GNG 5140

Design Project User and Product Manual

Submitted by:

Sustainable Food Production Team

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Introduction

Access to healthy and affordable food remains a pressing challenge. In regions like northern Ontario, the growing season is short, and extreme winters limit the potential for year-round local food production. The Sustainable Food Production project addresses this issue by exploring innovative, off-grid greenhouse systems that extend the growing season while maintaining affordability, ease of construction, and environmental responsibility.

This initiative was developed in collaboration with Deep Roots Food Hub (DRFH), a grassroots, volunteer-led non-profit organization based in West Carleton, Ontario. DRFH operates as a community farmer co-op that promotes food security and justice by supporting local cultivation, storage, and distribution of produce. In 2020, DRFH constructed an off-grid root cellar to store crops sustainably, marking a significant step toward food independence for the region. Building upon this success, DRFH requested the design of a new, energy-efficient greenhouse system to support active year-round cultivation.

Figure 1 Location of DRFH

Our team, working as part of the GNG5140 design course, was tasked with designing this next-generation “Super Greenhouse”. Our design was primarily inspired by the Chinese-style solar greenhouse, a proven solution in cold regions of northern China. These greenhouses use a south-facing slanted transparent roof, a thick insulated back wall, with passive solar heating to maintain warm temperatures inside.

This report aims to document the final greenhouse prototype developed for Deep Roots Food Hub, with a focus on its design rationale, structural performance, thermal behavior, and operational features. The structure of this report is organized as follows:

First, the problem context and design objectives are introduced, along with an overview of the prototype and its key components. Next, a step-by-step guide to site setup and system assembly is provided. Troubleshooting procedures and maintenance tasks are then outlined to assist non-technical users in managing the greenhouse. Finally, the product documentation section presents the technical design details, structural testing process, and thermal performance evaluation, supported by relevant calculations, figures, and design files.

This document is intended to support DRFH and other community organizations in implementing the greenhouse solution, as well as to assist future development teams in further optimizing the design.

Overview

On a global scale, we humans are facing a food production and sustainability issue. The average person requires 700–900 pounds of fresh produce and 500–800 pounds of staple crops per year. We are short on resources and space and our current method are worsening the state of the environment. A space and resource we are not currently using is areas in very cold reagoins, like north of Canada, which have good conditions like soil quality but can’t be farmed in due to the harsh weather conditions.

This project’s solution to this problem is sustainable greenhouses fit for such harsh conditions.

Based on the discussion with the client, a matrix of client requirements was designed (Table 1). By using this matrix, a list of critical benchmarking metrics was developed. These critical Benchmarking metrics are empirical and theoretical values required by the client to ensure that the design is functional for its intended use. Table 2 shows a list of these metrics.

Table 1 Client Requirement Matrix

ID	Description	Priority
1	Optimize solar gain, both in light and in radiation	5
2	Advanced insulation to prevent heat loss and improve efficiency	5
3	Structure must be buildable by volunteers with minimal skills	5
4	Greenhouse must be capable of mass food production	5
5	Temperature and radiation control through supplemental lighting & automation	5
6	Greenhouse must be self-sustaining, off-grid, and energy-efficient	5
7	Construction cost must be affordable and within budget constraints	4
8	Space to grow large trees and deep-rooted plants (12 ft deep)	4
9	Operation costs must be low, utilizing renewable energy from sources such as solar, wind, and geothermal	4
10	Efficient material storage with minimal heat loss from metal mesh walls	3
11	Optimized greenhouse shape & size to minimize front wall height	3
12	Minimize unnecessary digging to help with soil integrity and health and to reduce excavation costs	2

Table 2 Critical Benchmarking Metrics

Benchmark ID	Requirement ID	Description	Benchmark
A	3, 4, 8, 11	Optimized size of the greenhouse	3000+ Square feet (to meet food supply goals)
B	1, 3, 4, 8, 11, 12	Height of the greenhouse	12+ feet (to accommodate plant growth)
C	1, 5	Desirable temperature range	19°C to 25°C (with improved insulation)
D	2, 5, 6, 9, 11, 12	Energy loss minimization	≤ 2 to 2.5 W/m^2K (according to reasonable loss in cold climate)
E	5	Humidity control	60% to 90% (to support plant health)
F	6, 9	Renewable energy source requirements	> 75% solar, wind, and geothermal energy sourced
G	6, 9	Operational cost	≤ salary for 1 person operating per greenhouse area (fully self-sustainable system, minimal maintenance)
H	1, 5	Environmental control events (ex. Door opening, ventilation)	Max 3 times per day (to reduce heat loss)
I	2	Structural load requirements	Up to -45°C & ≥ 120km/h wind resistance
J	7, 12	Target cost	Under 100k (spray foam and gap at 100k, needs optimization)

The goal with this project is not to make a greenhouse that is completely new and unlike any other greenhouse, but it is to make the most sustainable greenhouse possible that is still functional in the harsh climate and is capable of mass food production. A greenhouse that meets all these criteria has never been done before.

Figure 2 Photo of the physical prototype showcased on design day

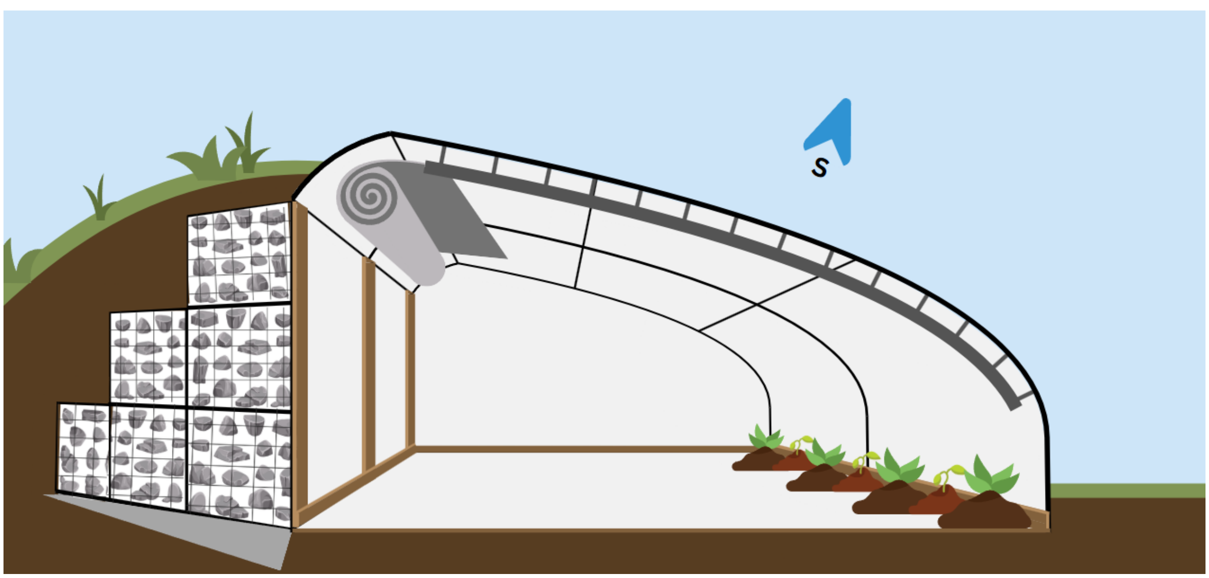

Figure 3 Diagram of the final prototype with all the suggested features implemented

Since the greenhouse is still in its early stages of development and will probably not be ready for a full prototype for a few semesters we focused on a few main concepts.
The followings are our key suggestions to the greenhouse design:

1. **Chinese-Style Greenhouse Design: [2]**

- South-facing slanted transparent wall to capture sunlight.
- Thick, insulated north wall (using gabion walls with soil) for thermal mass and heat retention.

Figure 4 The inside of a Chinese greenhouse

2. **Gabion Walls:**

- Walls made from wire cages filled with rocks, providing structural stability, insulation, and cost efficiency.

- Designed to withstand Canadian winters, supported by structural analysis.

3. Automatic Thermal Covers:

- A motorized system to deploy insulating thermal blankets inside the greenhouse to reduce heat loss at night.
- Made from reflective, insulating materials (aluminum and bubble wrap).

4. Roof Structure:

- Roof made of durable, insulated polycarbonate panels supported by a steel frame.
- Designed to resist heavy snow loads and maintain good sunlight transmission.

Additional Design Constraints Compared to the Existing Product

- More severe winter than Nebraska, USA that the design has to withstand
- Prolonged cloudy days would increase the heat demand of the thermal energy storage system.
- Energy demand of the heat pump may require additional costs towards the renewable source.
- Potential Operation cost due to energy demand caused by extreme duration of winter.
- Less skilled labor required to set up the structure

Cautions & Warnings

It is worth mentioning that even with all the sustainable feature working to their full potential, as of now the greenhouse will not be able to keep the needed temperature for the coldest weathers of north Canada and external heating and radiation will be needed.

For example, in the coldest period in Canada (that is, January winter), after the sun goes down, the greenhouse loses sunlight, if there is no Thermal Covers, the temperature inside the greenhouse will drop rapidly.

In addition, the internal temperature of the greenhouse in the summer is easy to overheat, this situation needs to be alleviated by the ventilation system, or through the sunshade net to reduce the incoming sunlight, otherwise the internal environment of the greenhouse is easily overheated during the summer day.

Getting started

This greenhouse system has been developed to offer a self-sufficient and sustainable food production unit for extreme cold climates such as northern Canada. The system flow begins with site preparation and ends in a fully operational greenhouse capable of supporting various crop types year-round.

Set-up Considerations

System Overview

Our cold-climate greenhouse

incorporates passive heating and insulation techniques to extend the growing season in northern regions. It includes three main structural components:

Curved Structural Frame

A lightweight arched roof made with clear polycarbonate and wooden supports. It allows sunlight to enter while maintaining durability and insulation.

Gabion Rock Wall

Built from wire mesh cages filled with rocks, this wall acts as a **thermal mass**—absorbing heat during the day and releasing it at night.

Sidewall

Perpendicular to the gabion wall, used to support the roof and isolate heat and air, is also the entrance and exit of the greenhouse.

Thermal Blanket (Roll Cover)

A transparent or insulated layer that can be manually unrolled to cover the greenhouse interior during colder nights, providing added protection from heat loss.

Ventilation system [7]

It relies on axial fans as the core for air circulation. Fans are mounted along the roof ridge to expel hot air from the upper zone, while fresh air is drawn in through lower vents. It can be controlled manually or automatically through the combination of sensors

These elements work together to regulate temperature without the need for active heating systems. The structure supports natural light, retains warmth, and is simple to operate. This system consists of both structural and environmental components designed for user-friendliness and harsh weather endurance.

Table 3 Main Components of the Greenhouse

Component	Input/output	Description
Gabion Wall	N/A	Provides thermal mass and wind resistance.
Steel Frame	N/A	Roof support
Polycarbonate Roof	Sunlight (input)	Traps heat and allows photosynthesis.
Sidewall	N/A	Assist with roof support

Thermal Blanket	Button control (input)	Insulates greenhouses at night.
Ventilation system	Airflow (input & output)	Maintain internal oxygen levels and remove excess heat

User Access Considerations

The greenhouse is intended to be operated by a small group of volunteers or agricultural workers. It is designed with the following access roles:

Table 4 Access Roles

User Type	Access Level	Notes
Operator (Client)	Full access to control system and planting areas	Should be familiar with AUTO functions
Volunteer Builder	Assembly only	No access to control box or power
Technician	Full system access	For maintenance, repairs, or upgrades

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Using the System

This greenhouse system was developed in direct response to a specific client's request to address the limitations of their current root cellar setup in Canada's harsh northern climate. The design integrates sustainable engineering, passive solar principles, and automation to fulfill practical, environmental, and social goals. Below is a breakdown of how the client's needs influenced the system's inputs, and the outcomes achieved through this design.

Client Requirements as Inputs

The design of the greenhouse is driven by a matrix of client-defined goals, with a particular focus on environmental conditions, ease of construction, and long-term sustainability:

1. Volunteer-Buildable Structure: The system must be constructed by volunteers with minimal technical training.

2. Use of Sustainable Materials: All components must adhere to environmentally friendly standards, aligning with sustainable building practices.

3. Cost Efficiency: The entire system should be designed with affordability in mind, without compromising structural quality or performance.

4. Scalable and Weather-Resistant: The Structural design ensures the design withstands extreme wind (≥120 km/h) and low temperatures (down to -45°C), making it suitable for future expansion in similar environments globally.

Outputs of the System

The performance of this system is defined by the following key deliverables, each aligned with client expectations but enhanced through this project's innovation:

1. Structural Integrity: The combination of a curved Chinese-style layout and reinforced gabion walls ensures long-term stability, even in extreme winter conditions. Structural simulations (via GEO5) validate the safety factors for overturning, sliding, and soil pressure resistance.

2. Thermal Efficiency and Climate Control: The passive solar orientation (south-facing) and thick insulated back wall maintain internal temperatures between 19°C and 25°C. Internal humidity is controlled within the 60%–90% range, promoting optimal growing conditions year-round.

3. Automation for Reduced Labor: The thermal blanket system operates automatically based on temperature or schedule and includes manual override capability. Future enhancements include remote access to increase ease of use and eliminate daily human intervention.

4. Cost-Effectiveness and Community Participation: By ensuring that the system is low-cost and easy to assemble, the greenhouse empowers communities to build and maintain their own food production systems, reducing reliance on industrial supply chains.

Troubleshooting & Support

Error Messages or Behaviors

The following table outlines potential issues, their possible causes, and course of actions to be taken:

Table 5 potential issues, their possible causes, and course of action

Issue	Possible Cause	Corrective Action
Thermal blanket fails to deploy	Motor malfunction, sensor error, power loss	1. Check power connections. 2. Manually override using the crank. 3. Inspect sensors.
Temperature drops below 19°C	Insufficient insulation, prolonged cloud cover	1. Deploy thermal blanket. 2. Verify backup heating (if installed). 3. Check for gaps in insulation.
Overheating (>25°C)	Ventilation failure, excessive sunlight	1. Activate axial fans. 2. Deploy shade cloth. 3. Open manual vents.
Condensation on walls/ceiling	High humidity, poor airflow, poor drainage	1. Increase ventilation. 2. Inspect dehumidifier (if installed). 3. Check for water inside the greenhouse and remove any unnecessary standing water
Structural instability	Heavy snow load, high winds (>120 km/h), or improper assembly.	1. For polycarbonate roof cracks, apply weather-resistant sealant as a temporary fix and order replacement panels. 2. For gabion wall issues, inspect wire mesh for corrosion or loose rocks. Tighten mesh or add rocks to stabilize. Contact a technician if the wall appears to shift.

Special Considerations

• **Extreme Weather**: In times of blizzards or when temperature drops below -45°C, monitor the greenhouse closely. The system is designed for harsh climates but will require external heating during the coldest periods of winter.

• **Volunteer Assembly**: as this structure is build by people who are not experts in construction, all that is build should be checked for integrity before starting operation.

• **Seasonal Adjustments**: In summer, ventilation should be prioritized to prevent overheating. In winter, make sure the thermal blanket is deployed every night to retain heat.

• **Power Dependency**: the greenhouse relies on renewable energy ,solar for electricity and some geothermal for heat. If energy sources fail (e.g., prolonged cloudy days), switch to other forms of power like batteries.

Maintenance

Perform regular checks to ensure optimal performance:

Table 6 list of regular checks needed

Component	**Maintenance Task**
Gabion Walls	Inspect for loose rocks or wire damage
Polycarbonate Roof	Clean debris and check for cracks
Thermal Blanket	Lubricate tracks, test motor function
Ventilation Fans	Remove dust, test airflow
Sensors (Temp/Humidity)	Calibrate and clean

The frequency of the checks depends on the season and the climate but all checks should **at least** be done bi-monthly.

Seasonal Preparation:

- **Winter**: Inspect insulation, test backup heating, and clear snow from roof.
- **Summer**: Clean ventilation ducts, apply shade cloth, and check irrigation systems.

Product Documentation

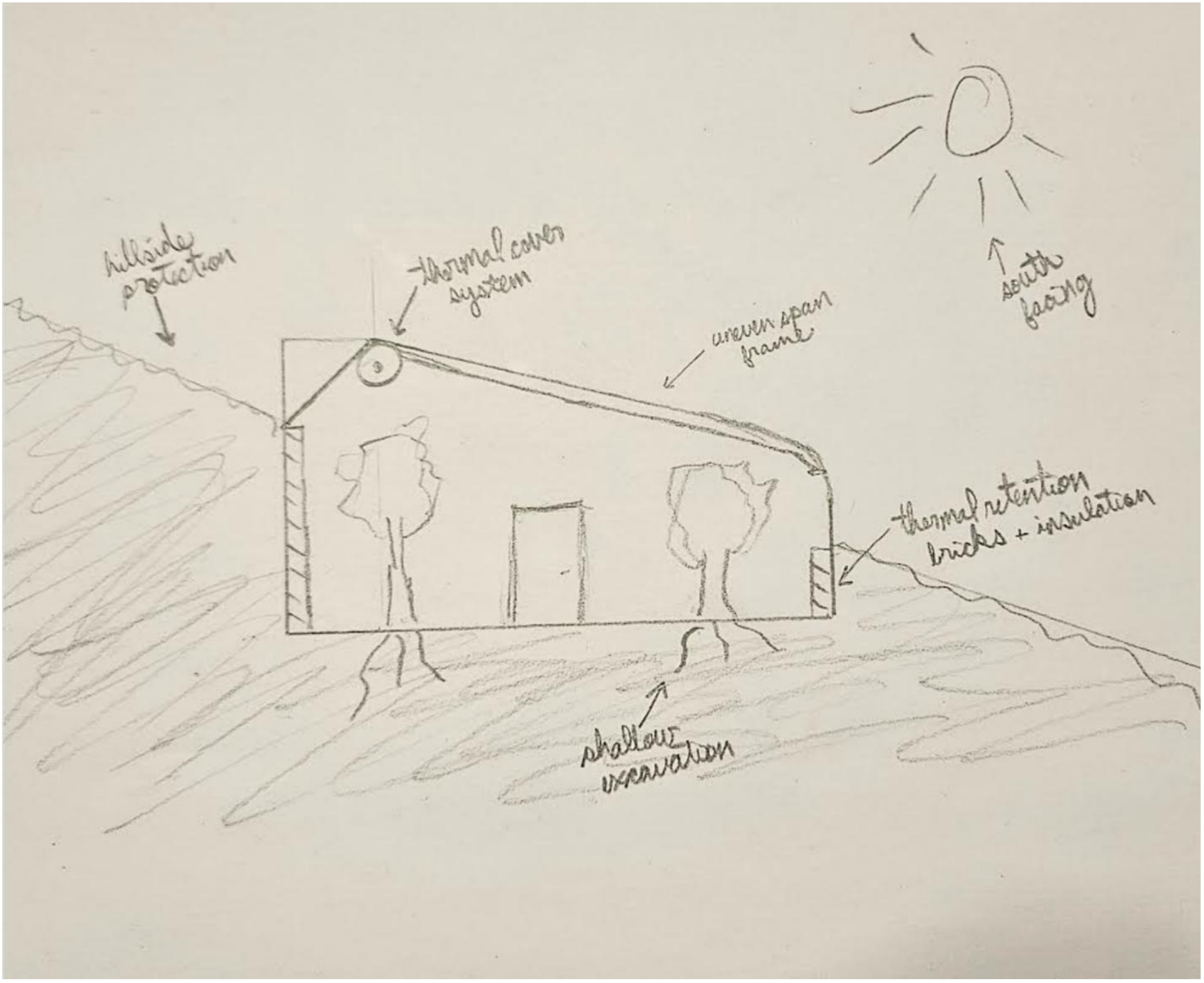

Figure 5 Concept Drawing Figure Concept Drawing

Since constructing a full-scale operational greenhouse was beyond the scope of this project due to cost, time, and logistical constraints, we instead developed a scaled-down physical model to represent key architectural and functional elements of our proposed Chinese-style passive solar greenhouse design. This model emphasizes structural concept, shape, and the thermal blanket mechanism that forms the core of our sustainable approach.

1. **Mechanical & Structural Representation**

For the main body of our physical prototype, we primarily used 3D printed PLA segments and ½-inch square wooden sticks, which were assembled using hot glue.

Purpose: Using 3D printing allowed us to accurately represent the curved steel tubing structure proposed in the full-scale design. Achieving that specific curvature and angle would have been very difficult with conventional prototyping materials like rigid wood or pre-molded plastic. The curved geometry follows a semi-arch design optimized for solar gain.

In addition, we wanted to test the general shape and proportions to assess spatial capacity and plant arrangement. Thanks to the model, we determined that an optimal interior layout would require planting in a descending size order across three layers:

Back row: Full-height trees (~3 m tall)

Middle row: Medium-sized shrubs and small trees (~2 m tall)

Front row: Short, sun-intensive crops (~0.5 m tall)

The model also helped us establish ideal proportions, with a height-to-width ratio of approximately 1:2. Since a compact structure improves heat retention, we concluded that scalability would be best achieved through length, giving the greenhouse a tunnel-like shape.

Feasibility Note: In the full-scale build, we planned to use galvanized steel tubing due to its durability and corrosion resistance. The unique curvature would require custom machining using a metal bender with a preset shape guide. While this would incur an initial setup cost, it would be a one-time investment, as all roof rods would be identical in shape.

a. Thermal Cover Rail Prototype

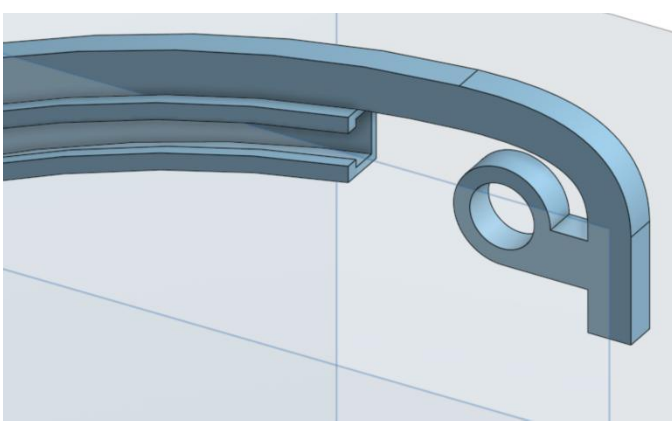

Figure 6 Railing CAD model zoom-in

This was the second iteration of our 3D model for the rail system supporting the thermal blanket roll. In our first attempt, the rail opening and the hole designed for the transverse rod (represented in the prototype by a BBQ skewer) were too small, preventing proper assembly.

To address this, we modified the CAD model by enlarging both the rod hole and the rail slot, and also scaled up the print overall. While the updated rod hole worked successfully, the rail slot still failed — but for a different reason.

Key Issue: We had not accounted for the complexity of overhangs in 3D printing. The rail entrance relied on clean internal geometry, but the printer generated very dense support material inside the rail during the print. These supports were difficult to remove, and in fact, we were unable to clear them entirely. As a result, the prototype rail entrance was obstructed, and we couldn't demonstrate the intended rolling mechanism for the thermal blanket.

Design Lesson: This iteration highlighted a key limitation of additive manufacturing when designing enclosed geometries. For future models, we would either redesign the rail in two parts (to avoid internal supports) or reduce the support density hoping it will be strong enough not to collapse the figure yet weak enough to remove without too much difficulty.

a. Gabion Wall Representation

Purpose: In our physical prototype, we used chicken wire and small rocks to represent the stacked gabion cage system proposed for the north-facing retaining wall in the full-scale greenhouse. This structure is intended to provide both lateral support against soil pressure and serve as a passive thermal mass, storing heat during the day and releasing it at night to help regulate internal temperature.

Prototype Observations: Even though the rocks used were small, once placed inside the wire mesh, the gabion sections became surprisingly heavy and awkward to move, especially relative to their size. This was an important insight, as it accurately reflected what would be expected at full scale: gabion walls filled with stone are weighty, rigid, and require deliberate placement during construction.

Working with chicken wire in our prototype revealed several practical difficulties that are reflective of full-scale construction with steel gabion mesh. The wire was sharp, springy, and difficult to control, often snapping back unexpectedly and causing minor scratches and cuts during assembly. It was also hard to shape and maintain form, which made it difficult to create uniform, secure enclosures.

This experience highlighted an important oversight in our original planning: the safety risks and physical demands of handling metal mesh, especially in a volunteer-based build. For cost efficiency, we had hoped this part of the construction could be completed with community or volunteer labor, but this prototyping phase made it clear that proper training, PPE, and supervision will be essential. At minimum, sturdy gloves, eye protection, and long sleeves should be required for anyone working with the mesh, even during initial cage assembly.

We also realized that anchoring the wire into a stable form required more force and coordination than expected, suggesting that the full-scale version will demand accurate jigs, strong fasteners, and likely two-person teams for safe and efficient handling. This reinforces that while gabion walls are low-cost in material, they still demand significant manual effort and safety planning during construction — an insight that will influence our scheduling, task assignments, and equipment planning in future phases.

Material Consideration: While we used any available small rocks for the model, at full scale, sourcing the appropriate rock fill (100–250 mm) becomes essential. It not only impacts the structural integrity of the wall but also the cost and logistics. Recycled rubble is ideal from both an economic and environmental standpoint, but its availability should be confirmed early in the design phase.

Feasibility Insight: Gabion walls were chosen over alternatives like poured concrete due to their lower cost, natural permeability, and reduced environmental impact. Concrete, while structurally reliable, would have significantly increased material and labor expenses, and it lacks the drainage capability and flexibility that gabion systems provide.

Through our prototype, we were able to observe how water naturally seeps through the rock-filled wire mesh, which mirrors the expected performance at full scale. This slow drainage helps prevent moisture buildup, cracking, and hydrostatic pressure, all common issues in rigid concrete walls. Additionally, gabion walls visually blend into the landscape and make use of recycled or locally sourced rock material, supporting both aesthetic integration and sustainability goals.

Our hands-on testing reinforced that while gabion systems require careful assembly, their long-term benefits in thermal mass, water management, and cost-effectiveness make them a strong choice for passive greenhouse infrastructure.

2. Thermal System Representation

Our prototype's key thermal feature is the retractable thermal blanket. To represent its layered construction, we combined two materials: bubble wrap and the reflective interior of a potato chip bag. This choice visually and functionally mimicked the dual-layered insulation we envisioned in the full-scale design.

Purpose: This component simulates the thermal curtain used to insulate the greenhouse roof at night. In the full-scale version, it would deploy automatically to trap heat and protect crops during colder conditions.

Design Insight: The reflective foil simulated the radiant heat-blocking properties of insulation materials, while the bubble wrap represented the air-layered thermal resistance. Together, they highlighted a key concept: the insulating air gap created between the polycarbonate roof and the thermal cover. This air pocket is crucial for maintaining internal temperature during nighttime or winter.

Through the prototype, we also realized that full foil coverage may not be necessary. Strategic placement of reflective areas — rather than 100% surface coverage — could offer better thermal regulation depending on the greenhouse's specific needs.

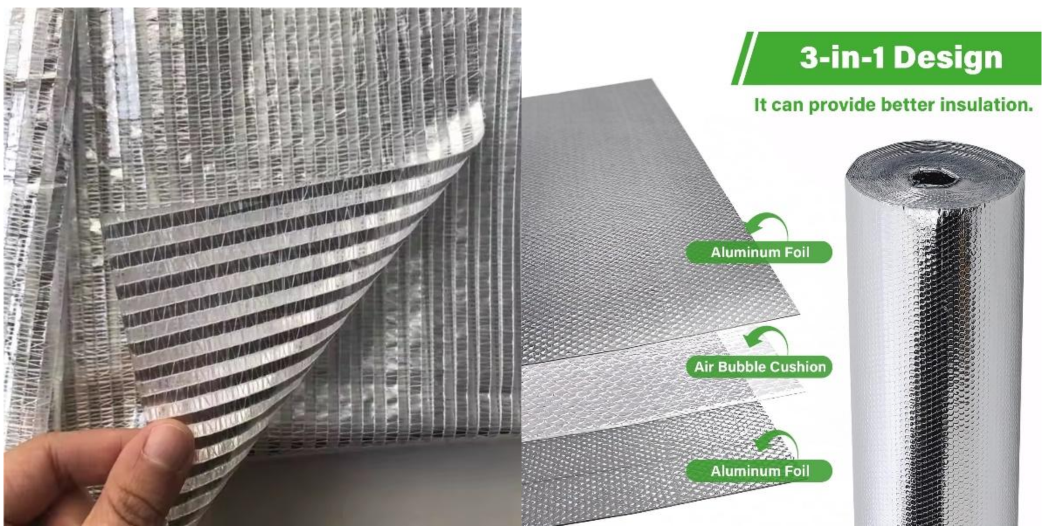

Figure 7 Example of 50% vs. 100% reflective coverage

Feasibility Note: In our materials research, feasible full-scale options included multi-layer polyethylene, woven thermal fabrics, and custom reflective insulation blankets. We identified viable options priced between $8–$12 per square meter, which offered a good balance between insulation performance and affordability.

Mechanism: The model's rolling mechanism was not automated, due to persistent issues with our Arduino setup. Originally, we intended for a small motor to handle both retraction and deployment, mimicking how a microcontroller would control larger motors in the real system.

The mechanism was designed to behave similarly to a garage door system — a rollable surface that travels along guided tracks and can be raised or lowered with minimal force using a single motor. This system ensures smooth, reliable motion while minimizing mechanical complexity. Although the automation wasn't functional in the prototype, the model successfully demonstrated the mechanical concept behind the roll-up thermal blanket and its guided movement.

3. Roof & Covering

To represent the transparent polycarbonate roof, we used clear plastic film in our prototype. The flexibility of the film made it ideal for attaching to the curved 3D-printed structural parts, allowing for easy assembly using hot glue. Its adaptability helped us mimic the intended roof geometry accurately.

Purpose: The plastic film simulated the polycarbonate multi-wall panels proposed in the full-scale design. It allowed us to visualize how natural light would enter through the south-facing slope, while also making visible the spacing and frequency of structural supports beneath the covering.

Design Trade-Off: Polycarbonate was chosen over glass in the real design due to its superior insulation, impact resistance, and lightweight properties, which reduce structural demands. While alternatives like polyethylene film were considered for cost savings, they offer significantly lower durability and thermal performance, making them less viable for long-term greenhouse use.

BOM

Below is a rough estimate of the material costs for constructing the greenhouse. The current bill of materials is based on a 200 sq ft structure; since the client is ultimately aiming for closer to 400 sq ft, the total cost would approximately double.

Our estimated total remains within the client's target budget of under $40,000 for the greenhouse portion, which aligns with their previous investment in a root cellar where spray foam insulation alone cost around $40,000.

While our prototype and design focus primarily on the core greenhouse structure, the client's overall budget of $100,000 is meant to cover a wider range of elements—including spray foam and other supporting infrastructure not directly addressed in our design scope.

Table 7 Bill of Materials for a 200 sqft Greenhouse

Category	Item	Quantity	Unit Price (CAD)	Total (CAD)	Notes
Structural Frame	Galvanized Steel Tubing (2" OD)	~80–100 ft	$3-4/ft	~$240–$400	Roof frame structure
	Steel cross braces / ties	~20–30 ft	$5/ft	~$100–$150	Lateral reinforcement
	Mounting brackets & anchors	~25–30 pcs	$2–$4/pc	~$90	Frame-to-base hardware
Foundation/Base	Concrete Slab (4 inches thick)	~18–20 m^2 (~200 sq ft)	$7.15/sq ft	~$1,430	4" slab across footprint
	Reinforced Rebar for Concrete Foundation	~200–250 ft	$1.20/ft	~$240–300	Reinforcement grid
	Formwork wood (reusable)	~15–20 m^2	$4–$5/m^2	~$80	For shaping base
	Gravel (drainage layer)	~0.5 m^3	$60/$m^3$	~$30	Beneath concrete
Gabion Wall (North Wall)	Gabion baskets (1m x 1m x 1.5m)	~7–8 units	$175/unit	~$1 225–1 400	Stacked (~3m height, ~6–7m length)
	Rock fill (100–250mm stones)	~20–25 m^3	Free (to find)	Free	Recycled rubble, find locally
	Connection items (ties, spirals, hooks)	Bulk	$100–200	~$150	Assembly components
Covering & Insulation	Polycarbonate Multi-Wall Panels (8mm)	~25–30 m^2 (~270–320 sq ft)	$2.30/sq ft	~$662–$994	UV-resistant, twin-wall, clear
	H-profile Aluminum Bars (single & double)	~12–16 m total	$8–$12/m	~$96–$192	Joining/sealing polycarbonate sheets
	Screws, washers, rubber seals	~200 pcs	$0.25–0.50/pc	~$75	For polycarbonate
	Rockwool (Stone Wool)	~8–10 m^2 (~85–110 sq ft)	$2.50/sq ft	~$215–275	For east & west insulation
Thermal Blanket System	Thermal blanket material	~25–30 m^2	$8–$12/m^2	~$250–350	Internal, retractable
	Rail tracks / guide system (aluminum)	~14 m (2 × 7m)	$15–20/m	~$250–280	For smooth guided rolling
	Roller tube (galvanized or aluminum)	~7 m	$20–30/m	~$150–200	Wraps thermal cover
	Electric motor & controller unit	1 set	$200–350	~$250–350	For automated deployment
Ventilation & Airflow	Mounting hardware, brackets, wiring	Full set	~$50–100	~$50–100	For installation
	Roof/window vents	2–4 units	$50–120/unit	~$200–300	Manual or automatic
	Fan (optional)	1 unit	$100–250	~$150 (optional)	For active airflow
Total Estimated Cost				**~$7 000–$9 000 CAD**	for 1x **200 sq ft** greenhouse

Main BOM links:

Gabion Baskets: https://www.ontarioagra.ca/product/gabion-baskets/?srsltid=AfmBOorLKBtOkPz2C_dEF2WMYuqr0xc2vqPfrlZANIGNwGZ4AMpbUY7Q

Polycarbonate Sheets: https://www.goodwinsgreenhouses.com/products/items/translucent-polycarbonate-multiwall-panels

Equipment list

1. Gabion Retaining Wall

Materials & Components: Gabion Cages, Connection Items:

Equipment & Tools: Excavation Equipment, Compaction Equipment, Cranes/Forklifts, Hand Tools & Measuring Instruments, Surveying Instruments:

2. Foundation

Materials & Components: Concrete or Stabilized Fill, Leveling Mortar:

Equipment & Tools: Excavators/Backhoes, Compaction Machines, Survey Instruments

3. Sidewall

Materials and Components: Bricks or AAC Blocks, Mortar, Waterproofing/Insulation Components (Optional)

Equipment & Tools: Masonry Tools, Layout and Measurement Tools, Compaction and Base Preparation Equipment, Finishing and Sealing Tools:

4. Roof Structural

Materials & Components: Metal Arch Frame, Polycarbonate Panels

Equipment & Tools: Fabrication Equipment for Steel Members, Lifting Devices, Installation Tools, Heat-welding Tools or Adhesive Systems, Measuring and Leveling Instruments, Surveying Equipment:

5. Thermal Cover
Materials & Components: Insulation Blanket or Roll, Mounting/Guide System, Fasteners and Sealing Components, Actuator or Motor (if automated), , Control Module (if automated)

Equipment & Tools: Cutting and Measuring Tools, Fastening Tools

6. Auxiliary Systems and Safety Equipment
Components: Construction Safety Equipment, Scaffolding and Access Equipment, Material Handling Equipment

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Instructions

1. Foundation System

Begin with a site survey and layout, where a detailed site survey is conducted using laser levels, total stations, or GPS to mark the exact location of the foundation trench according to the design drawings. During this process, it is important to verify local soil conditions and the water table to determine whether any soil stabilization, such as exchanging weak soil, is necessary. Once the layout is confirmed, excavation proceeds by using an excavator or backhoe to dig the foundation trench along the planned line, ensuring a depth of at least 0.6 m and a width approximately 0.15–0.20 m wider than the intended wall thickness. After excavation, the base is prepared by removing loose or organic materials from the trench bottom and then compacting the sub-base with a plate compactor or vibratory roller. In cases of soft soil, a layer of compacted gravel or a thin leveling mortar layer may be added to establish a stable, level foundation. A final inspection ensures that all dimensions and compaction parameters meet design specifications before proceeding.

2. Gabion Retaining Wall

For the gabion retaining wall, gather either prefabricated galvanized or PVC-coated wire mesh gabion units or on-site assembled cages, along with crushed stone or cobbles of suitable size (20–60 mm). The first row of gabion units is placed on the prepared foundation, carefully aligned and leveled using a laser level to ensure uniform load distribution. Each cage is then filled with stones, which should be well-compacted to minimize voids and enhance structural integrity. Subsequent gabion units are stacked and connected using specialized tie wires or connectors so that the wall becomes a continuous and integrated structure up to the planned height of 3 m. If the design includes stepped or angled geometries for drainage or other considerations, these must be carefully followed while maintaining consistent alignment and levelness. Regular quality checks during filling and tying confirm that connections between gabion units are secure and that the entire wall remains stable and plumb.

3. Side Wall

Perpendicular to the gabion wall, the side wall supports the greenhouse roof and helps enclose the structure. Construction starts by marking out the wall's footprint with a laser level and chalk line, followed by excavating a shallow trench if needed and compacting the soil to create a stable base. Bricks or AAC blocks are then laid in mortar, beginning with the first course checked carefully for levelness, and continuing upward in a running bond or appropriate pattern to the intended height. If rebar reinforcement is required by the design, steel bars are embedded in the mortar joints at specified intervals. Once the wall height is reached, any finishing steps, such as applying exterior sealants or insulating layers, can be undertaken. A final inspection verifies that the wall is vertically plumb, properly bonded, and sealed to provide both the structural support and thermal performance intended in the design.

4. Roof Structural System

The roof structure is formed by a curved metal arch frame covered with polycarbonate multi-wall panels. Fabrication of the metal arches involves cutting and bending steel tubes (for instance, 60 mm diameter, 3–4 mm wall thickness) into a parabolic shape spanning 6 m, with an arch rise that may be approximately 3.5 m for optimal load distribution. After these arches are cut, bent, and optionally welded with connection plates or braces, they are hoisted into position above the retaining and side walls using a crane. Each arch end is fastened to the supports using bolts or welded brackets. To increase lateral stability and create mounting points for the panels, transverse supports or purlins are installed at intervals (commonly around every 2 m) along the roof's length. Once the frame is secured and aligned, polycarbonate panels—often 16 mm or thicker to withstand heavy snow—are placed over the frame. These panels attach via self-tapping screws, clamps, or dedicated profiles, ensuring that edges overlap properly and are sealed with weatherproof tape or sealant to form a continuous, transparent, and insulated roof surface. A final check of the panel alignment and tension verifies that the roof is watertight, rigid, and able to resist wind and snow loads.

5. Thermal Cover

A thermal cover consisting of a multi-layer, reflective insulation blanket is positioned on or beneath the roof to further reduce heat loss in cold conditions. This system begins with installing guide rails or tracks along the arches, plus a spool or roller mechanism at one end. The reflective blanket (commonly featuring bubble wrap sandwiched between aluminum foil layers) is then trimmed to match the roof's dimensions. It is attached to the spool and carefully unrolled along the rails, providing an additional insulating layer. If the system is to be automated, a small motor or actuator can be connected to a microcontroller and temperature sensors, so that the blanket deploys or retracts based on nighttime conditions, manual override, or a scheduled program. Edges of the blanket can be secured using Velcro, hook-and-loop fasteners, or sealing strips, creating a controlled air gap that enhances insulation.

6. Ventilation System

The ventilation system relies on axial fans installed along the roof ridge to expel hot air from the greenhouse's upper zone, while lower vents near the base of the walls allow fresh ambient air to enter. To integrate this system, fans are first mounted onto sturdy, weather-resistant brackets at intervals along the roof ridge. Following this, electrical cables, circuit breakers, and a control panel are installed to power and manage the fans. Temperature sensors, or optional humidity/CO_2 sensors, are placed inside the greenhouse and wired to a control module that automatically starts or stops the fans when certain thresholds are crossed. A manual override switch is often included in the control panel for times when the operator wishes to adjust airflow manually. Thorough testing is carried out to confirm that warm interior air is effectively removed from the greenhouse's top region and that fresh air is adequately drawn in from below, ensuring balanced air circulation.

Testing & Validation

Temperature Testing **[2] [3]**

1. **Dimensions and Areas**

Footprint: 12 m × 6 m = 72 m².
Envelope area: For simplicity, we assume the roof area is 72 m², and the sidewalls (above ground) add another ~54 m², while the floor (semi-underground) is 72 m². However, because the greenhouse benefits from the insulating effects of the surrounding soil, the overall heat loss is moderated.

2. **Thermal Transmittance (UA)**

Due to the semi-underground design and extra insulation provided by the 3-m soil envelope, we assume the overall effective UA for the greenhouse envelope is approximately 100 W/K (instead of a much higher value for a non-insulated building). This is a conservative "net" value that takes into account the lower losses from the buried portions.

3. **Effective Thermal Mass (C)**

In a small greenhouse, not only the air but the soil and structural mass contribute to a very large effective thermal mass. Here we assume an effective C of about 2,000,000 J/K (2,000 kJ/K).

4. **Ambient Temperature Profile (T_ext)**

For January in Ottawa, we assume a sinusoidal ambient temperature profile with a minimum of approximately –19.3°C at early hours, rising to about –10°C—11°C near the afternoon and then dropping again. For our simulation, we use the formula

$$T_{\text{ext}}(t) = -15 + 5 \cdot \sin\left(\frac{\pi}{12}(t-4)\right)$$

with ttt in hours (t = 0–24). This yields, for example, about –19.3°C at 0 h, –15°C at 4 h, –10.7°C at 8–12 h, and back to –19.3°C at 24 h.

5. **Solar Gain (Q_solar)**

The roof (polycarbonate panels) receives solar radiation during daylight. We assume the effective solar gain on the roof (after accounting for transmittance, incidence angle, and losses) follows a sine function between 6 AM and 6 PM with a peak value of 8640 W on the entire roof area (72 m²). Specifically,

$$Q_{\text{solar}}(t) = \begin{cases} 8640 \cdot \sin\left(\frac{\pi}{12}(t-6)\right) & \text{for } 6 \le t \le 18, \\ 0 & \text{otherwise.} \end{cases}$$

(This corresponds to a peak solar flux of about 8640 W when the sine term equals 1 at noon.)

6. **Heat Loss by Conduction (Q_loss)**
   The overall conductive loss is modeled by

$$Q_{\text{loss}} = U A_{\text{eff}} \cdot \left(T_{\text{in}} - T_{\text{ext}}\right),$$

Where we lump the entire envelope into a net UA value of 100 W/K. For our lumped model, we use

$$Q_{\text{loss}} = 100 \cdot \left(T_{\text{in}} - T_{\text{ext}}\right) \quad (\text{W}).$$

7. **Energy Balance Equation**
   For each hourly interval (Δt = 3600 s), the change in the greenhouse's internal temperature is given by

$$\Delta T_{\text{in}} = \frac{\left[Q_{\text{solar}}(t) - Q_{\text{loss}}(t)\right] \Delta t}{C}.$$

We then update the internal temperature

$$T_{\text{in}}(t + \Delta t) = T_{\text{in}}(t) + \Delta T_{\text{in}}.$$

After calculation, the following is the internal temperature of the greenhouse in January (the coldest time) in Ottawa, Canada. The time not shown in the table is in the condition of no sunlight, the greenhouse be covered by thermal cover to keep heat.

Table 8 Internal temperature progression during the day

8AM	9AM	10AM	11AM	12PM	1PM
10℃	11℃	12℃	14℃	16℃	18℃
2PM	3PM	4PM	5PM	6PM	7PM
20℃	21℃	20℃	18℃	16℃	14℃

Structural Testing

The structural design followed a trial-and-error method, where over sever iterations of height, width, and slope combinations were simulated using the GEO5 platform. Our goal was to meet stability requirements for overturning, sliding, and bearing capacity, while still maintaining low material use and environmental impact. A visual representation of the various resistance types considered is presented below.

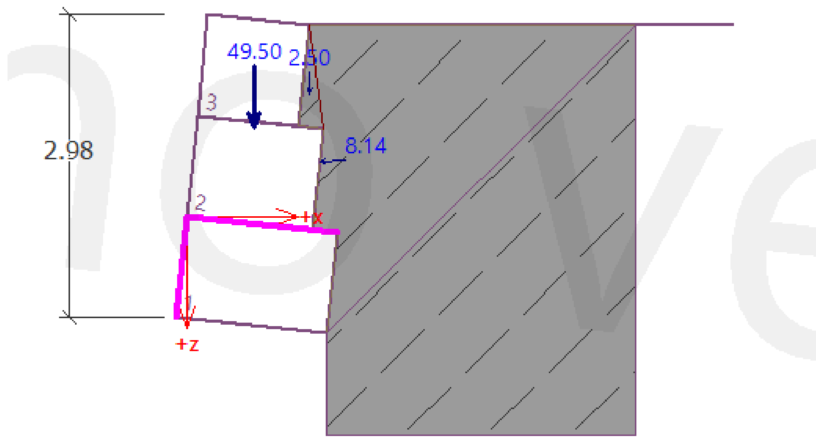

Figure 8 Testing for gabion wall

Initially, we proposed a retaining wall with a width of 300 mm and vertical orientation. However, the early simulations in GEO5 (Fine Software, GEO5 Geotechnical Software Suite, Fine Ltd., Czech Republic. [Online]. Available: https://www.finesoftware.eu, n.d.) showed this configuration was unsafe against overturning and bearing capacity limits. As a result, the design was revised multiple times, and the final optimized wall includes the following features:

- Total Height: 3.0 m
- Bottom Width: 1.5 m
- Top Width: 1.0 m
- Backward Slope: 6° from the vertical

This final design satisfied all safety factors for stability and soil interaction as confirmed in the GEO5 analysis.

Check for Overturning Stability

Calculating the Resisting Moment （M_{res}）

$$\boldsymbol{M_{res}} = \sum(\boldsymbol{Wi} \times \boldsymbol{di}) = \boldsymbol{36.69 kN/m}$$

$\boldsymbol{Wi}$: The body weight of the i wall

$\boldsymbol{di}$: the horizontal distance of each force to the toe of the wall (to the center of gravity)

Calculated overturning moment （M_{ovr}）

$$\boldsymbol{M_{ovr} = Ha \times h/3}\textbf{=4.39kN/m}$$

Ha: Active earth pressure (or horizontal force)

h: Action height (usually wall height)

Safety Factor

$$SF = \frac{\mathbf{36.69}\boldsymbol{kN/m}}{\mathbf{4.39}\boldsymbol{kN/m}} = 8.35 > 1.60$$

Conclusion: Joint for overturning stability is SATISFACTORY.

Check for Sliding Stability

Calculate the Resisting Horizontal Force （H_{res}）

$$\boldsymbol{H_{res} = \mu \times W = 30.67kN/m}$$

μ : coefficient of friction between the bottom and the foundation

W: Total wall weight (vertical force)

Calculate the Active Horizontal force （H_{act}）

$$\boldsymbol{H_{act} = \frac{1}{2} \cdot \gamma \cdot h^2 \cdot ka = 2.58kN/m}$$

γ : unit weight of backfill

h: The wall is high

Ka: Rankine or Coulomb

Safety Factor

$$SF = \frac{H_{res}}{H_{act}} = 11.87 > 1.30$$

Conclusion: Joint for slip is **SATISFACTORY**.

Check for Bearing Capacity against Transverse Pressure

Computed Transverse Stress (Q_{comp})

$$Q_{comp} = \frac{W}{b} = 40.00 kN/m$$

W: Total vertical load or self-weight per meter of wall (kN/m)

b: Effective bearing width (in meters)

Allowable Bearing Capacity (Q_{allow})

$$Q_{allow} = \frac{fc}{\gamma sf} = 11.32 kN/m$$

fc: Compressive strength of the bearing material (e.g., stone, concrete)

γsf: Safety factors(typically between 2.0 and 3.0)

$$Safety\ Factor = \frac{Q_{comp}}{Q_{allow}} \approx 3.53 > 1.00$$

Key stability checks, including overturning resistance, sliding resistance, and bearing capacity against transverse pressure, were conducted using both manual calculations and GEO5 simulations. Each criterion was met with significant safety margins, confirming that the structure is capable of withstanding anticipated loads under site-specific soil conditions. The results validate the design's suitability for volunteer-led construction, low-cost deployment, and long-term reliability in the extreme winter conditions of northern Ontario.

Conclusions and Recommendations for Future Work

Our team has successfully developed a range of design features aimed at helping the greenhouse withstand a harsh northern climate—particularly in terms of structural integrity, thermal retention, and passive environmental control. However, these solutions represent a strong starting point rather than a complete system.

Additional work will be needed to further preserve and regulate internal heat, optimize energy usage, and adapt the design to changing seasonal conditions. There are also several unresolved design choices and system integrations that will require focused development. For example, we suggest future teams consider adding a power source, with a battery and generator combination, potentially powered by renewable energy—inspired by the client's use of solar panels for their root cellar system.

Key Takeaways and Lessons Learned

- **Passive Solar Design is Highly Effective**: The Chinese-style slanted south-facing wall and insulated gabion back wall were very efficient in helping the greenhouse retain heat.
- **Structural Validation is Critical**: Iterative structural simulations using GEO5 significantly enhanced the design's safety and stability.
- **Community Accessibility is Achievable**: The project showed us that a large projects like a greenhouse system can be constructed with simple materials and techniques accessible to volunteers.

Limitations

- **Incomplete Automation**: While the thermal blanket system can be triggered automatically, the rest of the climate control features (ventilation, supplemental heating) rely on manual or semi-automated processes at the moment.
- **Power System Not Fully Integrated**: Although the design supports solar and geothermal energy sources, a full integration and testing of these systems is still needed in addition to considering the extra power sources needed for emergencies.
- **Extreme Temperature Mitigation**: Additional heating will be required to sustain acceptable temperature during long and especially harsh durations of winter.

Future Work

1. **Full Integration of Renewable Energy Systems**
   Test and implement a complete solar/geothermal hybrid system to power heating, automation, and ventilation in a fully off-grid setting.

   Wind turbines should also be considered.

2. **Development of a Sensor-Controlled Smart System**
   Introduce sensor-based controls to automate all systems reacting to the environmental factors (temperature, humidity, light) with real-time feedback for minimal human intervention.
3. **Scaling and Field Deployment**
   testing needs to be done to calculate the performance, energy consumption, and maintenance requirements. of a full-scale working prototype in cold-climate regions.
4. **Improved Insulation Materials**
   Explore advanced, cost-effective insulation materials that can further reduce thermal loss and enhance the performance of the north wall and roof structure.
5. **Cost Optimization**
   Continue exploring alternative materials or recycled components that reduce upfront costs without compromising structural integrity or insulation efficiency.

   The excavation needed for embedding the greenhouse in the ground is currently the most expensive part. Even though the alternative method of piling dirt onto the back wall is viable and much cheaper, it still costs a considerable amount and most probably will need external resources like special machinery.

Conclusion

The greenhouse prototype presented in this project shows great promise. In the future this design could evolve into the standard model for sustainable agriculture in northern climates.

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[8] Canadian greenhouse kits, existing option on market: https://greenhouseinthesnowcanada.ca/

APPENDICES

APPENDIX I: Design Files

Our Makerepo link: https://makerepo.com/jinzewan/2533.sustainable-food-prudoction
Our online microcontroller simulator: https://www.tinkercad.com/things/4TXxPWoxUTT-simple-sensors-glore/editel?returnTo=https%3A%2F%2Fwww.tinkercad.com%2Fdashboard

APPENDIX II: Other Appendices

Backfilled Soil:

Compacted in layers not exceeding 150mm to form a dense stable mass.

$$Effective\ Cohesion\ (c') = 0\ kpa$$

$$Effective\ angle\ of\ internal\ friction\ \Phi' pk = 40\ Degree\ (Typical)$$

$$Unit\ weight\ (Y) = 20\ KN/Cum\ (Typical$$

Foundation Soil:

Assumption of Firm Clay

$$Effective\ Cohesion\ (c') = 0\ kpa$$

$$Effective\ angle\ of\ internal\ friction\ \Phi' pk = 20\ Degree\ (Typical)$$

$$Unit\ weight\ (Ws) = 20\ KN/Cum\ (Typical)$$

$$Allowable\ Bearing\ Capacity\ qallow = 250\ kpa\ (Assumed)$$

Surcharge loading = Considered Nil

Disturbing Force / Moments:

$\alpha = 6\ Slope\ Angle\ of\ Backfill\ surface$

$\text{β} = 0\ acute\ angle\ of\ back\ face\ lope\ with\ vertical$

$\delta = 0\ angle\ of\ wall\ friction$

$\varphi = 40\ angle\ of\ internal\ friction\ of\ soil$

$$K_a = \frac{\cos^2 (\phi - \beta)}{\cos^2 \beta \cos (\delta + \beta)[1 + \sqrt{\frac{\sin (\phi + \delta) \sin (\phi - \alpha)}{\cos (\delta + \beta) \cos (\alpha - \beta)}}]^2}$$

Ka =	Active earth pressure Co-efficient
Φ′pk =	Angle of Internal Friction
Hr =	Height of the Wall
Pa =	Lateral Earth Pressure on wall'
ws =	Soild Denstiy