Best Practices in Low Carbon Greenhouse Construction and Operation

Includes:

Final Report

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Low-Carbon Greenhouse Construction and Operation in Ecology Park

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ERSC 3160H (Winter 2024)
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GreenUP ECOLOGY PARK

Acknowledgements

Both Ecology Park and Trent University are located on the traditional territories of the Michi Saagiig Anishinaabeg of Treaty 20 and the Williams Treaties. We acknowledge the Indigenous Peoples who have since time immemorial taken care of the lands upon which Peterborough, known to many as Nogojiwanong, 'place at the end of the rapids', exists.

As settlers on this territory, we are grateful to the Michi Saagiig Anishinaabeg for their care and teachings about the earth and all our relations. It is a privilege to be able to live and learn in this place and we commit to working towards true reconciliation and decolonization.

Thank you to GreenUP, the Trent Community Research Centre and our professor Dr. Watmough for engaging us to do this work. We are especially grateful for Hayley Goodchild and Vern Bastable of GreenUP, for their passion and support. It has been a pleasure to work with you on completing this project.

Authorship statement: We acknowledge that we all did equal work and we do not have any conflicts of interest in the context of this project. Therefore, we approve of this statement and take public responsibility for this project and its contents.

-Alyssa Scanga, Cerra Simmons, and Alisa Miniovich

Photo: Cerra Simmons

Table of Contents

Photo: Alisa Miniovich

About GreenUP

GreenUP is a **hub for collaborative, community-based action on sustainability and the environment** based in Peterborough, Ontario (GreenUP, 2024). Originally incubated as a project of the Kawartha World Issues Centre (KWIC), GreenUP incorporated in 1992 and became a registered charity. GreenUP is funded by grants from all levels of government, businesses, private foundations, and individual donors, as well as revenue from the GreenUP Store and Resource Centre and the **GreenUP Ecology Park Native Plant and Tree Nursery.**

GreenUP's mission is to **inspire and empower environmentally healthy and sustainable action** in Peterborough (GreenUP, 2018). Their programming falls under three pillars: *Teach, Act,* and *Engage.* Moving forward, they aim to develop critical infrastructure to enhance Ecology Park, foster diverse partnerships with other community organizations to support broad, strategic, and systemic climate and environmental action, and ensure organizational resilience by strengthening operational processes and building capacity.

Ecology Park

In 1993, GreenUP joined with Peterborough's Ecology Garden to create **Ecology Park** at Beavermead (GreenUP, 2018). Ecology Park features a **native plant and tree nursery,** workshops, school programs, summer camps, and an ecological demonstration centre. The nursery at Ecology Park is the only one within the City of Peterborough to focus primarily on native plants, and prices at Ecology Park are slightly below the regional average (GreenUP, 2024).

At present, there is about 100m^2 of space at Ecology Park earmarked for native plant propagation, whether in-ground or using raised beds. This includes pathway space between beds. In the off-season there is no access to washroom facilities, climate controlled indoor space, or power, making it **difficult for staff to use the space in winter for propagation** as is common for many grower-retailers. Some propagation is being done in the off-season at the GreenUP Store and Resource Centre at 378 Aylmer Street North, but this is not ideal.

GreenUP's five-year strategic plan for Ecology Park includes the development of a greenhouse to extend the Native Plant and Tree Nursery's growing season and improve its capacity. To this end, GreenUP has engaged a team of student researchers from Trent University through the Trent Community Research Centre to **investigate best practices for low-carbon greenhouse construction and operation at Ecology Park**.

The proposed greenhouse location is within a current market area, next to the road and close to the newly installed seasonal accessible washrooms on site.

Photo: Hayley Goodchild

Greenhouse Propagation

Peterborough has a cold, temperate continental climate with warm summers and **strong temperature seasonality** (*Figure 1*) (Trent University, 2022). While native plants are adapted to the local climate, the short growing season does not give grower-retailers much time to grow plants to sell. According to Hayley Goodchild, Coordinator of Native Plant Propagation at Ecology Park, GreenUP prefers to start plants from seed to maximize genetic diversity of native plants, however, this takes significantly longer so vegetative propagation is sometimes done for some slower-growing species (personal communication, Feb 22 2024). Greenhouses **extend the growing season** by providing a controlled climate for seeds to germinate much earlier so they are ready for spring, allowing a greater number of plants to be prepared, particularly from seed.

Although GreenUP is the only garden centre in Peterborough focusing primarily on native plants, several chain retailers and other garden centres have started to include small amounts of native plants in their stock (GreenUP, 2024). Online native plant retailers and backyard-scale growers may also pose growing competition to the GreenUP Nursery. Many grower-retailers build their plant stock for the upcoming season between November-March, which is not currently an option for GreenUP. In order to capitalise on this key season, **GreenUP will need a greenhouse** at Ecology Park.

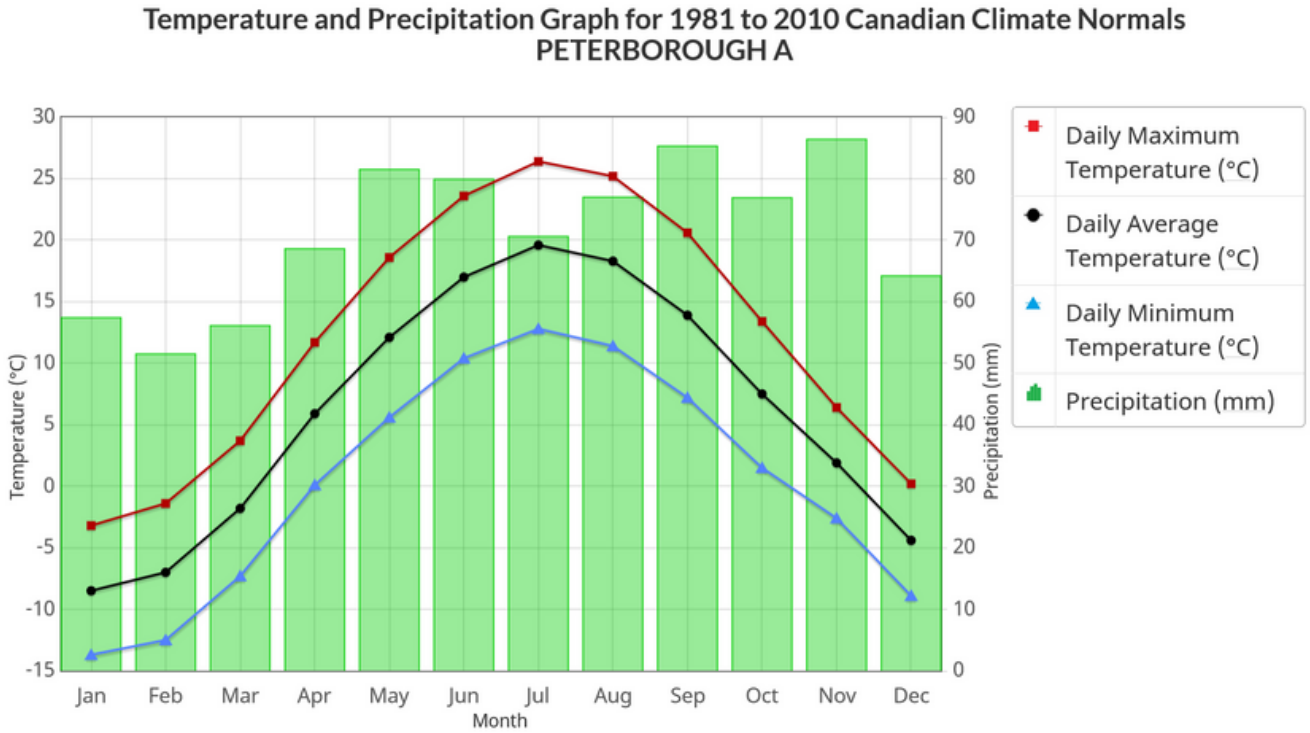


Figure 1: Canadian Climate Normals (1981-2010) for Peterborough. Sourced from Environment and Climate Change Canada, 2024.

Study Objective

GreenUP has recognized the need for a greenhouse in Ecology Park for several years. In their 2020 five-year plan for Ecology Park, they estimated costs at around $350,000. Hayley Goodchild confirmed that this budget was on the high-end but still reasonable and posed several questions to guide research on low-carbon greenhouse construction and operation.

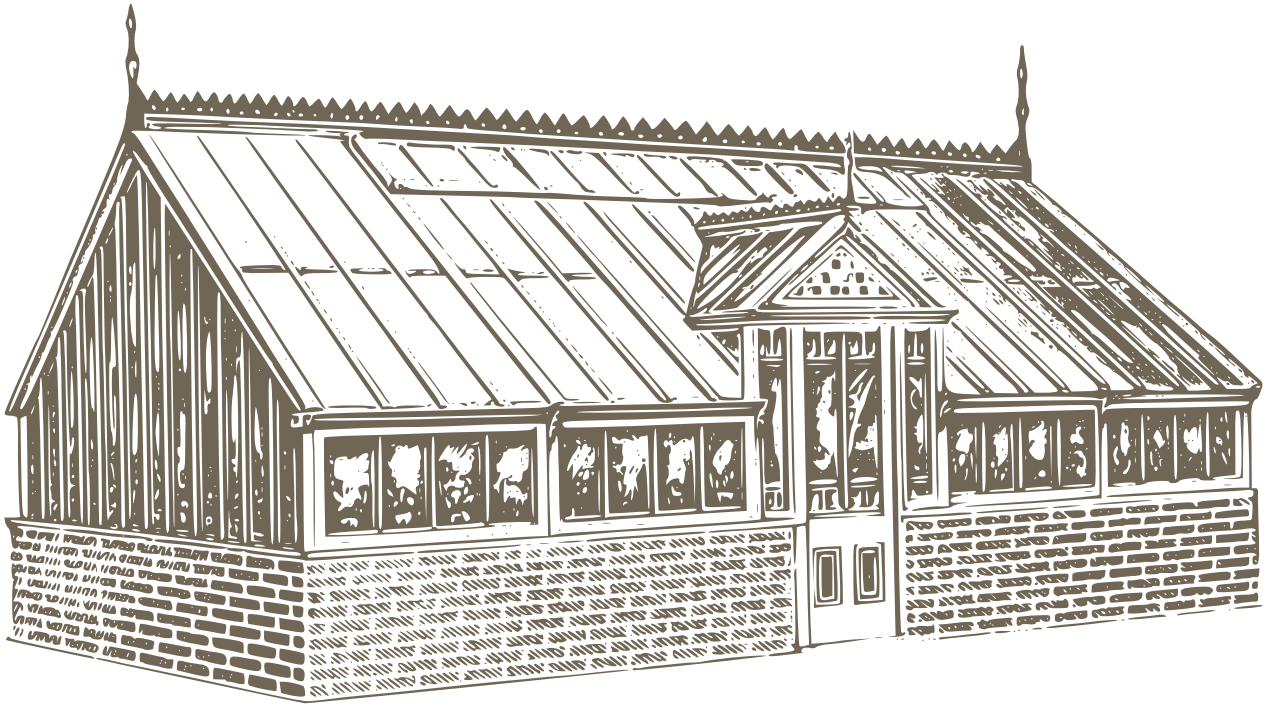
Primary Research Question:

- What models would be most suitable for GreenUP based on their long-term propagation goals and the constraints of Ecology Park?

Supporting Research Questions (integrated in discussion):

- What alternative greenhouse construction and operations exist in Southern Ontario and similar climate regions?
- What are the benefits and disadvantages of different greenhouse models?

Objective: Identify **greenhouse models that meet GreenUP's objectives** of a greenhouse that can support late winter plant growth and research, has relatively low carbon footprint, and can showcase innovative solutions. **Present three shortlisted greenhouse designs** for GreenUP to investigate further in their feasibility study.



Site Visit

Ecology Park is located at 1899 Ashburnham Drive and sits on five acres of land within Beavermead Park (GreenUP, 2024). It is accessible year-round and is easy to reach by public transit. The park is bordered on one side by Meade Creek and is connected to the Trans-Canada Trail. It is pedestrian-access only, excepting pickup orders of compost, mulch, or wood chips from Ecology Park Nursery.

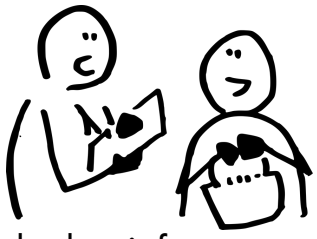
On the morning of February 7th, 2024, researchers went to Ecology Park to meet with GreenUP staff Hayley Goodchild (Coordinator of Native Plant Propagation) and Vern Bastable (Director of Ecology Park) for a **tour of the site**. This tour included learning about the design and features of existing buildings, understanding the current native plant propagation process, and a **visit to the proposed greenhouse site** (*Figure 2*). Goodchild provided a **map of the Park** and information on its operational plan for 2024.

Figure 2: Map of GreenUP's Ecology Park.The proposed greenhouse area is depicted with hatched red lines.

Conversations with Stakeholders

Bi-weekly meetings were held between the researchers and GreenUP. The first meeting involved GreenUP explaining their vision for the project and initiating a plan of action, which included the site visit. Subsequent meetings consisted of updates on the research process and opportunities for GreenUP to ask questions. The primary goal was to ensure GreenUP remained informed during the entire process and felt a sense of ownership over the project.

During the site visit, GreenUP staff provided information about Ecology Park and their goals for the greenhouse. They wanted the greenhouse to be made from **low-carbon materials**, **sourced locally** if possible. Additionally, they explained that infrastructure in the park is lacking so it would be important for the greenhouse to **operate self-sufficiently** or require very little infrastructure. Vern Bastable added that GreenUP has had some vandalism problems in Ecology Park because it is public space, so the greenhouse needed to be **made of resilient materials and/or easy to repair**. GreenUP staff also expressed a desire for a **staff bathroom**, but said this was "more of a nice-to-have" than a need. If researchers identified a greenhouse option that was not suitable for Ecology Park, Hayley Goodchild asked that they include their rationale for excluding it in the final report so GreenUP could understand their reasoning.



Literature Review

Both **academic sources and grey literature**, such as websites, were consulted to inform our short list of greenhouse materials and concepts. First, a search for preliminary information about common greenhouse practices and low carbon materials was conducted using the key terms "low carbon greenhouse", "sustainable building materials" and "small scale greenhouse". This yielded results from blog posts and custom greenhouse companies with reviews of typical practices and breakthrough technologies.

Next, the **Trent Omni** database and **Google Scholar** were searched for academic reviews of the materials found during the grey literature review. GreenUP wants the results of this project to be new and innovative; therefore only articles published after 2018 were included in the results of the literature review.

Objective and Criteria Design

To establish an organized approach for choosing three designs, the team created a **criteria list that was used to rank each option**. This was created based on the information in the Ecology Park master plan, the community-based research proposal, and meetings with GreenUP. In order for a design to be considered, **six out of eight** criteria had to be met. If more than three options scored six out of eight, only the top three concepts would be recommended to GreenUP. Six greenhouse options were explored and the top three highest-scoring greenhouse options were further investigated, conceptualized, and shared with the GreenUP staff. These three shortlisted greenhouses are expanded on within this report.

1. Budget: $200,000 - $350,000 CAD
2. Size: 300-500 ft^2
3. Zero/low carbon structure
4. Resilient materials/ easily replaceable
5. Winter-tolerant
6. Locally sourced materials*
7. Can run on existing infrastructure
8. Potential for staff bathroom

*Local is defined as within Ontario or Canada, but within North America is acceptable.

Review of Greenhouse Designs

1. Prefabricated Greenhouses

1.1 Royal Victorian Greenhouse

The first of two prefabricated greenhouse options is the **Royal Victorian Greenhouse produced by *Exaco Janessens*** (https://greenhouseemporium.com/products/exaco-janssens-royal-victorian-greenhouse/). This is from a New York based company that sells greenhouse kits in a variety of sizes and shapes. The VI46 model (13ft x 20ft) is from their winter selection which promotes materials that can withstand the weight of snow. The walls are made of 10mm twin-wall polycarbonate panels (panel b in *Figure 3*), and there are built-in ventilation windows on the gabled roof. A 15-year warranty is attached to the structure meaning that, should the walls be damaged for any reason, they can easily be replaced.

The glass is sealed together which increases the thermal efficiency of the structure, making it capable of reaching temperatures higher than a traditional greenhouse in the early spring (Greenhouse Emporium, 2023). Furthermore, the connecting joints are made of reinforced steel (green or black), and it comes equipped with a gutter system. The irrigation system inside the structure only requires a garden hose to run, meaning that it can run using the existing infrastructure at Ecology Park. However, given that it is a prefabricated structure, a washroom facility is not a feasible feature in this design. Ultimately, the price of this structure, before shipping and tax, is CDN $12,000 - 23,000 (Greenhouse Emporium, 2023).

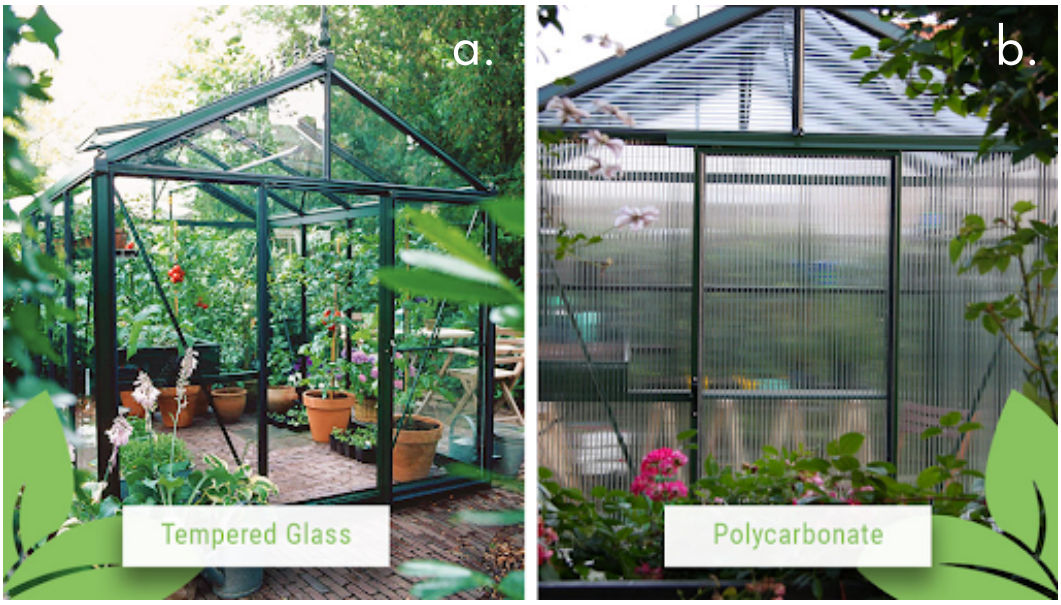


Figure 3: The V48 Royal Victorian Greenhouse by Exaco Janssens. Panel a displays the 4mm tempered glass option, and panel b shows the 10mm twin polycarbonate glazing that is proposed in this report. Image sourced from Greenhouse Emporium, 2023.

1.2 Harnois Greenhouse

The second prefabricated greenhouse option is the **Harnois Ovaltech 1** in the horticultural sector **produced by *Harnois Industries*** (https://www.harnois.com/en/greenhouses/models/). *Harnois Industries* is a Quebec based company, which means that it is local and accessible, that creates greenhouses within the horticultural, institutional, and commercial sectors that come in a variety of sizes. This specific greenhouse design was established to maximize the efficiency of natural ventilation and help create a climate suitable for strong, healthy crops. The Harnois Ovaltech 1 greenhouse includes X-rod anchor tubes and anchor plates for existing foundation, as well as anchor tubes for concrete foundation (Harnois, 2024). Further, it includes polyethylene films and polycarbonate sheets for the covering/body, and uses ridge vent panels, and a mid-roof vent for ventilation within the greenhouse (Harnois, 2024). This design could also include single or double doors.

The size of this greenhouse ranges with the width being available from 20 ft to 42 ft (Harnois, 2024). Moreover, these materials are low carbon and sustainable. Specifically, the polycarbonate sheets are a thermoplastic that can be melted down and reused multiple times rather than burning or breaking down (AC, 2024). Additionally, this greenhouse comes with a system that recovers and recycles rainwater. This subsequently means that there would not be a need to establish a water harvesting or irrigation system on site as this greenhouse includes one. All of the materials used for the construction of the Harnois greenhouse are durable and resilient and are made to withstand Canadian winters. As this greenhouse is prefabricated, it would not be possible to construct a bathroom within this design. The cost of this greenhouse would be approximately CDN $10,000 (Harnois, 2024).

OVALTECH I

Width	20'	25'	27'
Arch spacing	6'-6" (2 meters)	5'	5'
Inside clearance A	6'-7"	6'-9"	6'-9"
Total height B	9'-6"	11'- 2"	11'- 6"
Tubing dimensions	1-5/8" x 2-3/4"	1-5/8" x 2-3/4"	

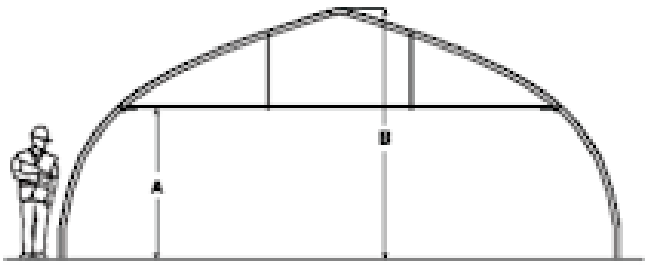


Figure 4: The measurements and rough sketch of the Harnois Ovaltech 1 greenhouse in the horticulture sector. Image sourced from Harnois Industries, 2024.

2. Innovative Greenhouses

2.1 Ethylene tetrafluoroethylene (ETFE) based greenhouse

Ethylene Tetrafluoroethylene (ETFE) is a newer product that has been designed specifically to improve the shortcomings of traditional greenhouse materials (Lamnatou et al., 2018). The benefits of this product are that the material is lighter and transmits more solar energy all while being stronger and more resilient to breakage than glass (Lamnatou et al., 2018). The second side of this benefit is that this makes ETFE an ideal building material for structures exposed to snow in the winter. Furthermore, it is not prone to degrading or yellowing with time, meaning that, although it is a plastic, it will not produce microplastics in Ecology Park in the future (Lamnatou et al., 2018). Lastly, despite being an innovative material, all markets consulted in the literature review by Lamnatou et al. suggest that it is relatively cost-effective, meaning that the remaining budget can be used to add some of the additional requested amenities. For these reasons, it was decided that ETFE would be a good material to center one of the greenhouse designs around.

This greenhouse design, conceptualized in *Figure 4* on the next page, includes steel framing for support, and a north-facing shed and tree shelter belt to provide additional protection. The shed is primarily designed to be an on-site germination station, however, there is the opportunity for a bathroom to be installed. Additionally, to make this a passive system, or rather a system that does not require connection to the main electricity grid, a solar panel and battery system is proposed to power an internal irrigation system or the UV germination lights. In terms of its carbon footprint, the ETFE material is advertised as zero carbon following installation (Lamnatou et al., 2018). However, there are some low carbon emissions associated with its manufacturing. It is up to GreenUP to decide whether this product still aligns with their vision because of this.

Ultimately, this material can be bought from a manufacturer in Colorado, USA, and it is recommended that GreenUP reach out to Ceres Greenhouses (www.ceresgs.com) during their feasibility study to learn more about their pricing. Due to its innovative design, this greenhouse can be constructed in any size, however this report proposes a 35 ft x 10 ft greenhouse with an attached 15 ft x 10 ft germination shed. The resulting area is 500 ft2, sitting at the upper end of the size outlined in the Ecology Park master plan (GreenUP, 2020).

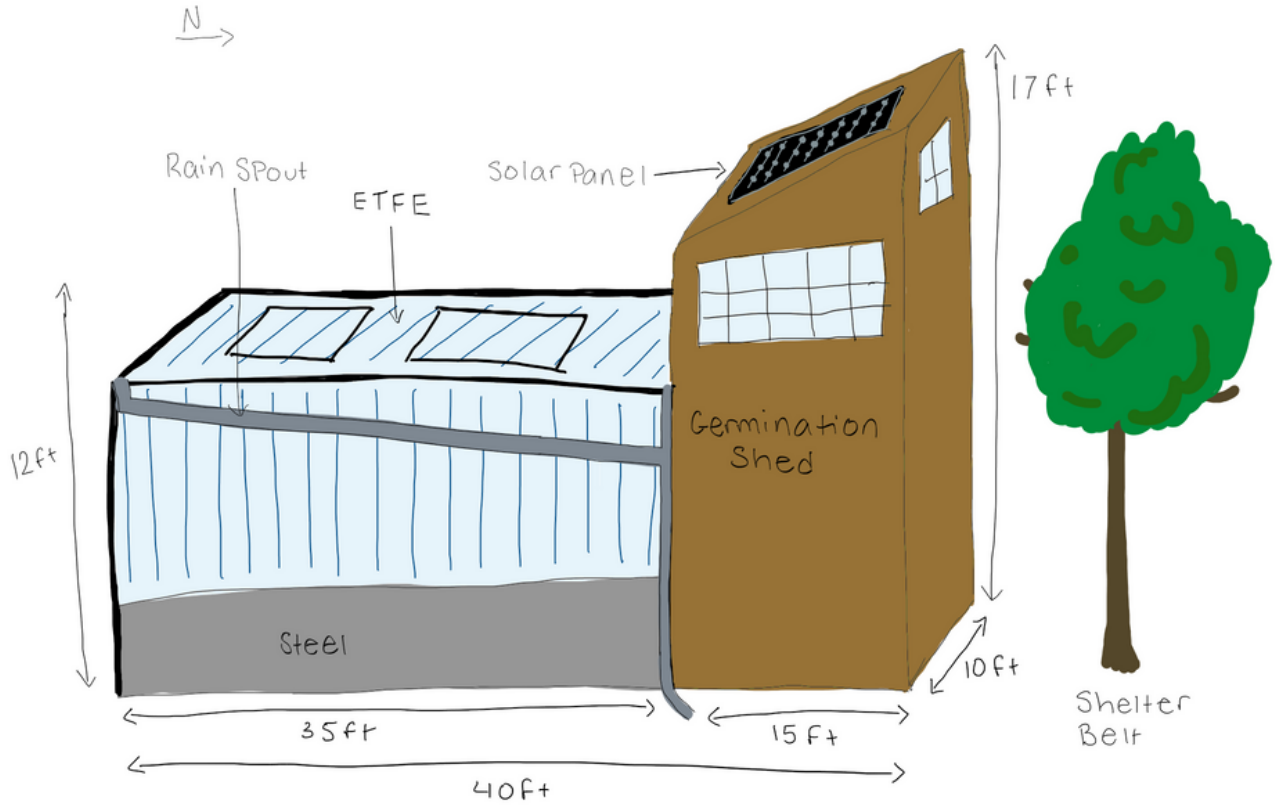


Figure 5: Conceptual drawing of the ETFE greenhouse design and proposed features.

2.2 Walipini Greenhouse

The word 'walipini' means 'place of warmth' in the Aymara Indigenous language of Bolivia and refers to an **underground pit greenhouse** (Benson Agriculture and Food Institute, 2002). The basic design of a walipini consists of a hole dug six to eight feet into the ground and covered with either a single or double layer of polyethylene glazing (Schaffer, 2021). The sun's rays enter through the light-transmitting roof and the earthen walls provide insulation, capturing and retaining heat during the day and reradiating it into the growing space at night (Benson Agriculture and Food Institute, 2002).

Findings

A walipini in Ecology Park could be any desired size, however the cost cannot be determined at this stage as materials would have to be sourced on a needs and wants basis. A 35 ft x 10 ft would be sufficient. Although the bulk of the greenhouse is underground, reinforcements for the dug walls are still needed (Scheffer, 2021). This can be done with low-carbon materials (see: hempcrete and papercrete in Figures 6 and 7) and using ETFE as the roof's light-transmitting material. The walipini is resilient, with only a small proportion of the greenhouse exposed and vulnerable to vandalism. A fence could be built surrounding the area to prevent individuals walking on the exposed panelling.

The walipini is not able to run on existing infrastructure. The greenhouse would require manual watering and it would be difficult to equip it with electricity or create a germination station with this design. Additionally, Bastable and Goodchild shared that the ground of Ecology Park has many miscellaneous waste materials below the surface, which would render the excavation required to dig out a walipini impractical. Another barrier is the shallow ground depth at the site given its close proximity to the river. Environmental assessments and permission from Otonabee Region Conservation Authority would be important in this case. It is likely not possible to install a staff bathroom in this greenhouse, unless a small shed was built on the surface near the stairs down into the walipini.

While the greenhouse construction materials are winter-tolerant, the walipini is not suitable for use in Peterborough. It is designed for regions closer to the equator, and the sunlight angle at this latitude will cast deep shadows over the growing area for large portions of the day (Schaffer, 2021). Additionally, in North America one would need to dig down eleven feet to achieve the same insulation as traditional greenhouse walls, much deeper than a Bolivian walipini (Schaffer, 2021).

Figure 6: A 'Walipini', or underground pit greenhouse. Image sourced from Schaffer, 2021.

2.3 Polycarbonate Hempcrete Greenhouse

The **polycarbonate hempcrete greenhouse** includes polycarbonate panels for the covering/body of the greenhouse and will have **hempcrete** as the base and structure of the greenhouse. These materials are all very low carbon. Polycarbonate panels can be used to create sustainable plastic building materials (AC, 2024), and hempcrete is a Biocomposite material; it is a mixture of hemp hurds, lime, and sand (Green, 2017). Hempcrete can also be used for insulation within the greenhouse. Further, all of the materials are local and accessible as they can be found within Canada.

Polycarbonate and hempcrete are very durable and resilient. Polycarbonate has a high-resilience capacity to face different weather conditions and it is suitable for the construction of shelter modules (AC, 2024). These materials are suitable for all climates, so they are tolerant to Canadian winter conditions. A water collection or irrigation system would need to be established on site, since this greenhouse is not prefabricated. The size of this greenhouse would be 400 square feet. It would stand at 40 ft long, 10 ft wide, and 12 ft tall, and would have room for a bathroom to be installed. The cost of this greenhouse design would be between CDN $20,000 - $50,000 (Venolia, 2022).

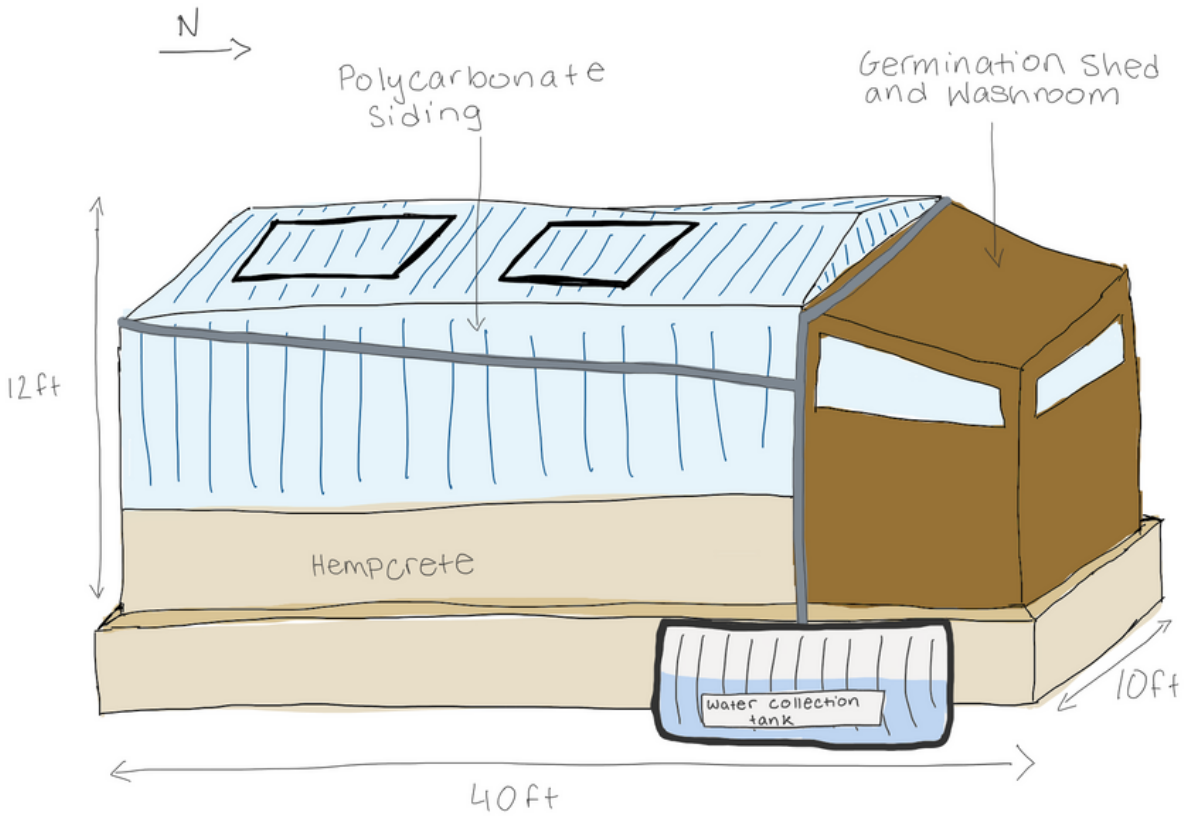


Figure 7: Conceptual diagram of the polycarbonate hempcrete greenhouse design and its features.

2.4 Timber Papercrete Greenhouse

The final option is the **timber papercrete greenhouse**. This greenhouse design includes timber that can be used for framing and flooring within the greenhouse (Nguyen, 2024). Further, polycarbonate panels will be used as the covering/body of the greenhouse to provide natural light while reducing heat loss (AC, 2024). Papercrete, which is a sustainable building material composed of recycled paper and cement (Sheth, 2018), will be used as the base and structure and it can absorb heat during the day and release it at night, helping to stabilize temperatures inside the greenhouse without relying heavily on external energy sources. Additionally, straw bales will be used to insulate the greenhouse, reducing the need for artificial heating in colder climates (Brown, 2022). All of these materials are local and accessible as they can be found within Canada.

Papercrete is a sustainable building material due to reduced amount of cement usage and recycled paper being put to good use (Sheth, 2018). It has numerous advantages in the construction industry, namely a low carbon footprint, recycled material usage, low embodied energy, high strength-to-weight ratio, high thermal insulation, high sound absorption, and is cost-effective (Sheth, 2018). Moreover, these materials are highly durable, resilient, and can withstand Canadian winter conditions. This design is not prefabricated, so there would need to be a rainwater collection system for irrigation established on the property. The size of this greenhouse would be 400 square ft. The greenhouse will stand at 40 ft long, 10 ft wide, and 12 ft tall. Therefore, it will have room to fit a bathroom (not pictured in *Figure 8*). Finally, the price of this greenhouse is between CDN $20,000 - $50,000 (Kienlen, 2019).

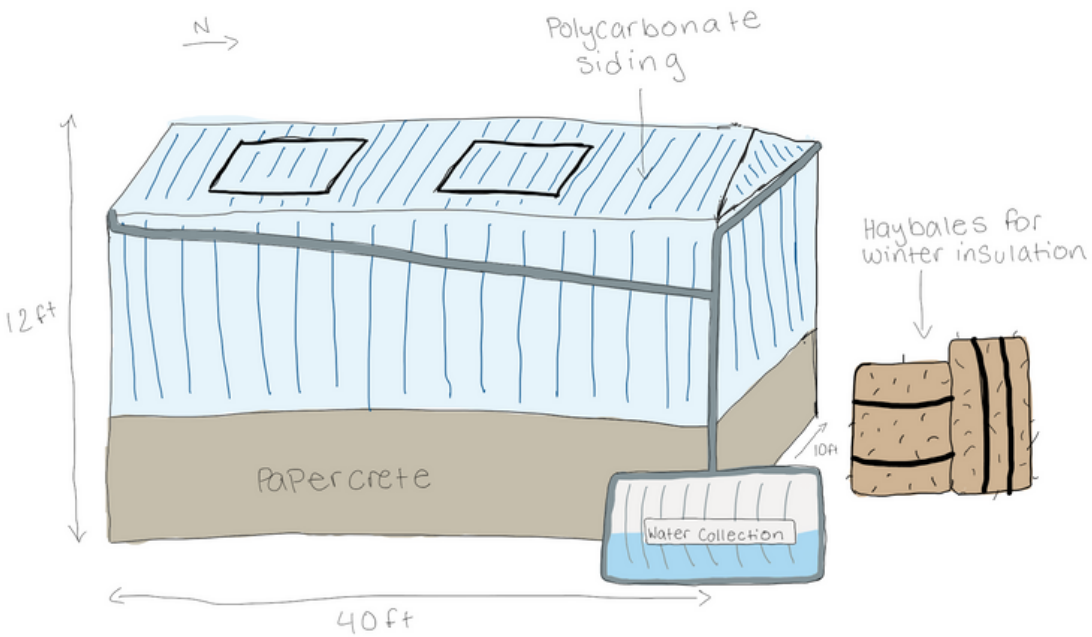


Figure 8: Conceptual diagram of the Timber Papercrete Greenhouse Design and features.

Summary of Results

Three of the options meet seven out of eight (7/8) of the necessary criteria. *(Table 1)*. The three shortlisted greenhouse options are the ETFE greenhouse with a shed, the polycarbonate hempcrete greenhouse, and the timber papercrete greenhouse.

Table 1: Application of suitability criteria to six proposed greenhouses.

	Victorian	**ETFE**	Walipini	Harnois	**Polycarbonate hempcrete**	**Timber papercrete**
In budget?	Yes	-	-	Yes	Yes	Yes
Local?	Yes	Yes	Yes	Yes	Yes	Yes
Low/zero carbon?	No	Yes	Yes	Yes	Yes	Yes
Resilient?	Yes	Yes	Yes	Yes	Yes	Yes
Existing infrastructure?	Yes	Yes	No	No	No	No
Winter tolerant?	Yes	Yes	No	Yes	Yes	Yes
Space for bathroom?	No	Yes	No	No	Yes	Yes
Desired size?	No	Yes	Yes	Yes	Yes	Yes
Total:	5	7	4	6	7	7

Rejected Greenhouses

Royal Victorian Greenhouse

The Royal Victorian greenhouse is not recommended for the Ecology Park greenhouse, primarily due to its size. Given that a key objective of the GreenUP greenhouse is to be able to compete with other plant retailers, the facility needs to be large enough to house a comprehensive germination and growth operation. Furthermore, while the polycarbonate siding is a relatively low carbon material, the retail company is not transparent about where materials are sourced from. Therefore, it cannot be confirmed that the production process before installation is also low carbon. Finally, there is no opportunity for an attached bathroom for staff as it is a prefabricated structure. Ultimately, only **5/8** criteria are met giving ample reason to not recommend this structure for the operation in Ecology Park.

Walipini Greenhouse

While this greenhouse option is innovative, it is not recommended for Ecology Park. This option scores lowest on the criteria ranking at **4/8**. The main limitation of this option is that it is not really designed for North American climates. Additionally, the combination of subsurface obstructions and Ecology Park's position in a flood plain make digging the Walipini pit unfeasible. It has been included because it presents some innovative ways to harness ambient energy in the earth to grow plant products. Smaller walipini-like ground plant beds could be something that GreenUP considers in the future should their commercial needs outgrow the size of the existing greenhouse. Normal plant beds could be dug slightly deeper into the ground and a polycarbonate or ETFE dome could be installed over to increase radiation over the localized area.

Harnois Greenhouse

The Harnois greenhouse was not chosen as one of the three final greenhouses because of a few factors. Firstly, the Harnois greenhouse would potentially need to have an additional ventilation system installed. There is a basic ventilation system within the greenhouse that operates passively, such as through vents that open and close automatically based on temperature differentials, but if a more sophisticated ventilation system were to be installed, this would need to be powered by electricity. This consequently means that extra features would need to be installed. Furthermore, this greenhouse is prefabricated which means that there is no space for a bathroom to be constructed. Therefore, although this option meets **6/8** criteria, it has not been selected for the shortlist.

Shortlisted Greenhouses

Polycarbonate Hempcrete Greenhouse

The polycarbonate hempcrete greenhouse is one of the possible options for construction. This greenhouse meets **7/8** of the proposed criteria, making it a favourable option. This greenhouse includes low carbon materials that are all locally accessible. All of the materials are durable and resilient, it fits within the set budget for this project, and it is not prefabricated so the size will definitely meet the target set by GreenUP. Furthermore, all the materials can tolerate Ontario winter conditions and there is space for a bathroom in this greenhouse. A limitation with this greenhouse is that there would need to be a water harvesting system established on site for this greenhouse to run successfully, however it has still been identified as a feasible option for GreenUP.

ETFE Greenhouse with Shed

This greenhouse was shortlisted to present to GreenUP because, apart from an unknown price point, this design meets all of the design criteria (**7/8**). An additional benefit is that the morals and motivation behind the innovation of the ETFE siding align with GreenUP's vision of having a cutting edge, sustainable greenhouse. Given that this design is 100% not prefabricated, there is more opportunity for GreenUP to make changes to the initial proposed structure in ways that might enhance its operation. Finally, the shed that has a triple role of weather protection, germination station, and staff bathroom is another benefit, and displays a maximization of the space available at Ecology Park.

Timber Papercrete Greenhouse

The timber papercrete greenhouse is the final shortlisted design option. This greenhouse also meets **7/8** criteria points. It includes materials that are durable, local, tolerable of Canadian winter conditions, and is ultimately low carbon. The price and size meet GreenUP's vision and even has the opportunity for a bathroom to be constructed with the remaining budget. Lastly, a water collection system is suggested in order to passively irrigate the plants in the structure.

Ultimately, the three chosen designs were shortlisted because they are all **uniquely innovated**. A benefit of this is that GreenUP has the ability to **combine aspects of each design** in the final greenhouse structure should they wish to do so. They also present a range of prices and local materials (from the USA to materials accessible in Peterborough) to meet future changes to the greenhouse budget.

It is recommended that GreenUP **contacts Ceres Greenhouses** to learn more about the exact price of the ETFE material. As students are unable to engage with companies to enquire about prices we cannot confirm that it will be within budget. However, the literature reviews of this product suggest that it is one of the more affordable sustainable greenhouse materials. We also recommend that the **feasibility of obtaining local materials for making the hempcrete and papercrete bases is investigated**. The core materials (paper and hemp discard) have the potential to be available within Peterborough County, which would reduce transport costs and carbon emissions. As Ecology Park is the site of many children's camps and school field trips, GreenUP may consider involving schools in this process, such as by having classrooms collect their used paper for papercrete.

Limitations

The chosen criteria used to evaluate the greenhouse designs supported an organized approach for our analysis. However, it is **not a perfect system**. We are aware that the stringent criteria may have excluded some options that may be otherwise viable. Therefore, it was decided that the designs that did not make the shortlist would still be included in the report to allow GreenUP to evaluate the designs through their own lens. Additionally, it is recognised that the criteria may have excluded some considerations. The first of which is the plants anticipated to be grown in the greenhouse. GreenUP has advised that a mixture of native and perennial species are expected to be grown here. The criteria does not account for the amount of light or energy required to grow these plants most effectively. Therefore, we cannot advise which siding material is the most suitable for this consideration. It is recommended that this is considered in the subsequent feasibility study conducted by GreenUP.

Conclusion

The first shortlisted greenhouse option is the **ETFE greenhouse with a shed**. This greenhouse employs innovative, low-carbon ethylene tetrafluoroethylene panels and includes an attached shed that functions as weather protection, a germination station, and staff bathroom. The proposed footprint is a 35 ft x 10 ft greenhouse with an attached 15 ft x 10 ft germination shed. The design meets 7/8 of the design criteria.

The second shortlisted greenhouse option is the **polycarbonate hempcrete greenhouse**. This greenhouse is composed of polycarbonate panels as the body of the greenhouse, and hempcrete, a Biocomposite material that is a mixture of hemp hurds, lime, and sand as a base and structure around the greenhouse (Green, 2017). This design stands at 40 ft long, 10 ft wide, and 12 ft tall, and it would also include a bathroom. Further, all materials are found locally and are low carbon. This option meets 7/8 of the proposed criteria.

The third shortlisted greenhouse option is the **timber papercrete greenhouse**. This option proposes that papercrete, which is a mixture of recycled paper and cement (Sheth, 2018), be used as the base and structure of the greenhouse, polycarbonate panels as the body, sustainable timber as framing and flooring inside, and straw bales as insulation. This greenhouse stands at 40 ft long, 10 ft wide, and 12 ft tall, and it would have space for a bathroom. This option also meets 7/8 of the criteria points.

These three greenhouse options reflect GreenUP's goals and objectives as they would all be made from low carbon materials that are environmentally friendly, sustainable, and innovative.

A greenhouse at Ecology Park will increase the scale and competitiveness of GreenUP's Native Plant and Tree Nursery, allowing them to continue their important work of providing native plants to the greater Peterborough community. It can also serve as a teaching tool, educating the many visitors of Ecology Park about sustainable design. **We are confident that GreenUP will be able to construct and operate a low-carbon greenhouse at Ecology Park that both meets their needs and aligns with their vision and values.**

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