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Kingston, ON K7L 3N9

Group T

March 24, 2023

Nathan Splinter

355 King Street W

Kingston, ON K7L 2X3

Dear Nathan Splinter,

Please find enclosed Group T's Final Report for Queen's Facilities Solar PV and Rooftop Sustainability project. It contains an introduction to the project, background information, the team's final three design options for different roof capacities, and an environmental assessment. Thank you for the opportunity to expand our experience with this project and your assistance along the way.

The following report outlines the steps for determining if solar panels would be feasible on Queen's University's buildings' rooftops. A rooftop type was chosen, and an initial building list was determined; however, none of these buildings' rooftop loading capacities were obtainable. Therefore, a design solution for roofs with low, mid-range, and high rooftop capacities was determined, with corresponding energy outputs and loading requirements for each option. A structural analysis was completed for each solar panel to determine the snow, wind, and dead loads acting on the building caused by the implementation of a solar panel. This was done to develop a framework for future solar projects at Queen's University and to allow for ease of solar panel choice when complete structural analyses have been completed.

A financial assessment was completed to determine the total costs associated with a solar project including procurement, implementation, maintenance of solar panels, and the number of solar panels needed to breakeven for the project's lifespan. An environmental assessment was completed to determine the impact the solar panels would have on the environment and climate change. Lastly, two innovative ideas have been presented to highlight the solar panels on Queen's University's campus.

Sincerely,

Ethan McMurchy

Maren Campbell, Hannah Kruizinga, Ethan McMurchy, and Daniel Pogue

Enclosure: Final Report

Group T

SOLAR PV AND THE SUSTAINABILITY OF ROOFTOPS

Final Report

Presented to Queen's Facilities

March 24, 2023

Disclaimer:

This report has not been prepared by professional engineers. The information within the document is accurate to the extent of knowledge by the authors. All authors are fourth-year Civil Engineering Undergraduate students at Queen's University. None of the enclosed work should be used for full design.

Our signature below attests that this submission is our Original Work

Following professional engineering practice, we bear the burden of proof for original work. We have read the Policy on Academic Integrity posted on the Civil Engineering departmental website

(https://engineering.queensu.ca/policy/academic-integrity) and confirm that this work is in accordance with the Policy.

Signatures	Name	Student Number	Date
	Maren Campbell	20101186	March 24, 2023
	Hannah Kruizinga	20100212	March 24, 2023
	Ethan McMurchy	20169377	March 24, 2023
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Executive Summary

Queen's Facilities is looking to determine the feasibility of installing solar panels on campus buildings for electricity cost reduction and environmental benefits. An assessment for installing solar panels on the campus was completed in 2010 and proved that the project was not feasible. The project includes determining which campus buildings would be feasible for solar panels installation while considering the financial, environmental, structural, historic, and aesthetic aspects. Stakeholders for the project include Queen's Facilities, staff and students, local businesses, the City of Kingston, the environment, and Group T. Constraints on the project include the project timeline of eight months, group members' experience, and limits of the buildings on which the solar panels can be implemented. Specifications, guidelines, and codes from Natural Resources Canada, Canadian Standards Association, National Building Codes of Canada, Ontario Building Code, Queen's University building design standards, and Electrical Safety Authority have been outlined.

A preliminary building screening outlined 16 buildings that would be used within the study. Buildings were screened based on if there is a sloped heritage roof, significant shading, currently under construction, too much equipment clutter on the roof, and if the roof was set to be replaced within the project's lifespan of 15-years. Next, a roof capacity feasibility assessment was set up to evaluate the live, dead, snow, and wind loads. Based on parameters of cost, weight, efficiency, and lifespan, monocrystalline panels were deemed the best option when compared to polycrystalline and thin film panels. It was recommended to purchase monocrystalline solar panels from Canadian Solar based on parameters of weight, efficiency, and wattage. The ballast attachment was evaluated to be the best mounting system based on set-up, cost, weight, and ease of maintenance/movement when compared to an attachment installation and foundation system. It was recommended to purchase the Renusol CS60 Ballast Mount from Solar Electric Supply Inc.

Further design options were included to accommodate buildings with a low, mid-range, or high roof capacity as roof capacities were not available from the client. The first option included a lighter copper indium gallium selenide cell thin-film solar panel. A rooftop would need to have a capacity greater than 5.67 kN per panel, and these cells would produce 267.15 kWh per year. The second option would use the monocrystalline panels as recommended. They would require a roof capacity greater than 6.51 kN per panel and would produce an annual energy output of 287.52 kWh per panel. The third option would use the same monocrystalline panels as the second option and be for buildings with a larger loading capacity as more panels would be placed. It was concluded that the project would cost an estimated

$2,804,000 for the 16 buildings selected. Based on the three design solutions, solar panels would produce $413 to $444 per panel in a 15-year lifespan, requiring 6,314 to 6,795 panels to break even within a 15-year payback period. A maximum of 6,656 solar panels can be placed within a conservative roof area. Further analysis of the placement would need to be done to deem this project feasible. It is estimated that implementing solar panels will reduce a total of 8,020.5 to 8,632.8 tonnes of CO2e depending on the chosen capacity per solar panel. Options for decommissioning this project include selling the panels for a significant portion of their initial value or recycling 90% by mass, with further research needed.

Adding solar panels to Queen's University's campus roofs allows for the opportunity to innovate. This can be done by adding small yew planters to hide the solar panels and having 'Green Rooms' in each selected building powered by the solar panels' energy. It is estimated that an individual planter would cost $307.28 and add a dead load of 0.81 kPa for an area of 2 m wide by 1 m in depth. The 'Green Room' would include repainting the rooms green and posting a plaque with information. This would cost $500 to $3000 depending on the size of the room, and costs would range for posted material based on Queen's Facilities decision on quality and quantity.

Climate change is affected by the project because solar panels have a positive impact on reducing carbon emissions. Implications of climate change on the project are increased sunlight and a higher risk for damage as it becomes warmer, wetter, and stormier. Safety guidelines to address potential hazards, financial risks, and potential life loss have been outlined.

The report will need updating in the future due to technology changes in solar panels and their attachment methods, financial inflation, and changes in weather due to climate change. Appendices in the report include a work plan, a complete list of buildings, and detailed calculations. Additional excel worksheets are attached in a separate file.

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1.0 Introduction

1.1 Project Details

Solar panels, known as photovoltaic (PV) cells, collect and convert solar radiation from sunlight into electrical energy (US Department of Energy 2022a). They are a renewable form of energy production and are an option when considering reducing reliance on fossil fuels. A complete solar panel system is produced when many solar panels are connected to the electrical grid and the energy can be used by connected buildings. Solar panels are modular and can be arranged in many ways to fit specific roof dimensions and capacities (US Department of Energy 2022b). Queen's Facilities is interested in the implementation of solar technology on Queen's University's buildings to reduce the reliance on fossil fuels and reduce energy costs on campus.

Queen's University is located in Kingston, Ontario, is one of Canada's oldest institutions, and is a contemporary area for academic research (Queen's University 2022a). Located off the northeastern side of Lake Ontario, the university seeks to grow in practices to become carbon neutral by 2040 through its development of the Queen's University's Climate Action Plan (CAP) (Queen's University 2022b).

Site maps of Queen's University's main campus and west campus are shown in Figure 1, Figure 2, and Figure 3. All images were taken from Google Earth.

Figure 1 Key map highlighting Queen's University across Kingston (Google Earth 2022)

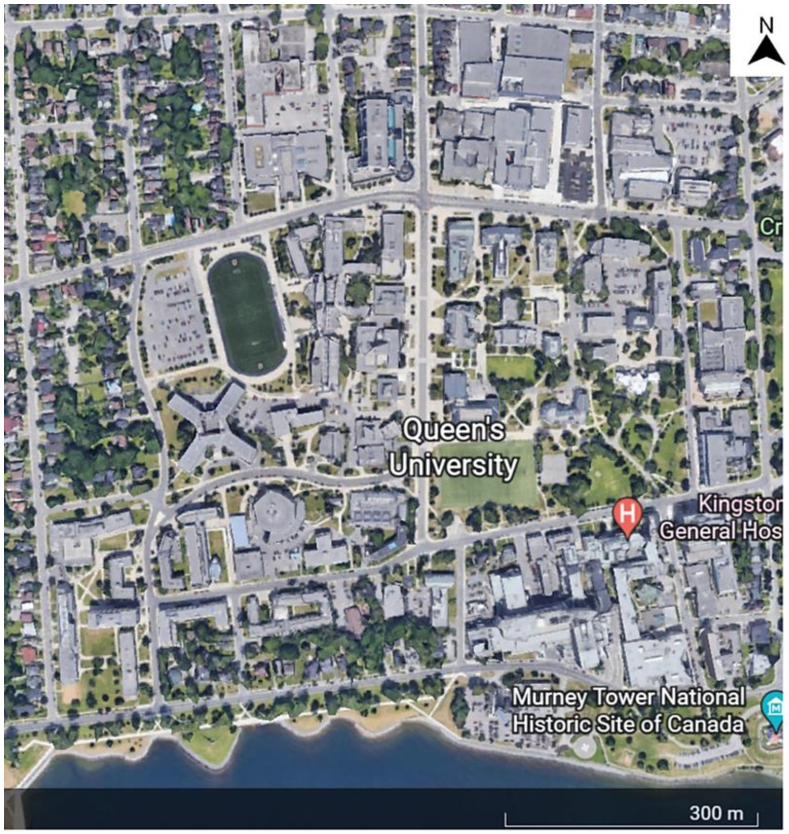

Figure 2 Queen's University main campus (Google Earth 2022)

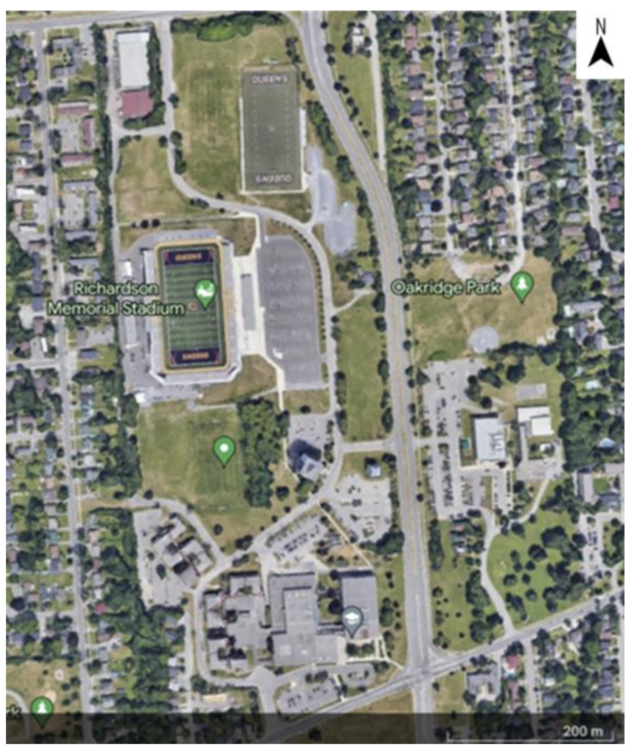

Figure 3 Queen's University west campus (Google Earth 2022)

1.2 Project Definition

Group T will work with Queen's Facilities to determine the installation feasibility of solar panels on campus buildings for reduction of fossil fuel use and electricity cost. The project includes determining which campus buildings would be feasible for solar panels installation while considering financial, environmental, structural, historic, and aesthetic aspects. Buildings will need to be reviewed and analyzed in terms of snow, wind, and weight loads to determine if they have acceptable roof capacity. Group T will develop a financial model with associated costs and develop an estimation of the rate of return for the solar project.

1.3 Project Scope

1.3.1 Overall Scope

The overall scope of the project is to determine the roof capacities and implementation possibilities of solar panels on Queen's University buildings. Objectives of this study corelate with Queen's Facilities' goal of being solar panel ready for current and future buildings. A further breakdown of the project includes four subsections: structural assessment, implementation options, financial breakdown, and environmental benefits as shown in Figure 4.

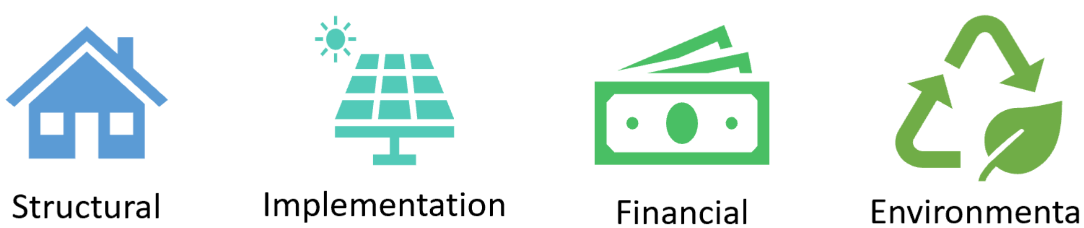

Figure 4 Visualization of the project's four subsections

1.3.2 Structural Scope

An initial building screening based on the historical distinction designation, and if the roof is shaded, steep, or being replaced in the project's lifespan of 15-years will be included. Structural assessments for the selected buildings will include snow, wind, dead, live, and combined loads. The report will not go into detail about how solar panels will affect the roof water drainage system due to the project's time constraints. A thorough structural analysis for each building will not be completed as roof capacities were not available.

1.3.3 Implementation Scope

An evaluation of the solar panel types and attachment options for the existing rooftops will be included in the scope. Kingston's climate and maximum electricity capacity of the panel type will be considered. The implementation design will be decided upon with an evaluation matrix and will include financial, environmental, and energy efficiency categories. How the electricity will be stored is not within the project scope.

1.3.4 Financial Scope

The financial scope will develop a cost breakdown of all aspects related to procuring, implementing, and maintaining the panels. It will include projections of the cost savings from the panels and a rate of return for the project. A time frame of 15-years will be used to determine the rate of return of the project and if it is financially feasible. An estimated future electricity production based on the energy produced from historical sun exposure will be developed. The average historical daily sun exposure will be used for inputs rather than multiple possibilities of the lowest or highest daily sun exposure due to the project's time constraint. Group T will not consider the change in demand for electricity as it is assumed the amount of electricity produced is below the needed energy. Group T will not develop a model for each building, but rather an overall model as the electricity will be assumed to be usable by all buildings. The project will focus on storing and using the electricity directly on campus due to time constraints rather than investigating the benefits of selling energy to the Ontario Energy Board.

1.3.5 Environmental Scope

The environmental scope includes the impact of solar technology on Queen's University's carbon footprint and investigate if the solar project will further the CAP (Queen's University 2022b). Calculations of the energy produced per year from the chosen solar panel type and the amount of solar panel needed will be completed. Investigation on wildlife and long-term impacts will be completed.

1.4 Stakeholders

The different stakeholders involved in this project include:

I. Queen's Facilities
II. Environment
III. Group T
IV. Staff and Students
V. Local Businesses/Community
VI. City of Kingston

The client, Queen's Facilities, is the primary stakeholder with a direct interest as it is their buildings that will be analyzed and evaluated. The buildings chosen will have to be adapted and maintained to accommodate the solar panels. The environment is a direct stakeholder as climate change is a growing issue and solar panels are an option to reduce carbon emissions. The changes to make large businesses such as a university more eco-friendly through reducing emissions would benefit the environment long-term. Group T has the highest direct interest as the solution and deliverable will reflect the skills acquired over their university careers and impact their academic success.

Staff and students have a tangential interest as these are the buildings they learn, work, and live in. Group T does not want to interfere with the daily lives of staff and students when installing solar panels. Local businesses all have a tangential interest as they rely partly on Queen's University students for additional customers. Owners would like individuals to choose Queen's University as their employment or post-secondary institution, so their business continues to have additional economic activity. Kingston residents who live near the campus have a tangential interest in the project because their lives will be impacted by the solar panel construction. This will impact their commute if streets are blocked by delivery or construction vehicles. Loud construction noises would affect the productivity of those on and around campus. The City of Kingston has a tangential interest in the project as a more environmental and economical solution for power would be important to the municipal government.

1.5 Constraints

1.5.1 Timeline

The first constraint is the project timeline of eight months. The group must be organized and efficient to produce a result that meets the client's expectations and complete assessments over the term as per the instructors' requests. Group T must follow schedules to complete this project efficiently. Another constraint is the experience of the group's members as the team is comprised of four fourth-year civil engineering students. This project will challenge the group to use their backgrounds to complete this project because no group member has experience in real-world solar design projects. Members all have experience working on school design projects in past courses and varying real-world experience.

1.5.2 Building Codes

A large constraint is both the Ontario Building Code (OBC) and the National Building Code of Canada (NBCC). The OBC takes precedence whereas the NBCC is used if there is a missing component. These outline technical provisions for the design and construction of new buildings, which include the addition of permanent objects to roofs, such as solar panels. These codes will determine and constrain the amount of load that can be placed on the roofs, the number of solar panels that can be placed, and therefore the amount of energy that can be produced. Queen's University has established building design standards that will constrain the design of the solar panel configuration on the roofs. These standards outline material use, electrical systems, and roofing guidelines that relate to solar panel installation (Queen's University Facilities 2022a). More information is outlined in 2.0 Specifications, Guidelines, Codes.

1.5.3 Building Limitations

Queen's University has many historical buildings that should be unaltered so they will not be eligible for solar panel installation. The eligible buildings will need to be structurally re-evaluated to determine if they can support solar panels. Considerations for the weight of the panels and snow loading will be calculated and evaluated. Site visits are a constraint as the rooftops of buildings on campus are restricted. The group will have to rely upon technical documents, drawings, and online sites such as Google Earth for roof information and photos. Lastly, roof size is a constraint because it limits the number of solar panels that can be placed, and energy produced as a result.

1.5.4 Solar Panel Limitations

The solar panels considered in this report have limitations that include the type of roofs being used and the installation process. The roofs that have been deemed eligible for this project are flat, resulting in the limitation of installation methods. Slanted roof installation methods are not needed as all buildings on campus that had slanted roofs were also heritage buildings, excluding them from the project for heritage protection.

1.6 Project Plan

Each member was given a subsection to lead as follows: Hannah Kruizinga was assigned Structural Lead, Ethan McMurchy was assigned Implementation Lead, Daniel Pogue was assigned Financial Lead, and Maren Campbell was assigned Environmental Lead. The planning documents for this project are shown in Appendix C – Work Plan and Group Dynamic and include key updates to the project. The project plan was redone to accurately reflect the work that needed to be completed and given a more appropriate timeline based on work to be completed.

1.7 Project Deliverables

Deliverables included in this report are a step-by-step assessment for future solar panel installation projects. The structural assessment includes a preliminary building selection flow chart and roof capacity feasibility for snow loading, wind loading, and load combinations. An excel template has been produced for future use for assessing structural capacities. The implementation section includes the evaluation of solar panel type and attachment options. Options for innovation additions to the project are included and discussed in terms of implementation steps, design choices, and cost. The financial assessment covers approximate costs for the project and an expected payback period based on estimated electricity produced. The environmental assessment includes carbon reduction totals for the project and how it will affect Queen's University CAP.

2.0 Specifications, Guidelines, Codes

2.1 Solar Panel Guidelines for Solar Panel Systems

Natural Resources Canada (NRC) has an extensive list of solar panel guidelines for solar systems (Natural Resources Canada 2013). These guidelines contain many design considerations and alterations for roof space, solar panel types, and mechanical and electrical room wall and floor space. All solar guidelines and codes mentioned have been tested and certified as per the Canadian Standards Association (CSA). A list of technical specifications that should be checked before the installation of solar panels on a roof is shown in Table 1.

Table 1 Natural Resources Canada technical specifications (Natural Resources Canada 2013), (Price and Smiley 2004)

Specification Number and Details	
1. On the Roof	
1.1	Builders should identify at least 3.7 m by 3.0 m of unobstructed area on the building plans (clear of chimneys, roof vents, skylights, gables, and other protrusions). The area should not be significantly shaded by building elements, surrounding buildings or mature trees at any time of the year.
1.2	Builders should ensure the roof area identified in specification 1.1 has an orientation ranging from east to west facing corresponding to azimuth angles of 90 degrees to 270 degrees from true north
1.3	Builders should ensure the roof area identified in specification 1.1 does not extend beyond the roof edges and is located above the wall line (away from overhang areas)

Specification Number and Details	
2. PV Conduit	
2.1	To prepare for Solar PV, one solar PV conduit of at least 2.5 cm in nominal diameter constructed of rigid or flexible metal conduit, rigid PVC conduit, liquid tight flexible conduit, or electrical metallic tubing (as per Section 12 of the Canadian Electrical Code Part 1 concerning “raceways”) should be installed. The conduit should be continuous from an accessible roof location to the designated wall space for the PV electrical hardware (continuous, as straight as possible; bends / elbows will be fine)
4. Termination of Conduits: Mechanical Room	
4.1M	Solar PV conduits must be properly sealed at the mechanical room penetration point and capped and sealed to maintain building fire ratings.
4.3M	There should be workspace allotted around the termination point of conduits in the mechanical room. For the solar PV conduits, 5 cm of vertical space between the termination point and any impeding element and 15.2 cm of horizontal space in one direction to allow future installers to access the conduit and snake wire through as required, will be sufficient
5. Mechanical and Electrical: Wall Space for Solar PV Hardware	
5.7	Wall space should be allocated in the mechanical room for the future installation of an expansion tank (if required) and pump(s) and/or solar PV system inverter, controls, and connection hardware: 91.4 cm by 91.4 cm will be suitable
6. Code Compliance	
6.1	Building, electrical, and plumbing work should be completed in compliance with the most current versions of the National Building Code of Canada, the Canadian Electrical Code, Part 1, and the National Plumbing Code of Canada including provincial/municipal amendments where applicable

Builders should refer to the NBCC and the OBC to ensure the roof can support added loads from solar panels. The installer must choose a solar system that meets all building code conditions. The solar panel installer may have to offer added reinforcement to transport loads to different parts of the roof depending on the structural capacity. Systems mounted should be no less than 45 degrees to remove snow naturally as Kingston has large snowfalls in winter months.

2.2 Queen's University Building Design Standards

Queen's University has building design standards to assist contractors during the planning, design, and construction stages of the University's preservation, renovations, and new capital projects. These standards are not intended for use as a specification, but instead can be combined with codes and regulations from the NBCC and OBC. The design standards represent the minimum acceptable standard, meaning if there are more strict requirements from another code, those must be used.

2.3 Electrical Standards

The NRC suggests electrical rooms should include cooling and not be in the lowest point of the building (Natural Resources Canada 2013). These standards state that mechanical services or water services should not run through electrical rooms unless they are directly serving the electrical room (Queen's University Facilities 2022b). Wiring should be installed in conduit to allow for changes, such as increasing the wire gauge and adding circuits. The main electrical distribution should be solidly grounded as isolated grounding systems are discouraged. The Queen's University campus power grid contains a 4,160-volt distribution system, so at least a 15,000-volt insulated phase conductor with an insulated bonding conductor is needed. Queen's University buildings requires a unit substation fed at 4,160 volts from the current campus grid. New buildings should have feeds constructed in loops within the current campus grid to ensure power reliability. There will be network switches, and cross connections of the feed-through network switches to keep flexibility. If the solar panels installed do not require high voltage levels, they can be connected to the Queen's University's campus grid. If the levels are too high for each building's capacity, they must be connected to an outside grid.

Electrical permits and inspections from the Electrical Safety Authority (ESA) may be required when electrical connections are part of the solar panel system (Norfolk County 2013). The electrical panel should be in an accessible location in order to connect the PV array to the electrical system (Lisell et al. 2009). To account for the PV and electrical grid energy, the electrical panel must have a substantial amperage rating. The total of the ratings for over current protection devices in all circuits distributing power cannot exceed 120% of the busbar rating. Once the electrical panel for the building and solar panels are chosen, it must be confirmed that the sum of the PV system energy and grid energy is less than 120% of the panel rating. The electrical panel must have room for a PV circuit breaker and should have an inverter and balance of system component next to it. For a solar panel system, there should be a conduit leading from the PV array to the many electrical components. To ensure the building is ready for solar panels, a metallic conduit has to run from the PV combiner box on the roof, to the balance of system components next to the electrical panel. With a grid-connected PV system, the ESA must examine the system before it is turned on (Norfolk County 2013).

3.0 Structural Assessment

3.1 Preliminary Building Screening

An updated building list was developed based on Queen's University's 3D campus map in Appendix A – Complete List of Buildings(Queen's University 2022c). Buildings were excluded if they have a sloped heritage roof or significant shading, if they are currently under construction, if there is equipment clutter, or if the roof is set to be replaced within the project's lifespan of 15-years.

The client provided a list of buildings that would be given historical distinction or have a sloped heritage roof. An example of these conditions is Ontario Hall, as shown in Figure 5, as it was built in 1903 and is one of Queen's University's most recognizable buildings (Queen's University 2022d).

Figure 5 Ontario Hall, Queen's University (Queen's University 2022d)

A site visit to the outside of each building was used to determine if there would be significant shading on the rooftops based on proximity to other buildings, to see if buildings were under construction, and to confirm the list of sloped heritage buildings. Google Earth was used to determine if a rooftop has too much equipment clutter. Information on when buildings' rooftops were planned to be renovated or replaced was included in the documents given by the client.

A flow chart was developed as shown in Figure 6 to illustrate the building screening process and will be useful as a standard procedure when assessing buildings in the future. Appendix A – Complete List of Buildings – Complete List of Buildings includes a compiled list of campus buildings and reasons for not selecting a solar panel analysis where applicable.

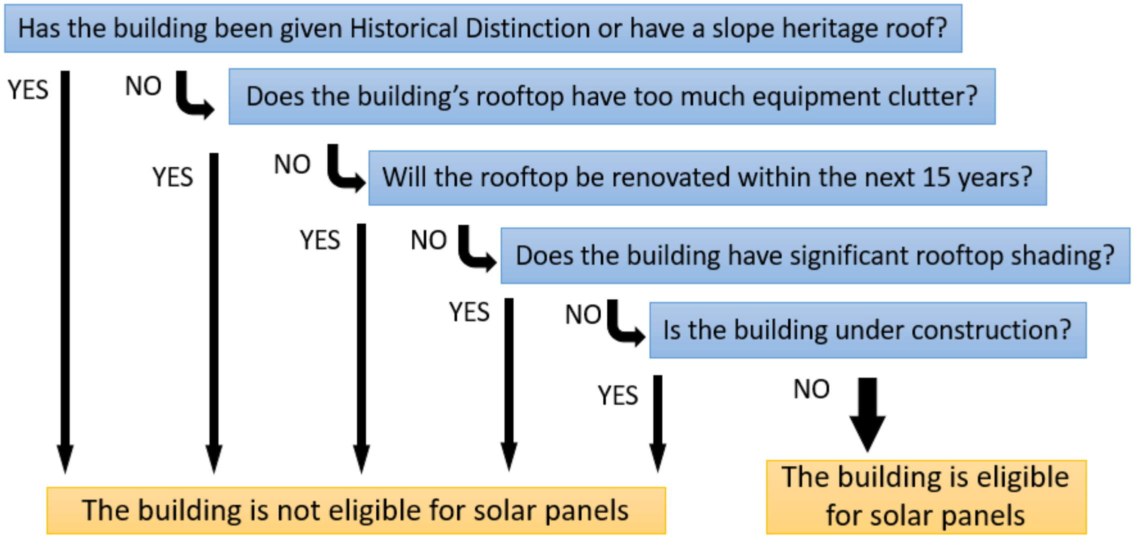

Figure 6 Preliminary screening for Queen's University campus buildings for solar panel selection

An identification map of all buildings that passed the initial screening are shown in Figure 7.

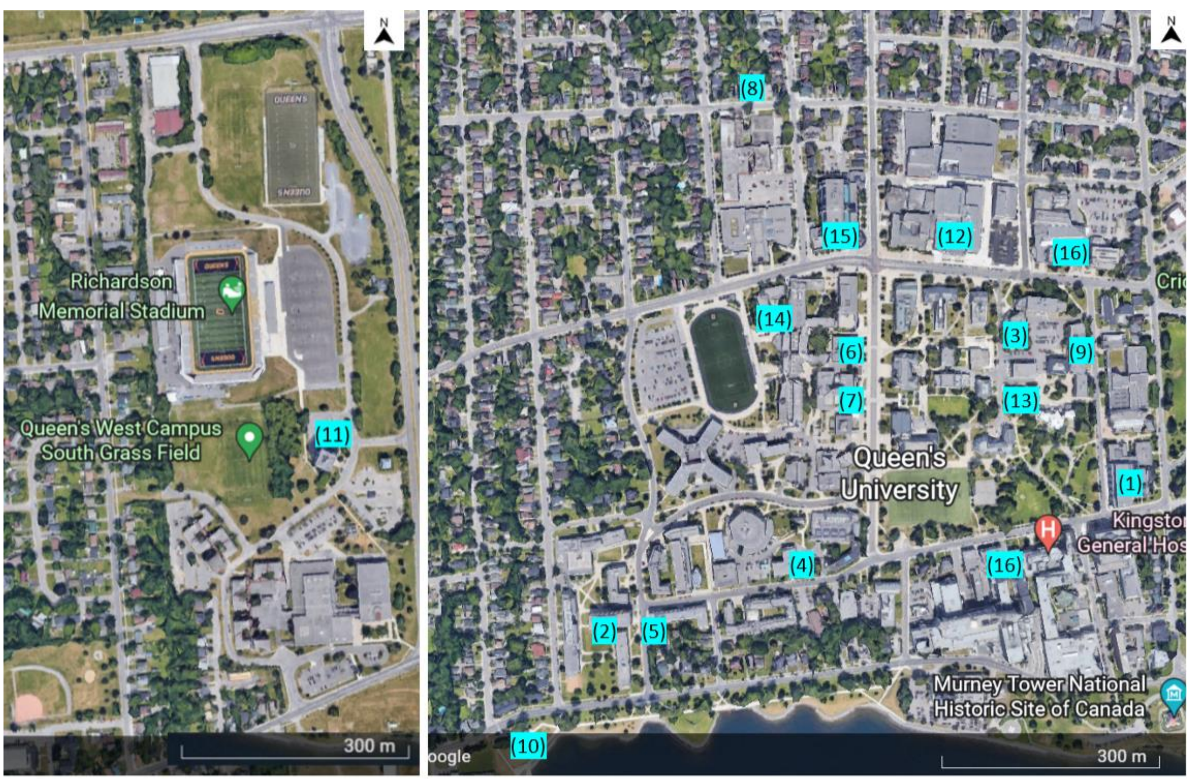

Figure 7 Site map highlighting initial buildings selection

A legend for Figure 7 is shown as Table 2 that corresponds a building to the number.

Table 2 Legend for building numbers for Figure 7

Number	Queen's University Building
1	Biosciences Complex
2	Brant House
3	Bruce Wing
4	Chown Hall
5	David C. Smith House
6	Dunning Hall
7	Ellis Hall
8	Harkness International Hall
9	Humphrey Hall
10	Isabel Bader Centre for the Performing Arts
11	John Orr Tower
12	Mitchell Hall
13	Old Medical Building
14	Robert Sutherland Hall
15	Stauffer Library
16	Walter Light Hall

3.2 Roof Capacity Feasibility

The structural components that must be evaluated include the live, dead, snow, and wind loads. The live loads and rooftop sizes were gathered from documents provided by the client. The standard minimum live load for a roof from the OBC was used for buildings where documents were not provided. Rooftop sizes for the majority of the selected buildings were found in the documents provided by the client. Rooftop sizes for Brant House, David C. Smith House, Isabel Bader Centre, Mitchell Hall, and Robert Sutherland Hall were measured using Google Earth. Dead loads were obtained from physical files from the client, while the OBC was used for builds which documents were not provided. A flow chart to determine the feasibility of the roof capacity is shown in Figure 8.

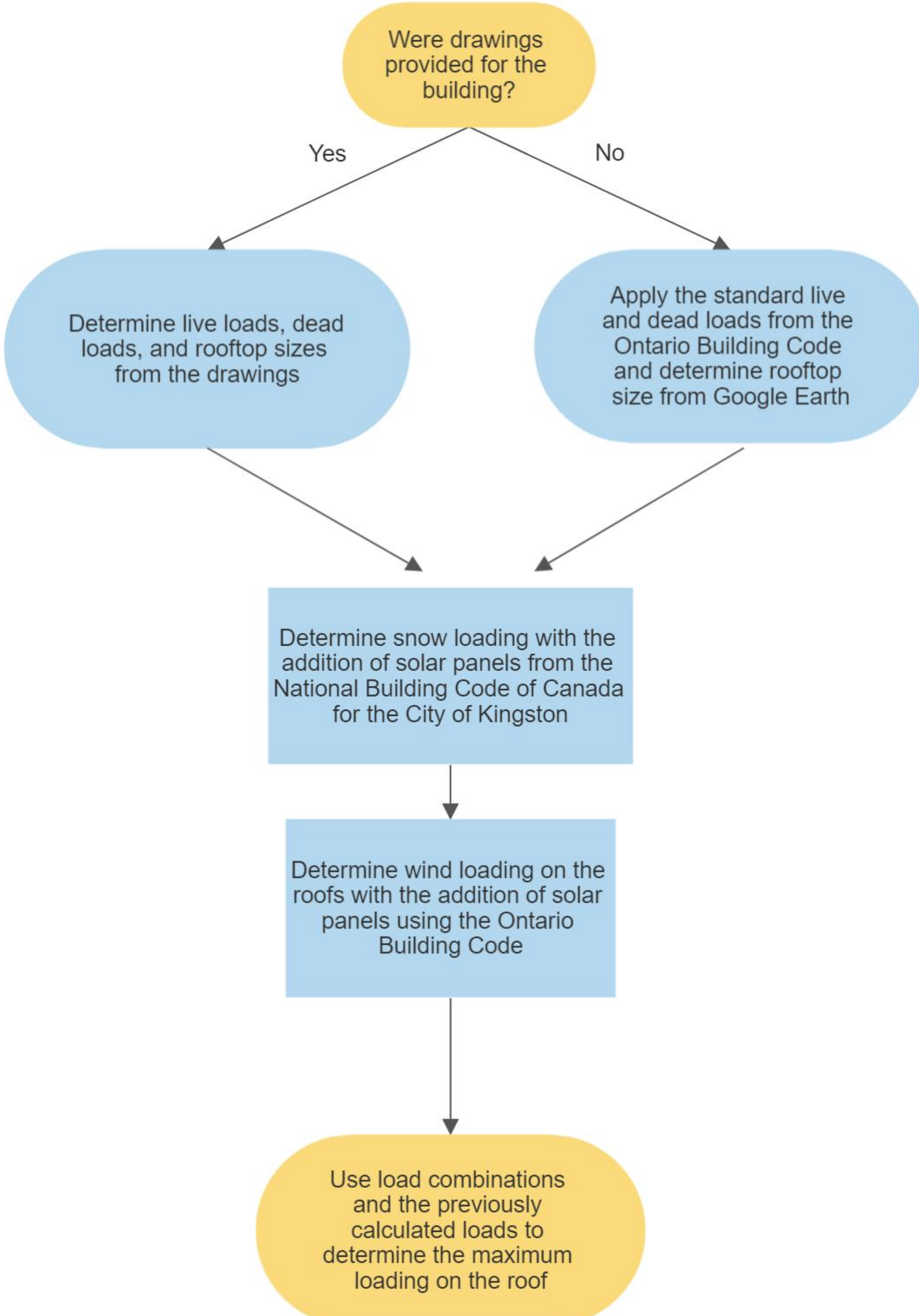

Figure 8 Loading decision flow chart

3.2.1 Roof Capacities

A list of the buildings, their rooftop size, and their minimum rooftop live loads from the preliminary building screening are included in Table 3. The minimum rooftop live load is a conservative value of the live load that the roof can handle without failing. The rooftop dead load is the current load sitting on each roof.

Table 3 Summary of selected buildings with rooftop live and dead load capacity

Queen's University Buildings	Rooftop Size (m^2)	Minimum Rooftop Live Load (kPa)	Rooftop Dead Load (kPa)
Biosciences Complex	2063	1.90	1.0
Brant House	1495	1.0	1.0
Bruce Wing	375	4.79	1.0
Chown Hall	636	1.0	1.0
David C. Smith House	1925	1.0	3.0
Dunning Hall	574	2.39	1.0
Ellis Hall	741	1.92	1.0
Harkness Hall	252	1.44	1.0
Humphrey Hall	513	7.18, 1.92 above penthouse	1.0
Isabel Bader Centre for the Performing Arts	3217	1.0	1.0
John Orr Tower	731	1.92	1.0
Mitchell Hall	6149	1.0	1.85
Old Medical Building	178	1.0	1.0
Robert Sutherland Hall	1023	1.76	1.44
Stauffer Library	2134	2.0	1.0
Walter Light Hall	626	1.76	3.0

Live loads are produced from temporary objects or people in or on the building. This includes maintenance by workers, and live loads produced during the life of the structure by movable objects such as planters and by people (Government of Ontario 2014). The minimum rooftop live load is the load that a roof can handle in addition to the dead load (Government of Ontario 2014). A typical roof is expected to hold a live load of 0.96 kPa. According to the OBC, the minimum specified live load for a roof is 1.0 kPa (Canadian Commission on Building and Fire Codes 2022). This was assumed to be the minimum rooftop live load in the buildings where information or drawings will not be obtained. The rest of the rooftop live loads were found in the documents provided by the client.

A dead load on a roof is defined as the weight of the roof structure itself, along with any permanently attached materials or structures on the roof. The dead load of an average asphalt-shingled, wood-framed roof is 0.72 kPa. As the roof material used becomes heavier, the dead load increases and reduces the amount of additional loading that can be applied. For example, clay-tiled roofs can have dead loads of up to 1.29 kPa.

3.2.2 Snow Loading

Kingston receives snow and ice each winter, so it is an important structural component that must be incorporated. The snow load is defined by the OBC as the load on a building surface subject to snow accumulation and can be found using Equation 1 (Government of Ontario 2014). The roofs are all flat, so snow-loading calculations have the same process for all of the buildings. The equation considers several factors including the importance factor for snow loads (I_s), 1-in-50 year ground snow load (S_s), basic roof snow load factor (C_b), wind exposure factor (C_w), slope factor (C_s), shape factor (C_a), and the 1-in-50 year associated rain load (S_r) (Government of Ontario 2014). The wind exposure factor, slope factor, and shape factor are all impacted by the addition of solar panels. The snow load can be calculated using Equation 1 and a summary of the values used are shown in Table 4.

Equation 1

$$S = I_s[S_s(C_b C_w C_s C_a) + S_r]$$

Table 4 Summary of values used to calculate snow load

I_s	S_s (kPa)	C_b	C_w	C_s	C_a	S_r (kPa)
0.9	2.1	0.8	1.0	1.0	1.25	0.4

The wind exposure factor accounts for the degree to which the roof is exposed to the wind. Roofs with no obstructions, and therefore more wind exposure accumulate less snow than roofs with obstructions. As solar panels will add obstructions to the roofs, a wind exposure reduction factor cannot be used as snow will accumulate and increase the roof load. The slope factor accounts for the roof slope which are not used in this study. Roofs with a slope of 30 degrees or more tend to accumulate less snow and have less roof loading, and this reduction factor takes that into account (Government of Ontario 2014). The shape factor includes roof obstructions in the value as the roof shape impacts where snow settles. The addition of solar panels increases the snow's ability to be stuck on the roof in crevices and around obstructions. The solar panels will change the shape of the snow drift on the roof and may increase drifting, adding significant additional weight to the roof. A value of 1.25 is used because there is a slight load increase on the roofs with solar panels (Government of Ontario 2014).

The importance factor is 0.9 for all Queen's buildings that are being considered, as they are normal importance buildings (Government of Ontario 2014). Normal importance means that buildings are not critical, post-disaster buildings such as hospitals. The 1-in-50-year ground snow load in Kingston is 2.1 kPa, and the 1-in-50 year associated rain load is 0.4 kPa as determined by the NBCC (Canadian Commission on Building and Fire Codes 2022). The basic snow load factor has a value of 0.8 determined by the OBC. The roof slope factor is determined to be 1.0 because the solar panels will be an obstruction on the roof and cause snow accumulation. The shape factor is 1.25, and the wind exposure factor was determined to be 1.0 (Government of Ontario 2014). The shape factor was taken to be the maximum value. Using Equation 1, the load due to snow is 2.25 kPa which must be considered in the design. This can then be combined with the live, dead, and wind loads to determine the full roof loading with solar panels.

3.2.3 Wind Loading

The impact that solar panels have on buildings' wind loading must be considered in the structural analysis when determining how many panels can be placed. The additional surface area from the solar panels allows the wind to act on a larger area and increases the wind loading on the building. The OBC defines wind loading as the external pressure on a surface of a building and can be calculated using Equation 2. A summary of the values used are shown in Table 5. (Government of Ontario 2014). The equation considers several factors including the importance factor for wind load (I_w), reference velocity pressure (q), exposure factor (C_e), topographic factor (C_t), gust effect factor (C_g), and external pressure coefficient (C_p).

Equation 2

$$p = I_w q C_e C_t C_g C_p$$

Table 5 Summary of values used to calculate wind load

I_w	q (kPa)	C_e	C_t	C_g	C_p
0.75	0.47	0.9	1.0	2.5	1.0

The importance factor for wind loading for all Queen's buildings that are being considered is 0.75, as they have normal importance (Government of Ontario 2014). The reference velocity pressure is based on a 1-in-50-year wind event and in Kingston is 0.47 kPa. The exposure factor is 0.9 as determined by the OBC. The topographic factor is 1.0 due to little topographic changes surrounding the buildings. The gust effect factor and external pressure coefficient are both impacted by adding solar panels. The gust effect factor is increased from 2.0 to 2.5 as a result. The external pressure coefficient is 1.0 due to the solar panels adding additional obstructions and more wind exposure (Government of Ontario 2014). Using Equation 2, the wind load is 0.79 kPa which must be factored into the structural analysis. This is a simplifying assumption that will be made to have a conservative specified wind load without completing a full structural analysis of each building being considered.

3.2.4 Load Combinations

Load combinations are completed by combining loads with safety factors to ensure a structure has the adequate structural capacity (Dominik 2022). Load combinations include snow, wind, dead, and live loads to find the maximum force a building is subjected to. This technical approach minimizes the risks that are associated with estimated loads and capacities. Load combinations consist of a characteristic load value, a partial factor, and a factor for a combination of variable loads. The structural members of the roof are designed for buckling, bending, and shear forces.

The load combinations are shown in Table 6. Case 5 does not apply to Kingston, as earthquake loading will not be critical. Each of the load combinations will be calculated to determine the maximum loading the roof will experience with the addition of solar panels (Canadian Commission on Building and Fire Codes 2022). This will need further investigation for future reports.

Table 6 Load combination cases (Canadian Commission on Building and Fire Codes 2022)

Case	Principal Loads	Companion Loads
1	1.4D	-
2	(1.25D or 0.9D) +1.5 L	1.0S or 0.4W
3	(1.25D or 0.9D) +1.5 S	1.0L or 0.4W
4	(1.25D or 0.9D) +1.4 W	0.5L or 0.5S
5	1.0D + 1.0 E	0.5L + 0.25S

4.0 Implementation

4.1 Solar Panel Types

The different types of solar panels are classified as monocrystalline, polycrystalline, and thin-film based on how the PV cells are made as shown in Figure 9. Except for thin-film panels, solar panels have solar cells made from silicon wafers. Thin-film panels are made up of different materials which will be explained in depth below. Once a type of solar panel is decided upon, a model can be chosen and implemented as the final design choice (Svarc 2020).

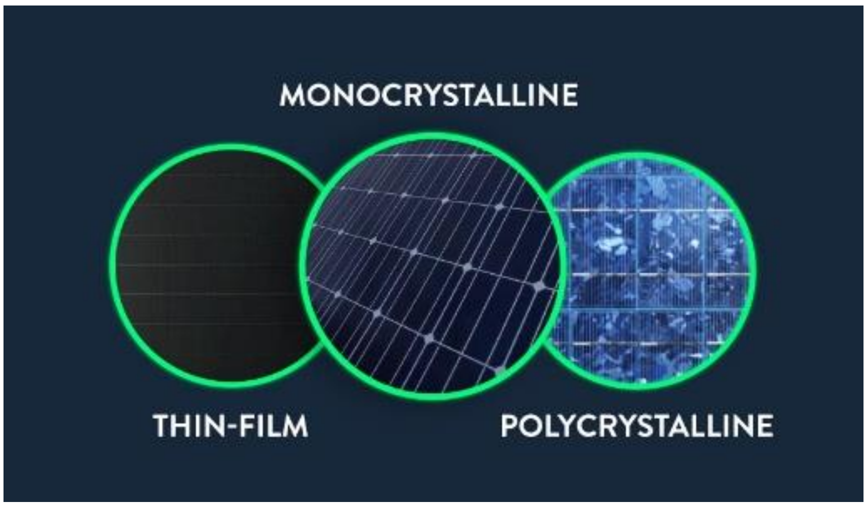

Figure 9 Solar panel types (Deege Solar 2021)

4.1.1 Monocrystalline Solar Panels

Monocrystalline solar panels are PV cells made from a single pure silicon crystal that are cut into wafers. These types of cells can be identified from their dark black colour and are a more expensive solar panel option. The higher cost is due to the solar panel being produced from one silicon crystal which wastes material during production. Passivated Emitter and Rear Cell (PERC) solar cells are an upgraded version of monocrystalline panels (Lutz 2022). They use a passivation layer that reflects light back into the cells which increases the amount of solar energy the cells absorb. It allows light of larger wavelength to be absorbed which lets more light be reflected and absorbed, resulting in more energy production (Lutz 2022). While it does absorb and produce more energy, it costs more to manufacture as it is a new technology so will not be considered further.

4.1.2 Polycrystalline Solar Panels

Polycrystalline solar panels are made up of different silicon crystals that have been melted together and formed by a mould into a panel (Svarc 2020). These panels typically have a traditional blue-silver mixture colour (Lutz 2022). Cost is reduced from the use of many different silicon crystals fused together, as there is less waste; however, the energy conversion efficiency and heat tolerance are lower due to the fusion of the crystals and the lower silicon purity.

4.1.3 Thin-Film Solar Panels

Thin-film panels are solar panels that are small and flexible. They do not require a frame backing which makes them easier to install and configure. The main difference between this type of panel and the previously mentioned panel types is the material of the cells. Thin-film panels are made up of different materials such as copper indium gallium selenide, cadmium telluride, and amorphous silicon, whereas the other solar panels are made of silicon. This is the cheapest but least effective type of solar panel due to the different materials (Lutz 2022).

4.1.4 Solar Panel Type Considerations

The types of solar panels will be weighted and evaluated based on their advantages and disadvantages as summarized in Table 7 to determine the best choice of panel.

Table 7 Summary of solar panel type, cost, average cost per watt, efficiency, power capacity, and durability (This Old House 2022), (Lutz 2022)

Type	Cost	Average Cost per Watt	Efficiency	Durability	Lifespan (years)
Monocrystalline	Highest Production Cost	$1.00 - $1.50	15%-20%+	Strongest	25-30
Polycrystalline	Balanced	$0.70 - $1.50	15%-17%	Less durable than monocrystalline	25
Thin-Film	Lowest Production Cost	$0.43 - $0.70	6%-15%	Weak due to being thin and flexible	10-20

The monocrystalline panels have the compromise of being the most expensive to make, but the most effective and efficient panel design. These panels are extremely durable and have a long life span of 25-30 years. Polycrystalline solar panels are considered the middle choice between the three options. The initial cost is lower than the monocrystalline panels due to the lower production cost; however, due to the method of production, polycrystalline panels are not as efficient and cannot handle hot temperatures. Polycrystalline panels also have a shorter lifespan when compared to monocrystalline panels. Lastly, thin-film panels are the least effective of the three types of panels, take up the most amount of space, and have the lowest life span; however, thin-film panels are significantly cheaper than the other two options and are flexible, allowing the panels to be arranged in unique ways and accommodate different types of roofs. Moving forward, this information will be considered to decide which panel type to use for the final design.

4.1.5 Solar Panel Type Evaluation

To determine the best type of solar panel, an evaluation matrix was developed as shown in Table 8. The evaluation matrix is scored on the categories of cost, weight, efficiency, and lifespan. The parameter of average cost per watt was not included as its own category as this is already contained in the cost evaluation. Likewise, durability was not included as it was incorporated under the lifespan category. Each category was given a multiplier based on its significance and impact on the project, and each panel type was given a value from 1 to 3 based on how it ranked against the other options. The final score is obtained by multiplying the rank by the multiplier and totalling the categories. It was decided to rank the panel types against each other rather than develop specific criteria for what each rank would be worth. As well, this gives the client the opportunity to change the multipliers in the future if one category becomes more important or governs the process.

The weight category was given the highest multiplier of 4 as the solar panel capacity is governed by it. The efficiency of the solar panels was given a multiplier of 3 as more solar energy converted to electricity will be beneficial. The cost was given a multiplier of 2 as it is a direct interest of the client; however, it is not as important given that the project relies on the buildings having enough structural capacity and the project being feasible in terms of potential electricity produced. The final category is lifespan, and this was given a multiplier of 1 as many solar panels have relatively similar lifespans. Table 8 is an evaluation matrix which will be used to determine the best panel to be used going forward.

Table 8 Evaluation matrix for type of solar panel

	Multiplier	Monocrystalline	Polycrystalline	Thin film
Cost	2	3	2	1
Weight	4	1	2	3
Efficiency	3	3	2	1
Lifespan	1	3	2	1
Total		**22**	**20**	**18**

From Table 8, monocrystalline panels have a total score of 22, polycrystalline panels have a total score of 20, and thin film panels have a total score of 18. Monocrystalline panels were determined to be the best due to their higher efficiency and longer lifespan with a compromise of the initial higher cost and heavier weight. The scores were very similar because they were ranked against each other rather than given a set parameter. As such, it is possible to move forward considering monocrystalline panels as the main panel option.

4.1.6 Solar Panel Recommendation

Monocrystalline panel options will be selected from different companies to be evaluated. A website called Solar Electric Supply Inc. was used to assist with choosing the correct panel. It is one of the main and most popular providers of solar panels (Solar Electric Supply, Inc. 2023a). Certain companies have grouped their solar panels and mounts into systems so that a potential buyer can see the total system as well as the square footage it can cover (Solar Electric Supply, Inc. 2023a).

Three companies that produce similar monocrystalline panels include REC, Canadian Solar, and Silfab. The REC panel for comparison will be the REC310NPBLK2 310W REC N-Peak All-Black Solar Panel. The Canadian Solar panel will be the Canadian Solar HiDM CS1H-340MS 340W, and the Silfab panel will be the Silfab Solar SLA-M 310 310W All-Black Solar Panel. Table 9 compares the three options based on weight, efficiency, and wattage.

Table 9 Summary of three companies' monocrystalline solar panel system (Solar Electric Supply, Inc. 2023b), (Solar Electric Supply, Inc. 2023c), (Solar Electric Supply, Inc. 2023d)

Product:	Weight (kg)	Efficiency	Watts
REC	18.0	18.6%	310 W
Canadian Solar	19.2	20.16%	340 W
Silfab	19.0	19.0%	310 W

From Table 9, the three main panel considerations are weight, efficiency, and wattage. These considerations are the most important when choosing the panel model as each company produces a solar panel that has similar lifespans and durability. Therefore, these panel aspects were not included as there is little difference between them. This table is not an evaluation matrix as the solar panel type has already been established but shows the different values of each parameter from all of the considered companies. From Table 9, it is shown that the product from REC has the lowest weight but also the lowest efficiency and wattage production. The Silfab panel has a higher weight but also a higher efficiency than REC. Lastly, Canadian Solar has the highest weight but also the highest efficiency and wattage production. From these values, the best option was chosen to be the Canadian Solar panel. It produces more watts and has better efficiency but is slightly heavier. Therefore, this was chosen as energy production is an important aspect of this project in order to be feasible. It is recommended that the Canadian Solar HiDM CS1H-340MS 340W panel be used as the monocrystalline option for the buildings that have been deemed feasible. The full statistics of the Canadian Solar panel are summarized in Table 10, and the panel is shown in Figure 10.

Figure 10 Canadian Solar monocrystalline panel (Volts Energies 2023)

Table 10 Summary of Canadian Solar product (Solar Electric Supply, Inc. 2023c)

CSI Model Number	CS1H-340MS
STC Rating	340.00 Watts
PTC Rating	317.6
Efficiency	20.16%
Open Circuit Voltage	43.7 V
Short Circuit Voltage	9.81 A
Frame Colour	Black
Origin	USA/Korea
Power tolerance	0/+5 Watts
Weight	19.2 kg
Length	66.9 inches
Width	39.1 inches
Height	1.38 inches

4.2 Attachment Options

To properly secure the solar panels to the roofs across Queen's University's campus, a safe and effective mounting system is needed. Solar panels will be installed on flat roofs as determined in 3.0 Structural Assessment, where a flat roof is defined to have a slope of less than seven degrees for solar panels (Almerini 2022). The following sections outline three different installation methods and the mechanics required for them.

4.2.1 Attachment Installation

Attachment installation involves drilling the solar panels directly into the roof to ensure they are secured. It is one of the most expensive options for installing solar panels, and to ensure a watertight fit, it requires careful chemical anchoring for extra adhesion around the drilled hole and mounting system (Solar Electric Supply, Inc. 2023a). This type of installation method is semi-permanent as the mounts are drilled into the roof, and it is also more expensive as it requires a contractor to install. It also requires a survey of the roof to find the correct positions to place the attachments. This method involves different types of equipment for proper installation, such as a drill and chemicals for anchoring. This type of system is used when the roof has no parapet walls to reduce the wind speed and wind load and shown in Figure 11.

Figure 11 Attachment installation (Solar System 2022)

The benefits of this type of installation method include strength and reliability. This method can secure the panels very well, and they would not be at risk of movement due to outside forces. The drawbacks to this attachment type include that is difficult to move panels around or replace should the need arise. Additionally, this attachment requires skilled contactors to install them properly and without roof damage.

4.2.2 Foundation System

The foundation system method attaches the panels to concrete blocks that sit on the roof. This system is typically used on a flat roof with parapet walls surrounding them. The footings increase the height of the panels which addresses the issues of parapet wall shadows (Kim 2022). This method requires no drilling into the roof itself and is cost-efficient. This method is considered semi-permanent because once the blocks are laid out and the panels are drilled into them, those panels will not be able to freely move unless they are taken out of the blocks, or the blocks are placed in another position. As they are semi-permanent, it allows for the orientation of the panel to be changed depending on the time of year and the direction of the sun as shown in Figure 12 (Melink Corporation 2021).

Figure 12 Foundation system (Solar First n.d.)

Benefits of this method include ease of movement. It is easier to move than other attachment installation methods as the panels are only drilled into the blocks. Therefore, new blocks could be placed in different formations on the roof and the panels could then be transferred over. The drawbacks include that this can be time-consuming for the workers.

4.2.3 Ballast Method

The ballasted method is the fastest and easiest attachment method. Once the solar panels are placed on the roof, heavy material is then placed on top of the solar rack. The panel then lays on the rack with the ballast and is held in place using gravity and the weight of the heavy-duty material (Bellini 2021). The amount of ballast that can be used depends on the roof load limit. This method allows for the orientation to be changed depending on the season and direction of the sun with little cost or equipment needed. The panel must simply be shifted around or lifted by a team of people and placed in their new formation. This method is shown in Figure 13.

Figure 13 Ballast mounting method (IronRidge 2022)

Benefits of this type of attachment method include a simplified set up process and ease of movement and configuration; however, a drawback to this attachment style is ensuring that the ballast is properly weighted, and it also adds additional required loading capacity to the roof.

4.2.4 Attachment Considerations

When the solar panels are installed, it is important to ensure the panel is configured at an angle of at least 5-10 degrees to ensure no dust accumulates on the panel (EnergySage 2018). The panel should be oriented in the direction that would get the most sunlight per day. Further considerations should made to research if it is better to have the solar panels at a higher elevation or if dual tilt systems should be installed.

4.2.5 Attachment Evaluation

To determine the best type of attachment method, an evaluation matrix was developed as shown in Table 11. The evaluation matrix is scored on categories of set-up, cost, weight, and ease of maintenance/movement. Each category was given a multiplier based on the significance and impact on the project, and then each attachment type was given a score of 1 to 3 based on how it ranked against the other options. The final score is obtained by multiplying the rank by the multiplier and then totalling the categories. It was decided to rank the attachment types against each other rather than develop specific criteria for what a rank would be worth as each attachment type is unique. This approach gives the opportunity to change the multipliers in the future if one category becomes more important or governs the process. Ease of maintenance/movement of the attachment was given the highest multiplier of 4, as it is the most important to be able to move the panels depending on where the sun is during the year. It is also important to the client to have the solar panels be easily removed or moved out of the way if renovations need to be done to the roof. Weight was given a multiplier of 3 as the roof capacity will determine how many solar panels and attachments can be placed on each of the roofs. Cost was given a multiplier of 2 as it is a direct interest of the client; however, it is not as important given that the project relies on the buildings having enough loading capacity. Set-up was given the lowest multiplier of 1 as each set-up process is different and depends on the type of roof that it is on.

Table 11 Evaluation matrix for attachment method

	Multiplier	Drilled Attachment	Foundation Attachment	Ballast Attachment
Set-Up	1	1	3	2
Cost	2	2	3	1
Weight	3	3	1	2
Ease of Maintenance/Movement	4	1	2	3
Total		**18**	**20**	**22**

From Table 11, the ballast attachment scored a total of 22, foundation attachment scored a total of 20, and drilled attachment scored a total of 18. The ballasted mount was determined as the best option for its ease of maintenance/movement and being the middle option for weight and set-up. The trade-off for this option is the higher cost. The drilled attachment option was deemed the least desirable as it has a difficult set-up due to necessary holes drilled into the roof to secure the solar panels in place. This removes the ease of maintenance and movement as it would be very difficult to rearrange the panels due the permanence of the attachment style. The scores were very similar because they were ranked against each other rather than given set parameter.

4.2.6 Attachment Recommendation

Solar Electric Supply Inc. has a ballast mount that is sold as a system with the panels included. The flat roof mounting system, Renusol CS60 Ballast Mount has a universal base design to accommodate all PV modules. This is an ideal choice if the solar panels need replacement or a different model is used in the future (Solar Electric Supply, Inc. 2023e). The model can be purchased at either a 10-degree or 15-degree tilt angle and has a simple and safe set-up process. Key characteristics of this mount are summarized in Table 12 and an image of the mount option is shown in Figure 14.

Table 12 Summary of Solar Electric Supply Inc. Renusol CS60 Ballast Mount characteristics (Solar Electric Supply, Inc. 2023e)

Characteristic	Amount
Weight	8.6 kg
Roof Pitch Range	0-5 degrees
Material	100% Recycled HMWPE (High Molecular Weight Polyethylene)
Size Range	Up To 1685 mm Long and Up to 1020 mm Wide
Orientation	Landscape
Ventilation	Slots on top, bottom, and sides
Ballast Size	Optimized for 4"x 8" x 16" block but gravel bricks or pavers can be used

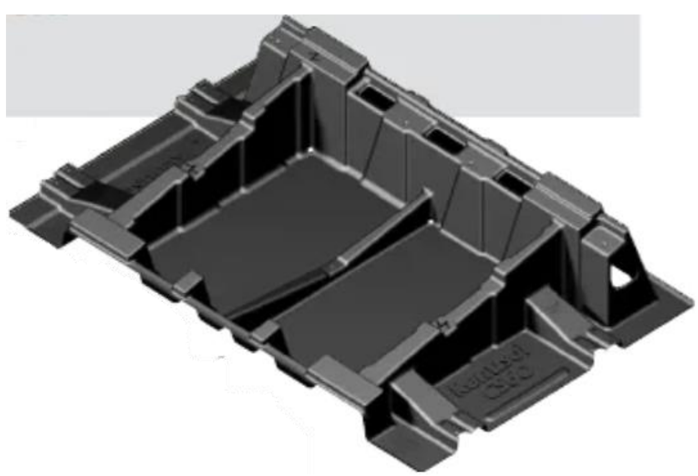

Figure 14 Renusol CS60 Ballast Mount (Solar Electric Supply, Inc. 2023e)

5.0 Design Solution

5.1 Limitations

Structural assessments must be completed to determine the feasibility of solar panels on Queen's University's roofs as they will add additional loading requirements. The buildings must have more loading capacity available than the total load of the solar panels and their attachments. The structural loading capacities of the roofs for the buildings initially chosen were not available, restricting the ability to calculate the number of allowable solar panels per roof. Three solar panel possibilities and an Excel model have been designed instead of determining solar panel configurations and total solar outputs for the specified building. A solar panel option, energy outputs, and required structural capacity have been determined for roofs with low, mid-range, and large structural roof capacities. This will allow for rapid determination of solar panel type and amount when a fully updated structural assessment has been completed for each building.

Some of the campus buildings designated to be used in this study are older and were developed with previous versions of the OBC (Queen's University Campus Planning and Development 1998). As such, they would likely not have the required loading capacity because the OBC has been revised over many years to include higher capacities for both wind and snow loading (Government of Ontario 2022). The updated codes do apply to any modifications done to a building such as adding solar panel systems. The expected loading would add an approximate 6.5 kN of weight and added forces per panel to a roof, which is a significant addition. The older building code allowed a snow load of 1.9 kPa and the current building code allowed for a snow load of 2.25 kPa, this indicates that the buildings that used the old building code would not have capacity for new structures (National Research Council Canada 2019).

Simplifying assumptions were made when calculating the loading of each solar panel which increases uncertainty in the load calculations. These were conservative assumptions that resulted in a larger loading value than would occur if a highly detailed structural analysis were completed. It appears that the solar panel loading is larger than would be handled by older campus buildings, which may not be the case if more in-depth calculations were done.

The structural roof capacity required for one panel is determined by using the dead load determined from the panel mass, and the previously determined wind, live, and snow loads and applying them to the load combinations outlined in the OBC. The maximum load combination yields the minimum roof capacity required for one solar panel and these calculations can be found in Appendix B – Detailed Calculations.

5.2 Solar Panel Outputs

As shown in Figure 15 and Figure 16, the maximum annual solar potential in Kingston is 1100 kWh to 1200 kWh, with the majority of the of energy potential occurring in the spring and summer months (Natural Resources Canada 2020).

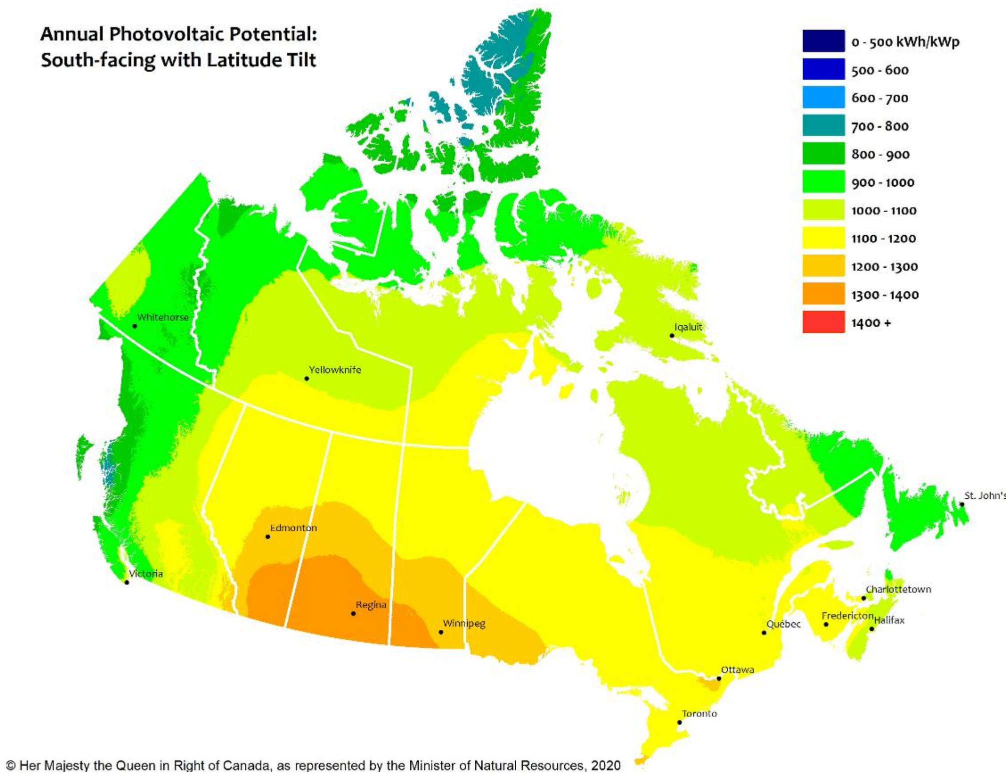

Figure 15 Annual PV potential for south-facing with latitude tilt (Natural Resources Canada 2020)

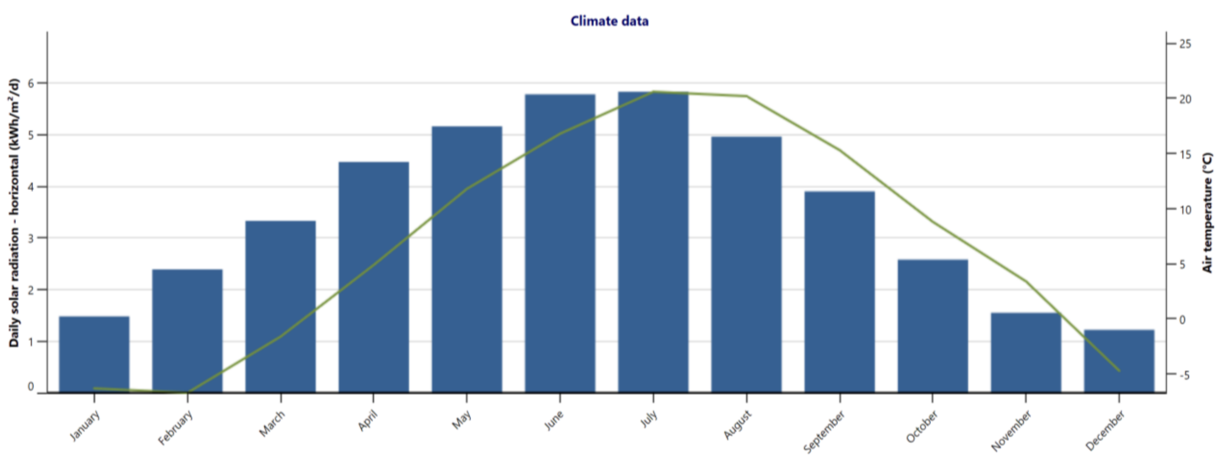

Figure 16 Climate data for average historical daylight solar radiation in Kingston (Natural Resources Canada 2020)

The maximum PV potential in Kingston was determined to be 1198 kWh, as shown in Table 13. Table 13 was reformatted from information provided by NRC and outlines the maximum monthly energy production potential from a solar panel based on its orientation. Using this data, the efficiency of each panel type can be multiplied by the maximum PV potential to determine the total energy output of each panel. This data was determined based on the panels being oriented in the most efficient position for light absorption, which was found to be south facing with a panel tilt angle that is equal to the latitude of the cell minus 15 degrees (Natural Resources Canada 2020). For Queen's University buildings on the main campus, this will result in a tilt angle of 29.22 degrees, as Queen's University's latitude is 44.22 degrees.

Table 13 Summary of yearly production kWh based on solar panel tilt (Natural Resources Canada 2020)

Month	South-Facing with Vertical (90 degrees) Tilt	South-Facing with Latitude Tilt	South-Facing with Tilt = Latitude + 15 Degrees	South-Facing with Tilt = Latitude - 15 Degrees	Horizontal (0 degrees) Tilt
January	77	74	79	65	36
February	86	91	94	83	53
March	94	117	115	113	84
April	69	111	102	115	99
May	64	121	106	131	125
June	59	122	104	134	135
July	65	130	112	142	142
August	69	121	109	127	119
September	71	101	96	101	85
October	74	88	88	83	57
November	54	57	59	52	31
December	62	59	63	52	28
Yearly Production (kWh)	**844**	**1192**	**1127**	**1198**	**994**

The yearly panel energy production calculations are in Appendix B – Detailed Calculations.

5.3 Design Options

Roof capacities are the limiting factor with determining the feasibility of the project. The structural loading capacities of the roofs for the buildings initially chosen were not available, restricting the ability to calculate the number of allowable solar panels per roof. As such, it was decided to develop three options for the client for different building types.

5.3.1 Option 1 – Low Roof Capacity

A lighter solar panel such as a thin-film allows options for buildings that have lower structural capacities and more equipment on the rooftops. There are three different types of thin-film panels as shown in Table 14, each with different efficiency values. As shown, a copper indium gallium selenide cell is the most efficient and maintains its low weight with a value of 11 kg per panel (Yang Tang 2017). Although thin-film panels produce less energy than other panel types, these buildings would not allow for a heavier, more efficient panel. Therefore, having a thin-film panel option generates a higher total energy production value by allowing panels on buildings that may have been previously excluded based solely on structural capacity.

Table 14 Options for thin film solar panels (Yang Tang 2017)

Thin - Film Panel Type	Panel Efficiency
Copper Indium Gallium Selenide	22.3%
Cadmium Telluride	22.1%
Amorphous Silicon	13.6%

Using a standard panel size of 1.5 m^2 and the PV potential in Kingston as shown in Table 14, a single copper indium gallium selenide cell would produce 267.15 kWh per year. The load requirement for one copper indium gallium selenide solar panel is 5.67 kN as summarized in Table 15 and Table 16, as determined by the maximum load combination of dead, snow, live, and wind loads.

Table 15 Summary of values used to calculate solar panel total combined load for Option 1

Solar Panel Area (m^2)	Solar Panel Mass (kg)	Solar Panel Weight (Dead Load) (N)	Live Load (N)	Snow Load (N)	Wind Load (N)	Total Combined Load for 1 Solar Panel (N)
1.5	11	107.91	1000	3375	1185	5671.39

Table 16 Summary of loading combinations for Option 1

Load Combination	Combined Load (N)
1.4D	151.07
1.25D+1.5L+1.0S	5009.89
1.25D+1.5S+0.4W	**5671.39**
1.25D+1.4W+0.5S	3481.39

5.3.2 Option 2 – Mid-Range Roof Capacity

For buildings with mid-range roof capacities, the recommend monocrystalline panels can be used. It is assumed that a roof with mid-range capacity will support a fewer number of monocrystalline panels and allow for high energy production. These panels weigh 19.2 kg, which results in a roof capacity requirement of 6.51 kN per panel as summarized in Table 17 and Table 18 (Bluetti 2023). Monocrystalline panels have an efficiency of 24%, which results in an annual energy output of 287.52 kWh per panel (Ameur et al. 2021).

Table 17 Summary of values used to calculate solar panel total combined load for Option 2

Solar Panel Area (m2)	Solar Panel Mass (kg)	Solar Panel Weight (Dead Load) (N)	Live Load (N)	Snow Load (N)	Wind Load (N)	Total Combined Load for 1 Solar Panel (N)
1.7	19.2	188.35	1000	3825	1343	6510.14

Table 18 Summary of loading combinations for Option 2

Load Combination	Combined Load (N)
1.4D	263.69
1.25D+1.5L+1.0S	5560.44
1.25D+1.5S+0.4W	**6510.14**
1.25D+1.4W+0.5S	4028.14

5.3.3 Option 3 – Large Roof Capacity

For buildings with a large amount of loading capacity available, more solar panels can be placed. The monocrystalline panel used in the mid-range option will still be used, resulting in the same energy and capacity requirement per panel; however, more panels can be added depending on the capacity which will greatly increase the overall power output on large roof capacity buildings.

6.0 Financial Assessment

6.1 Cost Estimates

An initial cost estimate was determined to be approximately $3,000,000 based on the solar panel type and attachment, maintenance, labour for installation, and transportation of the solar panels. The Canadian Solar system costs $526,400 per 3,041 m^2 (Solar Electric Supply, Inc. 2023a). The total area of the final list of buildings' roof space from Table 19 was determined to be 22,632 m^2; however, it is assumed that 50% of this space is useable due to solar panel configuration constraints and equipment existing on the roof. As such, four systems can be used within the 11,316 m^2, for a total of approximately $2,105,600, or $526,400 each. This price includes the cost of the solar panels and the roof connection. Using information provided from the clients, a 20-year maintenance cost was estimated to be $35,100 per building, which is $561,600. It was decided to use a conservative value greater than the chosen lifespan as the solar panel project would surpass it.

The average pay for a solar PV installer in Ontario is $70,186 per year, or $34 per hour (Economic Research Institute 2023). It is assumed that four groups of six solar PV installers are needed, and each group will complete four rooftops' installations. It is estimated that each rooftop will take one standard 40 hour work week. Each building is estimated to cost $8,160 as determined by six construction workers multiplied by 40 hours multiplied by $34 per hour. Therefore, the total cost of labour for the solar panel installation across the 16 buildings will be approximately $130,560. A project manager would be needed on site and would cost approximately $6,453 based on an average salary of $83,887 per year or $40.33 per hour, and the same working hours (Glassdoor 2023).

Locations that carry the selected solar panels were researched and the closest store to Kingston was selected. The solar panels will be transported from 205 Avenue Avro Point-Claire in Montreal, which is approximately 272 km from Queen's campus. All the solar panels will be able to fit in one truck, so one driver will be accounted for in the overall costs. The average salary for a truck driver in Montreal is $62,003 per year or $29.8 per hour (Salary.com 2023). It will take approximately eight hours to pick up the solar panels, deliver them to Queen's University, and drive back. The truck driver will be paid approximately $238 for the transportation. About 575 km will be travelled by the truck driver when accounting for 272 km each way, and a few extra km to pick up the solar panels. A big rig truck can travel at 2.55 km/L, resulting in approximately 107 L of diesel gas being used (FreightWaves 2020). The average price for diesel gas in Montreal on February 27, 2023, was $2.26/L. The total gas will cost about $508 (GlobalPetrolPrices 2023). A summary of the costs is shown in Table 19 and detailed calculations for all values are shown in Appendix B – Detailed Calculations.

Table 19 Summary of individual costs and total estimated cost of project

Expense	Cost	
Solar Panels/Roof Connection	$	2,105,600
20 year Maintenance	$	561,600
Solar PV Installer Labour	$	130,560
Project Manager	$	6,453
Truck Driver	$	238
Diesel Gas	$	508
Total Cost	$	2,804,692

6.2 Electricity Productions Cost Savings

It is assumed that Queen's University operates under the Tier 2 threshold electricity price plan of the Ontario Energy Board. The Tier 2 threshold is for non-residential properties that use above 750 kWh/month, and is priced at $0.103/kWh (Ontario Energy Board 2023). Based on the three design options as summarized in Table 20, electricity production cost savings over the 15-year payback period is produced in Table 21.

Table 20 Summary of design option annual energy produced per panel

Design Option	Annual Energy Produced Per Panel (KWh)
Low Capacity	267.15
Mid-Range Capacity	287.52
High Capacity	287.52

Table 21 Total electricity production cost saving

Total Electricity Production Cost Saving		
Year	**Low Capacity**	**Mid and Large Range Capacity**
2024	$27.52	$29.61
2025	$55.03	$59.23
2026	$82.55	$88.84
2027	$110.07	$118.46
2028	$137.58	$148.07
2029	$165.10	$177.69
2030	$192.62	$207.30
2031	$220.13	$236.92
2032	$247.65	$266.53
2033	$275.16	$296.15
2034	$302.68	$325.76
2035	$330.20	$355.37
2036	$357.71	$384.99
2037	$385.23	$414.60
2038	$412.75	$444.22

From Table 21, the total electricity production cost savings is $412.75 to $444.22 per panel in a 15-year lifespan depending on the three design solutions. To reach a breakeven point during the 15^{th} year, 6,314 to 6,795 solar panels are needed. The amount of surface area for solar panels is 11,316 m^2, divided by the needed roof space per panel of 1.7 m^2 yields a maximum of 6,656 solar panels that can be placed on the rooftops. A combination of design options would be used to reach a breakeven point. It can be considered that the total surface area is a conservative estimate of the amount roof space, so further analysis of the placement would need to be done to deem this project feasible.

7.0 Environmental Assessment

7.1 Environmental Considerations

Solar panels will impact Queen's University's carbon footprint as generating clean electricity will reduce the university's reliance on fossil fuels (Lutz 2022). Solar panels generate clean electricity, but the production of solar panels must be included in the environmental assessment as this process has some negative environmental impacts. The production of monocrystalline solar panels negatively impacts the environment primarily due to the use of silver paste, glass consumption, and electricity during production. These negative impacts include human toxicity, marine ecotoxicity, and metal depletion (Chen et al. 2016). During the manufacturing process water is used to cool the technology and hazardous materials made. Water use depends on the plant design, location, and the type of cooling system. Some manufacturing plants withdraw 2,300 – 2,500 L/MWh of electricity produced whereas dry-cooling technology reduces the use of water by 90% (U.S. Department of Energy 2012). Electrical use is considered offset after three years of implementation (Lawrence 2021). Hazardous materials include hydrochloric acid, sulfuric acid, nitric acid, hydrogen fluoride, 1,1,1-trichloroethane, and acetone; with the amount depending on the cell (U.S. Department of Energy 2012).

There is a downward trend of environmental impact associated with solar panel production. For every doubling of installed solar panel capacity, energy use decreases by 12%, and greenhouse gas (GHG) emissions reduced by 17% to 24% for both monocrystalline and polycrystalline panels (Louwen et al. 2016). This indicates that there is a break-even point associated with solar panel production, and the environmental benefits that come from solar panel usage outweigh the negative environmental impacts associated with panel production.

Queen’s University is committed to reducing its GHG emissions (Queen’s University 2022b). The use of solar panels reduces the need for GHG producing energy sources and the addition of solar panels aligns with Queen’s University’s CAP. The plan outlines indirect emissions from the generation of purchased utilities such as electricity as a Scope 2 emission source, which is shown in Figure 17 (Queen’s University 2022b). The solar panels would contribute to the reduction of Scope 2 emissions by reducing the amount of electricity purchased by the university. Furthermore, the use of solar energy fits the CAP’s defined reduction strategies of adopting other renewable energy generation approaches which indicates that the use of solar panels is already supported by the CAP (Queen’s University 2022b).

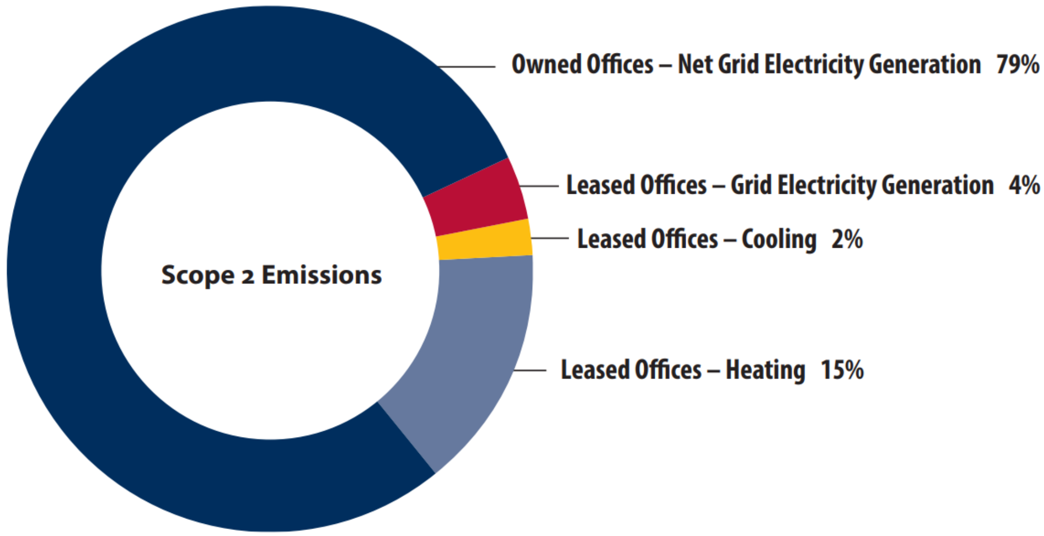

Figure 17 Queen's University Climate Action Plan scope 2 emissions (Queen's University 2022b)

Queen's University has been able to reduce its GHG emissions by 17% from 2008 to 2015, with many changes taking place during this time such as lighting programs and updating the steam boiler. Queen's University has engaged in an energy program that supports the implementation of energy solutions (Queen's University 2022b). The university is willing to change and adapt systems to save money and reduce emissions to meet its goal of becoming carbon neutral by 2040. Queen's must further reduces its consumption by 20,200 tonnes of carbon dioxide by 2030. In 2020, Queen's University's Scope 2 energy usage was 3,824 tonnes of carbon dioxide, and therefore there will be an estimated 90 tonne reduction in Scope 2 energy usage for all years after installation (Richards 2021).

The benefits of solar panels on Queen's University's buildings outweigh the negative environmental impacts associated with solar panel production. This is because the solar panels will consistently produce energy over their life spans, contributing to the reduction of fossil fuel use by Queen's University. Solar panels are environmentally viable and will help the university achieve the environmental goals detailed in the Queen's University's CAP.

7.2 Carbon Footprint

A solar panel's carbon footprint during use is roughly 20 times less than the carbon output of energy produced from fossil fuels. Solar panels require three years of operation to neutralize the carbon debt from manufacturing (Lawrence 2021). When estimating the carbon emission reduction of solar panels, the Peak Marginal Emission Factor (MEF) for each year needs to be considered. The MEF is the incremental change in carbon dioxide emissions as a result of an increase in demand. The changes in the demand for grid electricity and the impact of change are not evenly distributed across all generating resources (The Atmospheric Fund 2021).

It is assumed that solar panels would be implemented in 2024 and have a lifespan of 15-years. For years surpassing 2035, it is assumed that the MEF will increase due to the overall positive trend in values. As such, the value of 335 g CO_2e per KWh in 2035 will be used and this would be underestimating the carbon emission reduction. It is estimated that implementing solar panels will reduce 1.2 to 1.3 tonnes of CO_2e depending on the chosen capacity per solar panel. A breakdown for each year is shown in Table 22.

Table 22 Summary of carbon emission reduction (The Atmospheric Fund 2021)

	Total Carbon Emission Reduction (tonnes CO_2e) per Year		
Year	Peak MEF (g CO_2e / KWh)	Low Capacity (Tonnes CO_2e)	Mid and Large Range Capacity (Tonnes CO_2e)
2024	208	0.056	0.060
2025	321	0.086	0.092
2026	293	0.078	0.084
2027	279	0.074	0.080
2028	261	0.070	0.075
2029	283	0.076	0.081
2030	278	0.074	0.080
2031	329	0.088	0.095
2032	295	0.079	0.085
2033	304	0.081	0.087
2034	321	0.086	0.092
2035	335	0.089	0.096
2036	335	0.089	0.096
2037	335	0.089	0.096
2038	335	0.089	0.096
Total Carbon Emission Reduction (tonnes CO2e)		**1.205**	**1.297**

A visualization of the forecasted carbon emission reduction is shown in Figure 18.

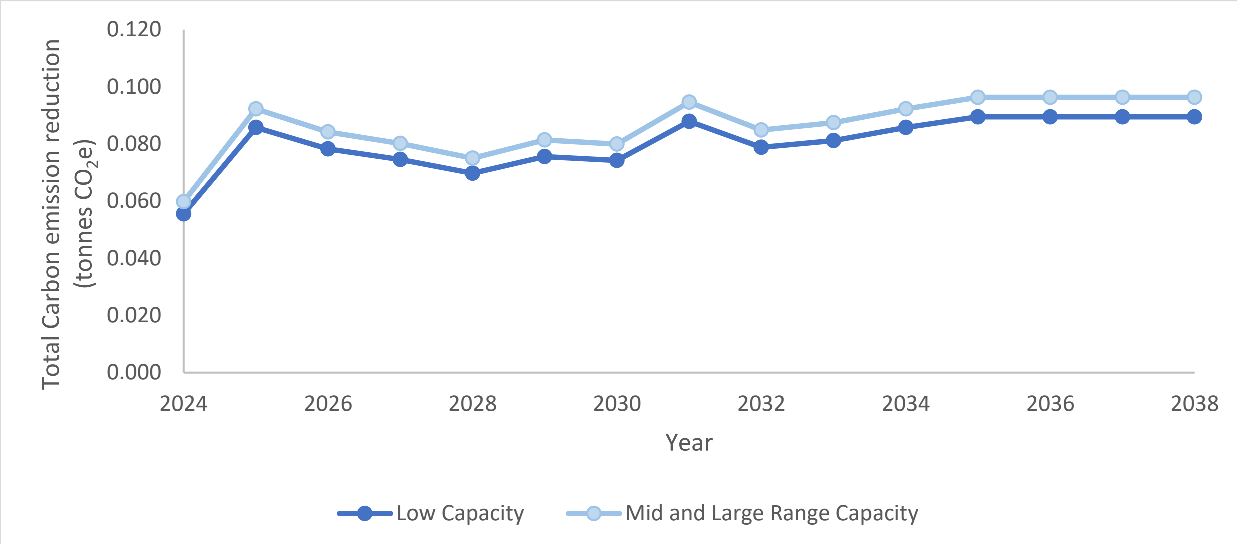

Figure 18 Forecasted carbon emission reductions

Based on the difference in values, implementing 6,656 solar panels for the 15-year lifespan will have a carbon emission reduction of 8,020.5 to 8,632.8 tonnes of CO2e, which would aid in approximately 40% of Queen's University's CAP to reduce its consumption by 20,200 tonnes of CO2e (Queen's University 2022b).

7.3 Wildlife Impacts

Wildlife of concern after implementation includes birds within the Kingston area as other animals are assumed to not interact with the roof of campus buildings. It can be considered that they reach high temperatures during the day which will harm birds if they decide to land on the panels. Rooftop solar panels do not disrupt natural habitats; however, birds may build nests under the solar panels which will be discussed more in the risk assessment. Overall, the benefits to birds by reducing carbon emissions outweigh the negative concerns (National Audubon Society 2020).

7.4 Long Term Impacts

Solar panels typically outlive their designed life span; however, when they need to be replaced with new, higher-performing technology there are several options. Used solar panels can be sold for a significant portion of their initial value or are 90% recyclable by mass. However, there is a lack of solar panel recycling plants, which results in old solar panels becoming waste. This is important as solar panels contain precious metals such as silver, in addition to wiring and manufactured parts, which will be reused to prevent scarcity in future years (Nunez 2014). Components such as power-management equipment, mounting systems, solar panels, and energy-storage devices are included in this percentage, and can be reused, refurbished, or upcycled (Canadian Renewable Energy Association 2023). Figure 19 outlines the recycling process for solar panels.

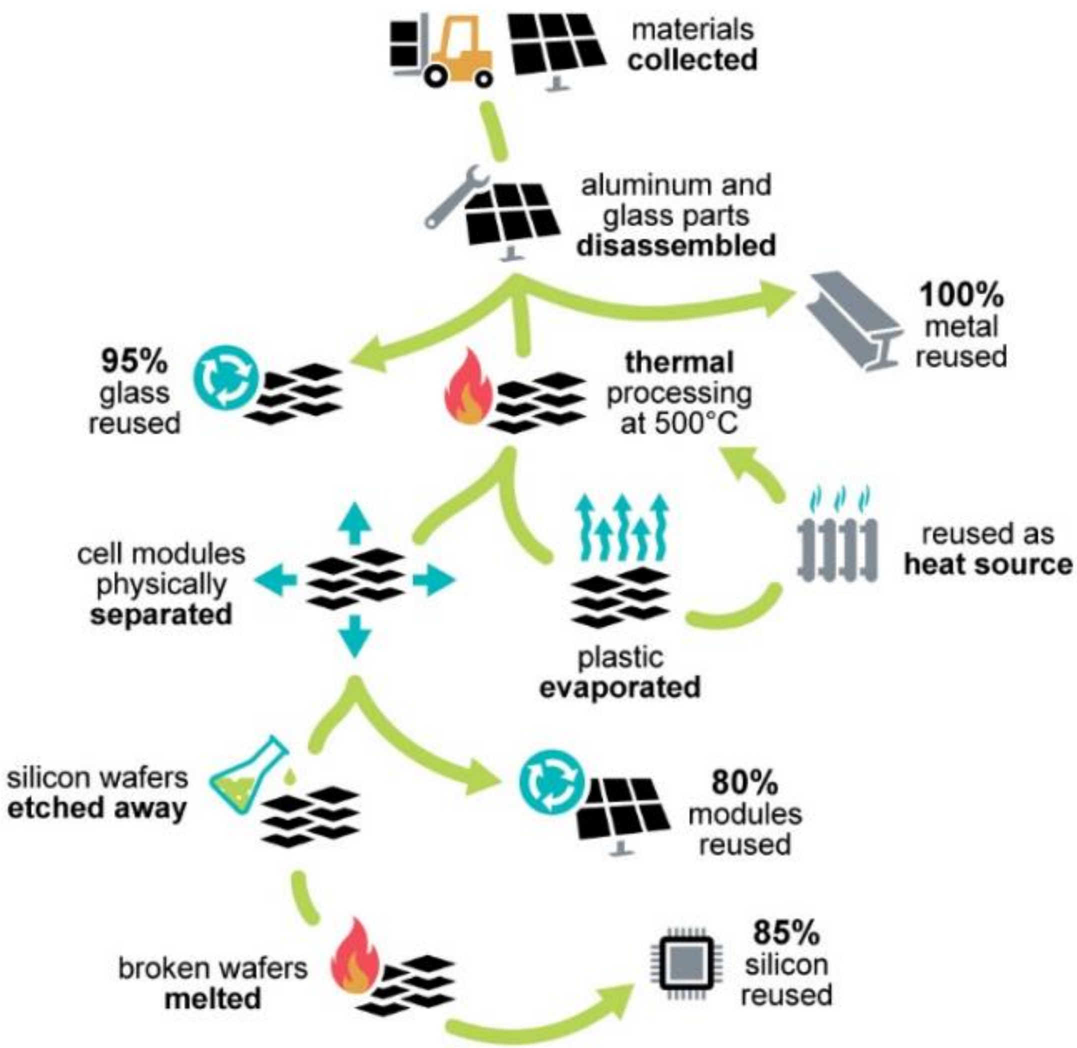

Figure 19 Recycling process for solar panels (Canadian Renewable Energy Association 2023)

The 10% by mass that is waste is of concern given the growing size of landfills and the amount of waste in the world; however, options for salvaging the entire panel are being researched and developed in Canada (McEwan 2022). As such, long-term impacts are thought to be minimized and outweigh the negative impacts of other energy-generating options.

8.0 Innovation

8.1 Rooftop Greenery

Solar panels can be hidden from street view to maintain the aesthetic value of the campus. This will be implemented through adding greenery to the street-facing side of the buildings' roofs. By adding arrangement of Hicks Yew as shown in Figure 20, they will not block the sun from hitting the panels but will conceal the panels from street view. Solar panels can lack aesthetic value and take away from the architectural importance of buildings. Rooftop greenery generates both new green spaces on campus and increases environmental benefits by way of carbon capture through plants. Although this space would not be accessible to people as it is on the roof, it would brighten the campus and would be aesthetically pleasing in all seasons as these plants do not become bare in the winter (Eckenwalder 2022).

Figure 20 Example of a potted yew (InstantHedge 2022)

Yews are a great choice for rooftop greenery as they require minimal maintenance, tolerate full to partial sunlight conditions, and are versatile with precipitation conditions. These plants can be blue/green or chartreuse/gold and stay colourful in the winter. These plants are considered one of the best evergreen trees for pots as they have a slow growth rate of 0.3 m per year and can range from 1.5 – 18 m in height and 1.5 – 6 m in width (Plant Addicts 2023). Using planters stunts the growth rate and size (Davey Trees 2021). An additional advantage of added greenery to building rooftops is that planters can delay and reduce run-off time, rate, and volume. It has been recorded that rooftop gardens can delay run-off rates by up to 45 minutes, reduce runoff rates by 75%, and absorb a minimum of 2 mm of rain before run-off occurs (Liu 2002).

Implementing potted yews requires a planter system that would allow ample drainage, is larger than the plant to allow growth space, and uses lightweight potting soil. The planters surface area will be no larger than 0.35 m wide as this will maintain a height of 1 m or less and will be filled up to 0.1 m below the top of the planter (Hedge Xpress 2013). As such, Grapevine Urban Garden Raised Planter Box, Recycled Wood and Metal, Rectangle will be used to home three yew plants as shown in Figure 21 (Rona 2023). The planter is FSC-certified as it is made from recycled pine and a powder-coated steel frame and weighs 19.30 kg. It has a 117 L capacity which will allow ample space for plants to grow deep roots. Garden Club 3-in-1 Soil Mix is the selected soil as it is lightweight, reduces soil compaction, helps retain water and nutrients, and contains porous soil (Canadian Tire 2023). A detailed cost breakdown for each unit, which would be used for 2 m^2 of space on each roof, is shown in Table 23.

Figure 21 Grapevine Urban Garden Raised Planter Box, Recycled Wood and Metal, Rectangle (Rona 2023)

Table 23 Cost breakdown for one potted yew (Greenhouse to Garden 2023), (Rona 2023), (Canadian Tire 2023)

Item	Amount	Cost/Amount	Cost (including tax)	Added Weight (kg)
Yew	3 ea.	$38.99/ea.	$132.18	42.98
Planter	1 ea.	$139.00/each	$157.07	19.30
Soil	117 L	$3.99/25 L	$18.03	52.88

It has been assumed that costs for shipping will be negligible as the product is bought locally and stores waive the fee when a large quantity of product is purchased. Therefore, the estimated cost for an individual planter is $307.28. A conservative approach was used to calculate a dead load of 0.81 kPa for an area of 2 m wide by 1 m in depth. This approach considered a fully saturated planter, where the water weight would be 29.25 kg, and considered the tree to be fully grown 1.5 m which is larger than the expected 1 m tall yew. Detailed calculations are shown in Appendix B – Detailed Calculations. This weight will need to be considered if implemented in conjunction to the existing roof infrastructure.

Considering the maintenance and upkeep of the plants, they would require a member of Queen's Facilities to prune them once a year in early spring and would require soaking the top 0.61 m of the soil before it freezes in fall to allow the plant to store up moisture for the winter months. Yews prefer well-drained soil and require minimal watering, resulting in a plant that is typically drought tolerant. However, the newly planted Yew bushes should be watered once a week for two months to establish the roots (Plant Addicts 2023). Pruning would require trimmers and compost bags to dispose of the waste properly. Each planter would require 29.25 L of water which would require multiple trips from a worker, so they do not strain themselves. The timing of these events would be when roof inspections occur to limit disruptions and rooftop access needs. After the project is completed, the plants can be left on the roofs, repotted and sold, or planted on campus given the long life span of 900 years (Mellor 2018). Solar panels would not be placed this close to the edge of a rooftop for maintenance purposes as well. Based on roof loading being significantly lower than adding solar panels, minimal maintenance required, and potential benefit to adding greenery to campus, it is both feasible and recommended to move forward with this option given that there is sufficient rooftop capacity.

8.2 Solar Panel Powered Green Rooms

Developing a 'Green Room' in each building with solar panels would add to the project and display the energy produced by the solar panel production. The room would have motion and light sensors to conserve energy when the room is not used or is adequately lit by the windows. An existing washroom will be used as a Green Room to minimize disturbance to the building's current use with hand dryers powered by solar panels as well. Implementing steps would be connecting the power generated by the solar panels to the electrical system of the washroom as well as the main grid. Costs would be associated with the overall hookup as stated in 6.0 Financial Assessment.

The washrooms will be painted green and have a plaque near the sink to explain how they are being powered by solar energy. Information about Queen's University's CAP and how solar panels work will be posted in stalls, as well as outside the washroom to showcase Queen's University's dedication to their CAP and reducing emissions. These superficial implementation options would cost $500 to $3000 depending on the size, and range for posted material based on Queen's Facilities decision on quality and quantity (Tribble Painting 2021). It is recommended that Queen's Facilities use reclaimed wood for the plaque. A suggested plaque is shown in Figure 22, with braille included below for accessibility for blind and partially sighted people. Queen's University's willingness to accept new technology and implement changes is highlighted through this addition and would be a benefit as it may be a memorable talking point among visitors and potential students.

Figure 22 Suggested 'Green Room' plaque (Walton 2023)

9.0 Climate Change

Climate change is a progressing phenomenon characterized by human-driven long-term shifts in temperature and weather patterns (United Nations 2023). Activities such as burning fossil fuels for power generation creates GHG emissions, contributing to warming in the Earth's atmosphere. Solar panels help reduce these emissions by producing emission-free power.

Climate change increases global surface temperatures, produces more severe storms, and impacts surface solar radiation which directly affecting future PV power generation. It is found that with climate change progressing at an average rate, the electric potential of solar panels is increased by 5%, and cloud cover is reduced by 4% (Hou et al. 2021). Climate change reduces the ozone layer thickness surrounding Earth and as the layer gets thinner it allows more solar radiation to reach Earth's surface as less solar radiation is reflected into space. Cloud cover and surface solar radiation is not a limiting factor for the longevity of solar panels as climate change is likely to increase the energy production of solar panels, keeping them useful for their full lifespan (World Meteorological Organization 2019).

In Kingston, climate change increases rainfall, blizzards, and more intense winds (Buis 2020). This will impact the attachment systems of the solar panels as they would have to withstand stronger wind forces. This is not a concern at this time, as attachment systems can be upgraded as needed to adjust to long-term weather changes. Climate change does not affect the outlook of this project, as the solar potential is not decreased, and increasing storm potential can be mitigated by updating the attachment systems when needed. This information should be reviewed in the future, as climate change data and the effects of climate change are likely to change in future years.

10.0 Risk Management

10.1 Health and Safety

Safety for both the public and workers is the highest priority in engineering. Safety guidelines should be present when installing solar panels. Worksites should be assessed before work begins to evaluate any potential risks and clear guidelines should be made. Safety risks include but are not limited to:

1. Fall and trip hazards
2. Working from heights
3. Unguarded machinery
4. Electrical hazards
5. Biological hazards
6. Physical hazards
7. Ergonomic hazards

Steps to clear the space to reduce the first and third safety risks. To address the second hazard, 1 m tall guardrails should be installed around the roof and workers will need to be harnessed as they will be working from heights (Occupational Safety and Health Administration 2022). Electrical safety will need to include confirming the power is turned off when connecting the solar panels. All workers should be familiar with solar panel handling guidelines before starting work. Biological hazards are related to installing the planters and other insects or animals as the work will be done outside. Physical hazards such as exposure to sunlight and hot temperatures from the solar panels will be considered. Covering the solar panels with opaque paper when they are unboxed will reduce the risks with heat (Prescott 2021). Personal protective equipment such as gloves, hard hats, clothing to cover arms and legs, sunscreen, protective eyewear, and steel-toed safety boots must be worn to reduce many of the physical risks to workers. Similar steps to reduce and manage risks should be taken when personnel are on the roof. Ergonomic hazards are related to frequent lifting, poor posture, repeating the same movements, and awkward movements. Two people will be required to lift the solar panel at a time to prevent injury or damage.

10.2 Financial Risks

The high capital cost of installing solar panels is the primary risk to consider, with even higher associated costs if they are not properly installed. Solar panel installations could damage and compromise the roof from drilling holes into it, resulting in greater expenses if the roof needs replacement. Energy production is unpredictable due to changing weather and energy only being produced during the daytime hours. Electrical prices can stay stagnant or even become cheaper as technology progresses. Cost considerations associated with solar panel maintenance as discussed in 6.0 Financial Assessment need to be considered as they are mainly capital costs. Risks from weather events can cause costly repairs. The majority of these risks can only be managed with a warranty as there is no control over the weather, whereas risks associated with improper installation can be minimized by hiring a reputable company that will take responsibility for this.

10.3 Potential Life Loss

There is a potential for life loss in many areas during construction as outlined. Following given steps to improve safety should manage and reduce the risk. Major safety risks after installation include the potential of electrocution if not installed properly, starting a fire if the solar panels generate too much heat, and becoming dislodged if panels are not attached properly. Structural failure from adding additional loads can lead to the loss of life within the building and around it. As such, these risks must be carefully considered, and the correct precautions should be taken. As mentioned in 2.0 Specifications, Guidelines, Codes, the specifications, guidelines, and codes will be followed to minimize these risks.

11.0 Maintenance and Operations

Steps need to be taken to ensure that the panels can effectively work year-round without losing any efficiency. Good maintenance of a solar panel includes cleaning off the face of the panel, ensuring that there are no cracks in the cells, making sure the mounts are placed at the correct angle and are not moving, removing snow if there is any on top of the panel during the winter months, checking for malfunctions or errors in the wiring/panel itself, and more. Maintenance would be completed by Queen's Facility staff who are properly trained to work on roofs and with this type of equipment; costs are included in 6.0 Financial Assessment.

To maintain solar panels there must be weekly routine checks on all solar panels to ensure that there are no cracks that resulted from anything ranging from birds to wind blowing objects at it. A 10-to-15-degree tilt is typically enough for the snow to slide off during the winter months. In extreme wet snow cases, snow can be attached to the solar panel and must be cleaned off by hand. The ballast mounts must also be checked to ensure that they have the correct amount of weight so the solar panels do not move or hit each other. If a panel is damaged, it will need to be assessed and replaced if deemed by the maintenance person. As discussed in the 6.0 Financial Assessment, the number of panels were bought in a system so there will be extra panels that can be used as replacements.

12.0 Recommendations

This report will need updating in the future due to technology changes in solar panels and their attachment methods, financial inflation, and climate change impacts. The total cost, panel options, attachment needs, structural analyses, and total power outputs will be different from this report as a result. The list of buildings will need to be updated based on each building’s roof replacement status and structural limitations. Using Figure 6 and Figure 8 as a guide, these considerations should be studied to develop an updated preliminary building list. Once a new building list has been generated, a comprehensive structural assessment should be carried out to determine each selected building’s maximum rooftop structural capacity. Research should be done to determine the best solar panel option for the campus rooftops based on updated financial information, solar panel availability, and any new technological information available.

The maximum number of solar panels that are able to be placed on each roof should be determined using this solar panel information and the maximum rooftop capacity. The layout of the panels on each roof can be decided by verifying the rooftop space available on each building as this may limit the number of panels that can be placed. Each building's structural drawings and updated information regarding existing roof structures should be examined when determining the solar panel layout. These panels should be placed at an angle of 29.22 degrees on the campus buildings, which may also impact the layout due to potential shading.

After the number of panels and the arrangement are finalized, the solar output capacity should be checked to determine if the energy produced is significant enough to impact the university's carbon footprint. Lastly, a cost analysis should be done to determine an exact cost for the project that includes all maintenance fees for the project's lifetime. In order for the project to be feasible, the lifespan of the solar panels should outlast the project's fiscal breakeven point. An additional energy and cost analysis would be completed to determine if any extra energy from the solar panels would be sold to the Ontario Energy Board. An evaluation matrix should be completed to determine if the project is feasible based on updated importance parameters with the capacity and cost information. This report should be fully updated in the future as too many constraints change over time for these findings to remain accurate.

13.0 Conclusion

The objective of this report was to determine the feasibility of installing solar panels on Queen's University's buildings. This included feasibility in terms of cost, energy production, and structural capacity. An initial building list was developed which included buildings that were not due for a roof replacement within the 15-year lifespan of a solar panel, did not have a historical distinction, and were not shaded. This resulted in a building list of 16 feasible buildings: Biosciences Complex, Brant House, Bruce Wing, Chown Hall, David C. Smith House, Dunning Hall, Ellis Hall, Harkness Hall, Humphrey Hall, Isabel Bader Centre for the Performing Arts, John Orr Tower, Mitchell Hall, Old Medical Building, Robert Sutherland Hall, Stauffer Library, and Walter Light Hall. The roof capacities for these buildings were not available, resulting in a scope change. The initial scope for the structural component of this report was to determine the number of solar panels that would be attached to each building. The scope changed to present a solar panel option framework for buildings with different roof capacities. This allows for ease of solar panel choice when the full building capacities are determined.

Full-loading calculations were not done in this report as they were not included in the scope of this project. Conservative assumptions made in this report were to simplify structural analysis of the wind and snow loading factors in each calculation. They produced loading values that are higher than if no simplifying assumptions were made. These were necessary due to time and informational constraints. A highly detailed full-loading analysis would be required for the snow and wind calculations. This results in a safe design that would be within the loading capacity of the rooftop, if solar panels were chosen using these values.

Further design solutions for the project included a low, mid-range, and high roof capacity. The first option included fewer and lighter thin-film solar panels. Copper indium gallium selenide cell would be used as it is the most efficient, producing 267.15 kWh per year, and requires a roof capacity greater than 5.67 kN per panel. The second option would use the recommended Canadian Solar monocrystalline panel in conjunction with Renusol CS60 Ballast Mount from Solar Electric Supply Inc. They would require a roof capacity greater than 6.51 kN per panel and would produce an annual energy output of 287.52 kWh per panel. The third option would use the same monocrystalline panels as the second option; however, would be for buildings with a larger loading capacity as more panels would be placed.

An estimated total cost of $2,804,959 for the total area of the added rooftop sizes of all 16 buildings selected. Costs included $2,105,600 for solar panels and roof connection, $561,600 for 20 years of maintenance, $130,560 for solar PV installer labour, $6,453 for a project manager, $238 for a truck driver, and $508 for diesel gas. As such, a minimum of 6,314 to 6,795 solar panels are needed to breakeven within a 15-year payback period depending on roof capacity; however, there is room for a maximum of 6,656 solar panels which allows a combination of types. It can be considered that the total surface area is a conservative estimate of the amount of roof space. Further analysis of the placement would need to be done to deem this project feasible. It is estimated that implementing solar panels will reduce 1.2 to 1.3 tonnes of CO2e per panel, or a total of 8,020.5 to 8,632.8 tonnes of CO2e depending on the chosen capacity per solar panel. Decommissioning this project has the option to sell the panels for a significant portion of their initial value or recycle 90% by mass.

Climate change is affected by the project as it has a positive impact on reducing carbon emissions. Implementing solar panels will be affected by climate change through increased sunlight and potential increased damage risk as it will be warmer, wetter, and stormier. Safety guidelines to address hazards, financial risks, and potential life loss associated with the project have been outlined in 10.0 Risk Management.

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Appendix A – Complete List of Buildings

A complete list of buildings is in Table 24 and those that pass the pre-screening are bolded for clarity.

Table 24 All buildings on Queen's University and reasons for not selecting if applicable

Buildings	Reason for not selecting if applicable
Abramsky Hall	Significant shading
Adelade Hall	Historical designation
Agnes Etherington Art Centre	Historical designation
Albert Street Residence	Sloped roof
Ban Righ Hall	Sloped heritage roof, significant shading
Beamish-Munro Hall	Significant shading
Biosciences Complex	
Botterell Hall	Roof replacement
Brant House	
Bruce Wing	
Cancer Research Institute	Roof replacement
Carruthers Hall	Sloped heritage roof
Cataraqui Buildings	Significant shading
Chernoff Auditorium	Roof replacement
Chernoff Hall	Roof replacement
Chown Hall	
Clarke Hall	Equipment cluttered rooftop & significant shading
Coastal Engineering Lab	Roof replacement
Craine Building	Historical designation
David C. Smith House	
Douglas Library	Sloped heritage roof
Duncan McArther Hall	Roof replacement
Dunning Hall	
Dupuis Hall	Equipment cluttered rooftop & significant shading
Ellis Hall	
Etherington Hall	Significant shading

Buildings	Reason for not selecting if applicable
Fleming Hall	Historical designation, roof replacement
Goodes Hall	Roof replacement
Goodwin Hall	Roof replacement
Gordon Hall	Sloped heritage roof & equipment cluttered rooftop
Gordon-Brockington Hall	Roof replacement
Grant Hall	Sloped heritage roof
Harkness International Hall	
Harrison-Lecain Hall	Significant shading
Haynes Hall	Roof replacement
Humphrey Hall	
Isabel Bader Centre for the Performing Arts	
Jackson Hall	Historical Designation
Jean Royce Hall Phase 1	Roof replacement
Buildings	Reason for not selecting if applicable
Jean Royce Hall Phase 2	Roof replacement
Jeffery Hall	Roof replacement
John Deutsch University Centre	Historical designation, under construction
John Orr Tower	
Kathleen Ryan Hall	Sloped heritage roof
Kinesiology and Health Studies Building	Equipment cluttered rooftop
Kingston Hall	Historical Designation
Lasalle Building	Significant shading
Leggett Hall	Roof replacement
Leonard Hall	Roof replacement
Louise D. Acton Building	Roof replacement
MacGillivray-Brown Hall	Roof replacement
Mackintosh-Corry Hall	Roof replacement
McLaughlin Hall	Equipment cluttered rooftop
McNeill House	Roof replacement
Miller Hall	Historical Designation

Buildings	Reason for not selecting if applicable
Mitchell Hall	
Morris Hall	Roof replacement
Nicol Hall	Sloped heritage roof & equipment cluttered rooftop
Old Medical Building	
Ontario Hall	Sloped heritage roof
Queen's Centre	Roof replacement
Richardson Hall	Significant shading
Richardson Laboratory	Significant shading
Rideau Building	Roof replacement
Robert Sutherland Hall	
School of Medicine	Roof replacement
Stauffer Library	
Stirling Hall	Roof replacement
Summerhill	Sloped heritage roof
The Law Building	Roof replacement
Theological Hall	Sloped heritage roof
Victoria Hall	Roof replacement
Waldron Tower	Roof replacement
Walter Light Hall	
Watson Hall	Roof replacement
Watts Hall	Roof replacement
West Campus Storage	Roof replacement

Appendix B – Detailed Calculations

Planter Loads:

ρ = Density of Yew is 670 kg/m^3 (kg-m3.com 2023)

h = Height: 1.5 m

d = Diameter: 0.33 m

g = Gravity = 9.81 m/s^2 (The Physics Classroom 2023)

Area = 2 m x 1 m = 2 m^2

$$Weight\ added = 3\pi\left(\frac{d}{2}\right)^2 h\rho = (3)(3.14)\left(\frac{0.33}{2}\right)^2(1.5)\left(\frac{670kg}{m^3}\right) = 64.47\ kg$$

$$Load = \frac{Force}{Area} = \frac{(64.47\ kg+19.30\ kg+52.88\ kg+29.25\ kg)\left(9.81\frac{m}{s^2}\right)}{2\ m^2}\frac{1\ kPa}{1000\ Pa} = 0.81\ kPa$$ (Study.com 2023)

Panel Loading:

$$Panel\ Dead\ Load = Mass\ \times 9.81\frac{m}{s^2}$$

$$Panel\ Dead\ Load = 19.2\ kg\ \times 9.81\frac{m}{s^2}$$

$$Panel\ Dead\ Load = 188.35\ N$$

$$Panel\ Snow\ Load = Panel\ Snow\ Pressure \times Panel\ Area$$

$$Panel\ Snow\ Load = 2.25\ kPa \times 1.7m^2 \times 1000\frac{N}{kN}$$

$$Panel\ Snow\ Load = 3825\ N$$

$$Panel\ Wind\ Load = Panel\ Wind\ Pressure \times Panel\ Area$$

$$Panel\ Wind\ Load = 0.79\ kPa \times 1.7m^2 \times 1000\frac{N}{kN}$$

$$Panel\ Wind\ Load = 1343\ N$$

Panel Loading (continue):

$1.4D = 1.4\ (188.35\ N) = 263.69\ N$

$1.25D + 1.5L + 1.0S = 1.25\ (188.35\ N) + 1.5\ (1000\ N) + 1.0\ (3825\ N) = 5560.44\ N$

$1.25D + 1.5S + 0.4W = 1.25\ (188.35\ N) + 1.5\ (3825\ N) + 0.4\ (1343\ N) = 6510.14\ N$

$1.25D + 1.4W + 0.5S = 1.25\ (188.35\ N) + 1.4\ (1343\ N) + 0.5\ (3825\ N) = 4028.14\ N$

Yearly Panel Energy Production:

$Panel\ Production = Yearly\ Production\ \times Efficiency$

$Panel\ Production = 1198\ kWh\ \times 0.24$

$Panel\ Production = 287.52\ kWh$

Solar Panels/Roof Connection:

$$Canadian\ Solar\ System = \frac{\$526{,}400}{3041\ m^2}$$

$Total\ Area\ of\ Roofs = 22{,}632\ m^2$

$$Usable\ Area = \frac{22{,}632\ m^2}{2} = 11{,}316\ m^2$$

$$\#\ of\ Systems = \frac{11{,}316\ m^2}{3041\ m^2} = 3.72{:}\ This\ is\ rounded\ up\ to\ 4$$

$$Cost\ of\ Solar\ Panel\ Systems = \frac{\$526{,}400}{System} * 4\ Systems = \$2{,}105{,}600$$

20-year Maintenance:

$$20 - year\ Maintenance\ Cost = \frac{Cost}{Building} * \#\ of\ Buildings = \frac{\$35{,}100}{Building} * 16\ Buildings = \$561{,}600$$

Solar Photovoltaic Installer Labour:

$$Solar\ Photovoltaic\ Installer\ Pay = \frac{\$34}{hour}$$

Solar Photovoltaic Installer Labour (continue):

$$\# \ of \ Workers = \frac{6 \ Installers}{Group} * 4 \ Groups = 24 \ Installers$$

$$Building \ Installation \ Time = \frac{8 \ hours}{day} * 5 \ days = 40 \ hours$$

$$Installer \ Pay = \frac{\$34}{hour} * 40 \ hours = \frac{\$1{,}360}{Installer} * 6 \ Installers = \$8{,}160/Building$$

$$16 \ Building \ Installation \ Cost = \frac{\$8{,}160}{Building} * 16 \ Buildings = \$130{,}560$$

Project Manager:

$$Project \ Manager \ Pay = \frac{\$40.33}{hour}$$

$$Total \ Project \ Manager \ Cost = \frac{\$40.33}{hour} * \frac{40 \ hours}{week} * 4 \ weeks = \$6{,}453$$

Truck Driver:

$$Truck \ Driver \ Pay = \frac{\$29.80}{hour}$$

$$Total \ Truck \ Driver \ Cost = \frac{\$29.80}{hour} * 8 \ hours = \$238$$

Diesel Gas:

$$Distance \ Travelled = 575 \ km$$

$$Big \ Rig \ Truck \ Mileage = \frac{2.55 \ km}{L}$$

$$Fuel \ Used = \frac{575 \ km}{2.55 \frac{km}{L}} = 575 \ km * \frac{1L}{2.55 \ km} = 225 \ L$$

$$Average \ Price \ of \ Diesel \ Gas \ in \ Montreal = \frac{\$2.26}{L}$$

$$Total \ Cost \ of \ Diesel \ Gas = 225L * \frac{\$2.26}{L} = \$508$$

The excel spreadsheet for structural analysis is shown in Figure 23.

	Input	Input					
Solar Panel Option	Solar Panel Area (m^2)	Solar Panel Mass (Kg)	Solar Panel Weight (Dead Load) (N)	Live Load (N)	Snow Load (N)	Wind Load (N)	Total Combined Load for 1 Solar Panel (N)
Light	1.5	11	107.91	1000	3375	1185	5671.39
Medium	1.7	19.2	188.352	1000	3825	1343	6510.14
Heavy	1.7	19.2	188.352	1000	3825	1343	6510.14

Load Combinations (Light)		Load Combinations (Medium)		Load Combinations (Heavy)	
1.4D	151.07	1.4D	263.6928	1.4D	263.6928
1.25D+1.5L+1.0S	5009.89	1.25D+1.5L+1.0S	5560.44	1.25D+1.5L+1.0S	5560.44
1.25D+1.5S+0.4W	5671.39	1.25D+1.5S+0.4W	6510.14	1.25D+1.5S+0.4W	6510.14
1.25D+1.4W+0.5S	3481.39	1.25D+1.4W+0.5S	4028.14	1.25D+1.4W+0.5S	4028.14

Number of Allowable Solar Panels	(TOTAL ROOF CAPACITY)/(ATTACHMENT LOAD PER PANEL + LOAD PER PANEL)

Figure 23 Structural analysis Excel

Appendix C – Work Plan and Group Dynamic

To ensure all project deliverables and assessments are completed efficiently and effectively, three project management tools were utilized. The work breakdown structure appealed to the team's need of having clear objectives and defined checkpoints. The responsibility assignment matrix (RAM) assigned roles to be responsible, accountable, consulted, and informed to each team member, assign due dates, and included the Group Manager and Client. The Gantt chart expanded on these tasks by setting out the time to be spent on a task and presented a visual timeline for how the project will develop. Both models will be revisited and adjusted every month to account for the progress of the project.

Major Tasks

The team developed nine phases that included prepare for the project and finish it, course assessments, and subsections as shown in Table 25. The initial phase included learning about the project through the client meeting, developing a group agreement to ensure accountability, and meeting with the Group Manager. Course assessment phases included a work plan, progress report, draft final report, and oral presentation. Each of these phases included steps to set-up and divide components, complete an initial edit, submit to the Group Manager for feedback, and submit the final assessment. Subsection phases looked to define the problem, complete research, develop and evaluate deliverables, and communicate results. These subsection phases included structural, implementation, financial, and environmental. All phases included client and Group Manager meetings.

Table 25 Work Breakdown Structure

Task Name	Due	Resource Names
1.0 Initial Phase	**Fri 22-11-11**	**Group T**
Started Bid	Fri 22-09-09	M. Campbell
Brainstorm and Prepare for Client Meeting	Tue 22-09-13	M. Campbell
Client Meeting	Wed 22-09-14	E. McMurchy
Client Meeting Summary	Wed 22-09-14	H. Kruizinga, D. Pogue
Prepare Group Agreement	Thu 22-09-15	M. Campbell, E. McMurchy
Group Manager (GM) Meeting	Fri 22-09-16	M. Campbell

Task Name	Due	Resource Names
2.0 Work Plan	**Tue 22-10-04**	**H. Kruizinga**
Brainstorm Problem	Wed 22-09-21	Group T
Define Problem and Scope	Wed 22-09-21	H. Kruizinga
Decide Subsection Leads	Wed 22-09-21	H. Kruizinga
Set-up Report and Divide Deliverables	Wed 22-09-21	H. Kruizinga
Preliminary Research - Structural	Sun 22-09-25	H. Kruizinga
Preliminary Research - Implementation	Sun 22-09-25	E. McMurchy
Preliminary Research - Financial	Sun 22-09-25	D. Pogue
Preliminary Research - Structural	Sun 22-09-25	M. Campbell
Develop Work Breakdown Structure	Sun 22-09-25	H. Kruizinga
Develop Gantt Chart	Sun 22-09-25	H. Kruizinga
Write Sections 1.1, 1.2, 1.3, 3.3	Sun 22-09-25	M. Campbell
Write Sections 1.4, 1.5, 3.2	Sun 22-09-25	E. McMurchy
Add Group Agreement to Appendix	Sun 22-09-25	E. McMurchy
Write Sections 3.3, 4.0	Sun 22-09-25	D. Pogue
Write Sections 2.0, 3.1	Sun 22-09-25	H. Kruizinga
Initial Edit	Mon 22-09-26	H. Kruizinga
Submit Work Plan to GM for Feedback	Tue 22-09-27	M. Campbell
GM Meeting and Update Meeting Log	Wed 22-09-28	H. Kruizinga
Edit Work Plan Based on Feedback	Fri 22-09-30	H. Kruizinga
Submit Work Plan	Fri 22-09-30	H. Kruizinga
Client Meeting - Submit Work Breakdown	Tue 22-10-04	H. Kruizinga
3.0 Structural Phase	**Wed 22-10-26**	**H. Kruizinga**
Obtain Supporting Documents from Client	Tue 22-10-04	H. Kruizinga
GM Meeting and Update Meeting Log	Wed 22-10-05	H. Kruizinga
Research Solar Panels	Wed 22-10-19	E. McMurchy
Research Snow Loading	Wed 22-10-19	M. Campbell
Research Roof Capacities	Wed 22-10-19	D. Pogue
Review Types of Buildings on Campus	Wed 22-10-19	H. Kruizinga

Task Name	Due	Resource Names
Develop Evaluation Matrix for Acceptable Buildings	Wed 22-10-19	H. Kruizinga
GM Meeting and Update Meeting Log	Wed 22-10-19	H. Kruizinga
Review and Update Snow Loading Documents	Wed 22-10-26	M. Campbell
Review and Update Roof Capacity Documents	Wed 22-10-26	D. Pogue
Evaluate Campus Buildings	Wed 22-10-26	H. Kruizinga
Client Meeting - Review Decisions	Wed 22-10-26	H. Kruizinga
GM Meeting and Update Meeting Log	Wed 22-10-26	H. Kruizinga
4.0 Implementation Phase	**Tue 22-11-08**	**E. McMurchy**
Set-up Meeting with Electrical Engineer Lead	Wed 22-10-26	E. McMurchy
Research Different Types of Solar Panel Install Methods	Wed 22-10-26	E. McMurchy
Research Transportation for Panels to Queens Buildings	Wed 22-11-02	H. Kruizinga
Research Cost Efficiency of Each Install Method	Wed 22-11-02	D. Pogue
GM Meeting and Update Meeting Log	Wed 22-11-02	E. McMurchy
Meeting with Electrical Engineer lead	Wed 22-11-02	E. McMurchy
Evaluation Matrix of Install Methods and Final Choice	Wed 22-11-02	E. McMurchy
Review Loading Documents to Ensure Safe Install	Tue 22-11-08	H. Kruizinga
Research Environmental Impacts of Solar Panels	Tue 22-11-08	M. Campbell
Revise Finding and Decision in Proper Format	Tue 22-11-08	E. McMurchy
Client Meeting - Review Decisions	Tue 22-11-08	E. McMurchy
5.0 Progress Report	**Fri 22-11-25**	**E. McMurchy**
Review Report Requirements	Wed 22-11-02	E. McMurchy
Set-up Report and Divide Deliverables	Wed 22-11-02	E. McMurchy
Update WBS and Gantt Chart	Wed 22-11-02	H. Kruizinga
GM Meeting and Update Meeting Log	Wed 22-11-09	E. McMurchy
Initial Edit	Mon 22-11-14	E. McMurchy
Submit Progress Report to GM for Feedback	Mon 22-11-14	E. McMurchy
GM Meeting and Update Meeting Log	Wed 22-11-16	E. McMurchy
Edit Progress Report Based on Feedback	Wed 22-11-23	E. McMurchy
Submit Progress Report	Wed 22-11-23	E. McMurchy

Task Name	Due	Resource Names
6.0 Modeling Phase	**Tue 23-03-14**	**D. Pogue**
GM Meeting and Update Meeting Log	Fri 23-01-20	D. Pogue
Apply Feedback from Progress Report	Fri 23-01-27	H. Kruizinga
Research Cost of Panels and Roof Installation	Tue 23-03-14	D. Pogue
Evaluation Matrix of Install Methods and Final Choice	Tue 23-03-14	E. McMurchy
Review Loading Documents to Ensure Safe Install	Fri 23-03-03	M. Campbell
GM Meeting and Update Meeting Log	Fri 23-01-27	D. Pogue
GM Meeting and Update Meeting Log	Fri 23-02-03	D. Pogue
Research Queen's University's Energy Consumption	Fri 23-02-10	H. Kruizinga
Research Solar Production Based on Number of Panels	Fri 23-02-10	H. Kruizinga
Research Impacts of Solar Projects on Wildlife	Fri 23-02-10	H. Kruizinga
Research How Solar Panels Impact Climate Change	Fri 23-02-10	H. Kruizinga
Compare Production to Energy Consumption	Fri 23-02-10	H. Kruizinga
Research, Model, and Write Innovation Section	Fri 23-02-10	H. Kruizinga
GM Meeting and Update Meeting Log	Fri 23-02-10	D. Pogue
Update Project Plan	Fri 23-03-03	H. Kruizinga
GM Meeting and Update Meeting Log	Fri 23-03-03	D. Pogue
Investigate Queen's Climate Action Plan	Fri 23-03-10	M. Campbell
Review the Long-Term Impacts of this Project	Fri 23-03-10	H. Kruizinga
Research Electricity Costs	Fri 23-03-10	H. Kruizinga
Determine Cost of Project	Tue 23-03-14	D. Pogue
7.0 Draft Final Report	**Fri 23-03-24**	**M. Campbell**
Review Report Requirements	Fri 23-03-10	M. Campbell
Set-up Report and Divide Deliverables	Fri 23-03-10	M. Campbell
Update WBS and Gantt Chart	Fri 23-03-10	H. Kruizinga
GM Meeting and Update Meeting Log	Fri 23-03-10	M. Campbell
Conclude Roof Needs for Future Solar Panels	Fri 23-03-10	Group T
Write Draft Final Report	Wed 23-03-15	Group T
Initial Edit	Fri 23-03-17	M. Campbell

Task Name	Due	Resource Names
Submit Draft Final Report to GM for Feedback	Fri 23-03-17	M. Campbell
GM Meeting and Update Meeting Log	Fri 23-03-17	M. Campbell
Edit Final Report Based on Feedback	Wed 23-03-22	M. Campbell
Submit Progress Report	Fri 23-03-24	H. Kruizinga
8.0 Oral Presentation	**Mon 23-03-27**	**M. Campbell**
Review Presentation Requirements	Fri 23-03-24	M. Campbell
Review Information to Present On	Fri 23-03-24	M. Campbell
Make Poster Board	Mon 23-03-27	M. Campbell
Prepare and Practice Presentation Points	Mon 23-03-27	M. Campbell
Give Oral Presentation	Mon 23-03-27	M. Campbell
9.0 Wrap-up Phase	**Fri 23-04-21**	**H. Kruizinga**
Apply Feedback to Draft Final Report	Fri 23-04-21	H. Kruizinga
Submit Final Report to Client	Fri 23-04-21	H. Kruizinga
Reflection - Experience Recorded	Fri 23-04-21	Group T

Responsibility Assignment Matrix

Each task was given a due date and assigned to a person(s) through four roles as shown in Table 26.

Table 26 Four Roles of Responsibly Assignment Matrix

Title	Description
Responsible	The person(s) who will complete the task
Accountable	The person who will make decisions, delegate responsibly, and coordinate steps to complete the task
Consulted	The person(s) who will be communicated with when decisions are made, or tasks are finished
Informed	The person(s) who will be made aware during the project is when it is complete

The RAM is shown in Table 27 and allowed for responsibilities to be clear as there is a range of involvement from different team members over the duration of the semester.

Table 27 Responsibility Assignment Matrix

Tasks	Due	Roles					
		MC	HK	EM	DP	C	GM
1.0 Initial Phase	**20-Sep**						
Started Bid	09-Sep	R	R	R	R	C	I
Set up Client Meeting	09-Sep	I	I	A,R	I	I	I
Prepare Group Agreement	15-Sep	R	I	R	I		I
2.0 Work Plan	**30-Sep**						
Brainstorm Problem	21-Sep	R	A,R	R	R	C	C
Define Problem and Scope	21-Sep	R	A,R	R	R	C	
Decide Subsection Leads	21-Sep	R	A,R	R	R	C	
Preliminary Research - Structural	25-Sep	I	R	I	I		
Preliminary Research - Implementation	25-Sep	I	I	R	I		
Preliminary Research - Financial	25-Sep	I	I	I	R		
Preliminary Research - Structural	25-Sep	R	I	I	I		
Develop Project Plan	25-Sep	C	R	C	C		
Write Work Plan	25-Sep	C	R	C	C		
Initial Edit	26-Sep	R	A,R	R	R		
Submit Work Plan	30-Sep	I	A,R	I	I		
3.0 Structural Phase	**26-Oct**						
Obtain Supporting Documents from Client	04-Oct	I	A,R	I	I	C	
Research Solar Panels	19-Oct	I	C	A,R	I	C	
Research Snow Loading	19-Oct	A,R	C	I	I	C	
Research Roof Capacities	19-Oct	I	C	I	A,R	C	
Review Types of Buildings on Campus	19-Oct	I	A,R	I	I	C	
Review and Update Snow Loading Documents	26-Oct	A,R	I	I	I	C	
Review and Update Roof Capacity Documents	26-Oct	I	I	I	A,R	C	
Evaluate Campus Buildings	26-Oct	C	A,R	C	C	C	
Client Meeting - Review Decisions	26-Oct	R	A,R	R	R	C,R	
4.0 Implementation Phase	**09-Nov**						
Research Different Solar Panel Installation Methods	02-Nov	I	I	A,R	I	C	
Research Transportation for Panels	02-Nov	I	A,R	C	I	C	

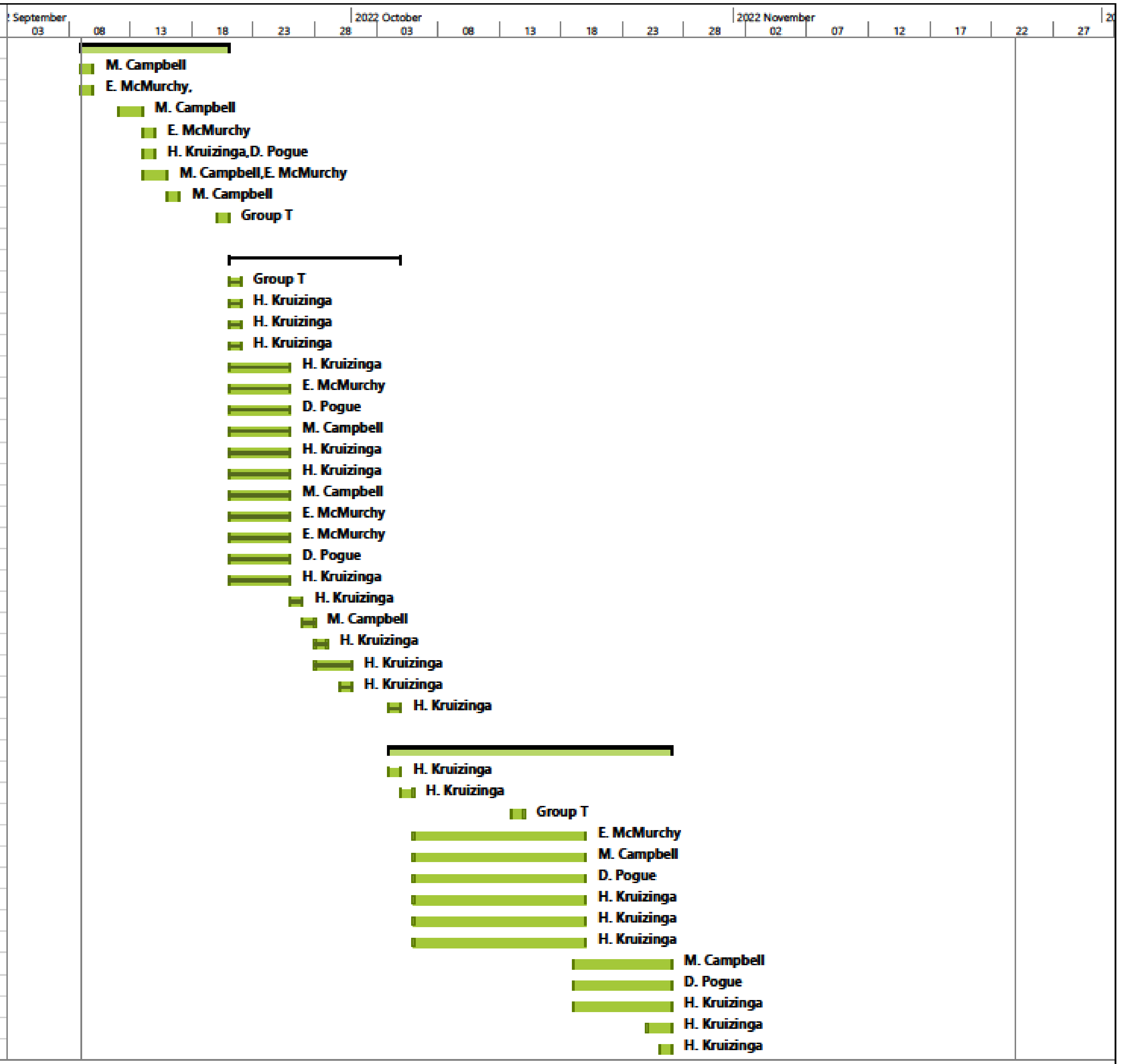
Tasks	Due	Roles					
		MC	HK	EM	DP	C	GM
Research Potential Electrical Connection Through Roof	02-Nov	A,R	I	C	I	C	
Meeting with Electrical Engineer lead	03-Nov	R	R	A,R	R	C,R	
Evaluation Matrix of Install Methods and Final Choice	04-Nov	C	C	A,R	C		
Review Loading Documents to Ensure Safe Install	08-Nov	I	C	A,R	I	C	
Research Environmental Impacts of Solar Panels	08-Nov	A,R	I	C	I	C	
Revise Finding and Decision in Proper Format	08-Nov	C	C	A,R	C	C	
Client Meeting - Review Decisions	08-Nov	R	R	A,R	R	C,R	
5.0 Progress Report	**25-Nov**						
Review Report Requirements	09-Nov	R	R	A,R	R		C
Update WBS and Gantt Chart	09-Nov	C	R	C	C		
Write Progress Report	14-Nov	R	R	A,R	R		I
Initial Edit	14-Nov	R	R	A,R	R		
Edit Progress Report Based on Feedback	23-Nov	R	R	A,R	R		
Submit Progress Report	23-Nov	I	I	R	I		
6.0 Modeling Phase	**14-Feb**						
Apply Feedback from Progress Report	27-Jan	I	R	I	I		
Research Cost of Panels and Roof Installation	14-Mar	I	I	I	R		
Evaluation Matrix of Install Methods and Final Choice	14-Mar	I	I	R	I		
Review Loading Documents to Ensure Safe Install	03-Mar	R	C	I	I		
Research Queen's University's Energy Consumption	10-Feb	C	R	I	I		
Research Solar Production Based on Number of Panels	10-Feb	C	R	I	I		
Research Impacts of Solar Projects on Wildlife	10-Feb	C	R	I	I		
Research How Solar Panels Impact Climate Change	10-Feb	C	R	I	I		
Compare Production to Energy Consumption	10-Feb	C	R	I	I		
Research, Model, and Write Innovation Section	10-Feb	C	R	I	I		
Update Project Plan	03-Mar	I	R	I	I		
Investigate Queen's Climate Action Plan	10-Mar	R	C	I	I		
Review the Long-Term Impacts of this Project	10-Mar	I	R	I	I		
Research Electricity Costs	10-Mar	I	R	I	I		
Determine Cost of Project	14-Mar	I	I	I	R		

Tasks	Due	Roles					
		MC	HK	EM	DP	C	GM
7.0 Draft Final Report	**24-Mar**						
Review Report Requirements	10-Mar	R	C	C	C		C
Set-up Report and Divide Deliverables	10-Mar	R	C	C	C		C
Update WBS and Gantt Chart	10-Mar	I	R	I	I		C
Conclude Roof Needs for Future Solar Panels	10-Mar	R	R	R	R		
Write Draft Final Report	15-Mar	R	R	R	R		
Initial Edit	17-Mar	R	R	R	R		
Submit Draft Final Report to GM for Feedback	17-Mar	I	R	I	I		C
Edit Final Report Based on Feedback	22-Mar	I	R	I	I		
Submit Progress Report	24-Mar	I	R	I	I		
8.0 Oral Presentation	**27-Mar**						
Review Presentation Requirements	24-Mar	R	C	C	C		C
Review Information to Present On	24-Mar	R	R	R	R		
Make Poster Board	27-Mar	R	R	R	R		
Prepare and Practice Presentation Points	27-Mar	R	R	R	R		
Give Oral Presentation	27-Mar	R	R	R	R		
9.0 Wrap-up Phase	**21-Apr**						
Apply Feedback to Draft Final Report	21-Apr	I	R	I	I		
Submit Final Report to Client	21-Apr	I	R	I	I	I	
Reflection - Experience Recorded	21-Apr	R	R	R	R		

Timeline Estimates

A Gantt chart was developed to outline estimated timelines and days associated to each task as shown in Figure 24, Figure 25, and Figure 26. Each task is given a summary item that corresponds to the nine phases and a person responsible to ensure it is complete.

ID	Task Name	Finish	Duration
1	**1.0 Initial Phase**	Tue 22-09-20	8 days
2	Started Bid	Fri 22-09-09	1 day
3	Set up Client Meeting	Fri 22-09-09	1 day
4	Brainstorm and Prepare for Client Meeting	Tue 22-09-13	2 days
5	Client Meeting	Wed 22-09-14	1 day
6	Client Meeting Summary	Wed 22-09-14	1 day
7	Prepare Group Agreement	Thu 22-09-15	2 days
8	Set up Group Manager (GM) Meeting	Fri 22-09-16	1 day
9	Attend GM Meeting	Tue 22-09-20	1 day
10			
11	**2.0 Work Plan**	Tue 22-10-04	10 days
12	Brainstorm Problem	Wed 22-09-21	1 day
13	Define Problem and Scope	Wed 22-09-21	1 day
14	Decide Subsection Leads	Wed 22-09-21	1 day
15	Set-up Report and Divide Deliverables	Wed 22-09-21	1 day
16	Preliminary Research - Structural	Sun 22-09-25	4 days
17	Preliminary Research - Implementation	Sun 22-09-25	4 days
18	Preliminary Research - Financial	Sun 22-09-25	4 days
19	Preliminary Research - Structural	Sun 22-09-25	4 days
20	Develop Work Breakdown Structure	Sun 22-09-25	4 days
21	Develop Gantt Chart	Sun 22-09-25	4 days
22	Write Sections 1.1, 1.2, 1.3, 3.3	Sun 22-09-25	4 days
23	Write Sections 1.4, 1.5, 3.2	Sun 22-09-25	4 days
24	Add Group Agreement to Appendix	Sun 22-09-25	4 days
25	Write Sections 3.3, 4.0	Sun 22-09-25	4 days
26	Write Sections 2.0, 3.1	Sun 22-09-25	4 days
27	Initial Edit	Mon 22-09-26	1 day
28	Submit Work Plan to GM for Feedback	Tue 22-09-27	1 day
29	GM Meeting and Update Meeting Log	Wed 22-09-28	1 day
30	Edit Work Plan Based on Feedback	Fri 22-09-30	3 days
31	Submit Work Plan	Fri 22-09-30	1 day
32	Client Meeting - Submit Work Breakdown	Tue 22-10-04	1 day
33			
34	**3.0 Structural Phase**	Wed 22-10-26	17 days
35	Obtain Supporting Documents from Client	Tue 22-10-04	1 day
36	GM Meeting and Update Meeting Log	Wed 22-10-05	1 day
37	Peer Review	Fri 22-10-14	1 day
38	Research Solar PV Panels	Wed 22-10-19	10 days
39	Research Snow Loading	Wed 22-10-19	10 days
40	Research Roof Capacities	Wed 22-10-19	10 days
41	Review Types of Buildings on Campus	Wed 22-10-19	10 days
42	Develop Evaluation Matrix for Acceptable Buildings	Wed 22-10-19	10 days
43	GM Meeting and Update Meeting Log	Wed 22-10-19	10 days
44	Review and Update Snow Loading Documents	Wed 22-10-26	6 days
45	Review and Update Roof Capacity Documents	Wed 22-10-26	6 days
46	Evaluate Campus Buildings	Wed 22-10-26	6 days
47	Client Meeting - Review Decisions	Wed 22-10-26	2 days
48	GM Meeting and Update Meeting Log	Wed 22-10-26	1 day



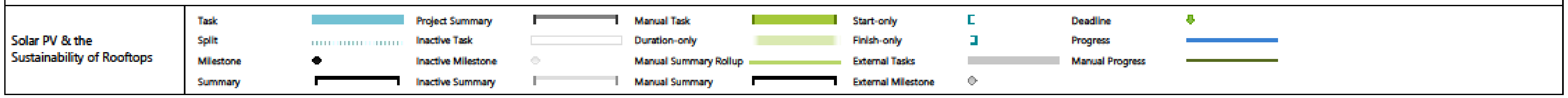
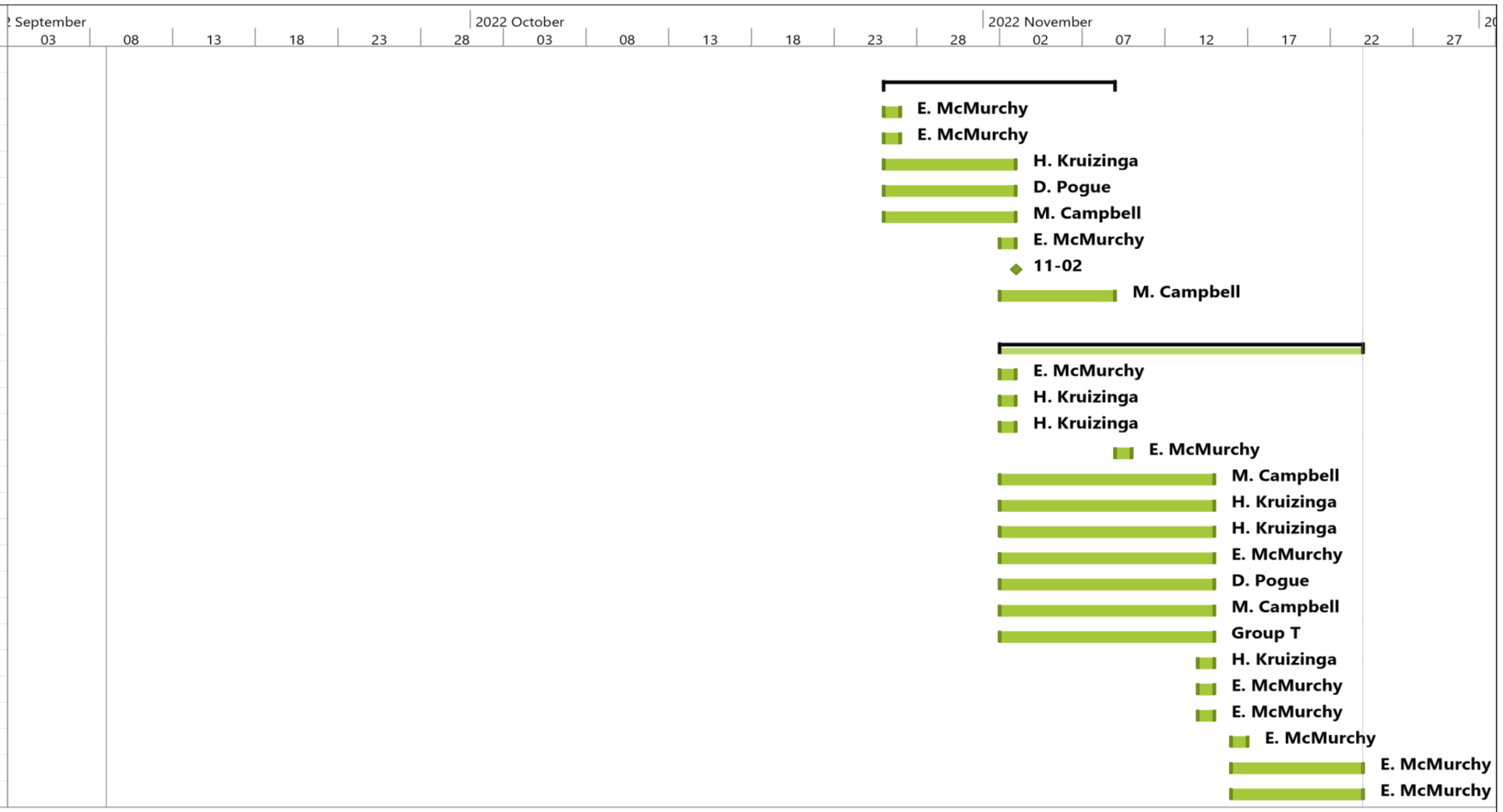


Figure 24 Semester 1a Gantt Chart

ID	Task Name	Finish	Duration
49			
50	**4.0 Implementation Phase**	**Tue 22-11-08**	**10 days**
51	Set-up Meeting with Electrical Engineer Lead	Wed 22-10-26	1 day
52	Research Different Types of Solar Panel Install Methods	Wed 22-10-26	1 day
53	Research Transportation for Panels to Queens Buildings	Wed 22-11-02	6 days
54	Research Cost Efficiency of Each Install Method	Wed 22-11-02	6 days
55	Research Potential Electrical Connection Through Roof	Wed 22-11-02	6 days
56	GM Meeting and Update Meeting Log	Wed 22-11-02	1 day
57	Meeting with Electrical Engineer lead	Wed 22-11-02	0 days
58	Research Environemental Impacts of Solar Panels	Tue 22-11-08	5 days
59			
60	**5.0 Progress Report**	Wed 22-11-23	**16 days**
61	Review Report Requirements	Wed 22-11-02	1 day
62	Set-up Report and Divide Deliverables	Wed 22-11-02	1 day
63	Update WBS and Gantt Chart	Wed 22-11-02	1 day
64	GM Meeting and Update Meeting Log	Wed 22-11-09	1 day
65	Update Transmissional Letter and Fix References	Mon 22-11-14	9 days
66	Edit Section 1	Mon 22-11-14	9 days
67	Write Section 2	Mon 22-11-14	9 days
68	Write Section 3	Mon 22-11-14	9 days
69	Write Section 4	Mon 22-11-14	9 days
70	Write Section 5,6	Mon 22-11-14	9 days
71	Write Section 8	Mon 22-11-14	9 days
72	Write Conclusion and Executive Summary	Mon 22-11-14	1 day
73	Initial Edit	Mon 22-11-14	1 day
74	Submit Progress Report to GM for Feedback	Mon 22-11-14	1 day
75	GM Meeting and Update Meeting Log	Wed 22-11-16	1 day
76	Edit Progress Report Based on Feedback	Wed 22-11-23	6 days
77	Submit Progress Report	Wed 22-11-23	6 days

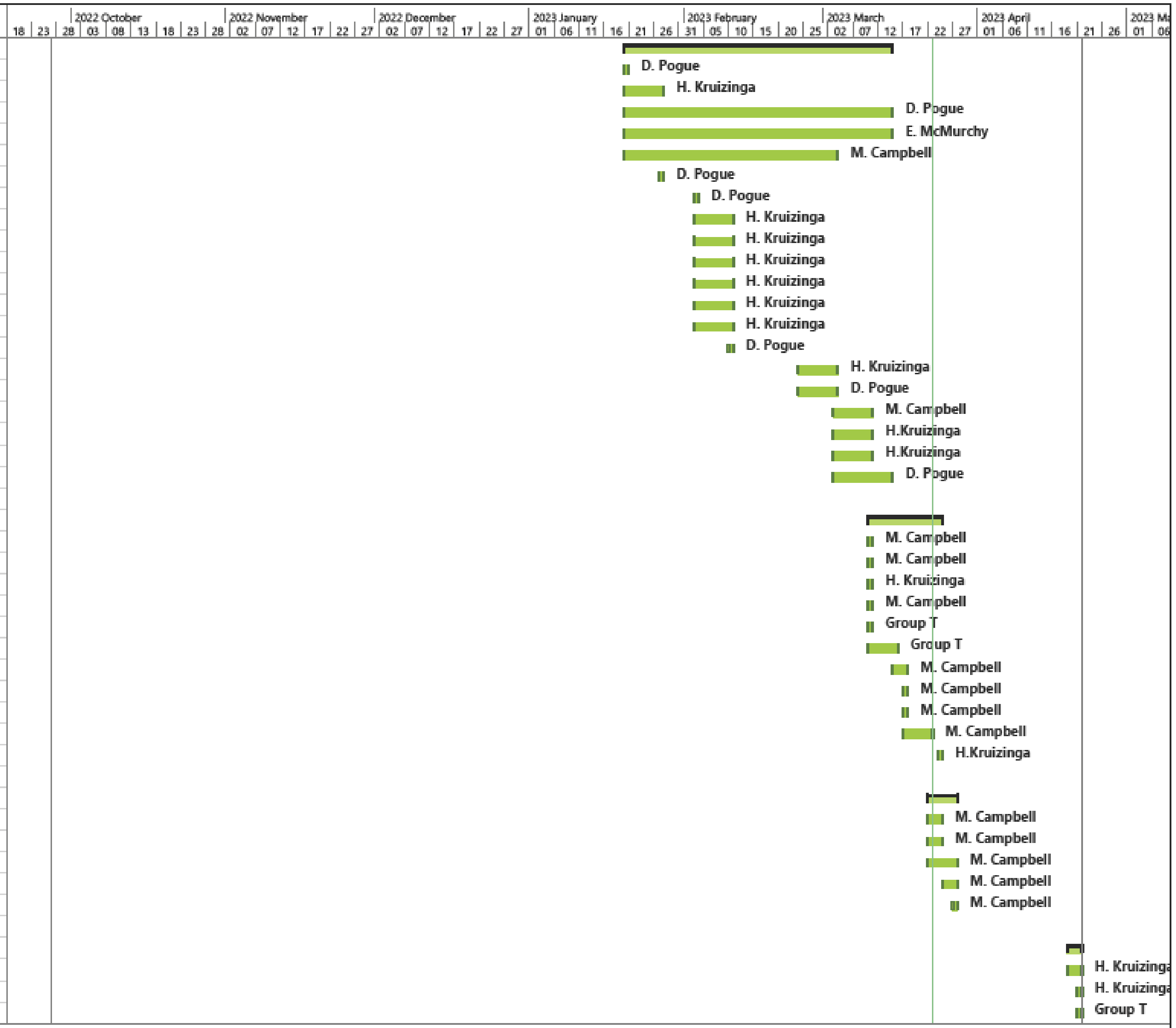


Solar PV & the Sustainability of Rooftops

Task	Project Summary	Manual Task	Start-only	Deadline
Split	Inactive Task	Duration-only	Finish-only	Progress
Milestone	Inactive Milestone	Manual Summary Rollup	External Tasks	Manual Progress
Summary	Inactive Summary	Manual Summary	External Milestone	

Figure 25 Semester 1b Gantt Chart

ID	Task Name	Finish
1	**6.0 Modeling Phase**	Tue 23-03-14
2	GM Meeting and Update Meeting Log	Fri 23-01-20
3	Apply Feedback from Progress Report	Fri 23-01-27
4	Research Cost of Panels and Roof Installation	Tue 23-03-14
5	Evaluation Matrix of Install Methods and Final Choice	Tue 23-03-14
6	Review Loading Documents to Ensure Safe Install	Fri 23-03-03
7	GM Meeting and Update Meeting Log	Fri 23-01-27
8	GM Meeting and Update Meeting Log	Fri 23-02-03
9	Research Queen's University's Energy Consumption	Fri 23-02-10
10	Research Solar Production Based on Number of Panels	Fri 23-02-10
11	Research Impacts of Solar Projects on Wildlife	Fri 23-02-10
12	Research How Solar Panels Impact Climate Change	Fri 23-02-10
13	Compare Production to Energy Consumption	Fri 23-02-10
14	Research, Model, and Write Innovation Section	Fri 23-02-10
15	GM Meeting and Update Meeting Log	Fri 23-02-10
16	Update Project Plan	Fri 23-03-03
17	GM Meeting and Update Meeting Log	Fri 23-03-03
18	Investigate Queen's Climate Action Plan	Fri 23-03-10
19	Review the Long-Term Impacts of this Project	Fri 23-03-10
20	Research Electricity Costs	Fri 23-03-10
21	Determine Cost of Project	Tue 23-03-14
22		
23	**7.0 Draft Final Report**	Fri 23-03-24
24	Review Report Requirements	Fri 23-03-10
25	Set-up Report and Divide Deliverables	Fri 23-03-10
26	Update WBS and Gantt Chart	Fri 23-03-10
27	GM Meeting and Update Meeting Log	Fri 23-03-10
28	Conclude Roof Needs for Future Solar Panels	Fri 23-03-10
29	Write Draft Final Report	Wed 23-03-15
30	Initial Edit	Fri 23-03-17
31	Submit Draft Final Report to GM for Feedback	Fri 23-03-17
32	GM Meeting and Update Meeting Log	Fri 23-03-17
33	Edit Final Report Based on Feedback	Wed 23-03-22
34	Submit Progress Report	Fri 23-03-24
35		
36	**8.0 Oral Presentation**	Mon 23-03-27
37	Review Presentation Requirements	Fri 23-03-24
38	Review Information to Present On	Fri 23-03-24
39	Make Poster Board	Mon 23-03-27
40	Prepare and Practice Presentation Points	Mon 23-03-27
41	Give Oral Presentation	Mon 23-03-27
42		
43	**9.0 Wrap-up Phase**	Fri 23-04-21
44	Apply Feedback to Draft Final Report	Fri 23-04-21
45	Submit Final Report to Client	Fri 23-04-21
46	Reflection - Experience Recorded	Fri 23-04-21



Solar PV & the Sustainability of Rooftops	Task	Project Summary	Manual Task	Start-only	Deadline
	Split	Inactive Task	Duration-only	Finish-only	Progress
	Milestone	Inactive Milestone	Manual Summary Rollup	External Tasks	Manual Progress
	Summary	Inactive Summary	Manual Summary	External Milestone	

Figure 26 Semester 2 Gantt chart