Designing A Net Zero Carbon Building in Northern Canada

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Abstract

The Government of Canada is committed to reducing greenhouse gas (GHG) emissions by 90% below 2005 levels by 2050. The Greening Government Strategy requires all new federal buildings to be net- zero carbon unless a cost-benefit analysis demonstrates otherwise.

Our study investigates the potential of achieving a Net Zero Carbon building in Northern Canada. Major challenges include fuel source availability, extreme cold weather, capital and operational costs, as well as GHG emission factors related to the electricity grid.

Using whole building energy and life-cycle cost analysis, we have investigated alternative HVAC plants and other measures that are financially feasible in reducing the GHG emissions of a new water treatment plant (WTP) in the Northwest Territories, Canada. WTPs add the additional challenge of high ventilation and process loads. Climate change, renewable energy systems, and future greening of the electricity grid are considered in this study.

Introduction

As part of the Federal Sustainable Development Strategy, the Government of Canada is committed to reducing greenhouse gas (GHG) emissions by 90% below 2005 levels by 2050. The Greening Government Strategy (Government of Canada, 2021) requires all new federal buildings to be net- zero carbon unless a cost-benefit analysis demonstrates otherwise.

This federal mandate may be easier to achieve in milder climates or major cities, where the building conditioning loads are lower, and resources are more readily available. But for buildings located in more extreme cold climates, such as Northern Canada, net-zero buildings are much harder to achieve.

The major challenges to achieving a net-zero design in Northern Canada are fuel source availability, extreme cold weather, capital and operational costs, as well as GHG emission factors related to the electricity grid.

Mal et al. (2019) discusses the challenges of net-zero energy housing in Canadian North, such as high fuel costs for space heating, lack of skilled labour, extreme cold temperatures and the mismatch of solar radiation available in summer and no solar in the winter when it is most needed. Pinto et al. (2022) discusses the difficulties of replacing diesel as a fuel source for power and heating in Nunavut, which is one of the three territories located in Northern Canada.

As the industry shifts towards net-zero buildings to meet the federal mandate to reduce GHG, there have been studies to determine what energy efficient strategies are appropriate for Northern Canada.

Mal et al. (2019) uses an energy model of a house in Yellowknife to investigate strategies such as a high performance envelope, optimized window-to-wall ratio, strategic ventilation, external shading, heat recovery ventilation, air-source heat pump, and a Building Integrated Photovoltaic/Thermal system (BIPV/T). Pinto et al. (2022) explore existing and potential low carbon energy sources such as wind, solar, hydroelectric, geothermal, tidal, biomass and nuclear.

Hakim et al. (2018) investigates the status of energy-efficient and net-zero energy schools in Canada. The authors identify best practices for construction by studying existing self-sufficient schools in the coldest parts of the US. Photovoltaic, optimized orientations, natural ventilation, daylighting, geo-exchange, solar thermal, high performance envelope/lighting/HVAC, and automated sensors are the energy-efficient strategies taken by outstanding US schools in cold climates.

Li et al. (2021) explores the life-cycle impact assessment of net-zero energy barns in Alberta, Canada. Heat recovery ventilation and photovoltaic panels are proposed for the barns. Tardifing et al. (2011) reviews the progress made in building net-zero energy commercial and residential buildings in Canada for the last decade. As per the study, net-zero buildings can be achieved by replacing fossil fuels with biomass (in limited situations) or solar space heating with supplementary electric heating. Further energy savings can be achieved by maximizing solar thermal energy and storage, using high efficiency heat pumps, and using electrical renewable generators (e.g. photovoltaic, wind, small hydro).

Our work builds upon previous studies and investigates the potential of achieving a Net Zero Carbon building in Northern Canada. Using whole building energy and life-cycle cost analysis, we investigated potential alternative

HVAC plant, envelope, and renewable energy strategies that are financially feasible in reducing the building's GHG emissions. The future greening of the electricity grid is considered in this study.

We focus our study on a water treatment plant (WTP) located in Yellowknife, Northwest Territories, Canada. Our company was engaged to provide a full design for the WTP. Since the WTP falls under the Greening Government Strategy, it is required to be net-zero carbon. Therefore, as part of the design process, we have investigated design solutions to achieve net-zero carbon. This paper presents our analysis methodology, results, and recommendations for the project, which may be generally applied to designing Net Zero Carbon buildings in Northern Canada.

Methodology

Energy modelling is a valuable tool during the design of new building projects to estimate energy use based on the local climate characteristics, system choices, and geometry. The purpose of energy simulations is to assist owners and design teams in recognizing opportunities to reduce energy use in their designs and evaluate the effectiveness of proposed energy-efficient measures. Integrated Environmental Solutions Virtual Environment (IESVE) software is used to perform this analysis.

Our approach is to create a Base Case energy model of the building design to test out different GHG reduction strategies. The Base Case represents the business-as-usual approach to designing the building, without considerations of achieving a Net Zero Carbon building. The Base Case design is typically just code-compliant and contains minimal energy/GHG savings features. A life-cycle cost analysis (LCCA) is also performed to evaluate the cost-effectiveness of each strategy. The following sections outline the special considerations of the model and LCCA inputs for this analysis:

Weather Data

The *CAN_NT_Yellowknife.AP.719360_CWEC.epw* weather file that was used in the simulations is a Canadian Weather for Energy Calculations (CWEC) file for Yellowknife, NT. This is the most representative location for which a weather file is available, based on proximity and similarities in heating degree days (HDD) to the actual building site. A variety of different weather files for the same location was reviewed and ultimately, this version of the CWEC files was used due it having the highest HDD. We chose this version to represent the **worst-case** scenario in terms of weather.

Carbon Emission Factors

Table 1 shows GHG emission factors from various energy sources/fuel types (Government of Canada, 2021) and are assumed to be consistent during the 40 years of the project's lifecycle.

The electricity GHG emission factors projection (provided by the client) for the Northwest Territories in the next 40 years of the project lifecycle are shown in the Figure 1 below. Note that the table is a forecast and actual electrical grid GHG emissions reduction will be dependent on conversion of the existing power plants to cleaner technologies.

Table 1: Carbon Emission Factors (Fossil Fuels)

Fuel Type	gCO_2/kWh
Light fuel oil	270.8
LPG	217.8
Wood Fuel	3.6

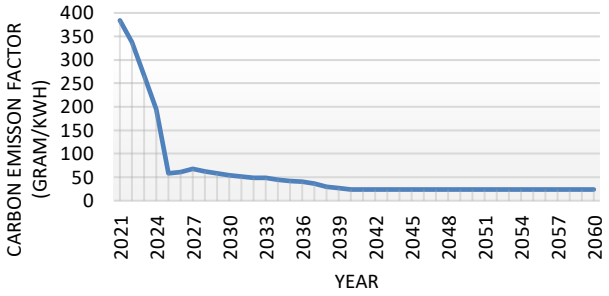

Figure 1: Carbon Emission Factors (Electricity)

Fuel Rates

Table 2 shows the fuel and utility rates from utility bill information provided by the client. These rates are all subject to a 2% inflation factor in years beyond 2021. A demand rate is typical from utility companies for large users, as they attempt to charge a certain price based on your maximum required electricity over a pre-determined period (15-minutes in this case). Actual fuel and utility prices can be volatile. These averaged rates will provide a solid baseline over an extended period, but small disturbances in the fuel supply chain could cause local peaks that are impossible to predict.

Table 2: 2021 Fuel and Utility Rates

Fuel Type	$/kWh	$/kVa
Light fuel oil	0.085	N/A
LPG	0.082	N/A
Wood Fuel	0.059	N/A
Electricity	0.187	$11.76

Shadow Carbon Pricing

Shadow carbon pricing is the voluntary use of a notional market price (a "shadow" price) for carbon in internal corporate financial analysis and decision-making processes. As requested by the client due to the Greening Government Strategy, a $300/tonne shadow carbon pricing rate will be used for the LCCA. This rate will be applied to all years and remain flat through the 40-year life cycle.

Inflation and Discount Rates

In the Net Present Value (NPV) calculations included in the Life Cycle Cost Analysis (LCCA) it was agreed upon to use a 2.0% inflation factor for any costs outside of 2021. In addition to the inflation cost, a discount rate of 2.1% is currently used in the LCCA.

Energy Model Overview

Figure 2 shows the energy model for the WTP. The model was built based on building design drawings and input from the mechanical, electrical, and architectural design teams. The building consists of the following space types: electrical, mechanical, corridors, laundry, breakroom, open office, stairs, storage, washroom, and workshop.

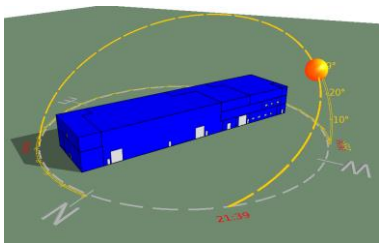

Figure 2: IESVE Energy Model of Giant Mine WTP

Table 3 summarizes the key energy model inputs and assumptions of the Base Case. The envelope is made up of insulated metal panels with code-compliant thermal performance. Glazing is standard performance triple paned windows, which is typical for this climate. The HVAC system is a mixture of heat recovery units (HRU), mixed-air air-handling units (AHU), and make up air units (MAU) that serves different parts of the building. Air-side heat recovery is implemented for most ventilation systems except the MAUs. Oil fired boilers and water-cooled chillers are typical design choices for this type of building and location. The proposed 6-pipe water cooled chiller is a heat pump system composed of linked, connectible modules. This type of chiller is capable of simultaneous heating and cooling, as well as heat recovery. Finally, there are some additional systems specific to this building type, such as combustion preheating and cold tank unit heaters (i.e., unit heaters that specifically offset the heat loss due to the cold tanks in the process area).

Table 4 shows the energy and GHG emission results for the Base Case (oil-fired boilers). Figure 3 shows the energy use breakdown for the Base Case. Space heating is the largest contributor to energy use, followed by central fans and receptacle.

It's important to note that high infiltration rates were modelled to account for the impact of the overhead doors and, generally, a conservative assumption for actual air leakage. This results in a higher space heating load and EUI than if a NECB code infiltration rate were modelled.

Table 3: 2021 Fuel and Utility Rates

Building Component	Model Input
Exterior Wall	5" Insulated Metal Panel R36 (IP), U-0.16 (SI)
Roof Construction	Insulated Metal Panel R44 IP, U-0.13 SI
Doors	Man: R7 IP, U-0.815 SI Overhead: R16 IP, U-0.352 SI
Glazing Assembly	U-0.24 IP, U-1.36 SHGC 0.4
HVAC System Type	**HRU-1/2:** Dedicated outdoor air system (DOAS), hydronic zone unit heater **AHU-1:** Mixed air single-zone constant volume system for recirculation **AHU-2:** Mixed air single-zone VAV system, reheat coils in office areas, 4-pipe FCU in mech/elec rooms **MAU-1/2/3**: DOAS, hydronic zone unit heaters
Energy Recovery	HRU-1/2, MAU-1/2/3: 85% sensible only (dual core) AHU-2: 72% sensible and latent (energy wheel)
Heating Plant	Oil-fired boilers, 85.7% efficiency
Domestic Hot Water (DHW)	Hydronic heaters
Cooling Plant	6-pipe water-cooled chiller, COP 5.2
Additional Systems	Combustion preheating Cold tank unit heaters
Infiltration	0.3 cfm/ft^2 of façade 1 cfm/ft^2 of façade for spaces with overhead doors

Table 4: Base Case Energy Consumption

End-Use	Energy (MWh/year)	EUI (kWh/m^2/year)
Interior Lighting	91	19.4
Receptacle	200	42.6
Space Heating (Oil)	3,764	798.9
SHW (Oil)	198	41.9
Space Cooling	1	0.1
Heat Rejection	3	0.7
Interior Central Fans	932	197.7
Interior Local Fans	90	19.0
Exhaust Fans	2	0.5
Pumps	20	4.2
Ancillary Power	13	2.8
Total	**5,313**	**1,128**

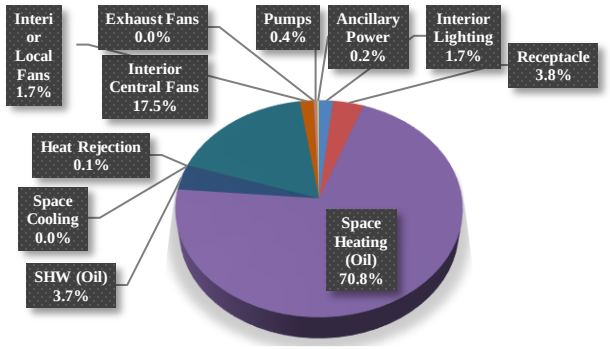

Figure 3: Base Case Energy Use Breakdown

Design Options Analysis

Table 7 shows a summary of the design options. The Design Options explore a variety of different fuel source combinations (e.g. oil, propane, biomass, electricity), different HVAC plant solutions, and other energy/GHG reduction measures (e.g. high-performance envelope, PV panels).

Table 7: Summary of Design Options

	Design Option	Details
Base Case	Oil Boilers	Oil boilers for heating and DHW
1	Propane & Electric	Propane and electric boilers Chiller condenser heat recovery High performance envelope
2	All Electric	Electric boilers High performance envelope
3	90% Mech Design: 720kW Biomass	Biomass, propane, and electric boilers Chiller condenser heat recovery High performance envelope Additional mechanical building
4	950kW Biomass	Same as Option 3 except: 950kW Biomass Boiler
5	2x530kW Biomass + 15kW PV	Same as Option 4 except: 2 x 530kW biomass boilers AHU-2 has dual core heat recovery 15kW PV (~83m^2 of collector area)
6	Net Zero Carbon	Same as Option 5 except: 1644kW PV (~9,126 m^2 of collector area)

Every Design Option is aimed to achieve a step further in reducing GHG. The first two Options are more conservative approaches, using propane and electricity (from the electricity utility provider) fuel sources, which are more conventional choices, but provide minimal improvements in terms of GHG. Options 3-5 explore biomass-based systems, with variations in boiler sizes, heat recovery improvements, and PV. Lastly, Option 6 is the Net Zero Carbon Option, where the use of PV is maximized to balance out the remaining GHG emissions.

Annual Energy Consumption

Figure 4 shows the project annual energy use for the Base Case and all the Design Options. Option 2 has the lowest EUI (before PV) due to its high efficiency electric heating plant, no additional biomass building, and no additional ancillary power required. Taking PV into account, Option 6 has the lowest EUI.

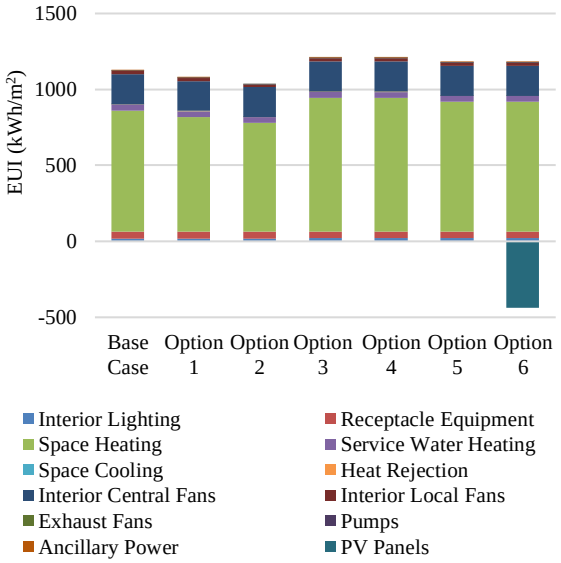

Figure 4: Annual Energy Consumption Comparison

Fuel Consumption

Figure 5 shows the projected annual fuel consumption for the Base Case and all the Design Options, and is summarized as follows:

- The Base Case uses a significant amount of oil for heating and DHW purposes.
- For Option 1, propane and electricity are used for heating and DHW.
- For Option 2, electricity is used for everything in the building.
- For the biomass options (Options 3-6), a mixture of biomass, electricity and propane are used for heating and DHW.
- The biomass boiler capacity increases through Options 3-5, which decreases the need for propane as a top-up during peak loads.
- For the Net Zero Carbon Option, the PV panels generate more electricity than the building consumes; hence, the negative fuel consumption value.

- Since biomass has the lowest GHG emission factor, the biomass options use the most biomass and therefore, will produce the least amount of GHG and hence provide the highest GHG savings.

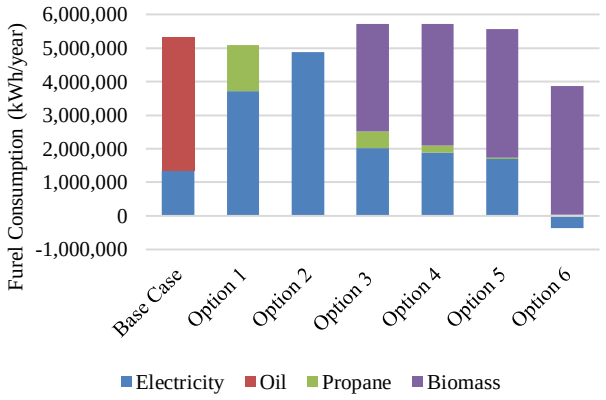

Figure 5: Annual Fuel Comparison

GHG Emissions over 40 Years

Figure 6 shows the annual GHG emissions of the Base Case and the six design options over 40 years. Since the Base Case mostly uses fuel oil and its GHG emission factor is projected to stay consistently high for the next 40 years, the building's GHG emissions don't decrease significantly over time. We see the most dramatic decrease for the Option 2: All Electric case, where emissions drop steeply in the first 5 years and then continue to drop over time. The biomass options take advantage of the decreasing electricity GHG emission factor and the very low biomass GHG emission factor to achieve overall low GHG emissions over time.

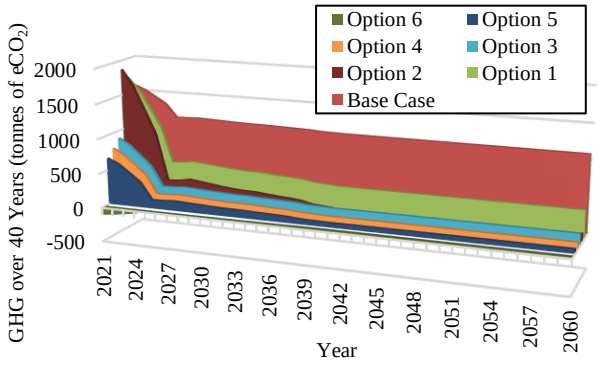

Figure 6: Annual GHG Emissions over 40 Years Comparison

Figure 7 shows the total GHG emissions over 40 years. Starting from Option 1: Propane & Electric, the subsequent options to the right offer increasing GHG savings. This is primarily due to reducing or eliminating fossil fuel-based energy sources (e.g., propane, oil) and replacing them with fuel sources (i.e., electricity and biomass) that have a decreasing or low GHG emission factor. Option 5: 2x530kW Biomass & 15kW PV and Option 6: Net Zero Carbon have the PV panels to decrease the use of electricity. The Net Zero Carbon Option has enough PV to offset the GHG from the other fuel source (i.e., electricity, biomass, propane) to achieve Net Zero Carbon after 40 years.

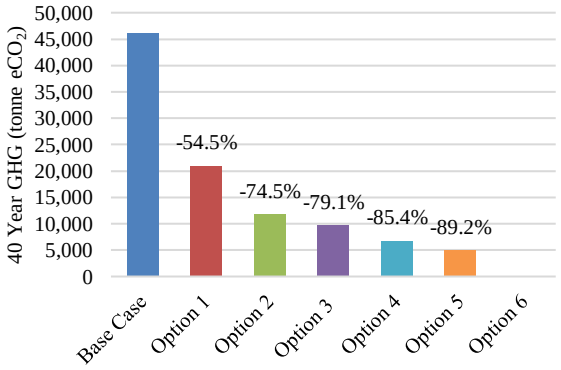

Figure 7: Total GHG Emissions over 40 Years Comparison

Life Cycle Cost Analysis (LCCA)

Figure 8 shows the NPV trend for all the options, including the Base Case, with full cost estimates available in Appendix B. Options 1, 2 and 6 all have a higher 40-year NPV than the Base Case. All the options require a larger initial investment to get the low emission/high efficiency technology installed. However, Options 3, 4 and 5 show that savings over the fuel-oil heavy Base Case will be achieved throughout the life of the project, and even as early as 15 years into plant operation.

The LCCA included utility costs, maintenance costs, and any anticipated replacements costs over the 40-year life. All of these costs were subjected to a 2% inflation rate. For each option, mechanical equipment (including boilers) was replaced between 25-40 years. The frequency of replacement was adjusted depending on if the equipment was used frequently versus standby only. The equipment replacements are estimates based upon experience and ASHRAE guidelines for typical service life, and the actual replacement time will be dependent on maintenance intervals and actual operation time.

For the PV panels, two components of replacement costs are included. The first component of replacement is capacity based to account for the 0.5% kW/year of power reduction that occurs as the PV panels age. Since the energy model did not include this power reduction, this was captured in the LCCA instead as a method to keep the PV panel array at full

power. The second component of replacement was related to PV panel lifespan as some of the panels will require replacement within the 40-year lifespan.

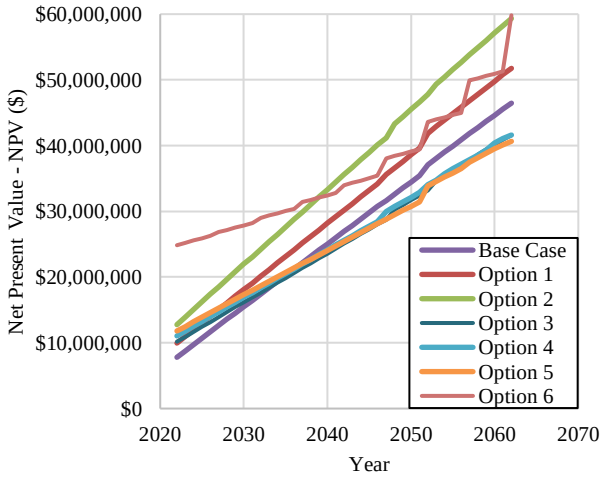

Figure 8: 40-Year NPV Comparison

Options 1 and 2 have a higher life cycle cost due to their higher reliance on electrical utilities. Even though the overall site consumption is lower, the higher cost of electricity causes the high life cycle cost. Options 1 and 2 are not recommended.

Options 3, 4 and 5 are all similar in terms of 40-year NPV, with slight differences in implementation cost due to different biomass boiler sizes. However, Option 5 has the highest implementation cost of these three options but the lowest 40-year NPV.

Option 6 (Net Zero Carbon) has a considerably higher implementation cost than the other options due to the large amount of PV panels required to achieve zero emissions. Although the utility costs remain low over the life of the system, the replacement and maintenance costs are much higher.

The changes in slope in the NPV graph (Figure 8) resemble future equipment replacement costs. It is important to note that incremental PV replacement costs were included to offset the PV panel life derating, which explains the multiple changes in slope seen in Option 6.

Discussion

A wood pellet biomass boiler system operates like many other types of fuel fired boilers, where heat is generated through combustion of wood pellets and that energy is transferred to a fluid (e.g. water/glycol solution) throughout the building(s) by circulation pumps.

A wood pellet biomass boiler has similar requirements to other boiler systems, which includes fuel storage, a fuel transfer system, and venting systems for the products of combustion. In addition to this, a biomass boiler generates ash from the combustion of wood. For wood pellets, the amount of ash created is around 1.0% of the mass of the wood pellet.

The most common fuel used in a biomass boiler is the wood pellets. Wood pellets are primarily created from mill residues such as sawdust, shavings, cut-offs, and stern wood. This combination of wood goes through a process that chips, dries, and forms the wood into a pellet shape.

The wood pellets suitable for commercial applications are graded either as A1, A2 or B and are required to meet certain benchmarks, as per *CAN/CSA-ISO 17225 Part 2: Graded Wood Pellets*. This ensures that wood pellet fuel is consistent between batches.

Wood Pellet Supply Chain

In order for a biomass (wood pellets) heating plant to be feasible: a reliable supply of biomass fuel is required. To evaluate the feasibility of biomass fuel to be utilized at the WTP site, research into wood pellet mills and supply to Yellowknife was completed to determine fuel availability, delivery frequencies, quantities, and methods.

Most of the wood pellets that are being supplied to the Yellowknife area are being supplied from Northern Alberta. Currently there are no wood pellet mills constructed in Yellowknife and there appears to be no plans to build one in the near future. Most wood pellets that are delivered to the Yellowknife area are currently produced by La Crete Sawmills. Based on our research, La Crete Sawmills is currently the only supplier capable of meeting the wood pellet demands of the WTP.

Wood pellet supply to Yellowknife is stable as this service has been provided to Yellowknife for over 15 years from La Crete Sawmills. Furthermore, a new sawmill and pellet plant is expected to begin construction and operated in the Hay River region in the near future for the purposes of meeting increasing Northern community wood pellet demands.

GHG Emissions Considerations

The benefit of using wood pellets, is that the combustion of wood releases as much CO_2 into the atmosphere as a tree absorbs over its lifetime. This makes heating with wood pellets a carbon-neutral option and an attractive climate-friendly solution where the reliability of combustion heating is required in northern climates.

The source of biomass for the pellets is wood waste from sawmill operations. This biomass would either be burned at the sawmill or landfilled if it was not converted into a value-added energy/fuel source. Therefore, wood pellet systems will provide cost effective heating to reduce greenhouse gas emissions without increasing electrical demand.

Conclusions and Recommendations

Table 8 shows a summary of the results. Apart from the Net Zero Carbon Option, Option 2 achieves the highest energy

saving; Option 5 achieves the highest GHG savings over 40 years; and Option 5 has the lowest NPV ($).

The implementation of Option 5 is recommended. This option includes several energy/GHG efficient features:

- A heating plant that includes two biomass boilers (530 kW each)
- A small additional mechanical building with an array of PV panels (15 kW) installed on its roof
- Improved air-side heat recovery for AHU-2
- Chiller condenser heat recovery
- A high-performance envelope

Although this option has the highest implementation cost of the options (excluding the Net Zero Carbon Option), it has the lowest 40-year NPV while achieving the best GHG savings of the five options. Moreover, with further investigation into the feasibility of wood pellet biomass boiler systems, the wood pellet supply chain, and biomass GHG emissions considerations, we are confident in recommending this solution.

Table 8: Summary of Results

	Energy (MWh)	GHG Savings in 40 Years (%)	Implemen-tation Cost ($)	40-Year NPV ($)
Base Case	5,313	N/A	6,830,000	45,650,000
1	5,092	-54.5%	8,940,000	50,875,000
2	4,879	-74.5%	12,770,000	59,463,000
3	5,723	-79.1%	10,180,000	41,468,000
4	5,714	-85.4%	10,320,000	40,972,000
5	5,567	-89.2%	11,130,000	40,046,000
6	3,515	-100.0%	24,500,000	59,104,000

Alternatively, Options 3 and 4 are also viable options. However, Option 3 will require the addition of a second biomass boiler in the future to achieve 80% GHG reduction. Option 4 does not require an additional boiler, so it is a better choice than Option 3 with minimal capital cost increase. Both options have a strong 40-year NPV compared to the Base Case.

The Net Zero Carbon Option (Option 6) does achieve the 100% GHG reduction, along with a noticeable overall energy consumption reduction. However, it does require a PV panel grid of minimum 1,650+ kW to achieve Net Zero Carbon. The PV array would require a very large area (i.e., 9,126 m^2 of collector area plus supporting equipment) near the plant to ground mount the PV panels. To put this size into perspective, the required area for the PV array would be several times larger than the entire WTP. It is also important to note that civil infrastructure costs have not been included and would need to be added to the estimate if further engineering was requested. Although the energy costs for this option are lower, the large PV grid considerably raises the implementation, maintenance, and replacement costs over the 40-year life, which results in a poor business case.

The only option that is strongly recommended to be avoided is Option 2, which relies heavily on electricity. Electricity is the most expensive utility to purchase and causes large operational costs. Furthermore, there is also a large capital cost required to install a substation upgrade, which is not included in this study. This option has less GHG reduction for a higher capital investment and results in a poor 40-year NPV.

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