d.). Additionally, due to their uncommon usage, these unconventional systems have, for the most part, not been optimized, resulting in many losses and decreased energy efficiency. For this reason, the energy consumption was larger than conventional grid energy.

In rethinking the design, our team wanted to remain in energy-related issues but decided to center the design challenge on more remote areas within Canada, such as the Northwest Territories. A common concern in remote areas, especially in northern parts of Canada, where the climate does not allow for extensive agricultural practices, is food insecurity. In an area that relies heavily on existing residential heating systems for most of the year, a change in systems would not be economically viable for most households. The design challenge thus evolved into utilizing the thermal energy from these established heating systems to supplement food production in these remote northern regions of Canada.

1.3 Identification of final design goal and criteria

Since the targeted problem is food scarcity in northern climates, the final goal of our design is to contribute to food security by growing plants in these types of climates using off-grid electricity. Some criteria taken into account are geographic, demographic, economic and environmental. Since northern climates have lower solar radiation, northern climates and surrounding regions are the targeted geographic locations. These areas tend to have a higher concentration of low-income households and therefore the project needs to be designed accordingly (The Daily — Canadian Income Survey: Territorial Estimates, 2018, n.d.). Affordability needs to be a key element for our design which includes a short and appropriate payback period. As for the environmental criteria, sustainability is considered to minimize this design's impact on the planet. The materials used are chosen according to this criterion and the design's overall impacts are assessed through a life cycle analysis.

2.0 LITERATURE REVIEW

2.1 Food scarcity and demand for vegetables in the Canadian north

Food insecurity is defined as a lack of "physical, social, and economic access to sufficient, safe, and nutritious food" (Food Insecurity Prevails in Canadian North, n.d.). Canada has a national average of 12.7% food insecurity amongst households, but those numbers are considerably higher in the northern territories (Food Insecurity in Northern Canada: An Overview, n.d.). The percentages of food-insecure households in the Yukon, the Northwest Territories and Nunavut are 16.9%, 21.6% and 57% respectively, much higher than the national average (Food Insecurity in Northern Canada: An Overview, n.d.). There are a variety of reasons for these disproportionately high rates including the remoteness of communities making importation expensive and difficult, but the main causes are all related to the anthropogenic climate change and colonialism that have disrupted indigenous foodways of the region. Indigenous people are also the most likely to be food insecure and a 2012 report by the United Nations stated that the Inuit people of Nunavut experience "the highest documented food insecurity rate for any [A]boriginal population in a developed country" (United Nations General Assembly, 2012). Although the primary causes of this food insecurity must be addressed and autonomy and access to traditional foodways are necessary, there remains a need for increased access to food in the interim, particularly perishable food such as fruits and vegetables. There have been a variety of approaches that have attempted to address food insecurity in the North. For example, a federal program entitled Nutrition North Canada provides subsidies to eligible retailers to lower costs for consumers. However, even with these subsidies, the average cost of feeding a family of four in the north was $21,948 annually in 2019 (Food Insecurity in Northern Canada: An Overview, n.d.). Over one-fifth of households in Nunavut are considered "low income", which is defined as a household income that is less than half the median after-tax income of all Canadian households (The Daily — Canadian Income Survey: Territorial Estimates, 2018, n.d.). The high cost of food combined with high rates of low-income households leaves food insecurity rates at dangerously high levels, even with subsidies in place.

2.2 Existing solutions and approaches

There have been a variety of territorial, federal and community-based attempts to address food insecurity in northern Canada, each with varying degrees of success ("Food Insecurity in Northern Canada: An Overview," n.d.).

Territorial mandates include the Nunavut Food Security Coalition and the Nunavut Food Security Action Plan, a result of the Makimaniq Plan: A Shared Approach to Poverty Reduction. The Makimaniq Plan was drafted by the Nunavut government in collaboration with Nunavut Tunngavik Incorporated in 2011 and included the commitment to create a Nunavut Food Security Action Plan (NFSAP) as well as the formation of the Nunavut Food Security Coalition (NFSC) (Coalition, 2014; Summit, 2011; "The Nunavut Food Security Coalition: History," n.d.). The NFSAP identifies 6 areas of action: Country Food (traditional Inuit food including game meat, foraged food, migratory birds and fish), Store-Bought Food, Local Food Production, Life Skills, Programs and Community Initiative, and Policy and Legislation (Coalition, 2014). This initiative showed great promise, due particularly to its intersectionality and focus on a wide variety of factors contributing to the state of food security within the region. Within the local food production section of the action plan four main objectives were outlined:

1. "Promote innovation by supporting research efforts and project initiatives that explore ways of producing food locally.
2. Develop a 5-Year Plan for Nunavut's Growing Forward Program.
3. Explore the financial and operational viability of local food production in Nunavut.
4. Empower Nunavummiut to produce food locally." (Coalition, 2014)

Despite the potential shown in this action plan, there is little evidence of its implementation. The NFSC was created to enact the action plan but as of the time of writing, there are only three completed actions published on their website: the completion of the action plan itself and two food price surveys conducted in 2013 and 2014 ("The Nunavut Food Security Coalition: Completed," n.d.). Despite its lack of implementation, the action plan is a valuable resource as it highlights the importance of innovation, research and empowerment towards producing local food.

Federally, the most significant attempt at addressing food insecurity in northern regions was the creation of the Nutrition North program which was introduced in 2011 and operates under the management of the department of Crown-Indigenous Relations and Northern Affairs Canada (CIRNAC) ("Food Insecurity in Northern Canada: An Overview," n.d.). The program states its aim to be "help[ing] to make perishable and nutritious food more accessible and more affordable than it otherwise would be to residents of eligible isolated northern communities without year-round surface (road, rail or marine) access" and operates by allowing registered food retailers, producers, distributors and suppliers to apply for subsidies (Government of Canada et al., n.d.). These subsidies should then be used to reduce the price at which the goods are sold, however, a 2014 report by the Auditor General stated that the managing department failed to verify whether or not the full subsidy was passed on to the consumers through price reductions (Government of Canada, Office of the Auditor General of Canada, 2014). The same report also stated that the department had not established community eligibility criteria that were fair, equitable or based on current need and had not collected the information necessary to manage the program or evaluate its success. A paper published in 2019 also found that rates of food insecurity in Nunavut increased by 13.2 percentage points after the full implementation of the program, which was between 31 and 43% higher than the predicted rates based on trends before the implementation, depending on the impact model used (St-Germain et al., 2019).

Even if the Nutrition North program had been successful in lowering rates of food insecurity, the program and other subsidy programs like it still leave northerners vulnerable to supply chain interruptions and inflating fuel prices. It has been increasingly recognized that there is a need for a shift in focus away from subsidy programs and towards solutions that increase autonomy, resilience and food sovereignty (Coalition, 2014; "Food Insecurity Prevails in Canadian North," n.d.). This is exemplified in a quote from food security researcher Karolina Stecyk stating "Efforts have to go beyond subsidy programmes and focus on innovative approaches and strategic thinking, such as strengthening the North's own food-producing capacities" ("Food Insecurity in Northern Canada: An Overview," n.d.). Due to the intense climate of the north, conventional agriculture is difficult to implement but the area has seen some success in growing food in greenhouses in a small number of community projects (Canadian Space Agency, 2021; "Iqaluit Community Greenhouse Society," n.d.; Mahoney, 2004).

The first of these projects, the Naurvik project, includes three retrofitted shipping containers in Gjoa Haven Nunavut that grow fresh food year-round (Canadian Space Agency, 2021). The system is hydroponic and uses wind and solar energy to provide the necessary power while remaining off-grid. Although the capacity is limited, only one pod is used for growing food while the remaining two are required for utility and power management, the project has been well-received due to its production of high quality produce, creation of local jobs for a handful of technicians and the fact that the creation process was driven by local Inuit input (Brown, 2020; “Unique Arctic project driven by local Inuit input,” n.d.). The first harvest of lettuce from the containers in 2019 was given to Gjoa Haven elders and local technician Betty Kogvik was quoted saying “It was so fresh, not like what we get in the store. Sometimes when we get [lettuce] in the stores it is almost rotten. The ones we harvested are really fresh and tasty," Kogvik said. "One elderly lady even danced with joy when she got her lettuce” (Brown, 2020).

The Iqaluit Community Greenhouse in Nunavut was established in 2001 by a group of residents who fundraised to purchase a 1000 sq ft prefabricated greenhouse to improve food security and contribute to research on northern agriculture (“Iqaluit Community Greenhouse Society,” n.d.). The greenhouse does not use any supplemental heating which limits its growing season to the beginning of June until the beginning of October. The annual cost of operation is around $4,000, most of which is supplied by membership fees, donations and occasional grants. Members of the Community Greenhouse Society all share the work of planting, weeding, and watering as well as the harvests whenever they occur. A minimum of one share of each harvest is also donated to local charitable organizations like the local shelters and the Iqaluit Food Centre (“Iqaluit Community Greenhouse Society,” n.d.).

The Inuvik Community Greenhouse in the Northwest Territories is the oldest of these initiatives, originally established in 1998 when a group of local volunteers began work to transform an old hockey rink into a space to grow food (Mahoney, 2004). The greenhouse has 170 plots available for members to rent as well as a second floor where they sell plants to help contribute to the costs of operation. This greenhouse is also passive, like the one in Iqaluit, and has a growing season from around the second week of May until the beginning of October (Mahoney, 2004).

These three projects demonstrate the opportunity for small-scale agriculture in the Canadian north and highlight the sense of autonomy and self-sufficiency that can come from strengthening food production. Although they have all been successful in their mandates there remain some limitations that inhibit the expansion of these sorts of initiatives. Firstly, there is a limited capacity; the Inuvik Community Greenhouse has waitlists for spots in the garden and the

Iqaluit and Gjoa Haven projects are located in even smaller spaces, lowering capacity (Mahoney, 2004). Secondly is the issue of heating and energy; the only project that grows year-round is the Naurvik project in Gjoa Haven and this required the implementation of wind and solar energy systems which greatly increases the cost and impact of this kind of project. Lastly is the reliance on donations and funding to establish these projects. The Naurvik project is funded by the Arctic Research Foundation, Agriculture and Agri-Food Canada, the National Research Council Canada and the Canadian Space Agency (Canadian Space Agency, 2021). The land used by the Iqaluit greenhouse is owned by the Nunavut Research Institute who has chosen to allow its operation without charging rent and is otherwise funded largely by donations and grants ("Iqaluit Community Greenhouse Society," n.d.). The Inuvik greenhouse relies on "government funding (both federal and territorial), local business support, volunteer-run bingos/yard sales/raffles, and the sale of bedding plants" to fund operations (Mahoney, 2004). This reliance on donations, grants and variable funding leaves these initiatives vulnerable to changes in funding and ultimately lowers the resilience of the system.

The recommendations of the Nunavut Food Security Action Plan to "promote innovation by supporting research efforts and project initiatives that explore ways of producing food locally" as well as "empower Nunavummiut to produce food locally", the lack of success of federal subsidy programs and the limitations of constructing greenhouses have inspired our team to explore ways in which produce can be grown off-grid, year-round and without the need for donations or unreliable funding (Coalition, 2014).

2.3 Wood stoves and their use in the Canadian north

Wood or pellet stoves were used as the primary heating source in 21% of Canadians' primary or secondary dwellings as of 2019 (Government of Canada, Statistics Canada, 2021). Although the popularity of wood-burning stoves as a primary residential heating source seems to be declining in recent years, due partially to the increased awareness of the negative impacts on air quality, there remain many reasons why a household might choose to heat their home with wood (Government of Canada, Natural Resources Canada, 2018; Lévesque et al., 2001). Firstly, heating via wood or pellets can provide an increased level of autonomy for households in remote locations, whose energy supply can be frequently interrupted by the extreme climatic events that are becoming more common as climate change continues to progress (Bélanger et al., 2008).

Secondly, wood and pellet heating is often the least costly option for households located in northern Canada; the number of heating degree days in the north is much higher than in other parts of the country and the remoteness of many of the communities results in exorbitant costs of importing other energy sources (*CER – Market Snapshot: Explaining the High Cost of Power in Northern Canada*, n.d.). The relative costs of various energy sources will depend on the individual community and market prices but one analysis of cost per kWh of heating in the Northwest Territories lists softwood as the cheapest heating source at approximately 7 cents per kWh, followed by pellets at approximately 8 cents per kWh (Northwest Territories: Industry, Tourism and Investment, 2012). Other heating sources like heating oil and natural gas were almost twice the price per kWh, an increase that has a massive financial impact when heating requirements are high (Northwest Territories: Industry, Tourism and Investment, 2012). The lower cost of heating with wood and pellet stoves could suggest that households using this as their primary heating source are more likely to be designated as low-income households and are therefore at a higher risk of experiencing food insecurity.

2.4 Thermoelectric generator

Thermoelectric generators (TEGs) are devices used to convert thermal energy into electrical energy. In order to function, they require a temperature gradient created by the direct exposure of one surface to thermal energy, and the other opposing surface at ambient temperature. These instruments consist of several thermopiles, which comprise a series of thermocouples, each made of a pair of dissimilar semiconductors, one p-type and one n-type (Jaziri et al., 2020). Semiconductors are commonly used in thermoelectric applications due to their desirable properties. Indeed, these materials, as opposed to metals, or conductors, have a decreasing resistance with increased temperature. This is ideal for applications dealing with high temperatures. Additionally, electrons in semiconductors require little energy to jump from the valence state to the conduction state. For example, silicon, the most frequently used semiconductor, requires approximately 1.12 eV at room temperature to surpass the energy gap between the valence and conduction states. On the other hand, the most common dielectric material, silicon dioxide, has an energy gap of 9 eV (Shur, 2005).

TEGs rely on a few thermoelectric phenomena, primarily the Seebeck effect, but also the Peltier and the Thomson effects. The Peltier effect is the inverse of the Seebeck effect. The latter describes the generation or absorption of heat due to electrical current flowing between semiconductors (Terasaki, 2011). The former describes the generation of an electrical current due to the absorption of heat. More precisely, the temperature gradient caused by heating one surface creates a diffusion in the charge carriers (holes or electrons), moving from the hot to the cold side. This diffusion in charge carriers creates an imbalance in the thermocouple, which is then equilibrated by the resulting internal electrical field. The voltage generated by the Seebeck effect is harvested by connecting a load to the thermoelectric materials. This can be observed in Figure 3. The Seebeck effect can be described by the following equation (Eq. 1), where S is the Seebeck coefficient, ΔV is the potential difference, and ΔT is the temperature gradient (Hofmann et al., 2019).

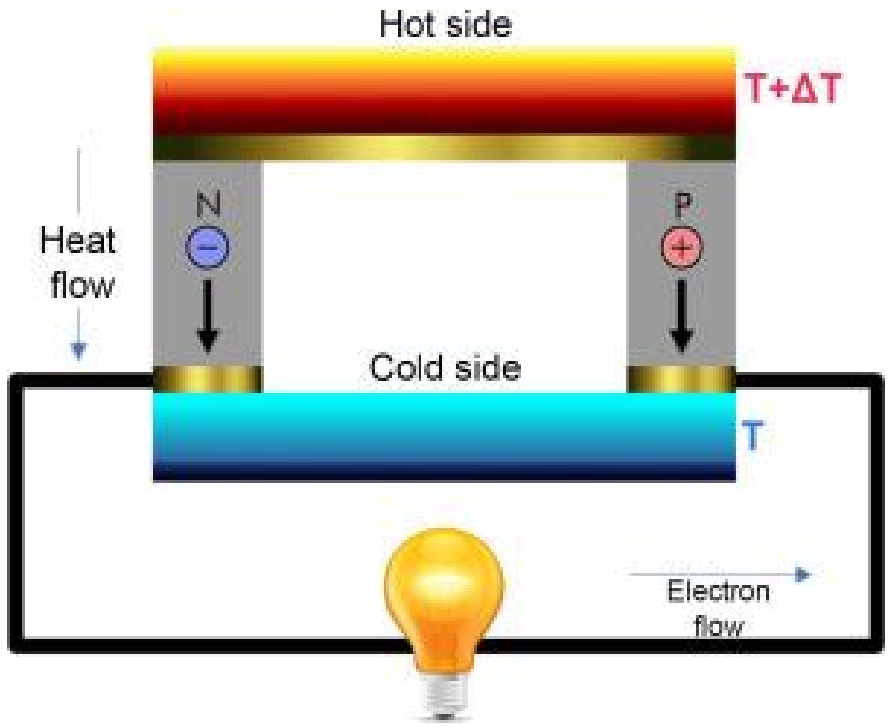

Figure 3. Thermoelectric generator principles (Bellucci et al., 2021).

$$S = \frac{\Delta V}{\Delta T} \quad (1)$$

A major constraint to keep in mind during our design process is that the temperature difference between the woodstove and the surrounding air needs to be as large as possible for a TEG to be productive. This is since this temperature gradient determines the amount of output electricity (Hofmann et al., 2019).

The Thomson effect is an effect that is generally neglected but is still present within the system. This effect describes that heat power is absorbed along the length of a rod whose extremities are at different temperatures. This heat absorption is proportional to the current flowing through the rod, as well as to the temperature gradient throughout the material. This proportion is described by the Thomson coefficient (Strohl et al., 1999).

The conversion efficiency of TEGs from thermal energy to electrical energy is highly variable. It depends on the properties of the employed thermoelectric materials, such as thermal and electric conductivity and resistance, the number of thermocouples and thermopiles used, the heat source, ambient air conditions, and so on. However, generally, the conversion efficiency of TEGs will not exceed 10% (Jaziri et al., 2020).

The TEG used in this experiment's prototype is a TECTEG generator and can supply 10W of power. The device has the best performance when placed directly onto a hot surface, such as a powered stovetop or the surface of a wood stove when it is burning. A small case fan is built into the device, to prevent the system from overheating. The fan starts automatically after a few minutes of being placed onto a hot surface (TECTEG, n. d.).

2.5 LED system

Plants, including various vegetables and herbs, require light, preferably from the sun, to perform photosynthesis, which is the process of converting light energy to fuel in the form of carbohydrates. This light can be supplied artificially through light-emitting diodes (LEDs). These lights have a low power consumption and heat output, as well as high luminous efficiency. The low power consumption and high light efficiency are ideal for situations where only small amounts of power can be supplied. The low heat output allows the LEDs to get within a closer range of the plants without causing them any heat damage, therefore maximizing space. Additionally, the spectral range of these lights coincides with the range that is optimal for plant morphogenesis (Ma et al., 2021). This is essentially the plant's development, where the external plant tissues will grow and expand into the plant's shape. The phenomenon entails coordination of cell division, growth and differentiation, to form a complex entity (Lecuit et al., 2019).

Various plants respond differently to the application of different light colours. Red and blue light have attracted the most attention due to their wide success with plants. However, the variability in preference for one colour or the other is very high among different plant species. When exposed to only blue or only red LED lights, different characteristics of various plant species are affected both positively and negatively. However, a study has shown that when exposed to a 1:1 blue-to-red LED light mixture, one physiological indicator, dry weight, increased in 17 taxonomic families (Ma et al., 2021). Many more studies are still required as to the effects of green and ultraviolet light on the growth of plants.

2.6 Sensor applications in agriculture

The applications of sensors in agriculture should be considered when designing for a passive small-scale garden. A 2010 publication by Pallavi et al. (2017) provides a variety of sensor technologies that exist to cover the different constraints in agricultural practices. Remote spectral sensing captures images of crop fields to obtain data on electromagnetic radiation, or sunlight, to provide feedback for improving watering practices. For example, spectral reflectance measurements determine irradiation using between visible, 400 to 700 nm, and infrared, 700 to 2500 nm, wavelengths. Spectrometers, radiometers and digital cameras are commonly installed on tractors or satellites for remote sensing. For food quality, electronic noses can assess volatile organic compounds (VOCs). Disease, spoilage and insect infestations can be identified with electronic noses by analyzing gases present during a product's harvest, processing, handling and packaging processes. Electrochemical sensors for pH and nutrient concentrations are used to assess soil quality for crops which correlates directly with crop yield and food quality. Sensors for assessing bacteria in crops are called biosensors. Biosensors are composed of a bio-probe for recognizing bio-molecules, or pathogens, and of a transducer that translates the analysis into comprehensible data. The most popular bio-probes, nucleic acids, proteins, enzymes, antibodies and phages, can detect chemical contaminants and food-borne pathogens. Due to their high precision, wireless sensor networks are increasingly being adapted for introduction into agricultural practices (Pallavi et al., 2017).

3.0 DESIGN APPROACH

3.1 Evaluation of heat capture potential

The northwest territories contain part of the Canadian Boreal forest, where spruce and larch are two of the dominant softwood tree species. For practical purposes, we will focus on larch. A cord of larch wood has the heating potential of 21.8 million BTU's, a cord being around 3.6 m^3 of wood (Kuhns & Schmidt, 1988). A log of firewood is typically 0.15 m wide by 0.4 m long. Assuming that a fireplace can accommodate approximately 6 logs, this is a volume of 0.36

m^3 of larch (Reed, 2013 & Winans, 2020). The heating potential of one wood stove full of firewood can then be calculated, as in Eq. (2).

$$\frac{21.8\ million\ BTU's}{3.6\ m^3} = \frac{Heating\ potential}{0.36\ m^3} \tag{2}$$

$$Heating\ potential = 2.18\ million\ BTU's = 2.3 * 10^9\ J$$

It is reported that Western Larch has a heating efficiency of $\eta_{heating}$ = 60% when combusted in an airtight wood stove (Reeb, 2013). By assuming a charring rate of β = 0.73 mm/min (calculated in terms of advancement of the charring front), one can calculate how long a 0.150 m wide log will take to be completely charred, in Eq. (3) (InnoFireWood, n. d.).

$$Char\ time = \frac{width}{\beta} = \frac{0.150}{0.00073} = 205.5\ minutes = 3.4\ hours \tag{3}$$

Given the fact that charred wood can still emit heat, the total burn time can be rounded off to t_{burn} = 4 hours (Regency Fireplace Products, 2019). Thus,

$$Q = \frac{\eta_{heating} * Heating\ potential}{t_{burn}} = \frac{0.60*2.3*10^9}{4\ hours*60\ minutes*60\ seconds} \approx 96\ kJ/s \tag{4}$$

A standard wood stove with a medium heating capacity (46 to 92 m^2) has dimensions of around 0.6 m x 0.6 m x 0.7 m, as presented below in figure 4, for a total surface area of 2.28 m^2 (Regency Fireplace Products, n. d.).

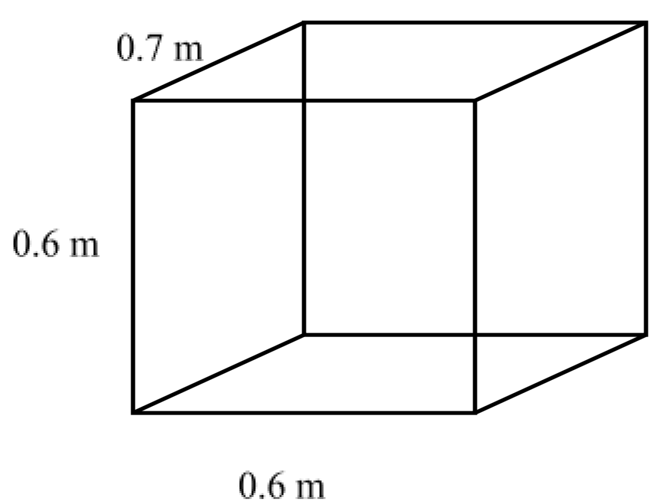

Figure 4. Dimensions of a medium wood stove.

It can be assumed that the stove is entirely made of cast iron (k = 52 W/mK), and there are no further losses from the stove (Engineering Toolbox, 2005). The temperature inside the wood stove is approximately 350ºC (T_{fire} = 623.15 K) and the temperature inside the household can be assumed to be 20ºC (T_{house} = 293.15 K) (InnoFireWood, n. d.). By assuming that the thickness of the stove is equal all around, with a thickness of s = 0.008 m, the heat rate supplied to the TEG resting on the wood stove can be calculated. The generator's surface area in contact with the stove measures 15 cm by 15 cm (TECTEG, n. d.). The amount of power supplied to the generator is determined in Eq. (5).

$$Q = (k/s) * A * dT = \frac{52}{0.008} *(0.15*0.15)*(623.15-293.15) \quad (5)$$

$$Q = 48.26\ kJ/s$$

The woodstove supplies the generator with a maximum of approximately 48 kJ/s.

3.2 Calculations of power supplied

The prototype TEG of our design has a set power output of Q_{out} = 10W. Assuming no further losses to the devices materials or the environment, and given a maximum efficiency of η = 10%, the following can be calculated:

$$Q_{out} = Q_{in} * \eta \quad (6)$$

$$Q_{in} = \frac{Q_{out}}{\eta} = \frac{10\ W}{0.10} = 100\ W = 100\ J/s$$

It can be deduced that 100 J/s of thermal energy must be supplied to the TEG device. By comparing this to the amount of thermal power supplied to the generator's surface area, the fraction of heat supplied to the TEG is obtained:

$$Fraction\ used = \frac{Heat\ used}{Heat\ generated} * 100 = \frac{100}{48260} * 100 = 0.2\% \quad (7)$$

The TEG uses 0.2% of the heat supplied by the wood stove for the assigned surface area.

3.3 Selection of appropriate plants

Production of lettuce heads was chosen to model our payback period for a variety of reasons including suitability for cooler temperatures, relatively short growing period between planting and harvest, ease of maintenance, nutrition value and precedent set by previous greenhouse projects in northern regions (Brown, 2020; “Lettuce,” 2020; University of Rochester Medical Center, n.d.).

Lettuce can tolerate cool temperatures down to approximately 4ºC and has an ideal range between 15 and 18ºC. This is ideal for growing indoors as the home temperature may drop during the night and temperatures near windows, which is an ideal placement for the system, can reasonably be assumed to be within this range. Most varieties of lettuce take around 45 days to mature but can be harvested partially or fully before then and enjoyed as microgreens (“Lettuce,” 2020). Lettuce is also a low-maintenance plant and does not require prior gardening or farming knowledge from the user. It also contains a wide variety of vitamins and minerals including high levels of vitamin A and beta carotene (University of Rochester Medical Center). Lastly, it was selected after the literature review showed success in growing lettuce and the social acceptability of the vegetable in existing northern greenhouses (Canadian Space Agency 2021; Mahoney 2004; Iqaluit Community Greenhouse Society).

Although calculations are based on the production of lettuce, the system can be adjusted to the specific needs of a variety of plants including the plant size and moisture requirements due to the adjustable stand as well as the possibility to adjust the moisture value at which the moisture indicator LED is illuminated. The flexibility of the system is particularly important as it gives the user the freedom to grow foods they are comfortable with and perhaps are used to harvesting in the summer months in surrounding areas. The possibility of growing local plants is an attractive prospect as it would allow for practices like seed saving and increase the cultural and social acceptability of the design.

3.4 Moisture sensor

A moisture sensor was integrated into the design to facilitate plant care for the users. Agricultural practices in general in these areas are already scarce, meaning that most users of this design will possibly not be experienced with growing plants. Additionally, space heating in older homes that are not air-tight could lead to the infiltration of dry and cold outside air, thus increasing the need for watering. Hot air also has lower relative humidity, increasing its potential for water uptake, possibly changing the watering needs of the plants (Hirsch, n.d.). Since the produce that users will be growing will not be native to these climates either, indicating when the plants need to be watered is very useful. The components included in this moisture sensor are the Arduino Uno R3 board, a capacitive moisture sensor v1.2, a red LED light, electrical wiring and a 3D-printed PLA storage box. The Arduino, moisture sensor and LED are connected as seen in Figure 5 below.

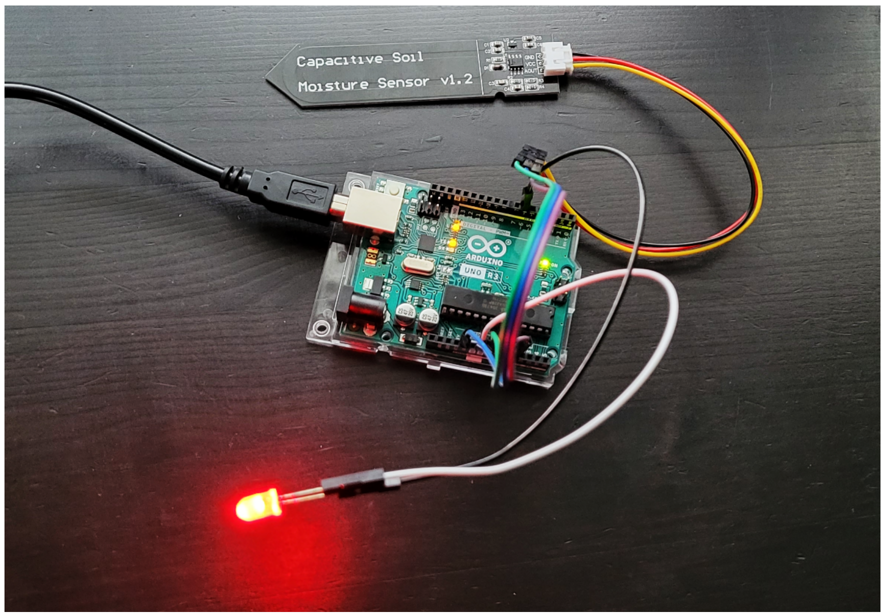

Figure 5. The set-up for the Arduino Uno with the capacitive moisture sensor and LED light.

The Arduino was programmed to indicate when the plant watering needs are not being met. For this, a “good moisture value” was set in the program as seen in Figure 6. Whenever the moisture sensor readings are below this good moisture value, the red light turns on, advising the user to water their garden. As the plants are watered, the moisture readings increase and surpass the good moisture value which turns the LED off. The good moisture value can be easily modified depending on the water needs of the selected plants. This moisture sensor set-up consumes a total of 0.57 W, which is only a small fraction of the 10 W of power supplied by the TEG. Therefore, this component can easily be wired to the rest of the design without draining its efficiency. The total power consumed by the moisture sensor set-up was calculated using the power equation as seen in Eq. (6) for the three main components of the moisture sensor system: the moisture sensor itself, the Arduino Uno and the LED. The overall power consumption of this set-up was found by adding together the power of each component.

$$P = V * I \tag{6}$$

```
#define msensor A1
#define led 6

int goodmoisture = 300;

void setup() {
 pinMode(msensor, INPUT);
 pinMode(led, OUTPUT);

 Serial.begin(9600);
}

void loop() {
 int msvalue = analogRead(msensor);
 Serial.print("Sensor value =");
 Serial.print(msvalue);
 Serial.print("\n");

 if (msvalue > goodmoisture) {
  digitalWrite(led, HIGH); }
 else {
  digitalWrite(led, LOW); }

 delay(1000);
 }
```

Figure 6. Code used to program the Arduino Uno for moisture sensing.

4.0 FINAL DESIGN

The final design, as demonstrated in Figure 7 below, involves a TEG (1) that will be placed on the surface of a wood stove (not shown). This device is then connected and provides power to a strip of remote-controlled LEDs (3), as well as to the Arduino moisture sensor (4). The LED lights are supported by a 3D printed tree-like structure (2) on either side of the herb garden, made of polylactic acid (PLA). The height of the lights can be easily adjusted by this structure to accommodate various types of plants of various sizes (see Figure 9). The tree imagery of this stand makes the structure aesthetically pleasing and recalls the greenery in its center.

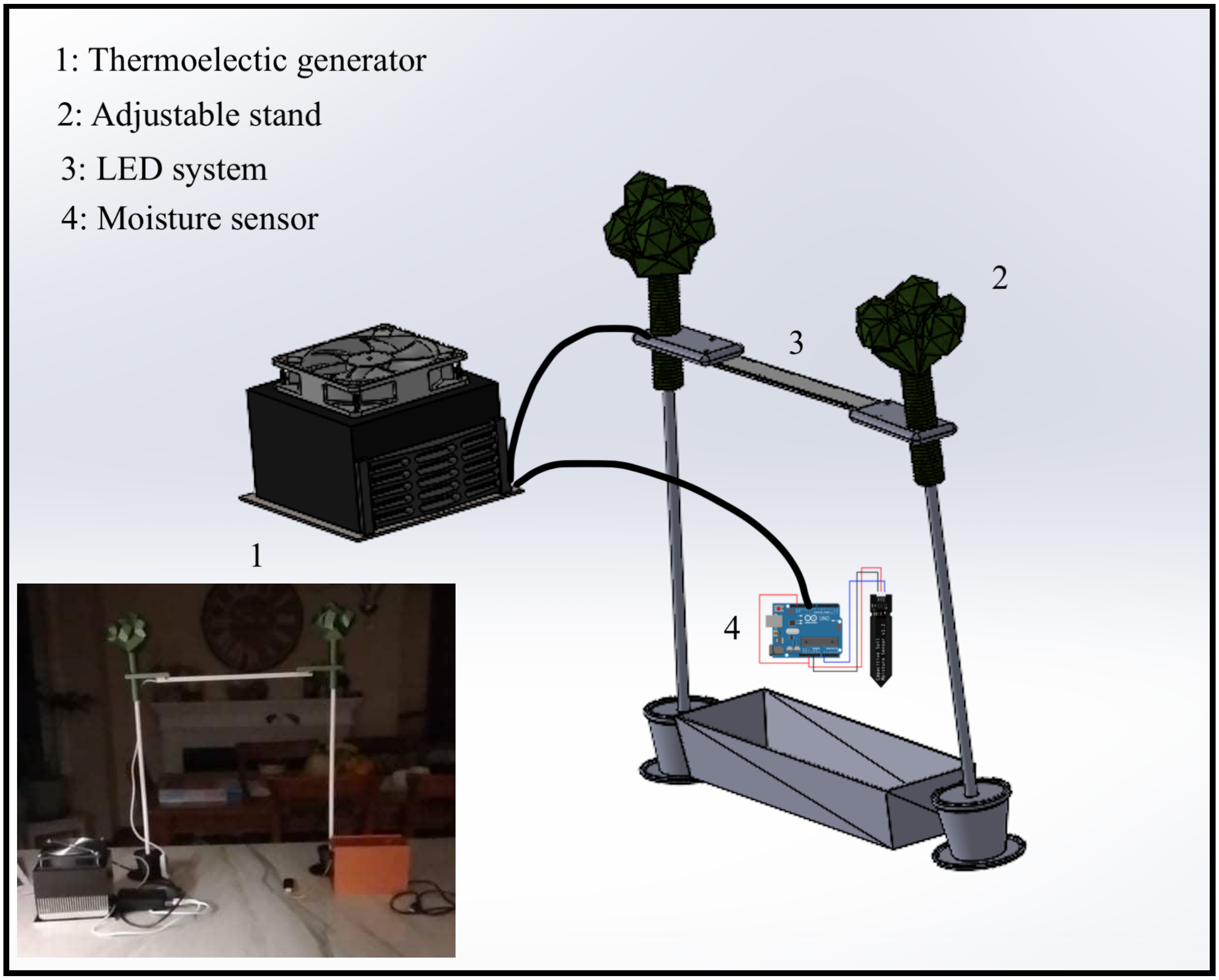

Figure 7. Final design and components involved with a picture of the final design (bottom left)

As for the moisture sensor system, a box was designed on AutoCAD and 3D-printed out of bronze-coloured PLA to protect and organize the Arduino Uno and electrical wires and can be seen in Figure 8. The box has holes for each connection and a simple separate sliding lid. The USB wire for the Arduino can easily access the Arduino through a hole in the back of the box. The red LED can stick out from an opening on top of the box's lid for the user to see from afar. The moisture sensor wires can easily slip through a gap between the lid and the box to access the potting soil. In Figure 8, the photo on the left shows a "dry soil" state with air as the moisture sensor reading and, on the right, a wet cloth was used to simulate watered soil showing that the LED light turns off when the plants are sufficiently watered.

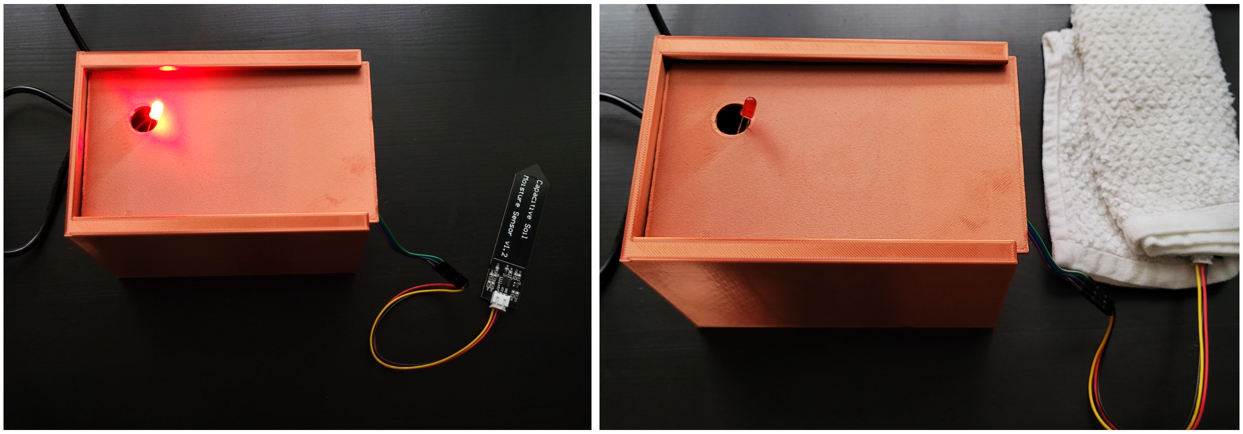

Figure 8. The moisture sensor set-up before (left) and after (right) simulated watering.

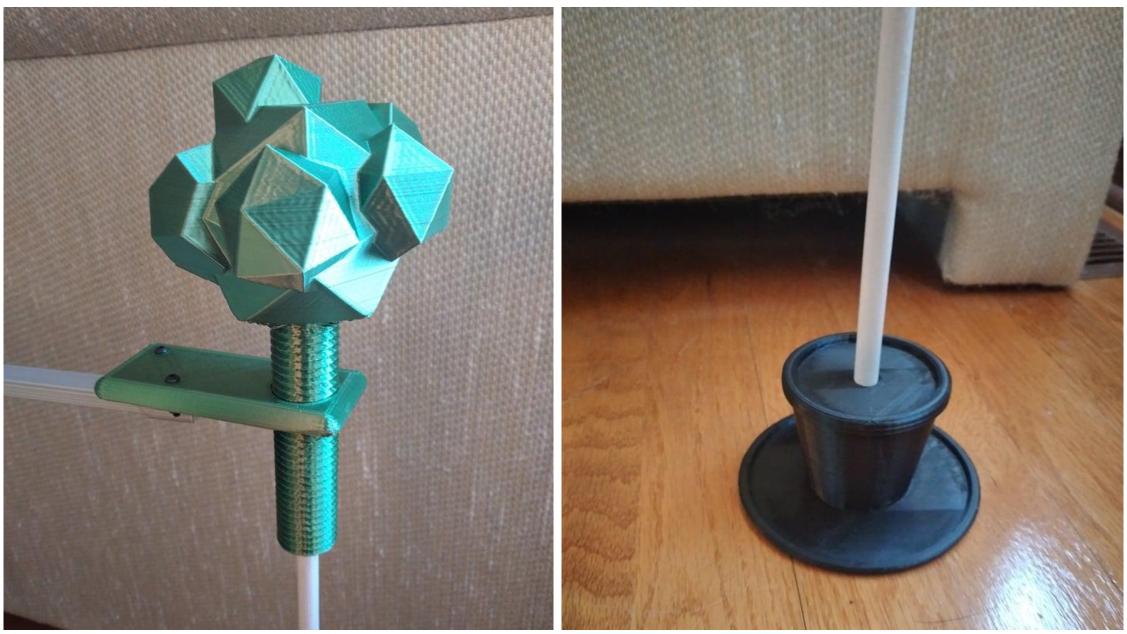

Figure 9. Adjustable 3D printed LED supports (left) and base (right)

5.0 EVALUATION OF DESIGN

5.1 Life Cycle Assessment (LCA)

The following section describes the life cycle assessment (LCA) of the proposed TEG for growing plants. The table below contains all components of the design as well as their main constituent materials. The extraction and processing of each material will be discussed, and the sustainability and end of life of the components will be assessed.

Table 1. Components of the design and their main constituent materials

Components	Materials
TEG	- Silicon-germanium alloys - Aluminum
Adjustable stand	- Polylactic acid (PLA)
LED system	- Aluminum-gallium-arsenide
Moisture sensor	- Copper

5.1.1 *Raw material extraction process to obtain materials required for design*

As described below, the raw material extraction process for the materials listed in Table 1 negatively affects the environment. This is principally due to the open-pit mining required to obtain all of the materials, excluding polylactic acid.

Silicon-germanium is an alloy composed of silicon and germanium. Although silicon is the second most abundant element in the earth's crust, it is too reactive to be found as a pure element (Silicon, n.d). Silica sand deposits are the primary source of silicon and are excavated via open-pit mines (Grbes, 2016). Germanium is mined in the form of copper, aluminum or lead ores (Gonzalez et al, 2018). Once extracted, these elements are typically transported by truck or by train to processing facilities. Wet silica sand can travel more than 100 km by truck, or 700 km by train to processing facilities (Grbes, 2016). Both the extraction and transportation of germanium and silicon require fossil fuels, which increases the negative impacts of these materials on the environment. Moreover, the process by which the minerals are extracted from open mines disrupts the surrounding environment since they occupy such a large area. Mining ores can also result in waterway and soil contamination since the process requires chemical reagents (Government of Canada, n.d.). Overall, the extraction process of both silicon and germanium will have negative effects on the surrounding environment.

Like the germanium element, aluminum, copper, gallium and arsenic are also mined using open pits (Staley, n.d.; University of Arizona, n.d; Foley et al, 2017). As described above, open-pit mining causes physical disturbances to the landscape, and the extraction of ores can contaminate waterways and soil. Aluminum is known to be toxic to aquatic life by impairing their metabolic processes (Rosseland et al, 1990). Although copper is an essential nutrient to animals at low concentrations, higher concentrations, which can occur due to mining processes, are toxic to aquatic organisms (EPA, 2007). Similarly, gallium and arsenic were both found to be deadly for aquatic species at low concentrations (Foley et al, 2017). As such, the extraction of aluminum, copper, gallium and arsenic can pose environmental consequences.

Because polylactic acid is made from renewable feedstock, the extraction process of these natural resources produces fewer greenhouse gases when compared to the open mine pit extraction processes highlighted above (Ghomi et al, 2021).

Overall, excluding PLA, the extraction process of the raw materials necessary for the design has ecological health concerns for the surrounding environment at which they are being mined.

5.1.2 *Processing of materials required for design*

The processing of the extracted materials has a significant carbon footprint due to the high temperatures required. These processes are briefly summarized below for each material from Table 1.

- ❖ Isolating silicon from silica sand requires enormous amounts of energy (usually in the form of fossil fuels) to heat the sand to 1900°C (Furgal and Lenora, 2020).
- ❖ Purifying copper demands high temperatures of approximately 1260°C to separate the copper from copper sulphide ores (University of Arizona, n.d).
- ❖ Although 30% of germanium comes from recycled sources, germanium that accompanies copper, zinc or lead must undergo a chemical treatment and distillation process to purify it (Gonzalez et al, 2018).
- ❖ Processing aluminum is a two-step operation that requires refining bauxite to acquire alumina and then smelting alumina to obtain aluminum (Bridenbaugh, n.d.). Gallium undergoes a similar process since it is often separated from aluminum (Foley et al, 2017).
- ❖ PLA is typically processed using either extrusion methods or injection moulded methods. The former uses approximately 2MJ/kg of electricity while the second uses 7.2 MJ/kg (Ghomi et al, 2021).

The processing of silicon, copper, germanium, aluminum and gallium negatively affects the environment through the enormous amount of energy required for their processing, which is likely to be fossil fuel-based in most countries. Moreover, similarly to the toxic waste that can be produced on the mine sites, these processing facilities produce waste that can infiltrate water and soil which consequently harms organisms (Foley et al, 2017).

5.1.3 *Use and end of life of design*

The proposed design is considered to be very durable given its long lifetime. The design's lifetime is based on the duration of the TEG. This particular generator could be used continuously for approximately eleven and a half years (TEGMART, n.d.). Given that the TEG would not be used 24 hours a day to provide light for plants, but rather closer to a period between 8 to 12 hours, the lifetime of the design would range from 23 to 34 years. LEDs are rated to have approximately 50,000 hours of continuous operation ("LED FAQs", n.d). For this design, they would last in the range of 12 to 17 years if they were on 8 to 12 hours a day. Thus, the users would have to replace the LEDs once before the design was no longer functional. The long lifetime of the design lessens its impact on the environment as it creates little to no waste.

From an energy consumption standpoint, TEGs are designed to exploit temperature gradients to provide energy; they exploit a negligible amount of heat from wood stoves and do not consume or produce any fossil fuels during their usage period. Thus, the design has little to no impact on the environment throughout its usage period and does not contribute to the production of greenhouse gases.

The materials used in the design can all be recycled if they are brought to the appropriate facilities. However, given that the design is designated for rural regions in Northern Canada, users might not have access to such facilities. In this case, the disposal of the design into landfills must be considered as a possible environmental impact.

5.2 Cost analysis and payback period

To analyze the incentive of consumers to purchase the design, the payback period was calculated for both the prototype our team fabricated, and a hypothetical design that includes stronger LEDs for Northern regions that experience 24 hours of darkness during the winter solstice. Tables 2 and 3 represent a breakdown of the cost of materials for our prototype and the hypothetical design.

The prototype that was designed has an output of 1000 lumens per square foot from the

LEDs. This system works best when combined with indirect light coming from a window since at least 7500 lumens per square foot are required to grow vegetables indoors (Leading Gear, 2020).

Table 2. Prototype cost breakdown.

Material	**Cost**
TEG (10W)	250$
LEDs (10W~ 1000 lumens)	25$
PLA	~20$
Arduino	25$
Moisture sensor	4$
Total cost (excluding Arduino and moisture sensor)	295$

The hypothetical design covers the cost required to construct a system that requires no supplementary outdoor light. Northern regions in Canada can experience several months of little to no light during the winter. To be able to grow vegetables indoors, the LEDs would need to provide at least 7500 lumens. Table 3, therefore, includes a TEG capable of producing 100W of power that would output 10 000 lumens from the LEDs.

Table 3. Hypothetical design cost breakdown

Material	**Cost**
TEG (100W)	300$ (Li et al., 2021)
LEDs (2 x 50W~ 10000 lumens)	50$
PLA	~20$
Total cost	370$

To calculate the payback period for both designs, the following assumptions were made:

- The cost of lettuce in the northern regions of Canada is approximately 7$ per head (Whitley, 2018).

- A single square foot of space can yield four lettuce heads (Urban Seedling, n.d).
- Lettuce reaches maturity after 45 days (Burpee, n.d).

The cost of the Arduino and moisture sensor was excluded from the payback period because a design of this small scale would not require a moisture sensor.

$$Payback\ period\ prototype\ = \frac{295\$}{4\ lettuce\ heads * 7\$\ *(365\ days/(year * 45\ days))} = 1.3\ years \quad (7)$$

$$Payback\ period\ hypothetical\ design\ = \frac{370\$}{4\ lettuce\ heads * 7\$\ *(365\ days/(year * 45\ days))} = 1.63\ years \quad (8)$$

As such, the design pays itself back in a period of 1.3 to 1.63 years. Although the payback period ranges from one region to another, these calculations demonstrate that the design is economically viable in regions where vegetables are extremely expensive.

5.3 Failure Modes and Effects Analysis (FMEA)

Table 4. Failure Modes and Effects Analysis

Function	Potential failure mode	Potential failure effect	SEV	Potential causes	OCC	Current process controls	DET	RPN	Action recommended
	How can this function fail?	What is the impact of the failure?	How severe is the impact from 1-10 where 10 is catastrophic	How does this failure mode occur	How frequently does this failure mode occur from 1-10 where 10 is very frequent	What are the existing measures to prevent this failure or detect a failure	How probable is the detection of this failure mode from 1-10 where 10 is an inconspicuous failure	Risk priority number given by SEV*OCC *DET	What actions can be taken to reduce occurrence or improve detection? To be provided for high RPN failures and failures with SEV = 9 -10
Collection of thermal energy via thermoelectric generator	Failure of fan	Lack of sufficient gradient for power production, overheating of TEG.	4	Debris becomes logged in the fan housing, the generator is dropped or fractured in a way that stops the fan from operating	2	Fan is located within a housing that prevents direct contact with the fan, minimizing opportunity for failure. Lack of LED illumination can also indicate failure.	5	40	
	Open circuit failure	Power is no longer supplied to sensor or LED system, damage occurs to TEG	8	Contact migration, corrosion and intermetallic formation (elaboration in following section)	2	System is set to be operated within the approved temperature range, lack of LED illumination can also indicate failure.	5	80	Ensure that the system is used only within the approved temperature range, explore alternatives to aluminum contact plates and gold wires.
Transfer of energy from TEG to LED and arduino system	Cord failure, USB connection failure	Energy generated by the TEG is not transferred to LED system or sensor	3	Damage to cords or USB connection	2	Cords are coated using a malleable plastic to avoid wear and degradation of encased wires	5	25	
Supporting structure for LEDs	Fracture or other damage to supporting structure	LED system no longer supported, sudden failure could result in damage to plants as LED system is located above the plants	5	Melting of PLA if subjected to temperatures higher than 60^{O}C, physical damage if knocked over or dropped (Polylactic Acid (PLA))	2	If damage occurs by dropping or knocking over, failure will be immediately recognizable	5	50	

The use of a failure modes and effects analysis process revealed the failure mode with the highest risk priority to be an open circuit failure, consequently, this failure mode will now be discussed in further detail. As mentioned in the literature review, TEGs make use of a pair of dissimilar semiconductors, one p-type and one n-type. The most frequently used pairing is n-type and p-type silicon making up the active thermoelements with aluminum used to provide a connection between elements while maintaining a low resistance (Kiely et al. 1994). A study evaluating the reliability of TEGs determined that the most common failure mode over the lifetime of these generators was an open circuit failure caused by 3 main issues: contact migration, corrosion and intermetallic formation (Kiely et al. 1994). A deeper analysis of these failure modes is relevant for this design due to the possibility of permanent damage occurring within the TEG, making this a severe failure mode. Although there is no immediate danger to human health and safety caused by this failure mode, it was given a high severity index due to the financial implications of a failure of this kind. As mentioned in the literature review, heating via wood furnaces is often the cheapest heating source and the primary purpose of this design is to help in addressing food insecurity, meaning the target demographic is likely to be designated as a low-income household. In the case where the user is within a low-income household, a failure of the device before it has reached the end of its payback period could have serious health and safety implications due to a lack of financial resources.

The first common cause of an open circuit failure is contact migration. This occurs when silicon/aluminum contact points are subjected to high temperatures; silicon has high solubility and diffusivity in aluminum so elevated temperatures can cause pits to form in the silicon, increasing the resistance and eventually causing an open circuit failure (Kiely et al., 1994). The second common cause of this failure mode is galvanic corrosion that can occur when two metals with dissimilar corrosion patterns are electrically connected, in this case, gold bond wire and aluminum contact pads. The last, and most dominant, cause of this failure mode is intermetallic formation (Kiely et al., 1994). This occurs when intermetallic phases arise at the interface between the gold and aluminum, causing voids to form which can then migrate or merge to ultimately cause an open circuit failure.

The study by Kiely et al. (1994) that identified these failure modes did so by subjecting the generators to temperatures that were above their operating ranges and concluded that at temperatures below 200ºC, these failure modes were not observed. In light of this, we will be including a label on the generator that advises the user that the design can only be used when the surface temperature of the stove is at 200ºC or below. The second precaution that can be taken is to ensure that gold bond wire is not used to connect the aluminum pads. Unfortunately, we were unable to confirm what kind of bonding wire was used in the TEG purchased for the prototype but our recommendation is to use copper bonding wire due to its lower cost, higher electrical conductivity and decreased likelihood of causing galvanic corrosion or intermetallic formation when in contact with aluminum (Breach, 2010).

5.3 Opportunities for further improvement

To identify any opportunities for improving our design, each component of the final product can be considered. One of the main components that has much room for expansion is the moisture sensor system. A light sensor could be integrated to track sunlight and LED light quantities to optimize the plant growing conditions. The code for the Arduino could be modified to turn off the LEDs whenever sufficient lighting is achieved. The Arduino could also be programmed to alter between the moisture sensor and the light sensor depending on the time of day to drain as little power away from the TEG as possible. The fan used to cool air for the TEG of our prototype produces a relatively loud and constant background noise which may be irritating for users and lower its social acceptability. This fan could easily be replaced by a quieter one during commercial manufacturing. A battery and a capacitor were both also considered to be integrated into the TEG for storing energy when the woodstove is not in use.

Applications of this design for capturing other sources of waste heat can be considered. Most households have a stovetop with a vent above it and our design could easily be adapted to this vent. Another potential source of residual heat is from greywater flowing through bath or shower pipes, although these are much more complicated for installing the design in terms of accessibility. Another potential heat source is electronics that are used intensively such as computers that overheat to the point of needing to be cooled with a fan. For all of these examples, however, the temperature gradient is significantly smaller compared to wood stoves lessening the growing potential of our design.

6.0 CONCLUSIONS

The great and growing food insecurity present within communities in the North, particularly indigenous groups, has fueled the need and efforts aiming for greater food sovereignty in northern Canada. Coupled with the heightening energy and climate crisis, the design proposed in this report aims to provide an economically viable, environmentally friendly and socially appropriate solution to this issue. The TEG-powered growing system allows communities in the Northwest Territories, and other northern regions, to reclaim autonomy of their nutrient intake and agricultural practices by providing them with the opportunity to produce vegetables and herbs within households, without the implication of additional energetic costs. The generator utilizes residual heat (<0.5%) from wood or pellet stoves, and supplements with electricity LED lights that will give plants the necessary lightwaves to flourish in these sun-scarce regions. The optional use of a soil moisture sensor ensures the longevity and prosperity of the plants. The total payback period of the system ranges from 1.60 years in optimal conditions to 1.63 years in suboptimal conditions. The use of various metals in the generator, as well as the soil sensor, does contribute to the design's carbon footprint and negative environmental impacts. However, due to the very long lifespan of the system, the system is still considered environmentally sustainable. A failure modes and effects analysis showed that the greatest risk of the system was a short-circuit within the generator. This was deemed the highest factor of risk, due to the financial implications of such a risk, which could ensue further consequences on the health and wellbeing of targeted households. This possible safety issue will be mitigated by providing a user manual indicating the safe temperature range of operation. Further improvements of the design were proposed, such as the interchangeability of the LED lights and moisture sensor connected to the TEG, a reduction in the noise level of the TEG's fan, the incorporation of a battery and capacitor, as well as the operation of our design on other hot surfaces.

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