Tab 1

Proposed Conceptual Design Specification
for
Wind/Solar Microgrid

Prepared for
Elliott Stambler
The Sustainability Office

Prepared by APS112 Team 036
Marcus Barbarie
Moira Boland
Marlena Fok
Frank Hao
Nirvaan Shah
Jonathan Xian

Faculty of Applied Science and Engineering
University of Toronto

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Executive Summary

The UofT Sustainability Office aims to cut carbon emissions by integrating renewable energy into a microgrid for the Medical Science Building. The current system relies on conventional energy, lacking a renewable solution. A microgrid will enable low-emission, self-sufficient power generation, reducing reliance on external grids and supporting UofT's sustainability goals.

The microgrid will generate, store, and distribute renewable power, aiming for net-zero emissions, cost efficiency, and reliability with minimal maintenance. It must meet all safety and environmental standards. Site limitations restrict the design to available land, making solar panels and wind turbines the only feasible energy sources. In developing the project, the Team has also taken into consideration key stakeholders including UofT staff affected by energy use, UofT Facilities for infrastructure integration, the City of Toronto for permits, and the Ministry of Municipal Affairs for regulations.

Transitioning from these project requirements to the conceptual design specifications, the design phase began with brainstorming ideas for all secondary functions. The modular nature of the brainstorming process allowed us to use a morph chart to combine components and generate 50 complete solutions. Resulting ideas were systematically refined through multivoting, and a graphical decision chart. The SCAMPER (Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, and Reverse) method, which generated 10 more solutions, evaluated advantages and merged ideas. This process yielded three final design solutions. These tools were used to expand the design space, narrow down solutions and find the solution that best fit the objective of the project.

Subsequent analysis with a Pugh decision matrix revealed clear tradeoffs among designs. The Tandem Iron-Air Microgrid, which combined dual energy capture methods, was discarded due to higher maintenance demands and costs, unproven emerging technology and turbine upkeep. The AC Flow Wind System, featuring a flow battery was rejected because its large electrolyte tanks proved inefficient for the limited space. Ultimately, Design 45—the Mono Solar Smart Grid—was selected as it best met the client's objectives by reducing natural gas use, lowering carbon emissions, and optimizing space through industry-proven solar panels and high-density batteries.

In the next phase of the project, the client will review this document. The team will receive feedback, refine designs, and test the project's ability to reduce carbon emissions which is the main objective of this project. The team will then prepare a final presentation, to illustrate the design, and present it to the client.

1. Introduction

The University of Toronto (UofT) St George campus, in downtown Toronto is an academic and research institution with extensive infrastructure with significant energy consumption [1]. Being the third largest consumer of electricity in the city, UofT relies almost entirely on conventional electrical sources, which emit heat-trapping greenhouse gases, contributing to climate change [1], [2]. The Medical Science Building (MSB) is a high-energy consumer [1].

The UofT sustainability office, which oversees the university's environmental initiatives [2], [3] has recognized this issue and identified the need for a transition towards green energy solutions – defined as energy sources that produce no greenhouse gas emissions. Their proposal includes a green energy microgrid on campus to mitigate dependency on non-renewable sources and lower carbon footprint (Appendix A). A microgrid is a small, local energy system that operates independently or in combination with the main grid by using nearby power sources and storage.

This report defines the design space needed to meet the client's requirements and evaluates the feasibility of implementing a microgrid on campus by analyzing its scope, objectives, and constraints. It also details the team's idea generation and selection process leading to the top three alternative solutions. These solutions were assessed against the project objectives to identify a proposed conceptual design. A plan to measure the success of the design is also described. The end of the report contains a set of references and appendices to provide further details about the project.

2. Problem Statement

The UofT's Sustainability Office seeks to reduce the campus's carbon footprint and mitigate dependency on non-renewables. However, high-energy-consuming facilities like MSB, which house numerous laboratories, remain heavily dependent on non-renewable energy sources, contributing significantly to overall energy consumption [1]. The gap is the lack of a renewable energy system on campus that effectively reduces carbon emissions [4].

To bridge this gap, there is a need for a green energy microgrid that provides sustainable energy [5] while ensuring reliability for UofT operations. The client needs a microgrid that can lower emissions and promote self-sufficient energy generation, reducing dependency on external power grids and decreasing carbon footprint.

The scope of this project has several key factors. As mentioned above, the MSB is a suitable candidate for a local microgrid since it has high energy demands and low renewable energy utilization [1]. Therefore, the microgrid infrastructure is restricted to this building to minimize line losses and reduce energy waste lost to thermal efficiencies [6]. Energy generation will be limited to solar photovoltaic and wind energy systems, as other renewable sources such as hydroelectric, geothermal, or biomass are not viable due to land use constraints and client restrictions (Appendix A) [7]. Lastly, the microgrid, which operates continuously on a daily basis, must remain connected to the city of Toronto's electrical grid to provide redundancy and support peak demand periods [6], [8].

3. Stakeholders

The Stakeholders section discusses individuals or groups who may impact or be impacted by the design. Stakeholders in Table 1 are ranked based on their level of impact, from highest to lowest. The ranking was decided through the figure in Appendix B.

Table 1: Stakeholders

Stakeholders	Interest Level (High/Low)	Impact Level (High/Low)	Relation and Impact to the Microgrid Project (Justification)
UofT	High	High	The UofT Sustainability office's 2050 climate-positive goal includes plans to replace "fossil fuels with electricity as the primary source for thermal energy" [3].
	High	High	The UoT recently underwent "The Landmark Project", which was meant to renovate the "downtown campus into a greener, sustainable and accessible park-like setting [9] . Considering that the UofT states that "sensitive low-scale and mid-scale institutional buildings that reinforce the existing character are permitted" in the area, any infrastructure related to the microgrid should also meet these attributes [10].
Ministry of Municipal Affairs and Housing	High	High	The Ministry is responsible for building codes in Ontario and implements/regulates land planning projects. The microgrid project, must accommodate all regulations.[11] [12]
UofT Facilities and Services	Low	High	The Property Management sector has relevant responsibilities, including property inspections and scheduled maintenance, which may be required for the upkeep of a microgrid [12].
UofT Students and Staff	High	Low	The majority of St George's fuel consumption is used to heat buildings for students and staff [12]
City of Toronto	Low	High	The City of Toronto has to approve the permit application for the project to begin[13]

4. Service Environment

Given the scope of the project, the service environment comprises the physical, virtual, and living elements within MSB on the University of Toronto St. George campus. Figure 1 contains an aerial view of the MSB, and Figure 2 presents a schematic showing the layout of the MSB (outlined in red).

Figure 1. Aerial View of The MSB [7]

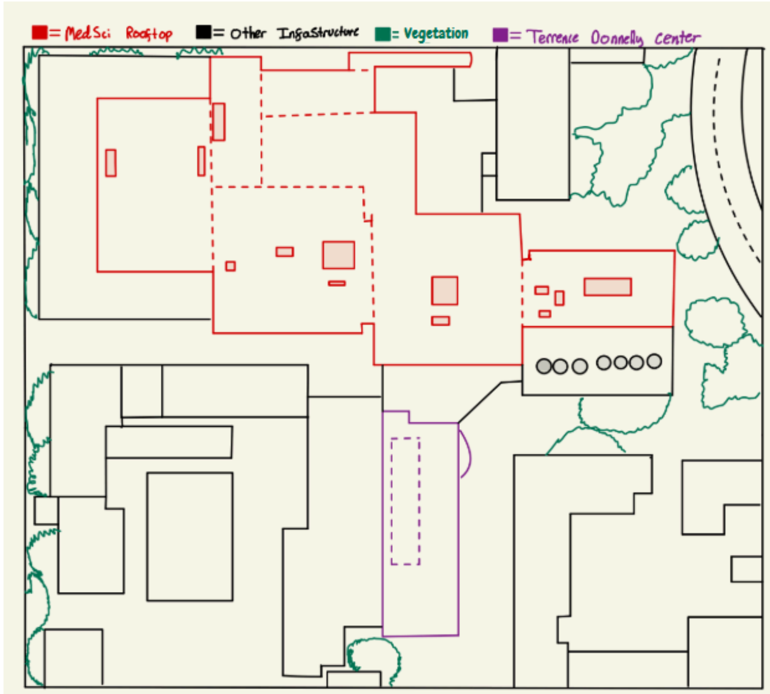

Figure 2. Bird's Eye View of MBS[7]

4.1 Physical

Figures 3 to 6 present climate information related to the service environment for the project.

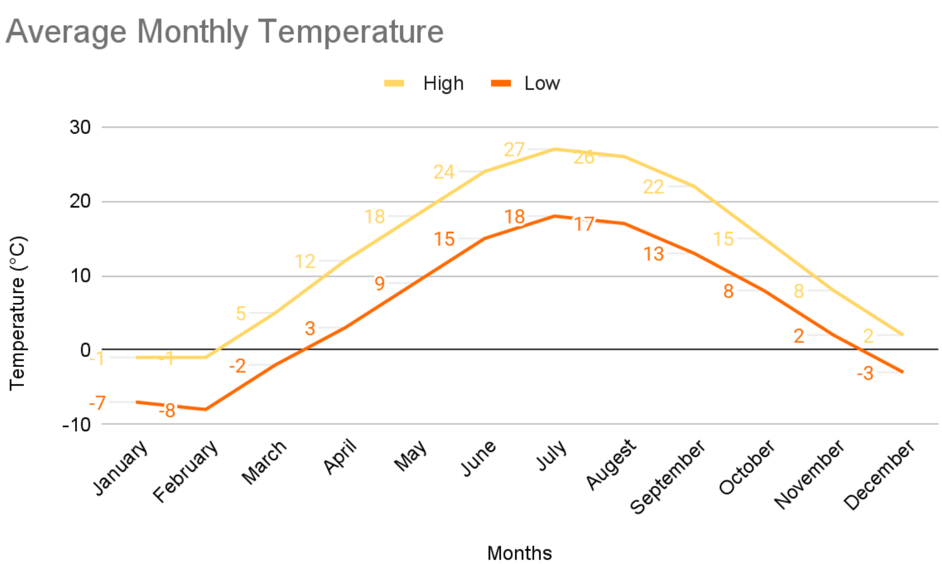

Figure 3. Average monthly temperature in Toronto.[14]

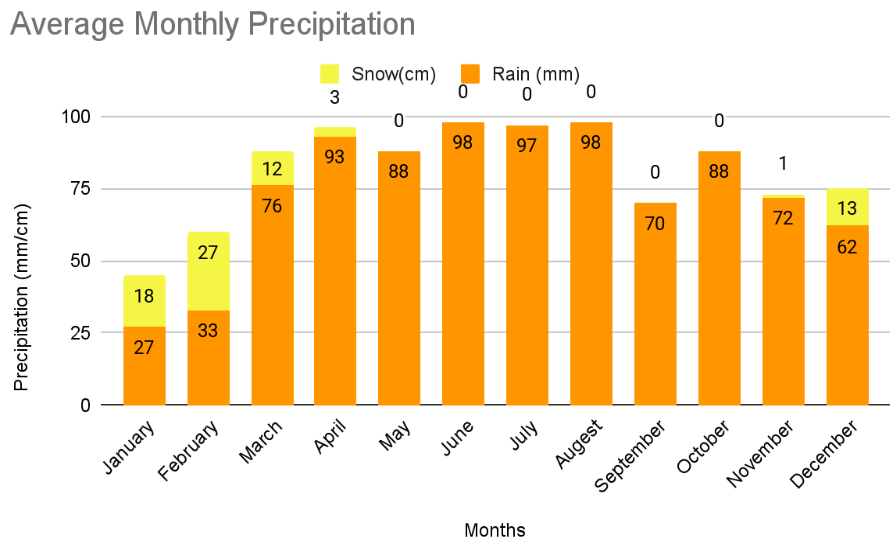

Figure 4. Average monthly precipitation in Toronto [14]

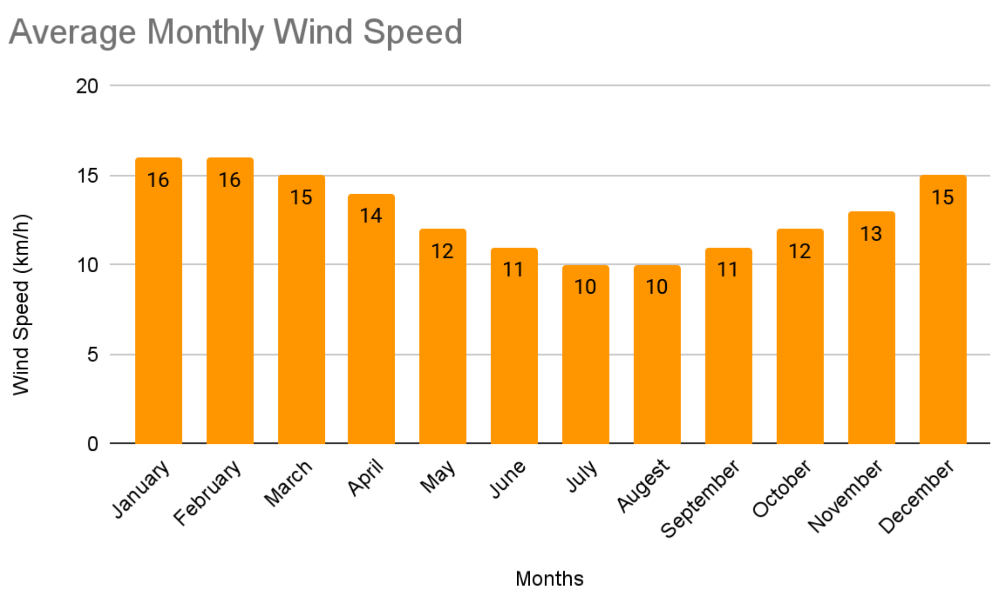

Figure 5. Average monthly wind speed in Toronto [14]

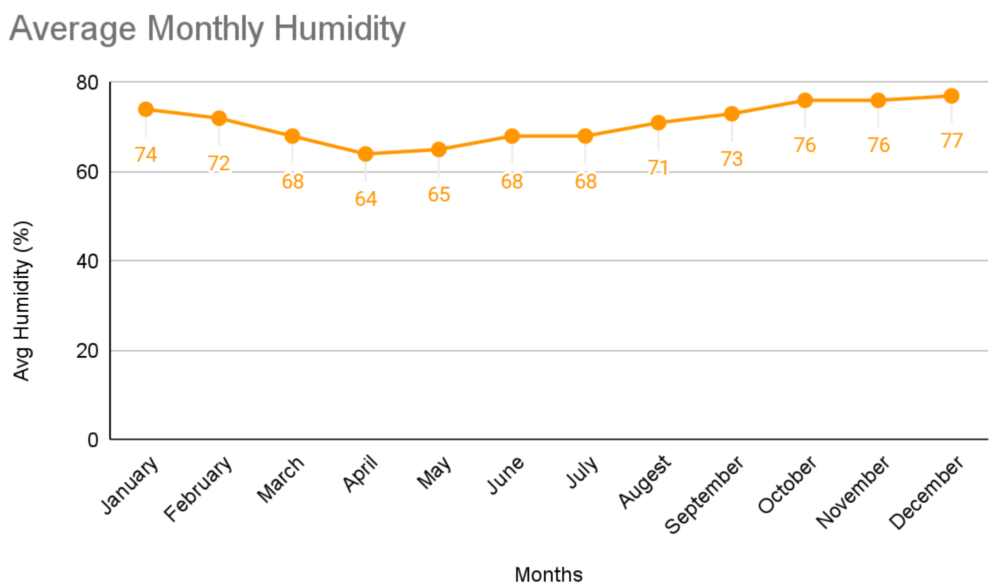

Figure 6. Average monthly humidity in Toronto. [14]

The physical environment table describes the climate, building functions and greenhouse gas emissions.

Table 2: Elements of Physical Environment

Physical Environment	
MSB, UofT	-Constructed Year: 1969 -Size: 71192m^2 -Energy Use Intensity (EUI) 1003 kWh/m^2 * [15] Roof area = 6000m^2 (Appendix C)
	-Building functions:[1] Lab: 84.2 % Academic: 12.9 % General: 1.3 % Athletics: 1.3 % Library: 0.4 %
Greenhouse gas emission	Total annual greenhouse gas emission of UofT: 96,660.1 tCO_2e Carbon footprint of UofT: 32.4 tCO_2e/$M [16]

4.2 Living

The living things table focuses on wildlife and staff.

Table 3: Elements of Living Things

Living Things	
Microbes	-Bacteria, Human pathogens, fungi, and prions (Found in rainwater, debris, soil and Feces of animals) [17]
Animals	-Insects: ants, bed bugs, cluster flies, cockroaches, fleas, and wasp [18] -Birds: peregrine falcons, chimney swifts, common nighthawks, barn swallows, geese [19]
People	MSB -Property Managers: Barry Espin, Jennifer Corinthios, Ted Kent, Mike Carere -Area Manager: John Walker [1] -Director of Operations: Gina John [20]

4.3 Virtual

The virtual environment table defines the Wifi, cellular network and energy.

Table 4: Elements of Virtual Environment

Virtual Environment	
Wifi	Provider: Roger Communication Inc. -Supports 802.11ax, 802.11ac, 802.11n, 802.11a and 802.11g wifi standards. -Internet speed is 44 Mbps. -Upload speed is 78 Mbps. -Unload latency is 16ms -Loaded latency is 200m [21] -Rogers Wireless's 5G coverage[25]
Energy	MSB:[1] -Electricity UI [kBtu/sqFt]: 124.95 -Steam UI [kBtu/sqFt]: 192.39 -Gas UI [kBtu/sqFt]: 0.6 [1]

5. Detailed Requirements

The following section defines the success factors of the project, including tables outlining the functions, objectives, and constraints.

5.1 Functions

The design addresses the need for a green energy microgrid at UofT. The functions are identified in Table 5. Secondary functions, which enable the primary function were formulated using a how-why tree in *Appendix D*.

Table 5: Primary and Secondary Functions

Primary Functions
• Capture and transform energy
Secondary Functions
• Capture Energy from renewable sources • Transform natural energy into electrical energy • Store electrical energy from the microgrid • Output the energy toward the UofT Infrastructure

5.2 Objectives

Table 6 outlines key objectives, supported by metrics, goals, and justifications. These objectives are success factors, providing measurable criteria to assess how the microgrid design aligns with the scope/requirements of the project. Pairwise comparison is used to rank the objectives in order of priority (Appendix E- Table B).

Table 6: Objectives

#	Objectives	Metrics	Goals	Justifications
O.1	Reduce Carbon Emissions	Metric Tonnes	Net zero carbon emissions 0 tonnes	Part of the 2050 carbon emission reduction initiative[22]
O.2	Fulfill Energy Generation Need	Kilo British Thermal Unit per Square Feet (kBtu/sqFt)	124.95kBtu/sqFt	Refer to *Table 4*, Energy. Amount of energy consumed/sqFt was determined using MSB energy consumption [1]
O.3	Operate without maintenance	Months	≥12 months	UofT Tri-Campus Energy Modelling and Utility Performance Standard[23]
O.4	Minimize cost of energy generation	Dollars (CAD) per kWh	≤ 15.8 ¢	Looking at the current cost of electricity, an objective was identified[24]
O.5	Uses space efficiently	m^2	≤6000m^2	Roof area available is fixed [7] (Appendix D)

5.3 Constraints

This section compiles constraints in legislation and the client. They are each provided with metrics and goals that must be attained with the design.

Table 7: Constraints

#	Constraint	The Design Must Meet:	Metric	Goals	Justification *Legal…*
C.1	Ontario Noise Laws	Worker Noise Exposure Limits[25]	Decibels	85	Maximum when workers are around
		Class 1 Area Wind Turbine Sound Limit[26]	Decibels	51	Maximum, downtown Toronto is classified as a class 1 area
C.2	Ontario Structural Safety and Load Requirements	Live Load [27]	KiloPascals (N/m^2)	Min 3.6	Maximum for building on a rooftop
		Dead Load[28]	KiloPascals (N/m^2)	Max 0.5	Maximum for building on a rooftop
C.3	Ontario Rooftop Fire Safety Requirements	Egress Requirements[27]	Number of Egress	Min 2	Minimum for a rooftop in use
		Combustible Material Safety[27]	Combustible Materials Labeled	100% Labeled	Requirement for solar panels
C.4	Canadian Bird-Protection Regulation	Glass Treatments Under 4 Meters Above Building [29]	% Glass Glazed	90%	Requirement for building on a rooftop
		Glass Treatments Over 4 Meters Above Building [29]	% Glass Glazed	100%	Requirement for building on a rooftop

6. Alternative Designs

6.1 Idea Generation Process

The following section outlines the idea generation process used to arrive at the final alternative designs. Methods such as Morphological charts, SCAMPER, and Pugh method are described within the context of the project.

Solar and wind were the only viable energy options given constraints. A mechanical/electrical microgrid sub-component was brainstormed to fulfill each secondary function (Appendix F - Table C). After feasibility checks/iterations (Appendix F- Figure E) sub ideas were transferred to a Morphological Chart (Appendix F - Figure E) and combinations of sub-ideas were iterated to reach 50 complete solutions. This allowed us to broaden possible solutions within the limited scope of solar and wind. Next, the SCAMPER method (Appendix H) optimized combinations of sub-components (Appendix F - Figure F). By utilizing these methods, we developed 60 diverse, well structured solutions. The process is illustrated in Figure 6.

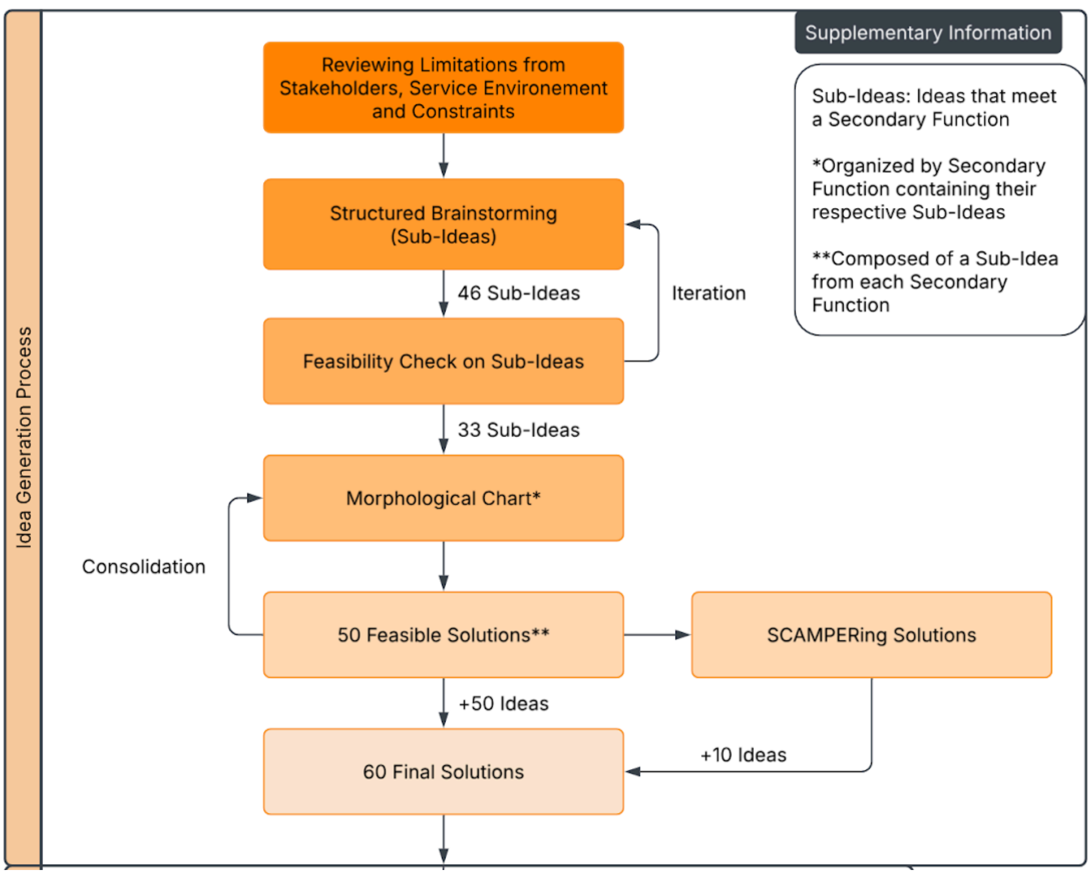

Figure 6. Idea Generation Process Flowchart

6.2 Alternative Design Selection Process

The next step was selecting the optimal design (Appendix F - Table F). Multivoting with 20 votes each determined the 10 best design solutions (Appendix G - Table G). Each team member had conducted research, thus multivoting could promote discussion and pool combined knowledge. Solutions were ranked in a Graphical Decision Chart based on top two objectives (Figure 8). Finally, the Pugh Chart was used to analyze the top three solutions against all objectives, providing a final solution (Appendix G - Table J). The Pugh chart could prioritize the relevance of trade offs in the context of our project. Balance between self-sufficiency and low maintenance versus maximizing energy output ensured the feasibility of running a microgrid on campus.The entire idea selection process can be seen in Figure 7.

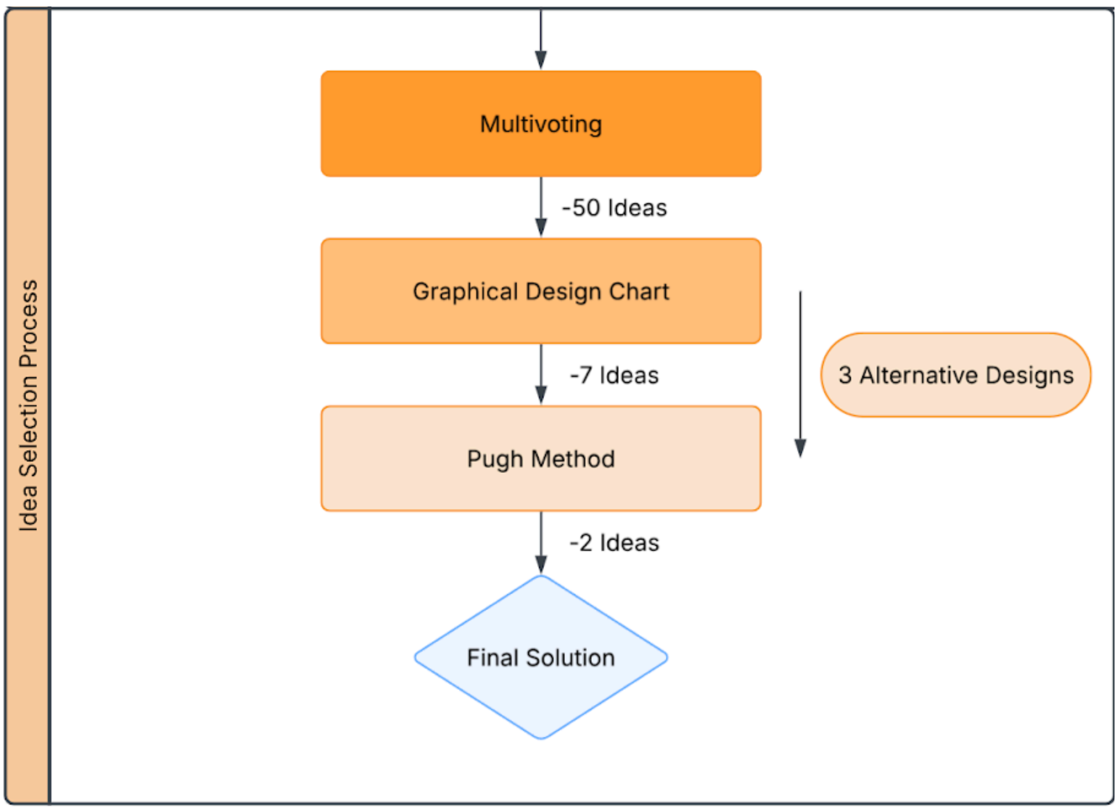

Figure 7. Idea Selection Process Flowchart

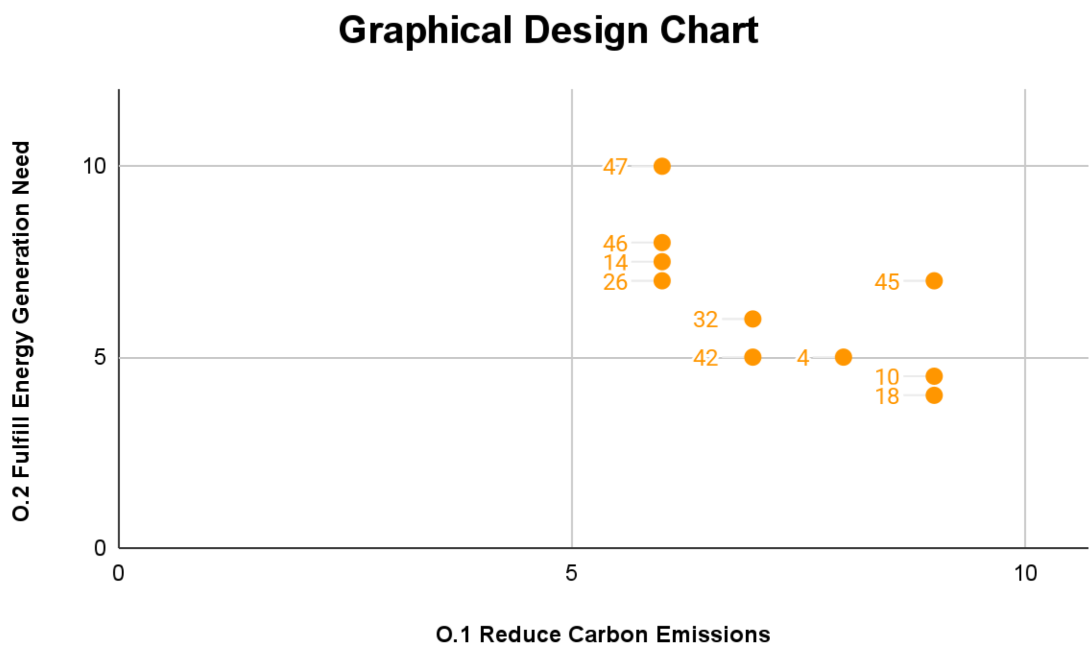

Figure 8. Graphical Design Chart Based on the top 2 objectives

6.3 Evaluation of Top Three Alternative Designs

The following section is a parallel comparison of the final three alternate design solutions. These designs were referenced against all functions, objectives and constraints.

6.3.1 The Mono Solar Smart Grid (MSSG)

The Mono Solar Smart Grid captures energy from stationary solar panels, transforms natural energy using monocrystalline silicon cells, stores energy with lithium-ion batteries and distributes energy through a smart grid and low-voltage distribution cables . The definition of Monocrystalline Silicon Cells, low-voltage distribution cables and lithium-ion Batteries can be found in Appendix H

The stationary solar panels (421 panels (Appendix I)) will be located on the rooftop, shown in Figure 9, with monocrystalline cells (MonoCells); lithium-ion batteries located on the lower rooftop (Figure 10). Smart grid, and the low voltage distribution cables will be integrated into the design. Table 8 below explains how the objectives are met for this solution.

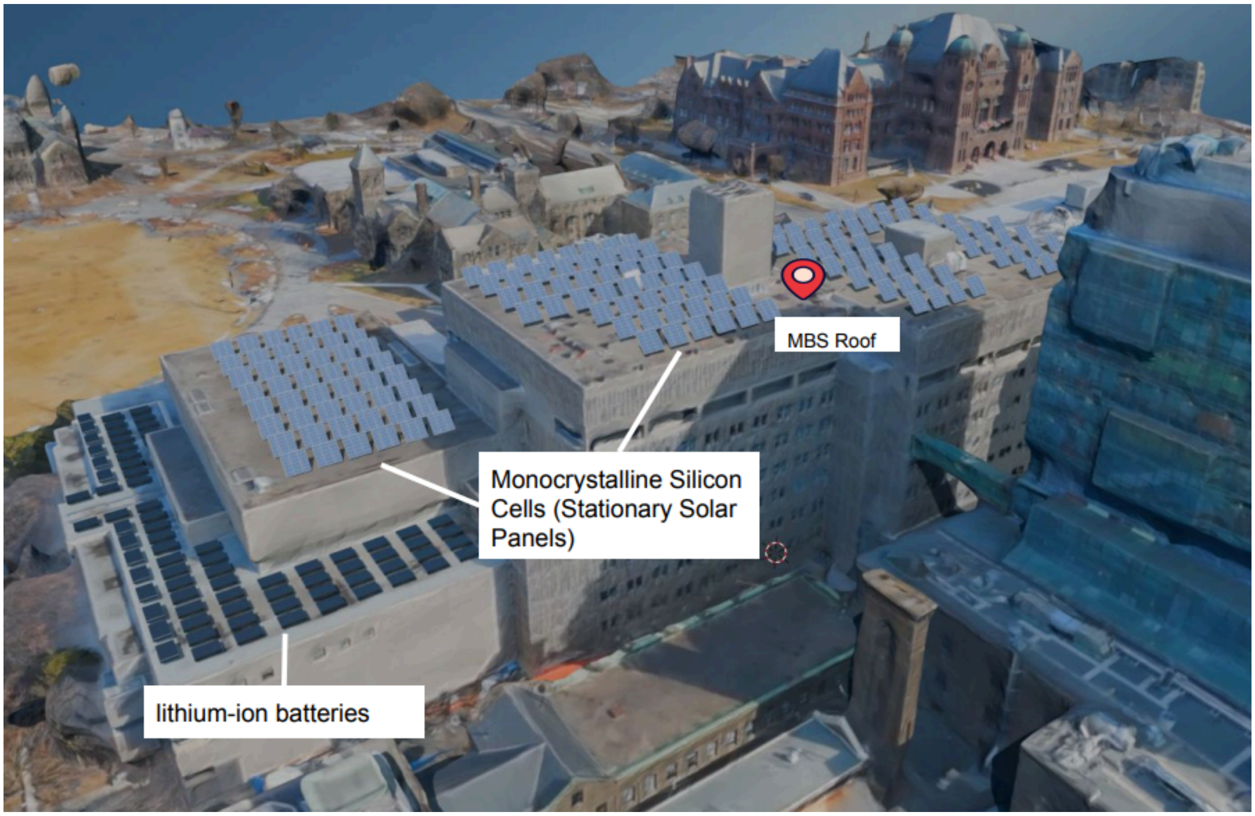

Figure 9 - The MSSG 3D Model

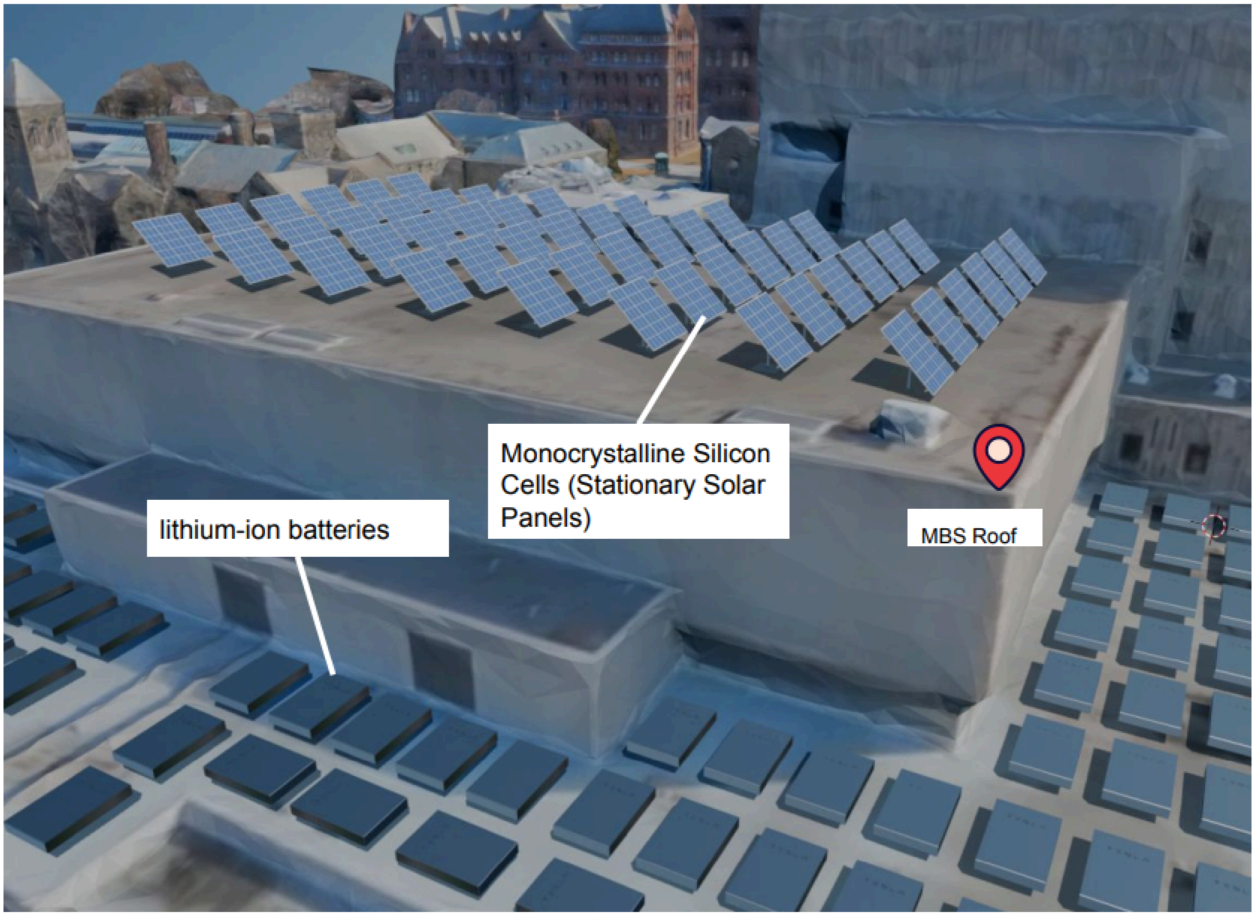

Figure 10 - Equipment view of MSSG

Table 8 - MSSG Objective Performance

Objectives	Performance	Justification
Reduce Carbon Emissions	Exceeds Goal: Net zero carbon emissions	-Solar/battery systems: reduce 80% of CO_2 versus traditional grid electricity. [30] -Smart Grid : Optimize energy distribution -Reduce emissions by 33% [31] [32].
Fulfill Energy Generation Needs	Exceeds Goal:124.95k Btu/sqFt	-MonoCells efficiency: “20-22%” [33] -Lithium-ion batteries: -Higher energy density -Increase the efficiency 95% [34] -Power Output(per m^2): 0.0141 kBtu/hr·ft^2[35]

Objectives	Performance	Justification
Operate without maintenance	Exceeds Goal: ≥12 months	-MonoCells: -Lifespans: 25–30 years [36] -Cleaning every 6 months[37] -Lithium-ion batteries life-span: 10-15 years [38]
Minimize cost of energy generation	Meets Goal:≤ 15.8 ¢	-MonoCells 20 - 25 dollars per kilogram[39] (Total weight = 2608 panels × 20 kg = 52,160 kg) -Lithium Ion Battery cost $100/KWH[40]
Fit within the designated roof space	Meets Goal:≤6000m	- The microgrid components < 6000m^2 (Appendix C)

6.3.2 AC Flow Wind System (AFWS)

This design uses vertical axis wind turbines (VAWTs) for energy capture, doubly fed induction generators (DFIG) for transformation, flow battery systems for storage and an alternating current (AC) microgrid for distribution. The definition of VAWT, DFIG, Flow Batteries and AC microgrid can be found in Appendix H.

The VAWT (48 turbines (Appendix I)) will be placed on the highest rooftop as shown in Figure 11. The DFIG will be connected to the flow batteries stored on the lower rooftop, shown in figure 13. The AC microgrid will be connected to the microgrid to distribute power to the buildings. Table 9 below explain how the objectives are meet for this solution

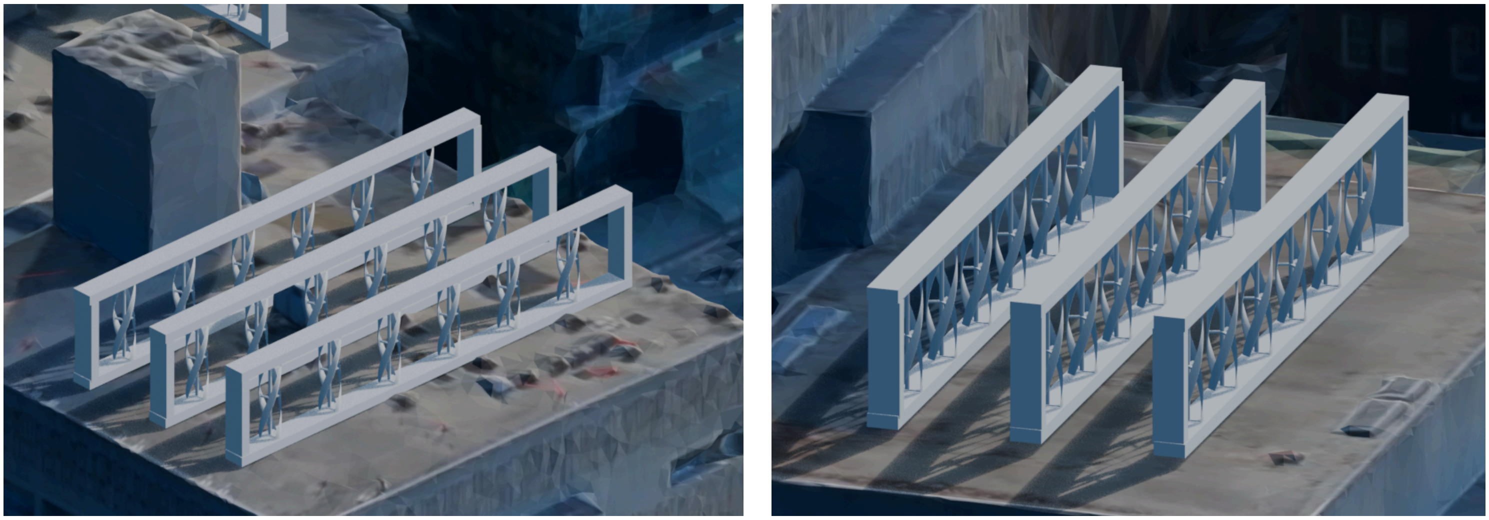

Figure 11 - AFWS Turbine Equipment

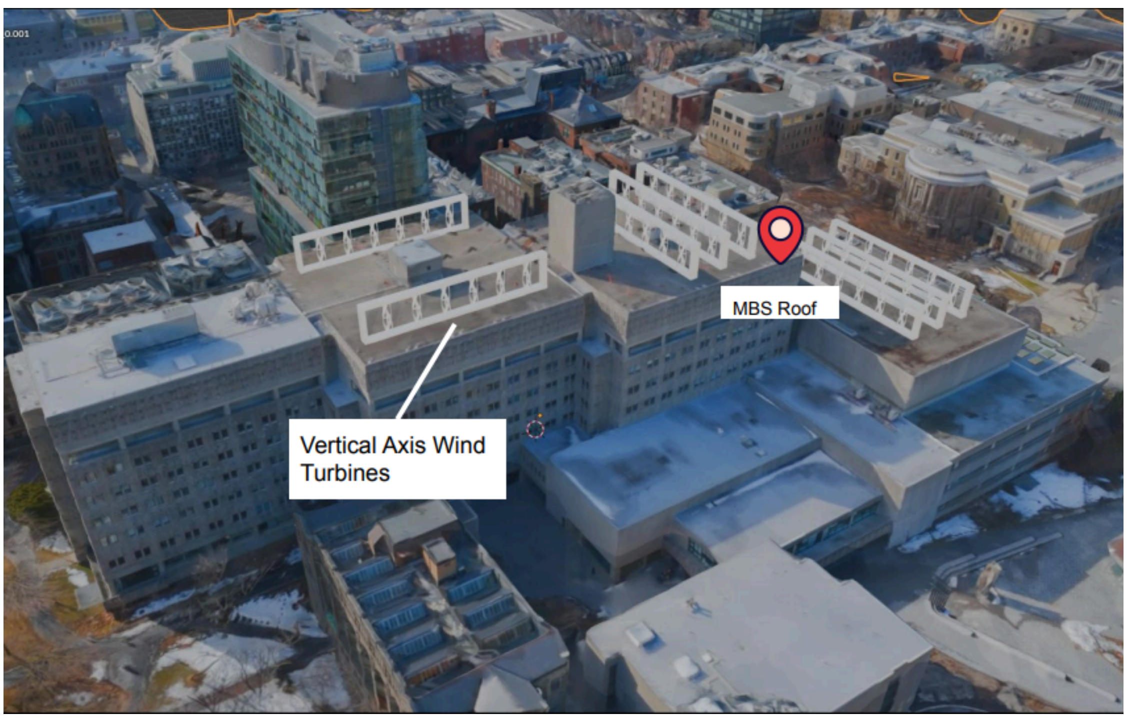

Figure 12 - AFWS Turbine Model

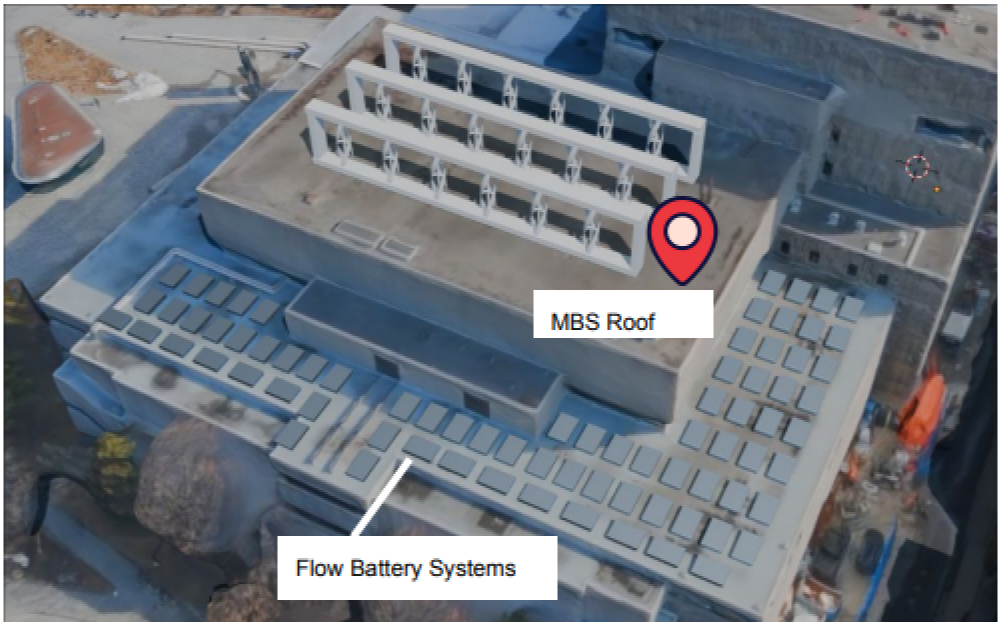

Figure 13 - AFWS battery storage

Table 9 - AFWS Objective Performance

Objectives	**Performance**	**Justification**
Reduce Carbon Emissions	Exceeds Goal: Net zero carbon	VAWT: -99% less CO_2 compared to coal-fired power plants, 98% less than natural gas, and 75% less than solar.[41] Flow battery: Saving 78% of emissions across lifecycle[42]
Fulfill Energy Generation Needs	Exceeds Goal:124.95k Btu/sqFt	-DFIG: increases efficiency 30% compared to traditional fixed-speed generators[43] -Flow battery system: -Supports large-scale energy storage, -Round-trip efficiency of up to 90%[44]
Operate without maintenance	Meets Goal: ≥12 months	-VAWT: -Lifespan of 15-25 years[44] -Maintenance every 6 to 12 months -Flowbattery system: lifespan of 20+ years[44]
Minimize cost of energy generation	Meets Goal:≤ 15.8 ¢	-Micro/roof mounted wind turbines: 500 - 4000 USD [45] -AC distribution lower transmission losses 15% [46]

Objectives	Performance	Justification
Fit within the designated roof space	Meets Goal:≤6000m	-Spacing between turbines based on rotor size, 2-4 times rotor length spacing perpendicular to wind flow and 8 to 12 between turbines with wind flow [45]

6.3.1 Tandem Iron-Air Microgrid (TIM)

This design captures energy using VAWTs (32 Turbines (Appendix I)) and bifacial solar panels(421 panels (Appendix I)), uses DFIG paired with tandem perovskite-silicon solar cells for transformation, iron air batteries for storage, and a smart grid for output. The definition of VAWTs, Bifacial Solar Panels, DFIG, Iron Air Batteries and Tandem Perovskite-silicon cells can be found in Appendix H.

The VAWT coupled with the bifacial solar panels will be placed on the roof. The DFIG will be incorporated into the design and tandem perovskite-silicon cells are solar panel components. The iron-air batteries will be stored on the lower rooftop.Table 10 below explain how the objectives are meet for this solution

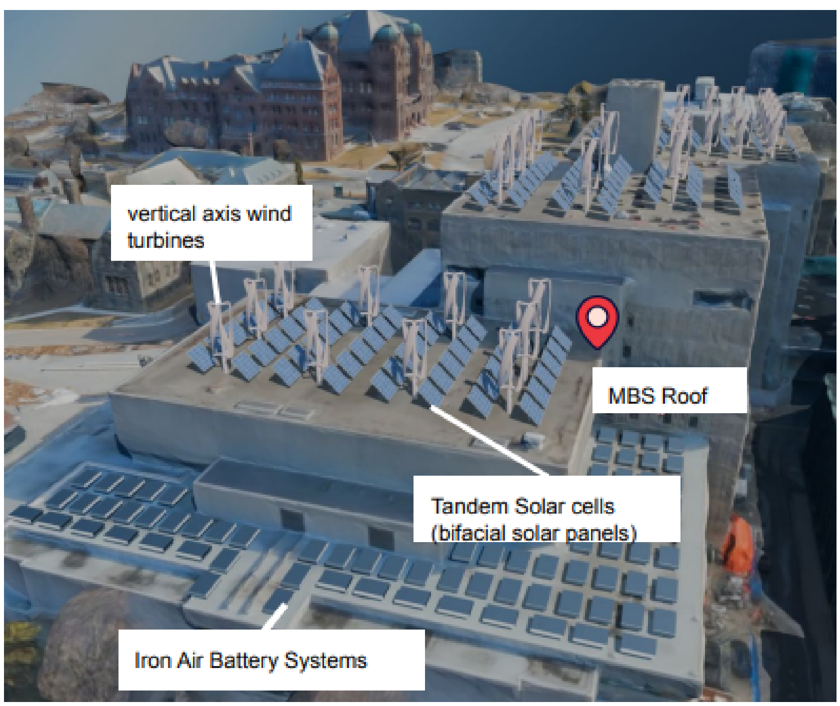

Figure 14 - TIM Aerial View

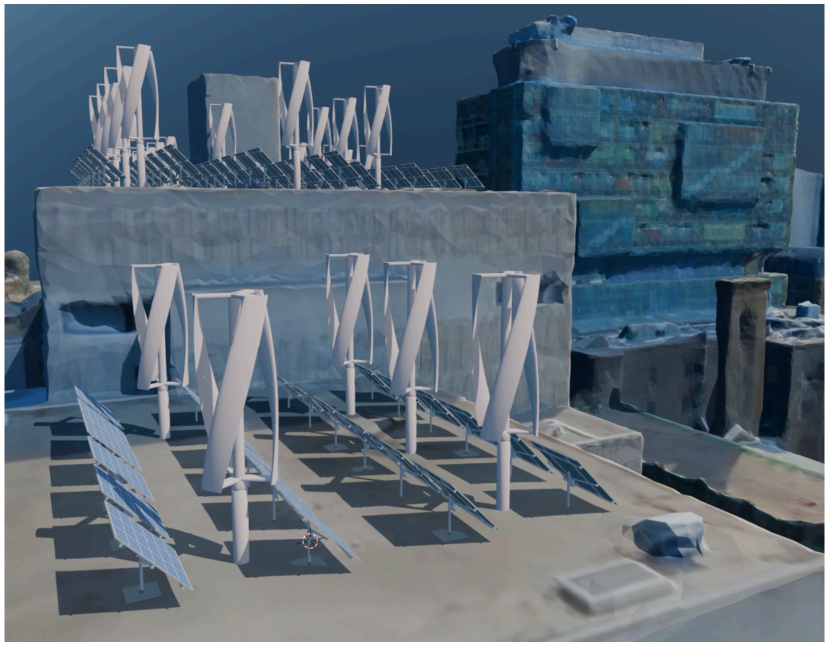

Figure 15 - TIM Equipment Model

Table 10 - TIM Objective Performance

Objectives	Performance	Justification
Reduce Carbon Emissions	Exceeds Goal:Net zero carbon emissions	-VAWT: -Provide consistent power: capture wind from all directions[47] -Capture energy from speeds 2m/s[47] -Bifacial solar panels: - Increase energy yield by 10-20%, capturing sunlight on both sides[44] As these components optimize the system, good energy management will reduce carbons emissions
Fulfill Energy Generation Needs	Exceeds Goal:124.95k Btu/sqFt	-DFIG increases efficiency 30% compared to traditional fixed-speed generators -Tandem Solar Cells: 31.6 %efficiency. -Power Output(per m^2): 285.1W/m² [48]
Operate without maintenance	Meets Goal: ≥12 months	-VAWT: lifespan 15-25 years[44] - Maintenance every 6 to 12 months [49] -Bifacial Solar Panels: cleaning both sides every 6 months

Objectives	Performance	Justification
Minimize cost of energy generation	Meets Goal:≤ 15.8 ¢	-Iron-air battery systems -Can reduce storage costs by 70% compared to lithium-ion[50]. -Bifacial Panels $15 - 20 per kilogram -Additional cost of VAWT: micro/roof mounted: 500 - 4000 USD
Fit within the designated roof space	Meets Goal:≤6000m	-VAWT 50% less land area than horizontal wind turbines[46]

7. Proposed Conceptual Design

The MonoSolar Smart Grid (MSSG) was selected as our final design as it best fulfilled the objectives in Pugh Chart analysis (Appendix F, Table H). It was able to satisfy the client goal to reduce natural gas use from the public grid through on campus energy generation. It met the client's goal to reduce natural gas use through on campus energy generation (Appendix-Table A). It met the objective of lowering carbon emissions (reduce 80% of CO_2 compared to traditional electricity grid), being able to achieve net zero status while maintaining low maintenance and fit within roofspace, critical for a university campus.

The Tandem Iron Air Microgrid maximized energy output by combining two energy capture methods, however this would incur increased maintenance and cost (Appendix-Table K). Turbine parts require lubrication and wear checks, and tandem solar cells are an emerging, unproven technology (Appendix G-Table K), conflicting with the client's need for reliability (2.0 Problem Statement).

AC Flow Wind System reduced carbon emissions using a flow battery without rare earth elements (lithium) and with high longevity (Appendix-Table K). However, large electrolyte tanks made it inefficient for limited space.

Mono Solar Smart Grid ensures reduced emissions and electricity production through renewable energy by using industry-proven solar panels that ensure reliability and lower maintenance, along with energy storage in high-density batteries that use space efficiently, given site limitations.

8. Measure of Success

The following section will help the team plan the next steps needed to assess the feasibility of the Mono Solar Smart Grid implementation. Prototyping and modeling cannot accurately determine energy production and CO2 emissions due to lack of access to the MBS roof. Furthermore, a small-scale prototype would not provide accurate measurements because it would not replicate the actual conditions of the system. Instead, we will rely on estimates.

8.1 Test Plan - Quantifying Reduced Emissions

The table below evaluates MSSG's emission reductions.

Objective Chosen	Objective: O.1 reducing carbon emissions. Justification: Ranked top objective in Project Requirements, highly relevant to Sustainability Office's goals. [3]
Steps	**Deliverables**
1 (03/24/25)	**Carbon Emissions Baseline:** Current carbon emissions from MSB building must be attained to estimate amount of emissions the proposed solution can displace. 1. Estimate energy consumption data of MBS through research 2. Research the carbon intensity of the local grid (kg CO_2/kWh) 3. Calculate: Baseline Emissions=Energy Consumption(kWh)×Grid Emission Factor(kgCO2/kWh)[51] Energy consumption assumed from historical data, Grid Emission based on the Toronto region.
2 (03/25/25)	**Estimate Solar Energy Production:** 1. Estimate microgrid production through an online calculator, considering energy loss, solar panel tilt etc [52] 2. Cross reference with personal calculations: Energy Output (kWh) = Solar Panel Area (m^2) × Solar Irradiance (kWh/m^2/day) × Panel Efficiency (22%) × 365 [53] 3. Triangulate data with credible secondary sources Justification: No rooftop access to gather primary data

3 (03/26/2025)	**Estimate Manufacturing Emissions:** 1. Estimate the carbon emission from manufacturing the microgrid through secondary data.[53] Justification: No access to measure of model manufacturing emissions of unique designs
4 (03/28/2025)	**Long Term Emission Reduction:** Compare the carbon emission produced by microgrids versus emissions generated by the public grid. Estimate time required to offset manufacturing emissions. [54] 1. Estimate how much carbon emission is saved each year compare to the public grid: CO_2 Savings (tons/year)=(Energy Produced by Microgrid (kWh/year)×Grid Emission Factor (kg CO_2/kWh))−(Energy Consumed from Grid (kWh/year)×Grid Emission Factor (kg CO_2/kWh)) 2. Determined ‘Payback Period” Carbon Payback Period= Annual Carbon Savings/Total Embedded Carbon[54] Justification: Must estimate the period to offset manufacturing emissions, and properly estimate overall emissions reduced.
5 (03/30/2025)	**Amount of emission saved:** After offsetting manufacturing emissions, estimate the emissions reduced over microgrid lifespan.[55] Justification: This step measures the objective, showcasing the success of the design.

The result will tell us the amount of time in years needed to reach the objective of net zero carbon emissions.

9. Conclusion

The University of Toronto Sustainability Office is working toward reaching carbon neutrality on the St. George Campus by 2050. As part of this effort, this report explores the implementation of a green energy microgrid on MSB, by first outlining key challenges, stakeholders, objectives, and constraints to direct its development. This document also details how and why morphological charts, SCAMPER, multivoting, graphical design charts and pugh methods were used to narrow down alternative designs space. This report presents a final conceptual design along with a methodology for estimating the microgrid's impact on carbon emissions. The next step will focus on calculating and assessing its performance and sharing these findings in the final presentation.

10. References

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<u>Appendices</u>

Appendix A- Notes taken during the client meeting

Below is a table with notes taken by one of the team members.

Table A. Moira Boland Notes

<table>
<tr><td colspan="2">Client Meeting Notes - Feb. 5th 2025</td></tr>
<tr><td>Definitions (Microgrid and Green Energy)</td><td>What do you define as green energy:

- Does not need to be net zero
- Harness natural resource of energy
- Green energy implemented into a small network of power consumption
- * at St George
- Reduce natural gas burn and drawing off the power grid

What does the client define as a microgrid:

- Could be a community of housing
- Just use a few building - 2 and four buildings to consider
- Buildings at uft have larger power draws and consumption
- Geographically speaking they should all be close together
- Uft does not have a specific microgrid of only a few buildings
- Wants the design very simple</td></tr>
</table>

Client Meeting Notes - Feb. 5th 2025	
Need	- Some buildings have power shortages - labs - Microgrids should have shirt distribution from your power source - Small installations on certain buildings - solar panels are exam centre - Reduce load on the grid and thermal load on the central steam plan - Tie in a network of solar panels or small wind turbines - Need a stockpile list of where we have solar panels, etc where we can draw off of. Otherwise, look at buildings with big empty roofs - Geothermal and biomass are out of scope - Portfolio client managers has a large fund for project implementation - Going underground is very expensive - No building off limits per say - A good start is empty rooftops
Limitations	- Real life implementation structural load analysis must be done for each structure due to the weight of the solar panels - Logistically, how many solar panels can we fit and what kind of electrical load is this reducing
Scope	- Leave an option to sell any unused power to the public grid, however we are looking at buildings that have a very high demand of power - Buildings should be around Med Sci
Energy Storage	- Two means of energy storage: electrical storage (cooling requirements, very expensive (battery) however possible) If we were supplementing hot water usage, we could have thermal storage. Vastly depends on where we want to implement everything - Energy load requirements and size of empty roofspace dictates how much we can generate and thus store

Client Meeting Notes - Feb. 5th 2025	
Objectives	- Could be operated component by component (modularity) - Show scalability - The driving force in feasibility is land use. Very Large constraint - Nothing ground mounted - roof or wall mounted - Palatable price for a decent amount of energy-saving
Constraints	- Do not ignore certain things because it might cost more (yet) - Noise pollution is a low priority, considering wind turbines or solar panels - The location (rooftop)lowers priority on aesthetic - Wind sheltering in Toronto - wind turbines are more difficult for implementation location, and the higher, the better - Stay away from anything too visible in King College Circle - For wind - Kings College Circle is out of scope - Keep any industrial-looking things away from Kings College Circle

Appendix B- Impact/Influence Graph

In the figure below is a graph that identifies the impact and influence of the chosen stakeholder.

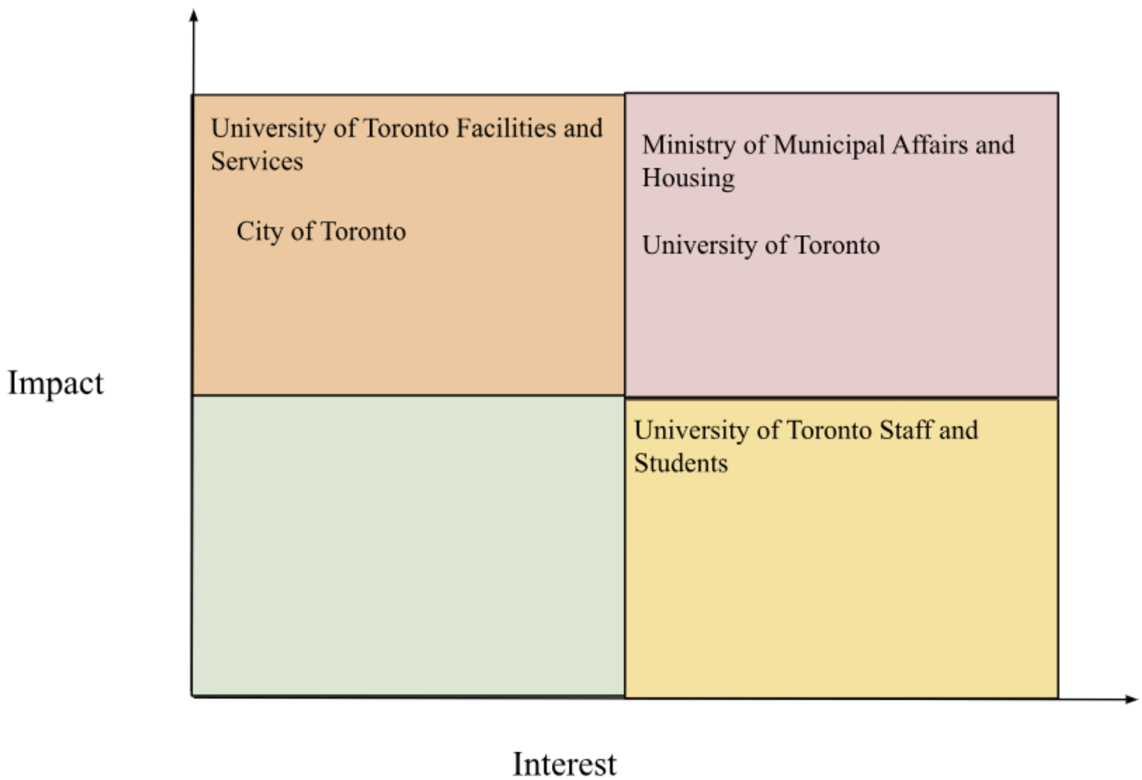

Figure A. Stakeholders Impact/Influence Graph

Appendix C - Roof dimension

To find the area of the roof on MBS the dimensions are estimated using google earth and then added together. Below are the calculations.

Google Earth Area Calculations (Microgrid Project)

$3753.73\ m^2$
$+2738.08\ m^2$
$+2834.24\ m^2$
$-159.54\ m^2$
$-94.84\ m^2$
$-300.00\ m^2$ ← Borders and smaller obstructing objects

$\sim 6000\ m^2$

Figure B. Calculations of Rooftop Area From Google Earth

Appendix D - How Why Tree

To find secondary functions a how-why tree was created and included below.

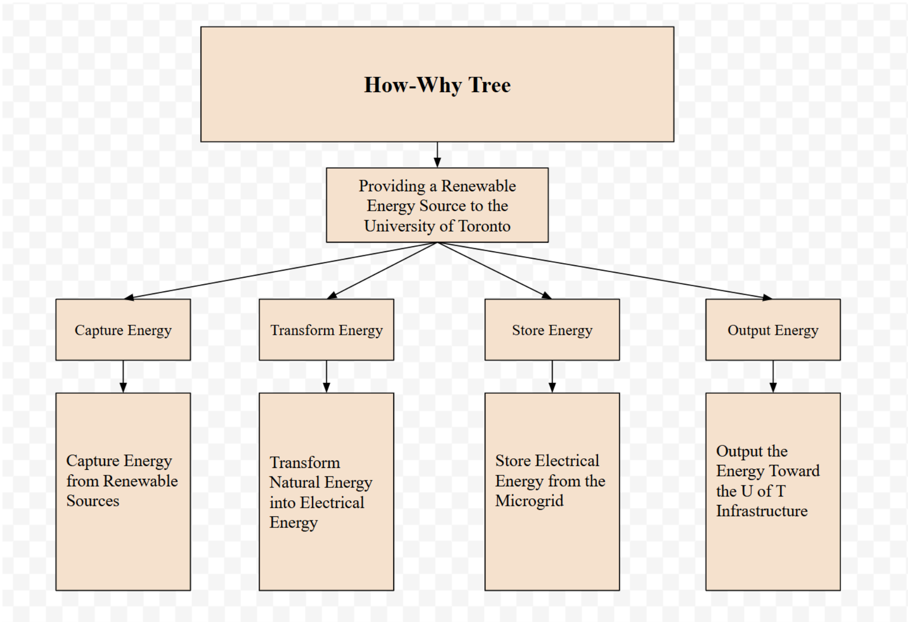

Figure C. How-Why Tree for Secondary Functions

Appendix E - Pairwise Comparison

The following table uses pairwise comparison to rank our objectives in order of importance. This will set a solid foundation for sections of the idea selections process such as the Graphical Decision Chart and the Pugh Chart. It will also help us define the Measure of Success of the project.

Table B - Pairwise Comparison

	Reduce Carbon Emissions	Fulfill Energy Generation Need	Operate without maintenance	Minimize cost of energy generation	Uses space efficiently	Sum
Reduce Carbon Emissions		1	1	1	1	4
Fulfill Energy Generation Need	0		1	1	1	3
Operate without maintenance	0	0		1	1	2
Minimize cost of energy generation	0	0	0		1	1
Uses space efficiently	0	0	0	0		0

Appendix F - Idea Generation Process Supporting Information

The table below are ideas brainstormed by the team.

Table C - Brainstormed ideas

Brainstorming
• 1 giant wind turbines • Wind turbines under solar panels • Wind turbines on roof ledge with solar panels • Wind turbine with blades coved with solar panels • Clear solar panels under regular solar panels • Lithium Ion Battery • Thermal Energy Storage

The figure below is an example of how the 50 solutions were generated using the morph chart. Refer to Appendix F, Table D for justification.

Capture Energy from renewable sources	Transform natural energy into electrical energy	Store electrical energy from the microgrid	Output the energy toward the U of T Infrastructure
Stationary Solar Panels	Thin Film Cells	lithium-ion battery storage	High-voltage Transmission Lines
Vertical Wind Turbine (open system)	Polycrystalline Silicon Cell	flow battery system	Busbars
Tunnel Air Flow to Vertical Wind Turbines	Monocrystalline Silicon Cell	sodium-ion battery	Low-voltage Distribution Cables
Dynamic Solar Panels (Move with the Sun)	Photovoltaic Cells	liquid air energy storage	District Heating/Cooling Systems

Figure D - Morphological Chart Ideas

The table below is the preliminary research the group has done in order to generate solutions meeting the secondary functions.

Table D - Research for the Morphological Chart Ideas

Capture Energy from renewable sources: [56] [57] [58] [59] [60] Transform natural energy into electrical energy: [61] [62] Types of batteries: [63] [64] [65] [66] [67] [68] [69] Output the energy toward the U of T Infrastructure: [70] [71] [72] [73] [74] [75] [76] [77] [78] [79]

The following Table has allowed us to rule out all the unfeasible solutions out of the Morphological Chart. Refer to Appendix F, Figure E for the feasibility check in the morph chart.

Table E - Feasibility Check Supporting Information

Ideas	**Feasible**
Organic Solar Cells Organic photovoltaics (OVPs) The disadvantages of organic cells are as follows: 1) Efficiency: Comparatively, silicon cell OPVS has far lower cell efficiencies 2) Lifespan: Silicon cells OPVs have a much shorter lifetime because organic materials deteriorate far more quickly when subjected to environmental factors. "(C.M Nkinyam et al., 9) [80] **Dye-Sensitized Solar Cells** - Sensitive to high and low temperatures, therefore has a limited endurance to operating temperature - The electrolyte consists of volatile organic solvents, which must be sealed cautiously. - Less efficiency than other solar cells - They are currently 12% the efficiency of first and second generations of solar cells. - Not ideal for large-scale applications as they will minimize the system's efficiency [81]	**No**
Resonant Wireless Power Transfer (RWPT) -Only efficient for short distances -Used more for medium power load cannot withstand power generated by solar panels -Not energy efficient when transforming from DV to AV [82] **Inductive Couplers** -Only efficient for short distances -Used more for medium power load cannot withstand power generated by solar panels -Not energy efficient when transforming from DV to AV [83]	**No**

Ideas	Feasible
Zinc Air battery -Short Battery life -Mostly non-chargeable application -Sensitive to Humidity -Limited currents -CO2 in the air reduces the conductivity [84]	**No**
Compressed Air Energy Storage -Stores energy by compressing air from underground reservoir and tanks -Requires underground storage -Requires high pressure [85]	**No**
Bladeless Wind Turbine - only tested on large scale - cylinder which oscillates when the wind hits - uses swirls and vortices[86]	**No**

Refer Table E for feasibility justification

	Primary Function			
	Providing Renewable Energy			
	Secondary Function			
	Capture Energy from renewable sources	Transform natural energy into electrical energy	Store electrical energy from the microgrid	Output the energy toward the U of T Infrastructure
1	Stationary Solar Panels	Thin Film Cells	lithium-ion battery storage	High-voltage Transmission Lines
2	Vertical Wind Turbine (open system)	Polycrystaline Silicon Cell	flow battery system	Busbars
3	Tunnel Air Flow to Vertical Wind Turbines	Monocrystaline Silicon Cell	sodium-ion battery	Low-voltage Distribution Cables
4	Solar Panel Platted Vertical Wind Turbine	Organic Solar Cells	zinc-air battery	HVAC Lines
5	Dynamic Solar Panels (Move with the Sun)	Perovskite Solar Cells	iron-air battery	Resonant Wireless Power Transfer (RWPT)
6	Solar Chimneys (Tower with Solar Panels)	Dye-Sensitized Solar Cells	liquid air energy storage	District Heating/Cooling Systems
7	Bladless Wind Turbine	Compressed Air Storage (CAES)	compressed air energy storage	Capacitive Coupling
8	Transparent Solar Panels	Photovalic Cells	pumped hydro storage	Inductive Couplers
9	Wind Tree	Doubly Fed Induction Generator	supercapacitor energy storage	Smart Grid
10		Squirrel Cage Induction Generator	solid-state battery storage	AC Microgrid Distribution
		Permanent Magnet Synchronous Generator	thermal energy storage	
			second-life EV battery storage	

Feasability Checked Morph Chart

	Primary Function			
	Providing Renewable Energy			
	Secondary Function			
	Capture Energy from renewable sources	Transform natural energy into electrical energy	Store electrical energy from the microgrid	Output the energy toward the U of T Infrastructure
1	Stationary Solar Panels	Thin Film Cells	lithium-ion battery storage	High-voltage Transmission Lines
2	Vertical Wind Turbine (open system)	Polycrystaline Silicon Cell	flow battery system	Busbars
3	Tunnel Air Flow to Vertical Wind Turbines	Monocrystaline Silicon Cell	sodium-ion battery	Low-voltage Distribution Cables
4	Solar Panel Platted Vertical Wind Turbine	Perovskite Solar Cells	iron-air battery	HVAC Lines
5	Dynamic Solar Panels (Move with the Sun)	Photovalic Cells	liquid air energy storage	District Heating/Cooling Systems
6	Solar Chimneys (Tower with Solar Panels)	Doubly Fed Induction Generator	supercapacitor energy storage	Capacitive Coupling
7	Transparent Solar Panels	Squirrel Cage Induction Generator	solid-state battery storage	Smart Grid
8	Wind Tree	Permanent Magnet Synchronous Generator	thermal energy storage	AC Microgrid Distribution
9			second-life EV battery storage	
10				

Figure E - Feasibility Check in the Morph Chart

Before Scamper

4	Vertical Wind Turbine	Doubly Fed Induction Generator	Sodium-ion battery	District Heating/Cooling Systems
10	Dynamic Solar Panels (Move with the Sun)	Perovskite Solar Cells	Liquid air energy storage	AC Microgrid Distribution
14	Stationary Solar Panels	Monocrystaline Silicon Cell	Supercapacitor energy storage	Busbars
18	Dynamic Solar Panels (Move with the Sun)	Polycrystaline Silicon Cell	Solid-state battery storage	District Heating/Cooling Systems
26	Vertical Wind Turbine (open system)	Permanent Magnet Synchronous Generator	Liquid air energy storage	High-voltage Transmission Lines
32	Sun Tracking Solar Panels	Tandem Solar Cells (Perovskite + Silicon)	Iron-air battery	Smart Grid
42	Dynamic Solar Panels (Move with the Sun)	Photovalic Cells	Second-life EV battery storage	Smart Grid
45	Stationary Solar Panels	Thin Film Cells	Supercapacitor energy storage	Smart Grid
46	Solar Panel Platted Vertical Wind Turbines	Doubly Fed Induction Generator + Perovskite Solar Cells	Thermal energy storage	Busbars
47	Dynamic Solar Panels (Move with the Sun)	Polycrystaline Silicon Cell	Sodium-ion battery	High-voltage Transmission Lines

After Scamper

4	Vertical Wind Turbine	Doubly Fed Induction Generator	Sodium-ion battery	District Heating/Cooling Systems
10	Dynamic Solar Panels (Move with the Sun)	Perovskite Solar Cells	Sodium-ion battery	AC Microgrid Distribution
14	Bifacial Panels	Monocrystaline Silicon Cell	Flow battery system	Busbars
18	Dynamic Solar Panels (Move with the Sun)	Polycrystaline Silicon Cell	Sodium-ion battery	District Heating/Cooling Systems
26	Vertical Wind Turbine (open system)	Permanent Magnet Synchronous Generator	Flow battery system	High-voltage Transmission Lines
32	Sun Tracking Solar Panels	Monocrystaline Silicon Cell	Flow battery system	AC Microgrid Distribution
42	Dynamic Solar Panels (Move with the Sun)	Photovalic Cells	Second-life EV battery storage	Smart Grid
45	Stationary Solar Panels	Monocrystaline Silicon Cell	Lithium-ion battery storage	Smart Grid + Low-Voltage Distribution Tables
46	Vertical Wind Turbine	Doubly Fed Induction Generator	Flow battery system	AC Microgrid Distribution
47	Vertical Wind Turbines + Bifacial Panels	ed Induction Generator + Tandem Solar Cells (Perovskite	Iron-air battery	Smart Grid

Figure F - SCAMPERing for 10 Solutions

Table F - 60 Final Solutions

Hybrid Systems
8. A solar-panel-plated vertical wind turbine made of photovoltaic cells, with solid-state battery storage, connected to low-voltage distribution cables. 15. Solar panel platted vertical wind turbine made of perovskite solar cells with sodium-ion battery connected to high-voltage transmission lines. 21. Solar panel platted vertical wind turbine with doubly fed induction generator with lithium-ion battery storage connected to busbars. 27. Solar panel platted vertical wind turbine made of thin film cells with second-life EV battery storage connected to busbars. 37. Solar panel platted vertical wind turbine made of monocrystalline silicon cells with liquid air energy storage connected to district heating/cooling systems. 47. Tunnel air flow to vertical wind turbines plus bifacial panels with doubly fed Induction generator and tandem solar cells (Perovskite + Silicon) with an Iron-air battery connected to a smart grid.
Wind Systems
2. Wind tree with a squirrel cage induction generator and supercapacitor energy storage connected to capacitive coupling. 3. Tunnel air flow to vertical wind turbines with permanent magnet synchronous generator and flow battery system connected to AC microgrid distribution. 4. Vertical wind turbines with doubly fed induction generator and sodium-ion battery connected to district heating/cooling systems. 11. Tunnel air flow to vertical wind turbines with a doubly fed induction generator and thermal energy storage connected to district heating/cooling systems.

12. Vertical wind turbine (open system) with squirrel cage induction generator and iron-air battery connected to capacitive coupling.

16. Wind tree with permanent magnet synchronous generator and liquid air energy storage connected to HVAC Lines.

19. Tunnel air flow to vertical wind turbines with permanent magnet synchronous generator and thermal energy storage connected to high-voltage transmission lines.

20. Vertical wind turbine with squirrel cage induction generator and flow battery system connected to AC microgrid distribution.

24. Wind tree with permanent magnet synchronous generator and supercapacitor energy storage connected to district heating/cooling systems.

26. Vertical wind turbine (open system) with permanent magnet synchronous generator and flow battery system connected to high-voltage transmission lines.

28. Wind tree with doubly fed induction generator and iron-air battery connected to smart grid.

34. Wind tree with doubly fed induction generator and supercapacitor energy storage connected to high-voltage transmission lines.

35. Vertical wind turbine (open system) with squirrel cage induction generator and second-life EV battery storage connected to low-voltage distribution cables.

40. Tunnel air flow to vertical wind turbines with doubly fed induction generator and lithium-ion battery storage connected to HVAC lines.

43. Wind tree with squirrel cage induction generator and iron-air battery connected to low-voltage distribution cables.

44. Vertical wind turbine (open system) with doubly fed induction generator and liquid air energy storage connected to AC microgrid distribution.

46. Vertical wind turbine with doubly fed induction generator + perovskite solar cells and thermal energy storage connected to AC microgrid distribution.

49. Tunnel air flow to vertical wind turbines with permanent magnet synchronous generator and solid-state battery storage connected to district heating/cooling systems.

50. Wind tree with doubly fed induction generator and second-life EV battery storage connected to capacitive coupling. 54. Tunnel air flow to vertical wind turbines with tandem solar cells (Perovskite + Silicon) and sodium-ion battery connected to a smart grid. 56. Tunnel air flow to vertical wind turbines, permanent magnet synchronous generator and supercapacitor energy storage connected to district heating/cooling systems. 58. Vertical wind turbine (open system) with permanent magnet synchronous generator and liquid air energy storage connected to high-voltage transmission lines. 59. Tunnel air flow to vertical wind turbines with doubly fed induction generator and iron-air battery connected to smart grid.
Solar Systems
1. Solar chimneys with perovskite solar cells, storing energy in lithium-ion battery storage and distributing the power out with low-voltage distribution cables 5. Transparent solar panels with polycrystalline silicon cell, storing energy in an iron-air battery and distributing power with busbars 6. Stationary solar panels with thin film cells, storing energy in a second-life EV battery storage and distributing power with HVAC lines 7. Solar chimneys with polycrystalline silicon cells, storing energy in a supercapacitor energy storage and distributing energy with a smart grid 9. Transparent solar panels with monocrystalline silicon cells, using lithium-ion battery storage and distributing the power with high-voltage transmission lines 10. Dynamic solar panels with perovskite solar cells, using sodium-ion batteries and AC Microgrid Distribution as a means of energy distribution 13. Solar chimneys with photovoltaic cells, using lithium-ion battery storage and smart grid to distribute energy 14. Bifacial panels with monocrystalline silicon cells, using a Flow battery system and distributing energy with busbars

17. Transparent solar panels with thin film cells, using a second-life EV battery storage and low-voltage distribution cables

18. Dynamic solar panels with polycrystalline silicon cells, using a sodium-ion battery and a district heating/cooling systems

22. Solar chimneys with thin film cells, using a sodium-ion battery and distributing energy with a smart grid

23. Stationary solar panels with photovoltaic cells. using an iron-air battery and capacitive coupling to distribute energy

25. Transparent solar panels with perovskite solar cells, thermal energy storage, and HVAC lines to distribute energy

29. Solar chimneys with monocrystalline silicon cells, using a lithium-ion battery storage and capacitive coupling to distribute energy

30. Dynamic solar panels with thin film cells, using a flow battery system and an AC microgrid distribution system

31. Stationary solar panels with perovskite solar cells, using thermal energy storage and district heating/cooling systems

32. Sun-tracking solar panels with tandem solar cells (Perovskite + Silicon), using a flow battery system and a Smart Grid to distribute energy

33. Transparent solar panels with photovoltaic cells, using a sodium-ion battery and HVAC lines a means to distribute energy

36. Stationary solar panels with polycrystalline Silicon Cells, using solid-state battery storage and busbars to distribute energy

38. Dynamic solar panels with monocrystalline silicon cells, using thermal energy storage and capacitive coupling to route the energy

39. Solar chimneys with perovskite solar cells, using a sodium-ion battery and an AC microgrid distribution system

41. Transparent solar panels with thin film cells, using a Solid-state battery storage system and High-voltage transmission lines

42. Dynamic solar panels with photovoltaic Cells, storing energy in a second-life EV battery storage and distributing it with a Smart Grid

45. Stationary solar panels with thin film cells, using supercapacitor energy storage and distributing energy with a Smart Grid

48. Solar Chimneys with photovoltaic cells, using a supercapacitor energy storage and an AC microgrid distribution system

51. Dynamic solar panels with perovskite solar cells, using liquid air energy storage and an AC microgrid distribution system

52. Stationary solar panels with monocrystalline silicon cells, using supercapacitor energy storage and distributing energy with busbars

53. Dynamic solar panels with polycrystalline silicon cells, using a Solid-state battery storage unit and a district heating/cooling systems

55. Dynamic solar panels with polycrystalline silicon cells, using a sodium-ion battery and high-voltage transmission lines

57. Dynamic solar panels with tandem solar cells (Perovskite + Silicon), using a solid-state battery storage and a Smart Grid to distribute the energy

60. Stationary solar panels with thin film cells, using a supercapacitor energy storage and a Smart Grid to distribute the energy

Appendix G - Idea Selection Process Supporting Information

The following table illustrates the voting process that the team took to select the 10 best solutions. Every member had a column in the table where they could vote for 20 solutions.

Table G - Multivoting Process for Idea Selections

	50 Different Combinations of Ideas				Votes (Everyone has 20 votes)						
#	Capture Energy from renewable sources	Transform natural energy into electrical energy	Store electrical energy from the microgrid	Output the energy toward the U of T Infrastructure	Marcus	Marlena	Jonathan	Nirvaan	Frank	Moira	Total Number of Votes per Idea
1	Solar Chimneys (Tower with Solar Panels)	Perovskite Solar Cells	Lithium-ion battery storage	Low-voltage Distribution Cables	☐	☐	☐	☐	☐	☐	0
2	Wind Tree	Squirrel Cage Induction Generator	Supercapacitor energy storage	Capacitive Coupling	☐	☐	☐	☐	☐	☐	0
3	Tunnel Air Flow to Vertical Wind Turbines	Permanent Magnet Synchronous Generator	Flow battery system	AC Microgrid Distribution	☐	☐	☑	☑	☑	☐	3
4	Vertical Wind Turbine	Doubly Fed Induction Generator	Sodium-ion battery	District Heating/Cooling Systems	☐	☐	☑	☑	☑	☑	4
5	Transparent Solar Panels	Polycrystaline Silicon Cell	Iron-air battery	Busbars	☑	☐	☐	☐	☐	☐	1
6	Stationary Solar Panels	Thin Film Cells	Second-life EV battery storage	HVAC Lines	☐	☐	☐	☐	☐	☑	1
7	Solar Chimneys (Tower with Solar Panels)	Polycrystaline Silicon Cell	Supercapacitor energy storage	Smart Grid	☑	☐	☑	☐	☑	☐	3
8	Solar Panel Platted Vertical Wind Turbine	Photovalic Cells	Solid-state battery storage	Low-voltage Distribution Cables	☐	☑	☐	☐	☑	☑	3
9	Transparent Solar Panels	Monocrystaline Silicon Cell	Lithium-ion battery storage	High-voltage Transmission Lines	☐	☐	☐	☐	☐	☐	0
10	Dynamic Solar Panels (Move with the Sun)	Perovskite Solar Cells	Sodium-ion battery	AC Microgrid Distribution	☑	☑	☑	☑	☑	☑	6
11	Tunnel Air Flow to Vertical Wind Turbines	Doubly Fed Induction Generator	Thermal energy storage	District Heating/Cooling Systems	☑	☐	☐	☑	☑	☐	3
12	Vertical Wind Turbine (open system)	Squirrel Cage Induction Generator	Iron-air battery	Capacitive Coupling	☐	☐	☐	☑	☐	☐	1
13	Solar Chimneys (Tower with Solar Panels)	Photovalic Cells	Lithium-ion battery storage	Smart Grid	☐	☐	☐	☐	☐	☐	0
14	Bifacial Panels	Monocrystaline Silicon Cell	Flow battery system	Busbars	☑	☑	☑	☑	☑	☐	5
15	Solar Panel Platted Vertical Wind Turbine	Perovskite Solar Cells	Sodium-ion battery	High-voltage Transmission Lines	☐	☑	☐	☐	☐	☑	2
16	Wind Tree	Permanent Magnet Synchronous Generator	Liquid air energy storage	HVAC Lines	☐	☐	☐	☐	☐	☐	0
17	Transparent Solar Panels	Thin Film Cells	Second-life EV battery storage	Low-voltage Distribution Cables	☐	☐	☐	☐	☐	☐	0
18	Dynamic Solar Panels (Move with the Sun)	Polycrystaline Silicon Cell	Sodium-ion battery	District Heating/Cooling Systems	☑	☑	☑	☑	☑	☑	6
19	Tunnel Air Flow to Vertical Wind Turbines	Permanent Magnet Synchronous Generator	Thermal energy storage	High-voltage Transmission Lines	☑	☐	☐	☐	☐	☐	1
20	Vertical Wind Turbine	Squirrel Cage Induction Generator	Flow battery system	AC Microgrid Distribution	☐	☐	☐	☐	☐	☐	0
21	Solar Panel Platted Vertical Wind Turbine	Doubly Fed Induction Generator	Lithium-ion battery storage	Busbars	☐	☑	☑	☐	☐	☑	3
22	Solar Chimneys (Tower with Solar Panels)	Thin Film Cells	Sodium-ion battery	Smart Grid	☐	☐	☐	☐	☐	☐	0
23	Stationary Solar Panels	Photovalic Cells	Iron-air battery	Capacitive Coupling	☐	☐	☐	☐	☐	☐	0
24	Wind Tree	Permanent Magnet Synchronous Generator	Supercapacitor energy storage	District Heating/Cooling Systems	☐	☐	☐	☐	☐	☐	0
25	Transparent Solar Panels	Perovskite Solar Cells	Thermal energy storage	HVAC Lines	☐	☐	☐	☐	☐	☐	0
26	Vertical Wind Turbine (open system)	Permanent Magnet Synchronous Generator	Flow battery system	High-voltage Transmission Lines	☑	☐	☐	☑	☑	☑	4
27	Solar Panel Platted Vertical Wind Turbine	Thin Film Cells	Second-life EV battery storage	Busbars	☐	☑	☐	☐	☑	☑	3
28	Wind Tree	Doubly Fed Induction Generator	Iron-air battery	Smart Grid	☑	☐	☐	☐	☐	☐	1
29	Solar Chimneys (Tower with Solar Panels)	Monocrystaline Silicon Cell	Lithium-ion battery storage	Capacitive Coupling	☐	☐	☐	☐	☐	☐	0
30	Dynamic Solar Panels (Move with the Sun)	Thin Film Cells	Flow battery system	AC Microgrid Distribution	☐	☑	☑	☑	☑	☐	3
31	Stationary Solar Panels	Perovskite Solar Cells	Thermal energy storage	District Heating/Cooling Systems	☐	☑	☑	☐	☐	☐	2
32	Sun Tracking Solar Panels	Tandem Solar Cells (Perovskite + Silicon)	Flow battery system	Smart Grid	☑	☐	☐	☑	☑	☑	4
33	Transparent Solar Panels	Photovalic Cells	Sodium-ion battery	HVAC Lines	☐	☐	☐	☐	☐	☐	0
34	Wind Tree	Doubly Fed Induction Generator	Supercapacitor energy storage	High-voltage Transmission Lines	☐	☐	☐	☐	☐	☐	0
35	Vertical Wind Turbine (open system)	Squirrel Cage Induction Generator	Second-life EV battery storage	Low-voltage Distribution Cables	☐	☐	☐	☐	☐	☐	0
36	Stationary Solar Panels	Polycrystaline Silicon Cell	Solid-state battery storage	Busbars	☐	☑	☐	☐	☐	☐	1
37	Solar Panel Platted Vertical Wind Turbine	Monocrystaline Silicon Cell	Liquid air energy storage	District Heating/Cooling Systems	☐	☑	☑	☑	☐	☐	3
38	Dynamic Solar Panels (Move with the Sun)	Monocrystaline Silicon Cell	Thermal energy storage	Capacitive Coupling	☐	☐	☐	☐	☐	☑	1
39	Solar Chimneys (Tower with Solar Panels)	Perovskite Solar Cells	Sodium-ion battery	AC Microgrid Distribution	☑	☐	☐	☐	☐	☐	1
40	Tunnel Air Flow to Vertical Wind Turbines	Doubly Fed Induction Generator	Lithium-ion battery storage	HVAC Lines	☐	☐	☐	☐	☐	☐	0
41	Transparent Solar Panels	Thin Film Cells	Solid-state battery storage	High-voltage Transmission Lines	☐	☐	☐	☐	☑	☐	1
42	Dynamic Solar Panels (Move with the Sun)	Photovalic Cells	Second-life EV battery storage	Smart Grid	☑	☑	☑	☑	☐	☑	5
43	Wind Tree	Squirrel Cage Induction Generator	Iron-air battery	Low-voltage Distribution Cables	☐	☐	☐	☐	☐	☑	1
44	Vertical Wind Turbine (open system)	Doubly Fed Induction Generator	Liquid air energy storage	AC Microgrid Distribution	☐	☐	☐	☐	☐	☐	0
45	Stationary Solar Panels	Thin Film Cells	Supercapacitor energy storage	Smart Grid	☑	☑	☑	☑	☑	☐	5
46	Vertical Wind Turbine	oubly Fed Induction Generator + Perovskite Solar Cel	Thermal energy storage	AC Microgrid Distribution	☑	☑	☑	☑	☑	☐	5
47	nnel Air Flow to Vertical Wind Turbines + Bifacial Pan	d Induction Generator + Tandem Solar Cells (Perovskit	Iron-air battery	Smart Grid	☑	☑	☑	☑	☑	☐	5
48	Solar Chimneys (Tower with Solar Panels)	Photovalic Cells	Supercapacitor energy storage	AC Microgrid Distribution	☑	☐	☐	☐	☐	☑	2
49	Tunnel Air Flow to Vertical Wind Turbines	Permanent Magnet Synchronous Generator	Solid-state battery storage	District Heating/Cooling Systems	☐	☑	☐	☐	☐	☑	2
50	Wind Tree	Doubly Fed Induction Generator	Second-life EV battery storage	Capacitive Coupling	☐	☐	☑	☑	☐	☑	3
51	Dynamic Solar Panels (Move with the Sun)	Perovskite Solar Cells	Liquid air energy storage	AC Microgrid Distribution	☐	☑	☐	☐	☑	☐	2
52	Stationary Solar Panels	Monocrystaline Silicon Cell	Supercapacitor energy storage	Busbars	☐	☐	☑	☑	☑	☐	3
53	Dynamic Solar Panels (Move with the Sun)	Polycrystaline Silicon Cell	Solid-state battery storage	District Heating/Cooling Systems	☑	☐	☐	☐	☐	☑	2
54	Tunnel Air Flow to Vertical Wind Turbines	Tandem Solar Cells (Perovskite + Silicon)	Sodium-ion battery	Smart Grid	☐	☑	☐	☑	☐	☑	3
55	Dynamic Solar Panels (Move with the Sun)	Polycrystaline Silicon Cell	Sodium-ion battery	High-voltage Transmission Lines	☑	☐	☑	☐	☐	☑	3
56	Tunnel Air Flow to Vertical Wind Turbines	Permanent Magnet Synchronous Generator	Supercapacitor energy storage	District Heating/Cooling Systems	☑	☑	☐	☑	☐	☐	3
57	Dynamic Solar Panels (Move with the Sun)	Tandem Solar Cells (Perovskite + Silicon)	Solid-state battery storage	Smart Grid	☐	☑	☑	☐	☐	☐	2
58	Vertical Wind Turbine (open system)	Permanent Magnet Synchronous Generator	Liquid air energy storage	High-voltage Transmission Lines	☐	☐	☑	☐	☐	☑	2
59	Tunnel Air Flow to Vertical Wind Turbines	Doubly Fed Induction Generator	Iron-air battery	Smart Grid	☑	☐	☐	☑	☑	☐	3
60	Stationary Solar Panels	Thin Film Cells	Supercapacitor energy storage	Smart Grid	☐	☐	☑	☐	☑	☐	2
				Your Number Votes	20	20	20	20	20	20	

The following table ranked each of the solutions based on the 2 objectives to create the graphical Decision Chart. The justification for the ranking can be found in appendix G, table I.

Table H - Graphical Decision Chart Ranking

					2 Most Important Objectives Ranked from 1-5			
10 Candidate Ideas					O_1 Reduce Carbon Emissions	O_2 Fulfill Energy Generation Need	Result for Objective 1	Result for Objective 2
4	Vertical Wind Turbine (open system)	Doubly Fed Induction Generator	Sodium-ion battery	District Heating/Cooling Systems	8	5	8	5
10	Dynamic Solar Panels (Move with the Sun)	Perovskite Solar Cells	Sodium-ion battery	AC Microgrid Distribution	9	4.5	9	4 5
14	Bifacial Panels	Monocrystaline Silicon Cell	Flow battery system	Busbars	6	7.5	6	7.5
18	Dynamic Solar Panels (Move with the Sun)	Polycrystaline Silicon Cell	Sodium-ion battery	District Heating/Cooling Systems	9	4	9	4
26	Vertical Wind Turbine (open system)	Permanent Magnet Synchronous Generator	Flow battery system	High-voltage Transmission Lines	6	7	6	7
32	Sun Tracking Solar Panels	Monocrystaline Silicon Cell	Flow battery system	AC Microgrid Distribution	7	6	7	6
42	Dynamic Solar Panels (Move with the Sun)	Photovalic Cells	Second-life EV battery storage	Smart Grid	7	5	7	5
45	Stationary Solar Panels	Monocrystaline Silicon Cell	Lithium-ion battery storage	Smart Grid + Low-Voltage Distribution Cables	9	7	9	7
46	Vertical Wind Turbine	Doubly Fed Induction Generator	Flow battery system	AC Microgrid Distribution	6	8	6	8
47	Vertical Wind Turbines + Bifacial Solar Panels	ed Induction Generator + Tandem Solar Cells (Perovskite	Iron-air battery	Smart Grid	6	10	6	10

Table I has a compiled version of all the research done to rule out the three best solutions in the Graphical Decision Chart Process.

Table I - Graphical Design Chart Research

Research Summary - Graphical Design Chart	
Capture (Energy Capturing Systems)	**Vertical Wind Turbine** ● Carbon Emission: 368 tonnes CO_2 per MW [87](pg 36) ● Efficiency: Conversion of 35-40%, but in particular configurations could increase by 15% [88], [89] **Stationary Solar Panel** ● Carbon Emission: 250g per KW = 250 tonne per MW[90] ● Efficiency: Conversion of 20-40%[91] **Dynamic Solar Panel** ● Carbon Emission: No significant research available, however estimated to be higher than stationary solar panel and lower than vertical wind turbines. (Dynamic solar panels would have more components than stationary solar panels, but not enough to surpass wind turbines) ● Efficiency: more effective than stationary solar panels by 7.2%[92](research paper had 3 testing results. The averaged increase in performance in % has been calculated which = 7.2%) **Bifacial Solar Panels** ● Carbon Emission: No significant research available, however due to having 2 sides of solar panels, the carbon emissions is estimated to be higher than both stationary and dynamic solar panels, but still under wind turbines ● Efficiency: More effective than stationary panels by 10-21%

Research Summary - Graphical Design Chart	
Batteries (Energy Retention Systems)	**Iron Air Battery** ● Although Iron Air batteries have higher storage densities, their efficiency is not reliable which is why we ruled out the Lithium Ion Battery as a safer option. [93], [94] **Flow Battery** ● Flow batteries have a high carbon footprint in their production. 183 kgCO2/kWh for flow and 168 kgCO2/kWh [95] ● Lithium-ion batteries have a higher efficiency than Flow Batteries: 90% and 80%, respectively. [96] **Sodium Ion Battery** ● Sodium Cells have a much lower GWP rating than lithium-ion batteries, at only 62.68 Kg CO2 eq/ kWh. [97] ● Still in the early stages of its production, so we cannot be certain of its energy retention, and the raw supply chain is not well-established on the market.[98] ● **Second-life EV battery storage** ● Producing an Electric Vehicle Battery emits up to 100 kgCO2e/kWh[99] EV batteries retain about 70 to 80 % of their original capacity. Since these EV batteries are 2nd-life lithium-ion batteries, this means they will be 20 to 30 % less efficient than new lithium-ion batteries. [100] **Conclusion:** After this research, the lithium-ion battery is still the most reliable energy storage system. **Note:** The Lithium Ion Battery was used as a benchmark as it is currently the most widely used battery type.

The following table ranked the three final solutions based on all objectives. The justification for the ranking can be found in appendix G, table k.

Table J - Pugh Chart Chart

	Objectives	Solution 47	Solution 45	Solution 46
1	Reduce Carbon Emissions	1	0	1
2	Fulfill Energy Generation Need	1	0	-1
3	Operate without maintenance	-1	0	-1
4	Minimize cost of energy generation	-1	0	-1
5	Fit Within the Designated Roof Space	-1	0	0
Final Sum		-1	0	-2

Table K has all the research done in the Pugh Chart to compare the final three solutions using all the objectives.

Table K - Pugh Chart Research

45	
Reduce Carbon Emissions	**Stationary Solar Panels:** ● Solar and battery systems can reduce up to 80% of CO_2 emissions compared to traditional grid electricity. [30] ● 10 kW solar roof typically reduces carbon emissions by about 4 tons annually[101] **Lithium-ion battery storage:** ● Using lithium-ion batteries in homes can reduce carbon emissions by 20-50% compared to relying on solar alone.[102] ***Smart Grid + Low-Voltage Distribution Cables*** ● Reduce carbon emissions by 33%[78]

45	
Fulfill Energy Generation Need	***Monocrystalline Silicon Cell:*** ● 15 to 23% efficiency ● Power Output(per m^2): Over 160 watts[35] ***Lithium-ion battery storage:*** ● High efficiency between 90 and 95%[34] ***Smart Grid + Low-Voltage Distribution Cables*** ● Smart Grid: Reduce energy losses by ~25%[31] ● Low-Voltage Distribution Cables: energy losses of~ 4%[72]
Operate without maintenance	***Monocrystalline Silicon Cell:*** ● cleaning every 6 months[37] ● Lifespan:25+ years[35] ***Lithium-ion battery storage:*** ● Life span of key component: 15 years[103]
Minimize cost of energy generation	***Monocrystalline 20 - 25 dollars per kilogram [39]*** ***Lithium Ion Battery cost $100/KWH[40]*** ***Smart grids lower cost in long term [104]***
Fit Within the Designated Roof Space	Lithium ion batteries have highest energy densities. Used in electronics and electric transportation because of small size [40]

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Reduce Carbon Emissions	***Vertical Wind Turbine:*** ● 99% less carbon emission compared to coal-fired power plants, 98% less than natural gas, and 75% less than solar.[105] ***Flow battery system:*** ● Saving 78% of carbon emissions across all lifecycle phases (manufacturing, use, and end-of-life) [42]
Fulfill Energy Generation Need	***Vertical Wind Turbine:*** ● 40–150 W/m^2 ● 20% to 40% of wind turns into energy [106] ● ***Flow battery system:*** ● Flow batteries typically have a round-trip efficiency of 65%–85% [107]
Operate without maintenance	***Vertical Wind Turbine:*** ● maintenance every 6 to 12 months (Inspections, Lubrication, Testing, Replacements, Monitoring:) ● Lifespan: approximately 25 years [49] ***Flow battery system:*** ● Annual maintenance visit [108]
Minimize cost of energy generation	***Micro/roof mounted wind turbines: 500 - 4000 USD[109]*** ***Flow Battery - low production cost, safe materials, long lifespan[110]***
Fit Within the Designated Roof Space	***Spacing between turbines based on rotor size, 2-4 times rotor length spacing perpendicular to wind flow and 8 to 12 between turbines with wind flow [110]***

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Reduce Carbon Emissions	***Vertical Wind Turbines + Bifacial Solar Panels:*** ● Solar and battery systems can reduce up to 80% of CO_2 emissions compared to traditional grid electricity. [30] ● VAWT:-99% less carbon emission compared to coal-fired power plants, 98% less than natural gas, and 75% less than solar.[105] ***Smart Grid:*** ● Reduce carbon emissions by 33% [31]
Fulfill Energy Generation Need	***Vertical Wind Turbines + Bifacial Solar Panels:*** ● produce up to 30% more energy than traditional monofacial solar panels [111] ***Doubly Fed Induction Generator + Tandem Solar Cells (Perovskite + Silicon):*** ● Tandem Solar Cells: 31.6 %efficiency. ○ Power Output(per m^2): 285.1 W/m² [48], [112] ***Iron-air battery:*** -round-trip efficiency of around 50-60% [94] ***Smart Grid:*** ● Reduce energy losses by ~25% [31]
Operate without maintenance	***Vertical Wind Turbines + Bifacial Solar Panels:*** ***Vertical Wind Turbine:*** ● maintenance every 6 to 12 months (Inspections, Lubrication, Testing, Replacements, Monitoring:) ● Lifespan: approximately 25 years [113] ***Bifacial Solar Panels:*** ● cleaning both sides every 6 months [37] ***Iron-air battery:*** ● Lifespan: 30 years [94]
Minimize cost of energy generation	***Bifacial Panels $15 - 20 per kilogram [35}*** additional cost of wind turbines: micro/roof mounted: 500 - 4000 USD [109]

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Fit Within the Designated Roof Space	***Spacing between wind turbines [110]***

Appendix H - Definitions

Monocrystalline Cells: Photovoltaic panels made from a single sheet of silicon [29]

Lithium Ion Batteries: Rechargeable and are charged and discharged by lithium ions moving between the negative and positive electrodes [114]

Smart Grid: Network that uses digital and other advanced technologies to manage the transport of electricity[104]

Low Voltage Distribution Cables: Max 1k distribution for safety [115]

AC Generator: Both rotor and stator windings are fed with three-phase AC supply[43],

Flow Battery: Electrolyte containing electroactive elements that reversibly convert chemical energy to electrical energy[116]

AC Microgrid: Where current changes direction periodically, typically in a sinusoidal pattern

Bifacial Solar Panel: Can Capture light on both sides [111]

Tandem Perovskite-silicon Cell: Photo-valic cell based on a light-harvesting active layer composed by a perovskite-structured material [117]

SCAMPER Method-(Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, and Reverse)

Appendix I- Calculation for the alternative design

Below are calculations for the 3 proposed designs.

Table L- Calculation

Number of Mono Cells
All calculation based on standard test conditions (STC) [116] Medical science Roof : 5000m^2 (rough estimate with Google earth) Useable roof: 5000 * 0.7 = 3500 (70% 0f Roof) Commercial Size monocrystalline solar panel: 2.1 m tall and 1.1 m wide, area of about 2.3 m^s. [117] For spacing and mounting: 3m *3m = 6m + 2.3 m = 8.3[118] Number of Solar panels = 3500/8.3= 421 panels [119]
Number of VAWT
Wind speed: 13m/s (3.1 Physical environment) Medical Science Roof : 3500m^2 Based on 3D model: 48
Number of Solar panels/VAWT
Number of wind turbines = Based on 3D model Number of Solar panels: 421