1100 – 100 Sheppard Ave. East
Toronto, Ontario, M2N 6N5
416 218 7025 | sa-footprint.com

Net Zero Carbon Roadmap

03042-006

For

McMaster University

Project Location

McMaster University Campus, Hamilton, Ontario

Footprint Project Number

03042-006

Date

2020-11-06
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Executive Summary

PURPOSE

As detailed in RFP 0878-2020, McMaster is committed to a safe and sustainable campus. As part of this commitment, McMaster would like to create a net zero carbon strategy. Footprint, using a campus energy model, has provided this report, detailing a pathway for McMaster to achieve a zero carbon campus, implementing key changes in phases over the next 30 years.

KEY FINDINGS

Key findings of this study include:

- Baseline campus carbon emissions are 40,400 tons of carbon dioxide equivalent (CO_2e) annually
- A plan is proposed whereby the campus emissions are reduced by 75% by 2030 and by 90% by 2050. Purchasing carbon credits or installing additional renewable energy generation capacity may need to be considered for the remaining 10% of emissions reductions.

RECOMMENDATIONS

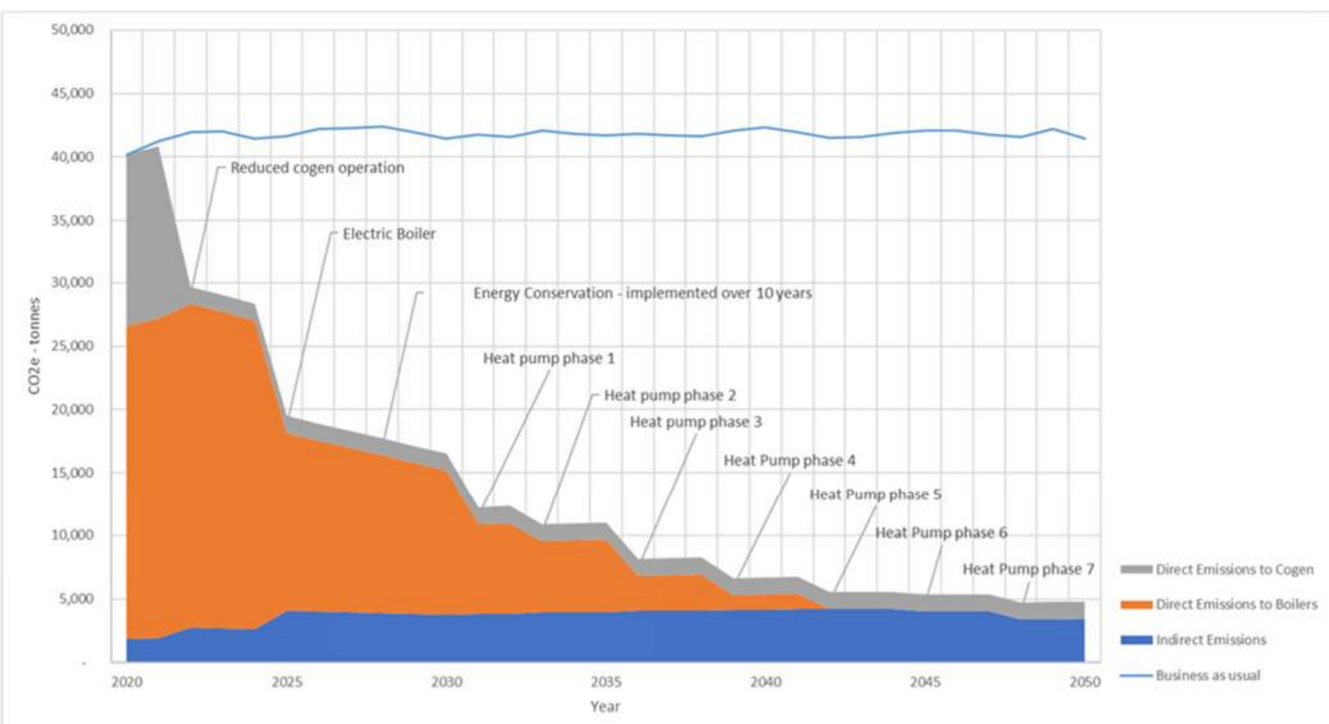


Figure E1: Recommended Emissions Reduction Path and Components

Plan Component	Budget Cost in millions	Utility Cost Impact without Class A and Peak Shaving	Utility Cost Impact with Class A and Peak Shaving	Emissions Savings Tonnes CO_2e[1]
	Near Term Projects			
Energy Conservation Measures	$17.4	Decrease $1.1M/year	Decrease $0.8M/year	9,900
Reduced Cogeneration Operation	-	Increase $3.1M/year	Increase $129k/year	8,300
Electric Boiler Installation	$4.0	Increase $6.1M/year	Decrease $127k/year	9,200
	Potential Future Projects			
Ground Source Heat Pump - Closed Loop	$86.7	Increase $1.9M/year	Neutral	22,300
Waste Water Heat Recovery	$3.7	Included above	Included above	Included in GSHP
Reactor Heat Recovery	$4.2	Included above	Included above	Included in GSHP
	Alternate Heat Pump Solutions			
Ground Source Heat Pump - Open Loop	$65.4	Increase $1.9M/year	Neutral	22,300
Air Source Heat Pump Chiller/Heaters	$29.6	Increase $2.1M/year	Increase $300k	-

1 – Note that interaction between measures means the savings from individual measures do not total to the cumulative plan reduction

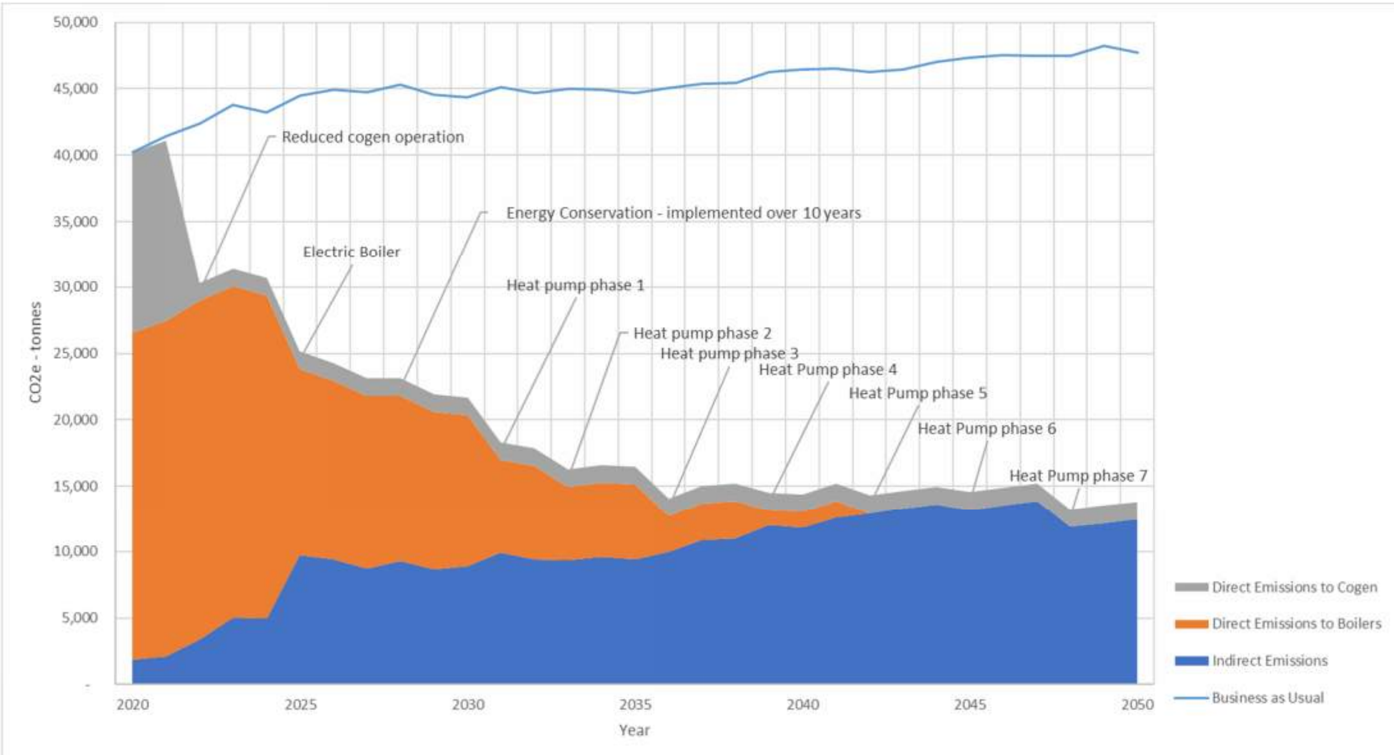


Figure E1A: Carbon Emissions Reduction Path with Indirect Emissions Factor Growth

Introduction

OBJECTIVE

This study was performed at the request of Debbie Martin, Assistant Vice President and Chief Facilities Officer, of McMaster University to provide an analysis of the main campus carbon emissions and develop a plan for reaching the goal of net zero carbon by 2050.

The aim of the study was to:

- Establish McMaster's baseline energy use and carbon emissions of the buildings within scope and vehicle fleet;
- Evaluate the current emissions and energy usage;
- Identify methods of carbon reduction;
- Illustrate potential pathways of carbon reduction which integrate and sequence the various recommendations;
- Identify a detailed carbon reduction target and recommended path.

The report provides an analysis of the main campus carbon emissions and a plan for reaching the goal of Net Zero Carbon by 2050.

MCMASTER UNIVERSITY MAIN CAMPUS – SUMMARY & STATS

The McMaster University main campus consists of over 50 buildings dedicated to student life, athletics, campus operations, arts and academic research. The main campus covers over 200 acres and located in the west end of Hamilton just south of Cootes Paradise. The total indoor gross floor area of the campus is 400,000 m^2. The university has approximately 30,000 students and typically operates all 12 months of the year.

The buildings on campus are connected to a district energy system that produces steam for heating energy and chilled water for cooling energy. The steam and chilled water are distributed to each building on campus through an underground district energy piping network. The district plant equipment is housed at the E.T. Clarke Centre and adapts to meet the heating and cooling needs of all buildings on campus simultaneously as the building loads change throughout the year.

The campus currently emits about 40,400 tons of carbon dioxide equivalent (CO_2e) annually. Ninety-five percent (95%) of the total emissions are direct emissions from the combustion of natural gas in the boilers and cogeneration unit for the production of steam and electricity. Direct emissions also result from the combustion of diesel fuel in campus generators and both gasoline and diesel in the campus fleet of vehicles. The remaining emissions are indirect emissions from grid electricity consumption.

Campus Buildings Description

BUILDING TYPES

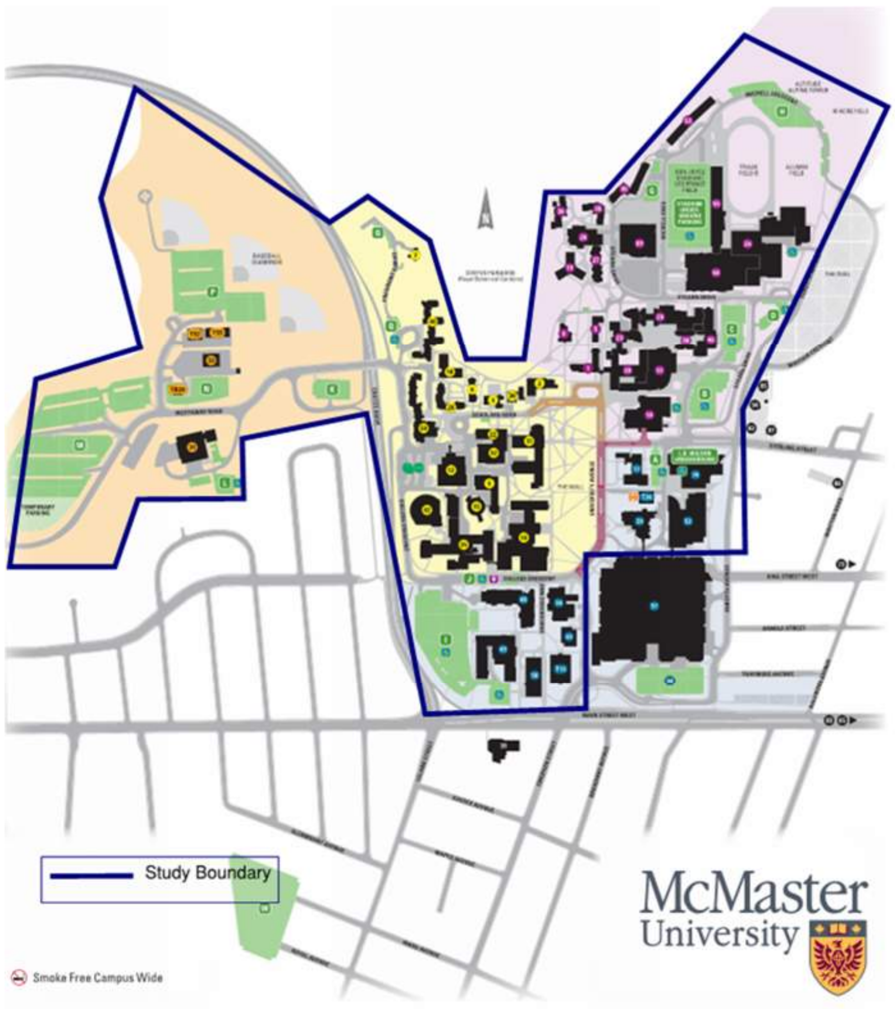


Figure 1: Project Boundary

Fifty-five (55) buildings were included in the analysis. All of the buildings are part of the main campus including the Campus Services Building and the Applied Dynamics Lab. The buildings on campus can be placed into four general building types:

- Student Residences
- Institutional
- Libraries

- Laboratory Facilities

The campus is comprised of buildings dating back nearly one hundred years, from 1929 for Edwards, Hamilton, University, and Wallingford Halls to the recently completed Peter George Centre for Living and Learning (PGCLL).

The residence buildings tend to be grouped together on the main campus. The two main clusters of residence buildings are in the north and northwest sections of campus. There are 13 residence buildings on campus. These buildings house on-campus students with food services being available at Mary E. Keyes and the Commons Building.

The institutional building types include all lecture and classroom buildings, faculty offices, graduate studies, and administrative buildings. This building type is by far the most abundant on campus and are located in all areas of the campus.

There are two major libraries on campus – Mills Memorial and HG Thode. These libraries give students space to study together, conduct research, and collaborate.

Laboratory Facilities are buildings that conduct research experiments and therefore have high ventilation requirements. These buildings include the Nuclear Research Building, the Applied Dynamics Lab, and ABB Science Building.

The McMaster University Medical Centre (MUMC) is not included within the scope of this study. The hospital is fed with electricity from the Campus transformer substation. While the hospital has its own central plant equipment, it is also fed with steam and chilled water from the McMaster district energy system and does provide hot water to the Michael Degroote Centre for Learning and Discovery (MDCL). Utilities provided to the hospital are submetered and not included within this report. The hot water to MDCL is included in this analysis.

CONSTRUCTION TYPES

Building construction on campus spans nine decades leading to a wide variety of building materials and construction techniques being used. The oldest buildings on campus are constructed largely of stone. The windows in these buildings are typically single pane and the window-to-wall ratios are low on all sides. The interiors of these buildings have gone through renovations, but the exterior aesthetic is original.

Buildings constructed between the 1960s and 1990s are largely brick or concrete in their exterior facades. These buildings have increased window-to-wall ratios compared to the older buildings on campus. Buildings such as the Burke Science Building and the Information Technology Building also incorporate the stone exterior to follow the example of the older buildings. The buildings of the Arts Quad and the residence buildings of this time use combinations of brick and concrete veneers for their exterior wall construction.

The newest buildings on campus follow modern construction techniques and architectural styles. The exterior cladding of these buildings are largely window glass, insulated exterior cladding, and spandrel constructions. PGCLL is an example that shows the newer, highly-glazed design. The Engineering Technology Building is nearly an all vision glass exterior. This style can also be seen in recent additions to buildings including the Gerald Hatch Centre and the Dr. Robert and Andrée Rhèaume Fitzhenry Studios and Atrium.

MECHANICAL SYSTEMS

All buildings on the main campus are connected to the district energy system. The buildings have steam to hot water heat exchangers transferring the heat to the building heating water. Hydronic heating provides much of the heating within campus buildings. Ventilation air is heated by either steam coils or glycol hydronic coils. Some buildings also use steam for humidification.

Domestic hot water also uses the steam distribution network to heat incoming domestic water. The buildings are split between instantaneous hot water systems and hot water storage tank systems. The instantaneous systems utilize the steam network to heat domestic water instantaneously and distributed to the building. Controllers coined “the Brain” control the amount of hot water being generated and distributed to the building. The storage tank systems use the steam distribution system to heat the incoming domestic water, storing it for use when needed.

Hydronic cooling in the campus buildings is fed directly from the district energy chilled water system. In some buildings, process chilled water is utilized using chilled water to chilled water heat exchanger loops. Cooling is delivered through a combination of air handling units and zonal fan coil systems.

DISTRICT ENERGY SYSTEM

The main McMaster University campus is serviced by a district energy heating and cooling plant located in the ET Clarke Centre. Steam boilers generate steam that is distributed throughout the campus via an underground distribution network. Chillers in the ET Clarke Centre generate chilled water that is used for nearly all of the campus cooling requirements. All buildings on the main campus are connected to this district energy system, In addition to supplying the campus, the boilers and chillers in the ET Clarke Centre provide back up steam and cooling for the McMaster University Medical Centre operated by Hamilton Health Sciences.

District Energy Plant Operation

DISTRICT ENERGY PLANT EQUIPMENT

Boilers

The district energy plant currently has two natural gas fired boilers: boiler 5 with a steam production capacity of 200,000 lb/hr and boiler 2 with a 100,000 lb/hr capacity. Both boilers are equipped with an Oxygen trim system to optimize air-to-fuel ratio by examining the excess air in the flue gas stream. The waste heat boiler from the cogeneration unit has a further 108,000 lb/hr of capacity. Boiler 5 was commissioned in 1972 and is viewed at its end of service life. The design peak steam demand is 225,000 lb/hr for both the campus and hospital. The minimum heating and DHW steam load for the campus was estimated in the range of 10,000 lb/hr. There is a planned replacement of boiler 5 with two 120,000 lbs/hr dual-fired natural gas/oil steam boilers to maintain the plant capacity and N+1 capability.

Table 1: Summary of Steam Supply and Demand

Steam Producer / Consumer	Production Capacity / Demand (pph)	
Existing Boiler #5 (Production) era 1972	200,000	Production
Existing Boiler #2 (Production)	100,000	Production
Co-Gen Waste Heat System (Production)	108,000	Production
Planned Replacements of boiler 5	2 x 120,000	Production
Maximum Campus & Hospital Demand [Can Ecosse Report] (Demand)	320,000	Demand
Campus Winter Peak [ops staff report]	120,000	Demand
Hospital Winter peak [ops staff report]	40,000	Demand
Current Absorption Chiller, Hospital and Campus, Steam Demand	32,000	Demand
Campus Minimum Steam Demand, Heating & Domestic Hot Water	10,000	Demand

Cogeneration Unit

In 2017, a 5.7 MW capacity cogeneration unit was installed at the McMaster campus in the E.T. Clarke Centre. The unit consists of a natural gas fired turbine connected to an electrical generator. The turbine exhaust is ducted into a water-tube boiler section and the exhaust alone is capable of producing 30,000 lb/hour of steam when the unit is running at full fire. The natural gas fired burner in the water-tube boiler section can generate a further 70,000 lb/hour of steam .. The exhaust stream joins with boilers 3 and 5 to be exhausted out the E.T. Clarke Centre main stack. The cogeneration project included the installation of an absorption chiller to provide increased summer steam load.

The cogeneration unit currently operates continuously to generate electricity to offset the campus electrical draw from the Ontario electricity grid.

Cooling

The total nominal cooling capacity of the chilled water system is 10,000 tons. The chiller plant consists of three 1,000 ton centrifugal chillers, a 5,000 ton centrifugal chiller and a 1,000 ton double effect steam absorption chiller. Generally, chilled water is distributed to the campus at 39°F, which is determined largely by the requirements of the Museum of Art. There is a year-round need for cooling in the university. Per the Renteknik report of 2018, cooling demand ranges from 1,000 tons in lower ambient conditions to 8,000 tons for outdoor temperatures over 30°C. Note that Facility Services is currently contemplating cooling tower modifications and replacement, which would in part facilitate cooling tower free cooling during low ambient conditions.

According to a 2019 Renteknik Group Commissioning Report, the chillers typically operate at loads of 1,000 tons or greater at an efficiency of between 0.5-0.7 kilowatts per ton (kW/ton). Auxiliary components of the cooling including pumps and cooling towers increase the cooling plant operating power requirement to between 1.4 kW/ton at low loads to 0.8 kW/ton at loads above 4000 tons.

STEAM LOAD DURATION CURVE

Daily steam production logs for the period of 2017 through 2019 were received from Facility Services. The figure below shows the average daily steam production of the McMaster plant including steam provided to the hospital. The daily average steam production was at or below 40,000 lb/hr for half of the days in the three year period. The maximum daily average steam production was 141,000 lb/hr. In 2019, the annual steam production was 495 million pounds of steam, 402 million pounds were used by the campus with the remainder going to the McMaster University Medical Centre. During 2019, 39% of the district energy steam production was from the cogeneration unit.

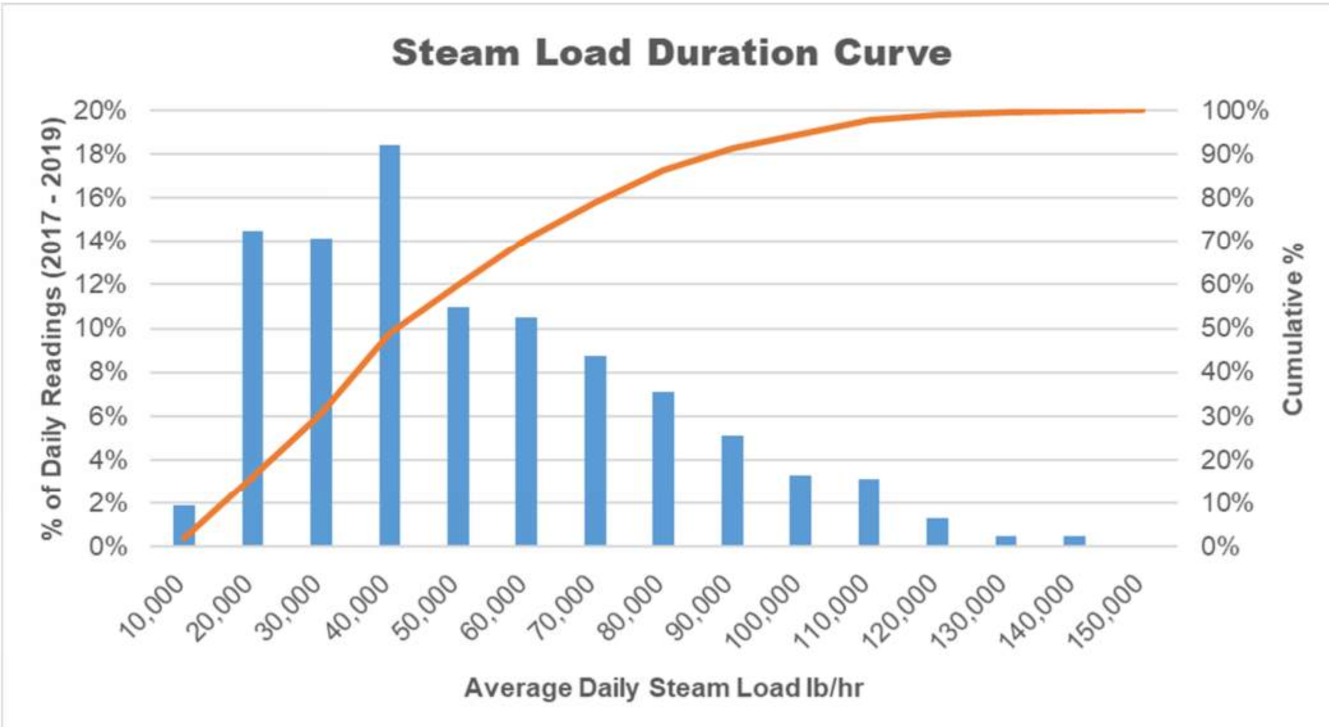


Figure 2: Steam Load Duration Curve

BOILER REPLACEMENT PROJECT

Planning is underway for the installation of two new steam boilers in the district energy plant – replacing older boilers at the end of their service life. Boiler #4 was already decommissioned and removed in 2018. It was a 160,000 pounds per hour (lbs/hr) capacity. Existing Boiler #5 is a packaged boiler with a capacity of 200,000 lbs/hr that is due for replacement.

The replacement project is detailed in the 2019 report by Can Ecosse Engineering Inc. The proposed new boilers are to be dual-fired with natural gas and fuel oil. Both have a steam production capacity of 120,000 lbs/hr. The intent of the project is to enable the plant to have a peak capacity of 320,000 lbs/hr with N+1 capacity. Natural gas firing efficiencies of the replacement boilers selections are 83.5%.

Utility Rates

NATURAL GAS RATE

The current large volume natural gas rate for McMaster University averaged approximately $0.14/m³ of natural gas in 2019. This is equivalent to $0.013 per equivalent kilowatt-hour (kWh) of natural gas energy. This is a very favourable natural gas rate due to large volume purchasing in conjunction with other institutions. By contrast, current commercial natural gas rates in Ontario are typically $0.26/m³ of natural gas.

Canada has implemented a Carbon tax that is in effect in Ontario in the absence of provincial carbon pricing. This carbon pricing is to be included in the rates paid for natural gas. In 2020, the Carbon tax is $30/tonne of CO_2e and current legislation provides for an increase of $10/tonne per year up to $50/tonne in 2022. There is no carbon pricing certainty beyond 2022. A carbon price of $10/tonne equates to $0.019/m³ of natural gas. As of 2020, at $30/tonne, the current natural gas rate includes $0.057/m³ for carbon pricing. That increases to $0.094/m³ by 2022. Forecasts on future carbon pricing range from $50 - $200/tonne by 2030. For the purposes of this report, a continued increase of $10/tonne to 2030 and $5/tonne will be shown as an indication of the impact of carbon pricing on operations costs. The figure below shows only the impact of this carbon pricing forecast on the McMaster natural gas rate.

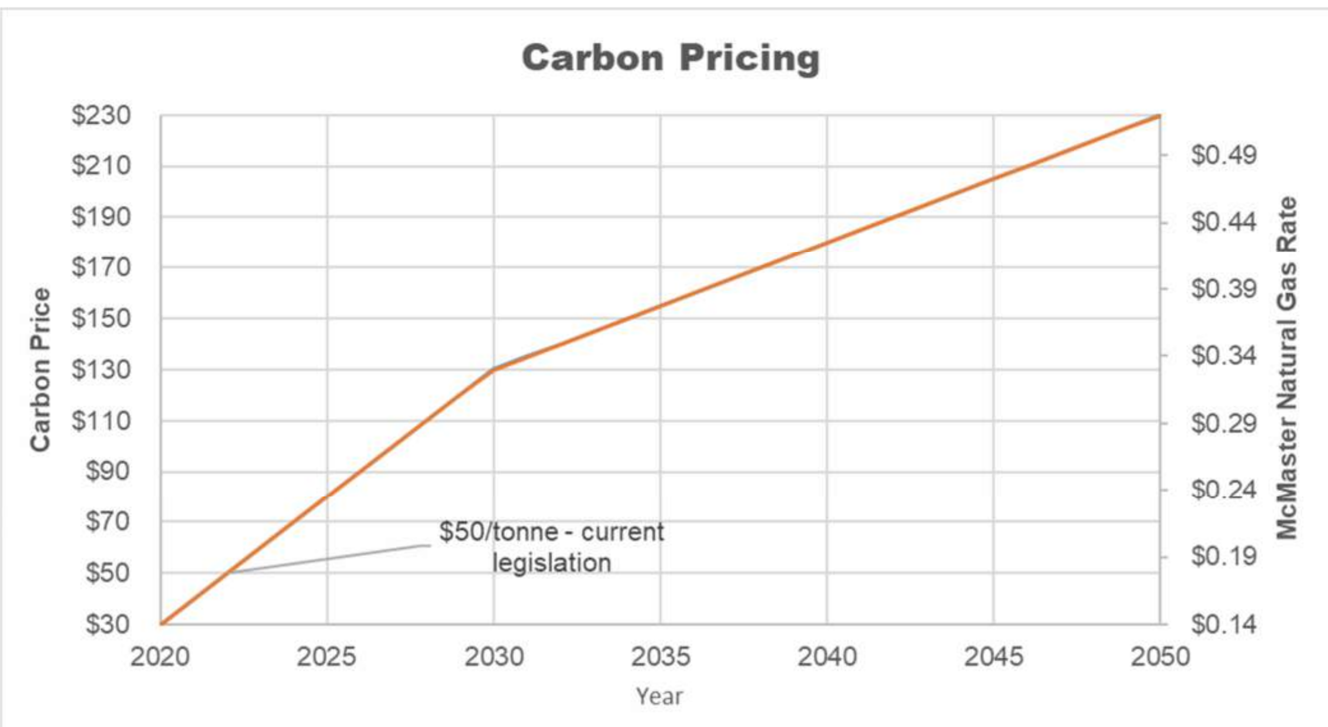


Figure 3: Carbon Pricing

ELECTRICAL RATE

The current electrical rate for the McMaster Campus is approximately $0.115/kWh.

Currently, McMaster has opted to be under the Class B designation for Global Adjustment despite having a peak draw in excess of the 5MW threshold (due to the operation of the cogeneration system, refer to the Campus Electrification section for further details). The University was a class A participant from 2014 through 2017 – prior to the introduction of the cogeneration unit. Peak demand factor was lowered by shutting down HVAC systems to reduce load on the chillers during the summer months, named "Chasing the Peak Initiative".

Much of the discussion in this report regarding reducing carbon emissions of the McMaster campus focuses on shifting the energy use of the campus from natural gas to electricity. In order to achieve this transition without a significant increase in utility operating costs, the electrical rate paid by the campus must be minimized.

There are two components to the electrical rate in Ontario. The cost of the electricity consumed is the Hourly Ontario Electrical Price or HOEP. For the past several years, the HOEP has averaged $0.02/kWh due to a relatively high generator supply in the province relative to the provincial demand. The HOEP was 13% of the campus electrical charge in 2019.

The second component is the Global Adjustment or GA. This represents the cost of satisfying pre-existing contracts for electrical generators providing power to the grid above the HOEP buy in price. Global adjustment is calculated one of two ways depending on whether consumers are "Class A" or "Class B". Global Adjustment was 87% of the campus electrical charge in 2019.

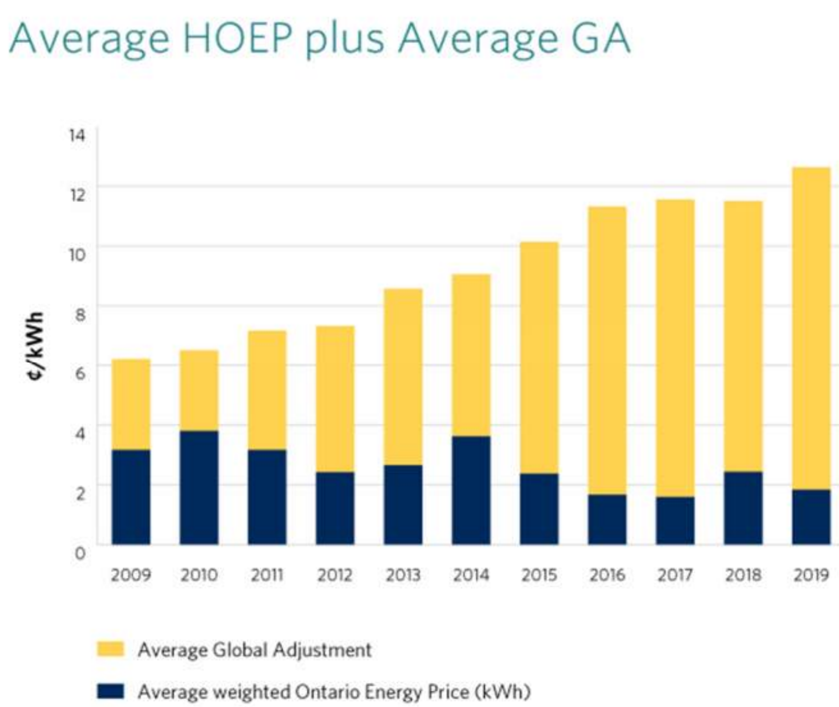


Figure 4: Average Hourly Ontario Electrical Price and Average Global Adjustment

Class B consumers pay global adjustment based upon their electrical consumption. The rate is set monthly and has averaged $0.099/kWh over the past several years. Generally class B is for smaller electrical consumers.

Class A is set up to encourage large users to reduce their peak electrical demand during periods of provincial electrical peaks. Class A consumers pay Global Adjustment based upon their Peak Demand Factor. Peak Demand Factor is calculated annually as:

$$\text{Peak Demand Factor} = \frac{\sum Customer\ peak\ demand\ during\ 5\ provincial\ demand\ peaks}{\sum Provincial\ demand\ during\ 5\ provincial\ peaks}$$

To determine the monthly amount of GA a class A customer pays, the peak demand factor (PDF) is multiplied by the total provincial global adjustment amount for that month. In 2019 the global adjustment averaged $1,082 million per month. As such, each kW of peak during the provincial peaks represented a monthly cost of $49/kW or an annual cost of $587/kW.

Table 2: 2019 Peak Demand Factor Calculation

IESO Maxima	ON Peak MW	Campus MW
05/07/2019 16:00	22,294	14.0
20/07/2019 16:00	22,103	9.1
29/07/2019 16:00	22,129	9.9
19/07/2019 11:00	22,368	10.3
04/07/2019 17:00	21,684	13.5
Total	110,578	56.8
	Peak Demand Factor	0.0005137

The table above shows the campus only power demand during the 5 provincial peaks in 2019.

The cogeneration unit was operational for three of the five peaks in 2019 but was down for maintenance prior to July 15th. The peak demand factor for next year is estimated to be 0.000333.

Class B is beneficial to customers with lower kWh consumption relative to their peak demand. Class A is beneficial to customers with higher consumption relative to their peak demand. Load factor is defined as the average load divided by the peak load. Customers with a load factor below about 0.6 benefit from Class B GA while customers with a load factor over 0.6 benefit from Class A. The McMaster cogeneration unit complicates the GA evaluation. It is able to generate about 40% of the campus electricity thereby reducing the load factor. But it is also able to shave the peak which increases the load factor.

If the campus is a Class A consumer and is able to completely remove itself from the grid during the five provincial peaks, then the peak demand factor for the campus is zero and no global adjustment is paid. In this case, the campus pays only the HOEP. The challenge is that the time of the provincial peaks is not known in advance.

During its time as a Class A consumer, the campus was successful in reducing its peak during the provincial peaks largely through end user actions under the “Chasing the Peaks” initiative. However, this was viewed as disruptive to campus activities.

In order to achieve significant reduction during the provincial peaks, the campus needs to install and operate peak shaving generators. The cogeneration unit can act in this capacity and reduces the campus peak by approximately 35%. Further peak shaving generator capacity of 10 MW are required to fully reduce the campus peak demand factor during the provincial peaks.

Prior to the economic downturn in 2008, Global Adjustment represented only 20% of the electrical rate. At the moment the feed in contracts for several nuclear generators in the province of Ontario are coming up for renewal over the next several years. The current contracts between these nuclear energy providers and the IESO provide for a favourable rate to be paid for power from these generators if they are operating. This leads to the nuclear generators bidding into the hourly market with very low rates and occasionally zero or negative rates. The top up paid to the generators comes from the global adjustment and represents nearly half the annual amount. As such, there is a risk that with the renegotiation of these contracts, the HOEP will increase in coming years diminishing the proportion of the rate that is global adjustment and diminishing the rate savings associated with the peak shaving measure. The risk of this change to electrical rates in Ontario needs to be factored into the Campus's carbon emissions reduction plan.

Supplemental note – the November 2020 Ontario budget statement indicated a forecast 15% reduction in global adjustment.

Campus Energy Model

METHODOLOGY

The first step in mapping out a path to net-zero carbon for the McMaster campus is understanding where energy is being used. To this end, an energy model of the McMaster main campus was developed. The energy model provided two key estimates:

- The allocation of campus emissions by building across the campus;
- The contribution by energy end-use to the current campus emissions.

Using the results of the energy model we were able to gain insight into the energy consumption patterns of the different buildings allowing us to develop unique energy conservation and emissions reduction strategies.

The energy model for the campus was developed in the Intelligent Community Design (iCD) software tool from Integrated Environmental Solutions (IES). The iCD platform allows for the development of large scale energy models using space prototyping and campus mapping capabilities. Behind the iCD interface runs the IES-Virtual Environment (IES-VE) hourly energy simulation software. The iCD interface allowed the use of a two-step analysis whereby the campus mapping and building data entry was performed in the iCD interface, but an intermediary step allowed a tuning of the model in the IES-VE software before the campus simulation was run. This allowed access to the full suite of IES-VE modelling parameters for enhanced tuning and control of the energy model input parameters for individual buildings where required.

For this analysis, the campus energy model was run using the Canadian Weather for Energy Calculations 2016 data set from the Hamilton – Royal Botanical Gardens weather station.

Figure 5 below shows the resulting building energy intensity mapping of the campus in kWh/m² from the energy model. Figure 6 below shows the greenhouse gas emissions intensity in kg- CO_2e/m^2 by building.

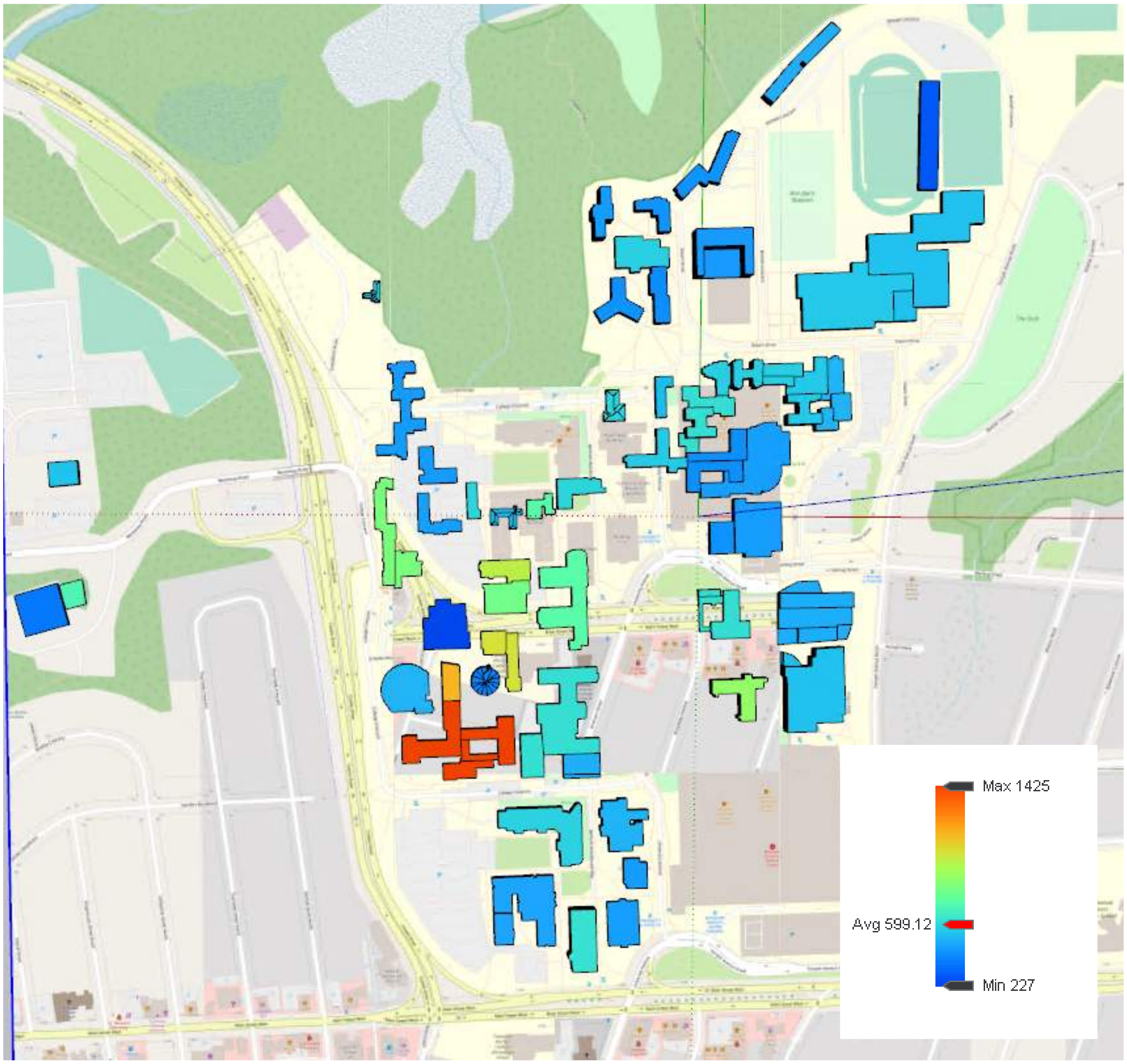


Figure 5: Modelled Campus Energy Map

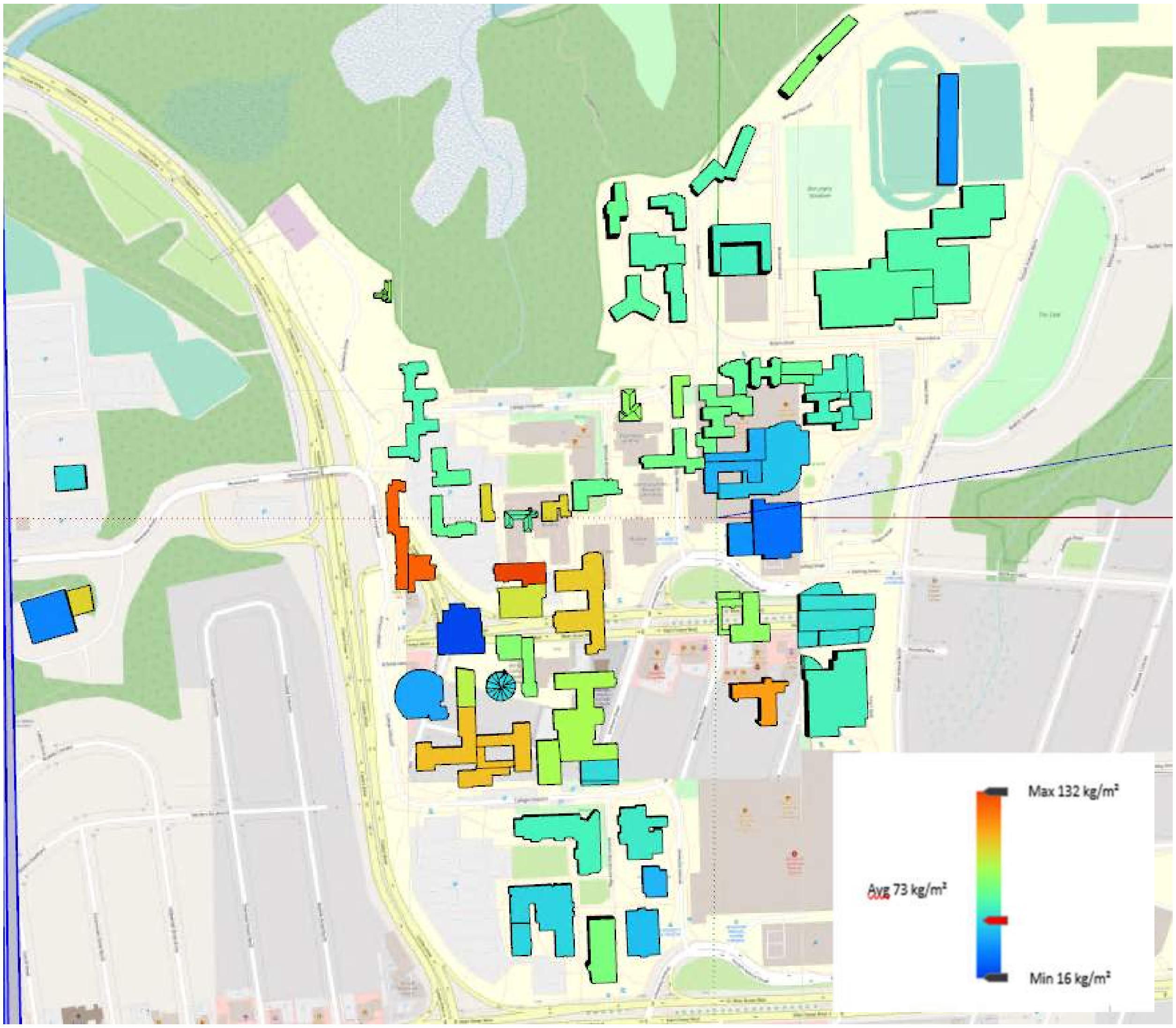


Figure 6: Modelled Carbon Emissions per Building

McMaster provided the campus-wide energy usage data as a basis for this investigation. Facilities Services also provided comprehensive electrical submeter data for all campus buildings and steam submeter data for several buildings. This energy consumption information facilitated the validation and calibration of the energy model at the building level.

Current Carbon Emissions

MAIN CAMPUS OVERALL CARBON EMISSIONS

Campus utility billing information and sub-metering data was analyzed to establish baseline carbon emissions, segregate emission sources and inform carbon reduction targets.

Overall greenhouse gas (GHG) emissions in tonnes of CO_2 equivalent (CO_2e) since 2015 are summarized in Figure 3 below, by emission source. “NG” represents the emissions resulting from natural gas purchased by the campus and combusted on site while “Elec” represents the portion of emissions resultant from electricity purchased from the grid and consumed on site.

The natural gas consumption constitutes the “Direct Emissions” produced directly at the campus as a result of gas-combustion whereas the electricity consumption constitutes the campus “Indirect Emissions” which are the emissions resulting from the production and supply of the electricity the campus draws from the provincial grid.

There is a notable increase in the campus emissions between 2017 and 2018 / 2019. In part, this is due to the operation of the cogeneration unit installed on the campus at this time. In addition, two buildings came online during that period. The Peter George Centre for Living and Learning added a gross floor area of 32,000 m² to the campus while a 4,200 m² addition was built on the Arthur N. Bourn Science Building.

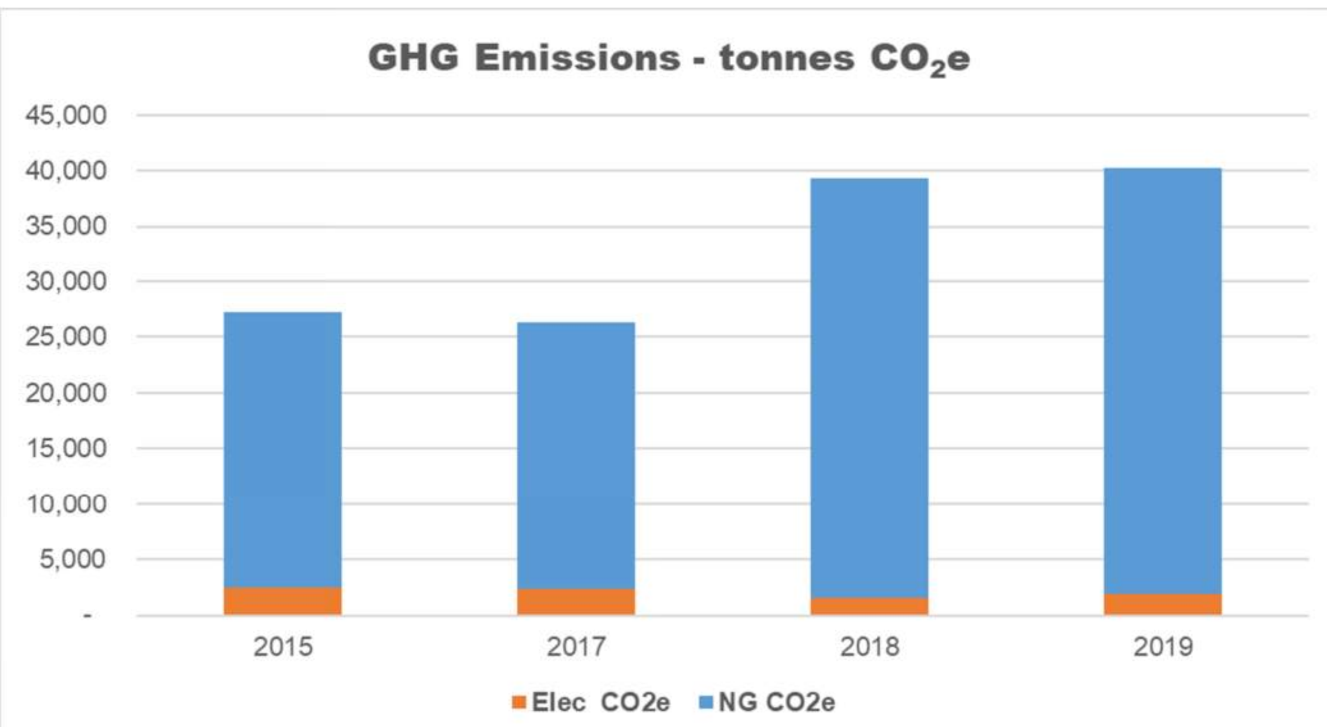


Figure 7: University Campus Annual GHG Emissions

BENCHMARKING

2017 was the final year that the *Energy Use for Public Buildings in Ontario* was compiled and shared. The figures below show the McMaster Campus energy and greenhouse gas intensity in relation to the other twenty-one universities across Ontario. In 2017, McMaster ranked among the better performing campuses in terms of both energy and GHG intensity. Note that this was prior to significant operation of the cogeneration unit. For comparison, the 2019 greenhouse gas emissions intensity is also plotted. Note that several of the other universities with higher GHG intensity values also have cogeneration units on their campuses as indicated, resulting in higher direct GHG emissions from increased combustion on site if the cogeneration units are operated more frequently than just being used as peak shaving equipment targeting the IESO top-5 grid peaks.

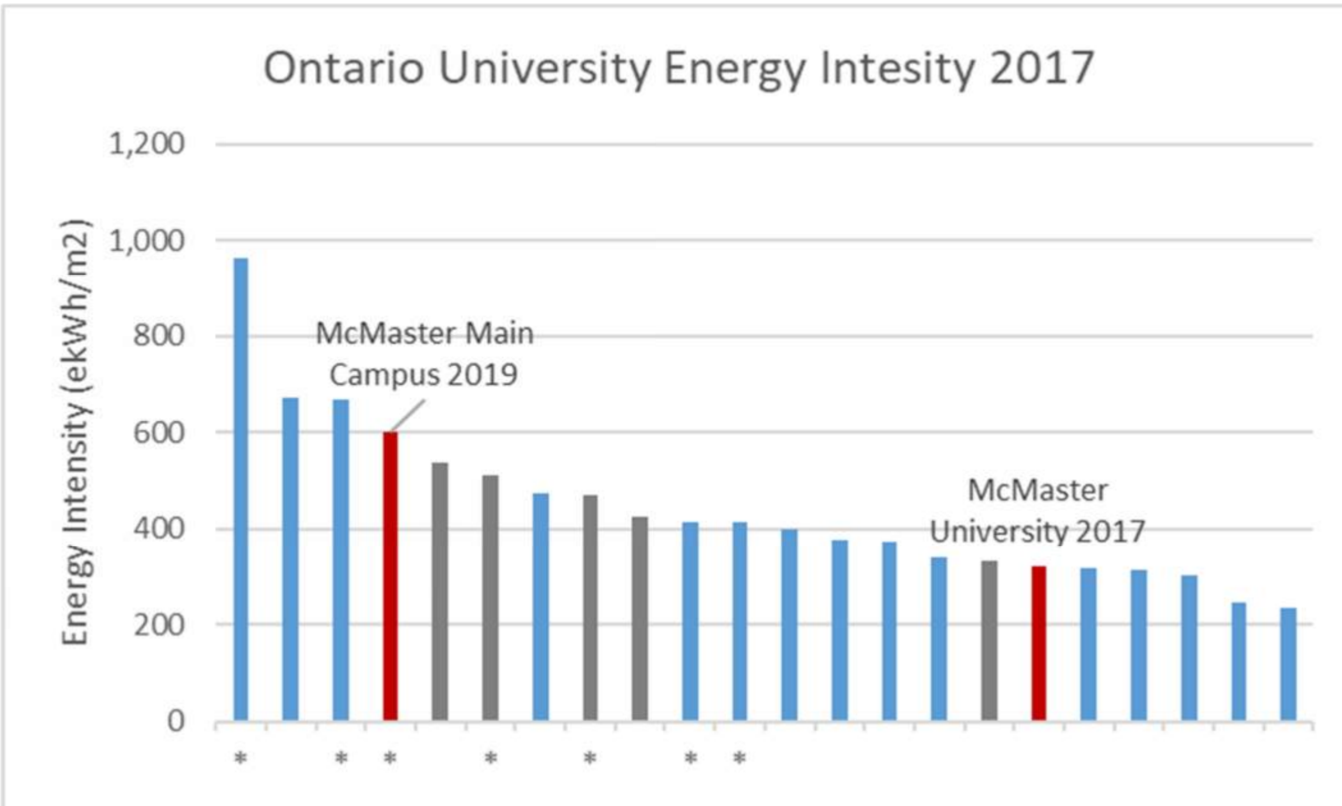


Figure 8: 2017 Energy Intensity – Ontario Universities

Source: Energy use and greenhouse gas emissions for the Broader Public Sector – data.Ontario.ca – most recent data 2017.

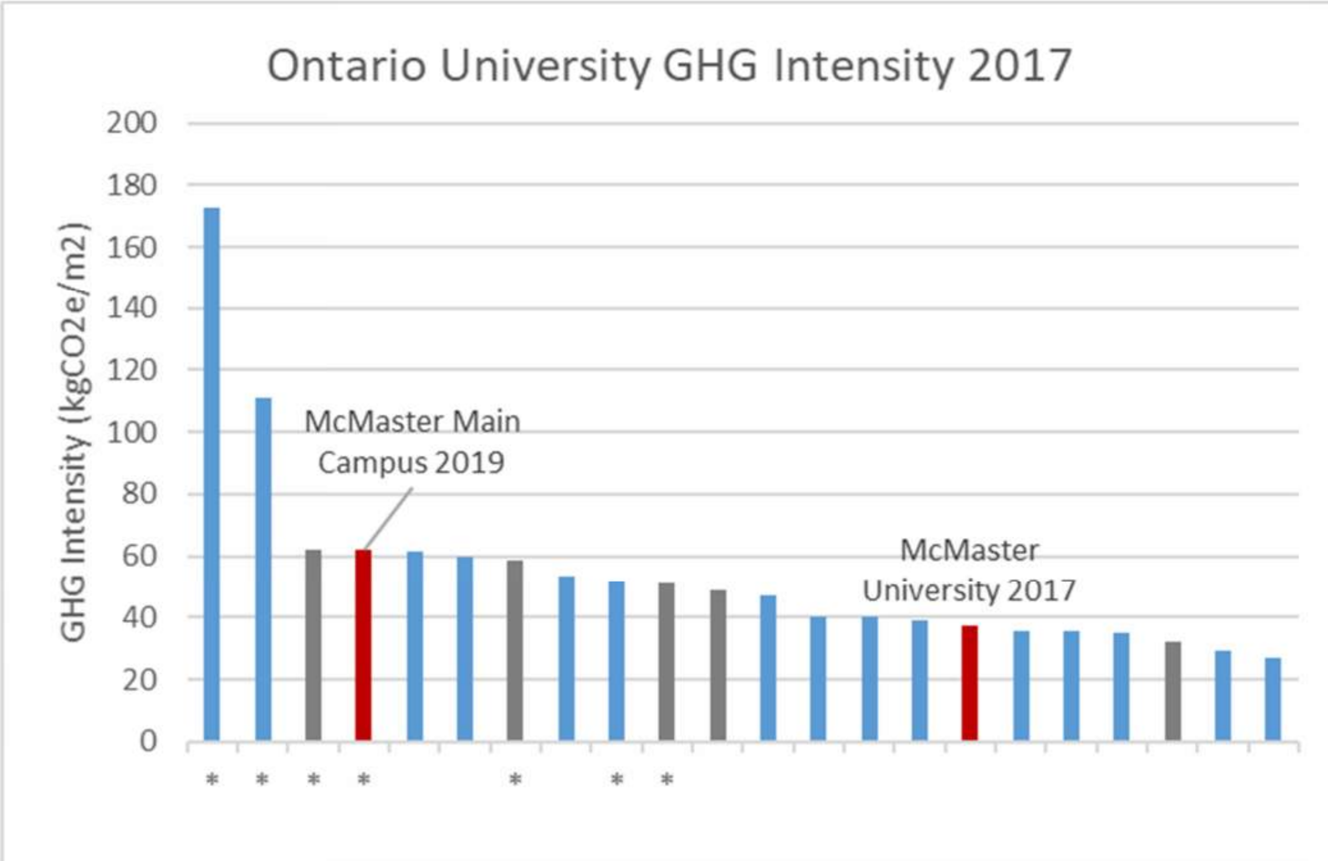


Figure 9: 2017 Greenhouse Gas Intensity – Ontario Universities

Source: Energy use and greenhouse gas emissions for the Broader Public Sector – data.Ontario.ca – most recent data 2017.

CARBON EMISSIONS

The figure below illustrates that although electricity accounts for approximately thirty percent of the campus's overall energy consumption, natural gas produces the majority of the campus carbon emissions. In total, natural gas combustion, almost entirely concentrated to the steam boilers in the district energy plant, contributes approximately 95% of the total campus overall emissions.

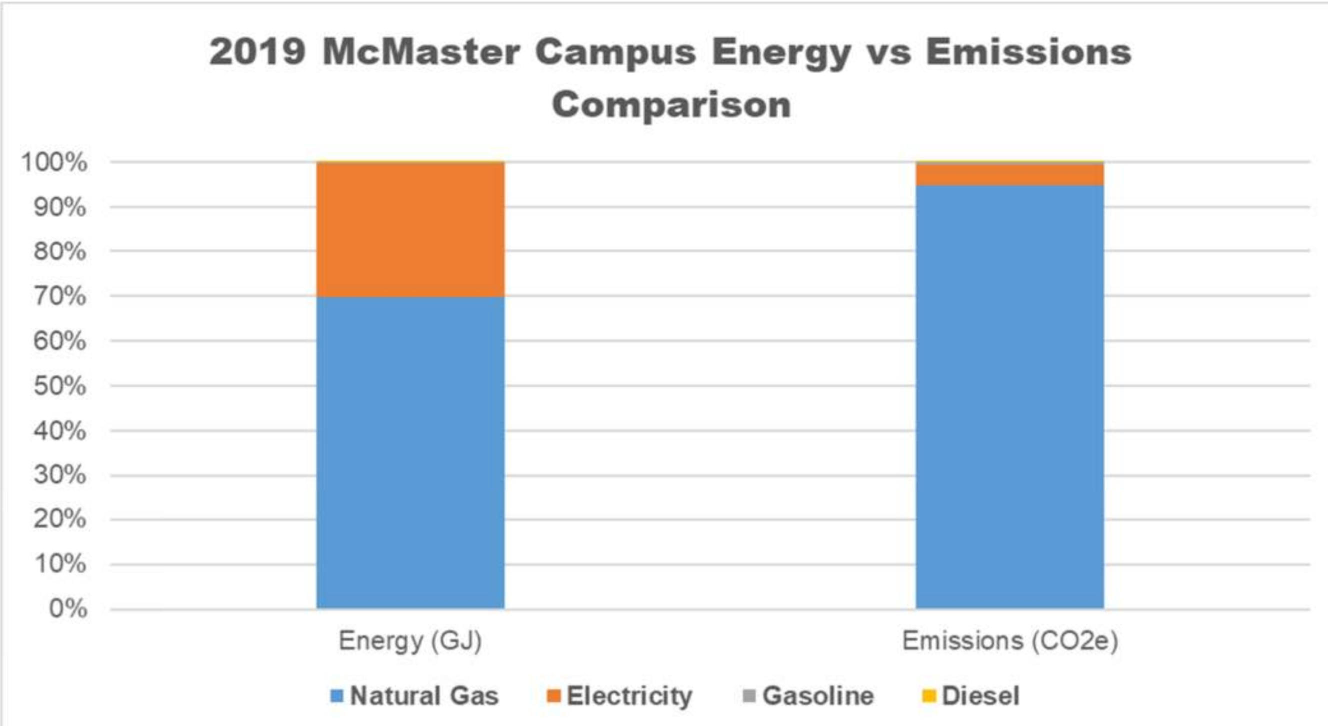


Figure 10: 2019 Energy and Greenhouse Gas Comparison

Table 4 summarizes the 2019 energy and emissions for McMaster Campus.

Table 4: Emissions Summary

	Energy (GJ)		Emissions (CO_2e)	
Natural Gas	766,911	69.6%	38,351	94.9%
Electricity	332,719	30.2%	1,856	4.6%
Gasoline	2182.0	0.2%	156	0.4%
Diesel	639.6	0.1%	48	0.1%

DIRECT EMISSIONS

Direct greenhouse gas emissions are produced on the campus itself from the combustion of natural gas, diesel fuel and gasoline. Combustion of natural gas in the Campus boilers and cogeneration unit is overwhelmingly the single greatest source of greenhouse gas emissions on campus, representing 95% of the overall campus emissions.

The emissions factors for natural gas combustion, diesel fuel and gasoline were sourced from the *National Inventory Report 1990 – 2018: Greenhouse Gas Sources and Sinks in Canada* published in April 2020. The emissions factors provide the quantity of equivalent CO_2 produced based upon the quantity of input energy. The emission factors used for this study are summarized in Table 2 below. These emissions factors include the methane (CH_4) and nitrous oxide (N_2O) in the combustion exhaust along with the Carbon Dioxide (CO_2) and are expressed in mass of equivalent CO_2 emissions taking the global warming potential (GWP) of CH_4 and N_2O into account.

Table 5: Direct Emissions Factors

Energy Source	CO_2e	Unit	Source
Natural Gas	1,899	g/m^3	2018 NIR
Diesel Fuel	2,690	g/litre	2018 NIR
Gasoline	2,315	g/litre	2018 NIR

INDIRECT EMISSIONS

A portion of the campus carbon emissions are a result of the electricity the campus draws from the Ontario electrical grid and the emissions created in the production and transmission of that electricity. These are termed indirect emissions.

The annual average emissions factor for electricity in Ontario is 30g of CO_2e per kilowatt-hour (kWh) of electricity, according to the 2020 National Inventory Report. The Ontario electrical grid has a relatively low emissions factor compared with other jurisdictions due to the composition of the energy sources feeding into the grid.

Table 6: Indirect Emissions Factors

Energy Source	CO_2e	Unit	Source
Electricity	30	g/kWh	2018 NIR

As shown in the figure below, in 2019 only 6% of the annual electrical production was from fossil fuel fired sources.

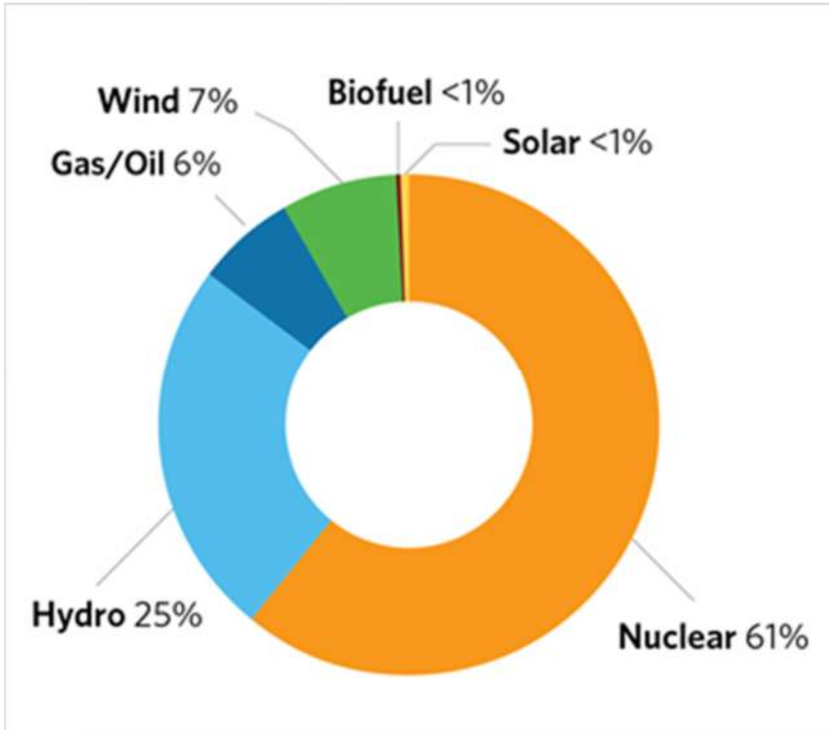


Figure 11: Ontario Electrical Supply – Yearly Output by Source 2019 (IESO)

Natural gas fired generation facilities comprise 29% of the generation capacity in Ontario. They are currently operated as peaking facilities – operating when the electrical demand is highest. The natural gas plants can also be staged up and down more rapidly than other energy sources so are operated at the margin to ensure nimble response to grid supply and demand changes. At peak and at the margin then, the Ontario grid emissions factor is higher than the annual average. The IESO projects greater use of the natural gas fired generation stations as provincial electrical demand increases.

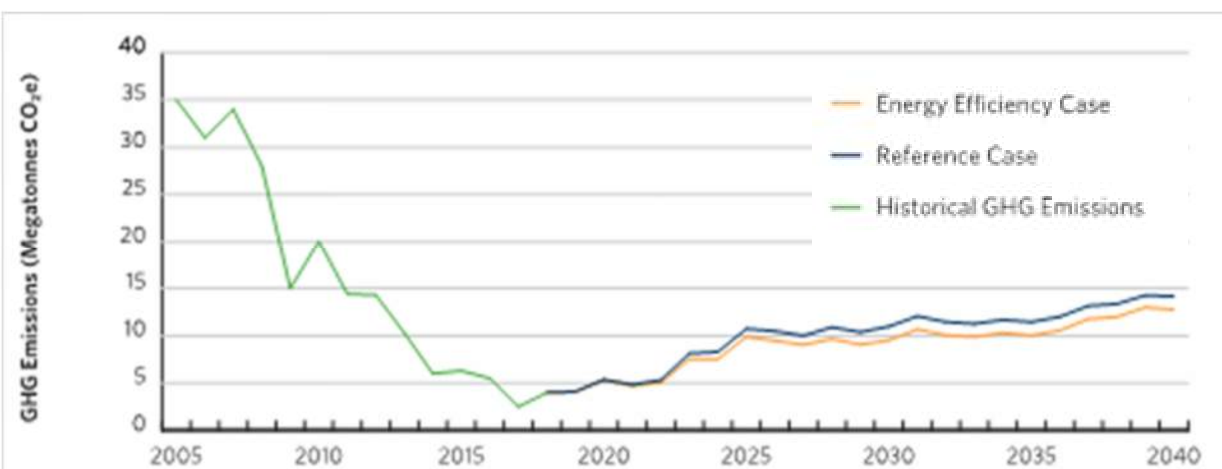


Figure 12: Projected GHG Emissions for Ontario Electricity Sector (IESO, 2020)

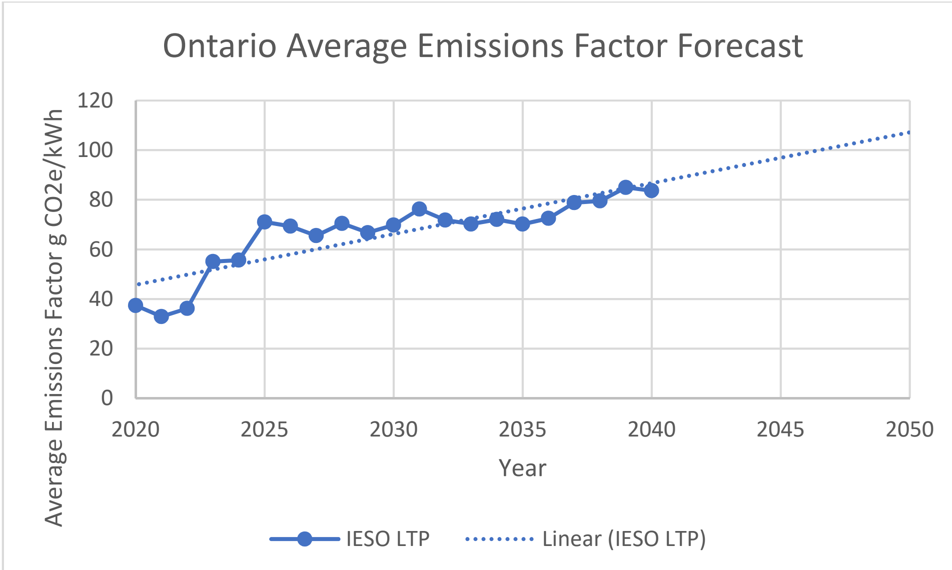


Figure 12A: Forecast GHG Emission Factor for Ontario Electricity Sector

Figure 12A above shows the forecast average emissions factor for electricity in Ontario based upon the reference case in the IESO Annual Planning Outlook, published in January 2020. The plan provides an emissions forecast out to 2040 and the data has been extrapolated linearly out to 2050. This suggests based upon the forecast growth of electrical demand in Ontario and based on current generation plans, the fraction of electricity generated by natural gas-fired plants in Ontario will increase from 6% to 18.6% by 2040.

EMISSIONS BY BUILDING TYPE

As detailed above, an energy model of the campus was developed and calibrated using the utility billing and sub-metering data available. One of the resulting outputs of the model is an emissions intensity factor for each building quantifying the estimated carbon emissions attributed to each building. The graph below visualizes percent of campus carbon emissions per building type.

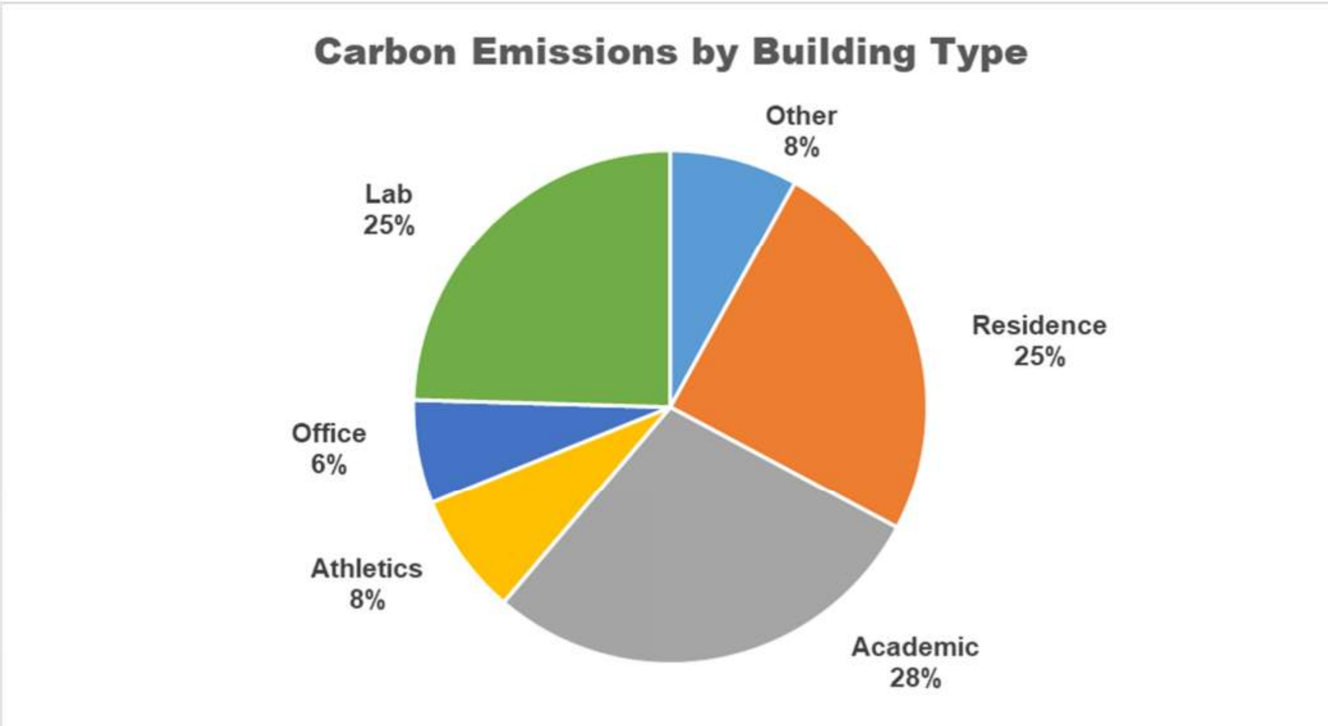


Figure 13: Carbon Emissions by Building Type

EMISSIONS VISUALIZATION

The figure below shows how the McMaster campus GHG emissions are divided by type, energy source, end-use and building type. The bar thickness is proportional to the CO_2e emissions quantity. Direct emissions result from combustion of fossil fuels on site and make up the largest proportion of the McMaster campus emissions. Natural gas is the largest energy source contributing to the campus emissions. Space heating of the campus buildings is the single largest end use contributing to campus emissions followed by domestic hot water (DHW) heating. The classroom, research and residence buildings on campus all comprise large shares of the total campus emissions.

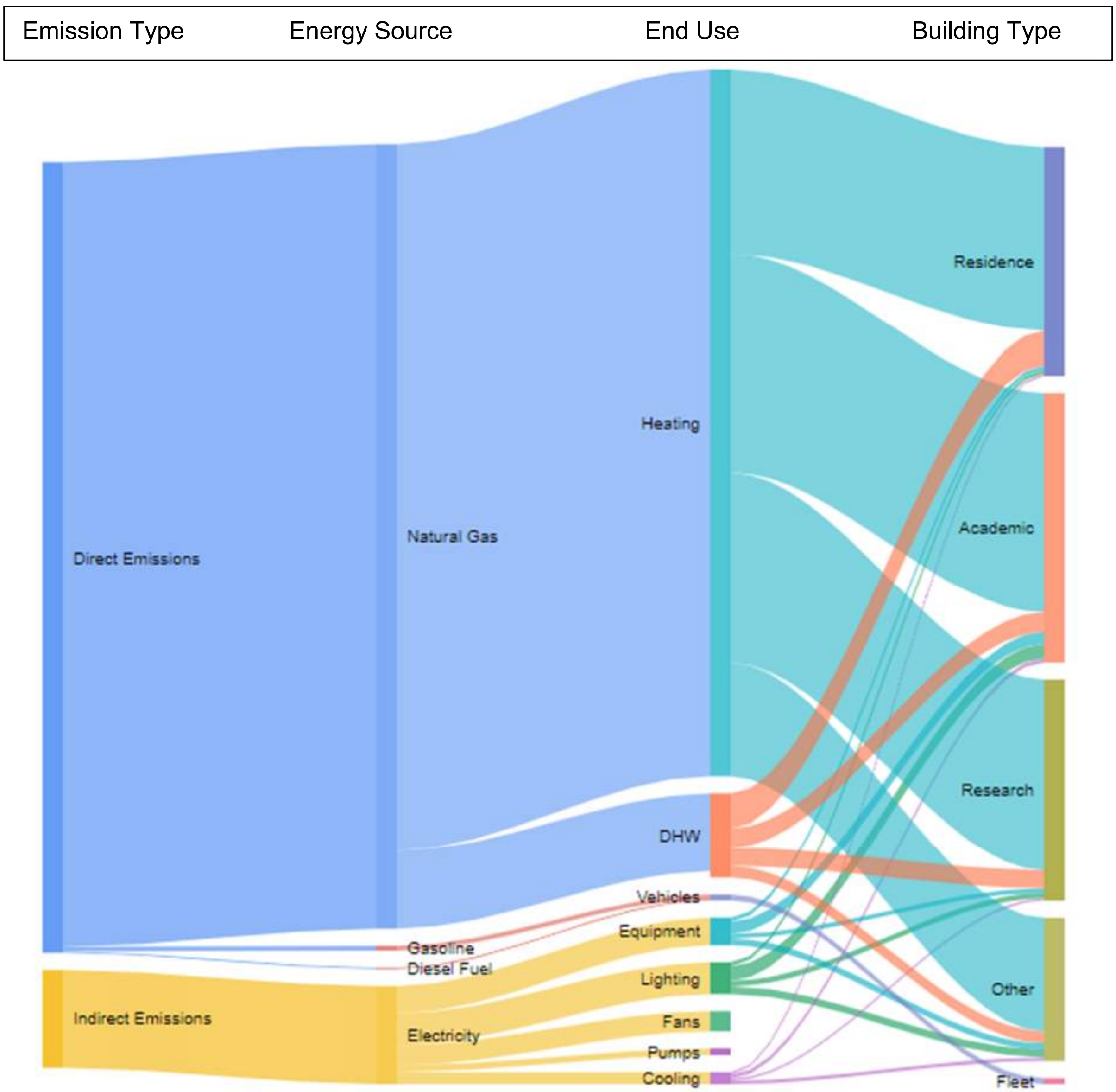


Figure 14: Sankey Diagram of McMaster Campus CO_2e Emissions

VEHICLE EMISSIONS

Total emissions from campus vehicles were estimated based on gasoline and diesel invoices. Gasoline invoices ranged from July 9th, 2019 to March 31st, 2020 showing a total gasoline consumption of 49,206 litres (L). To estimate annual gasoline emissions, the average gasoline consumption per day was calculated and extrapolated for the rest of the year. Based on this data, an estimated 67,520 L of gasoline is purchased annually. Using an emissions factor of 2.315 kgCO_2e/L for gasoline, the estimated GHG emissions from gasoline consumption is 156 tons CO_2e. The same methodology was used to estimate the emissions associate with diesel fuel consumption. The estimated annual diesel fuel consumption is 17,744 L. Using an emissions factor of 2.69 kgCO_2e/L for diesel, the estimated GHG emissions from diesel consumption are 47.7 tonnes CO_2e.

Although the emissions from vehicles make up a small percentage of the campus total, there are measures that can be taken to reduce these emissions. Vehicles currently used for Special Constable Operations can by changed to fully electric vehicles. Currently, there are eight fully electric passenger vehicles available in Canada that are not considered luxury models. Any of those models could replace the current hybrid vehicles. At the moment there are no fully electric commercial vehicles available to replace the van, pickup truck, and shuttle bus fleets; however, multiple car companies are developing electric pickup truck and vans which will be commercially available in the near future. As the electrification of vehicles continues, it is anticipated that all vehicles will have available electric options long before 2050. While changing the vehicle fleet to electric will have a small impact on total campus emissions, it is more visible than other phases of carbon reduction.

BUSINESS AS USUAL (BAU)

In order to forecast the campus emissions out to the year 2050, a baseline or “business and usual” scenario was developed. Figure 15 illustrates the magnitude of carbon emissions in the case where no emissions reduction measures are implemented.

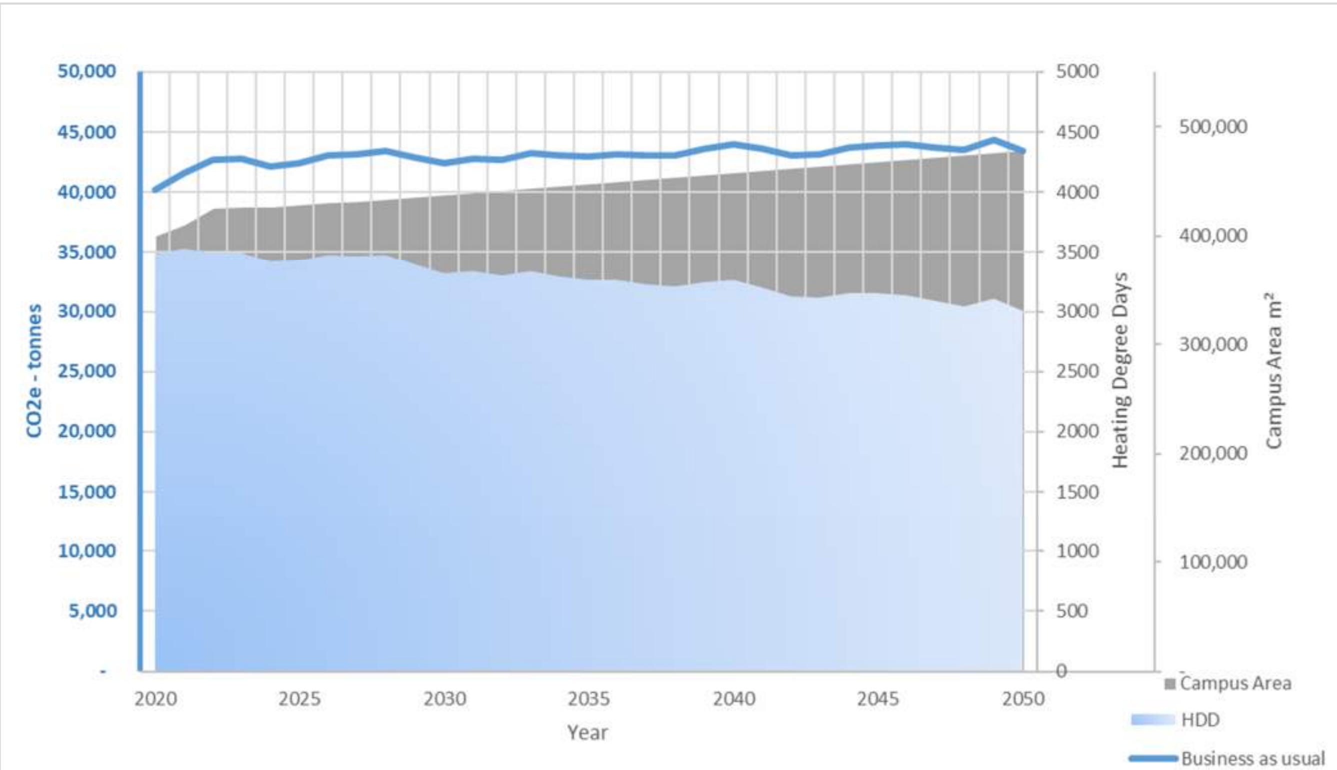


Figure 15: Baseline Emissions Forecast

Under this baseline, is anticipated the overall emissions of the campus will steadily increase over time to ~43,000 tons CO_2e annually by 2050. The increase in energy use on campus is driven by the addition of new buildings. Known projects that are in construction or design are included over the next four years. These know projects represent a floor area of 25,594 m². Beyond that an average growth factor of 2,000m²/year has been applied which adds 52,000m² or 13% to the campus area over the subsequent 26 years.

Over time, the anticipated impact of climate change will be to reduce the heating requirement of the campus. Currently, Hamilton averages 3,500 heating degree days (based on an 18°C balance temperature). It is forecast that over the 30 years to 2050, the heating degree days for Hamilton will reduce to 3,000 per year. This study has used data from the climate atlas climateatlas.ca as the basis for heating degree day forecasts.

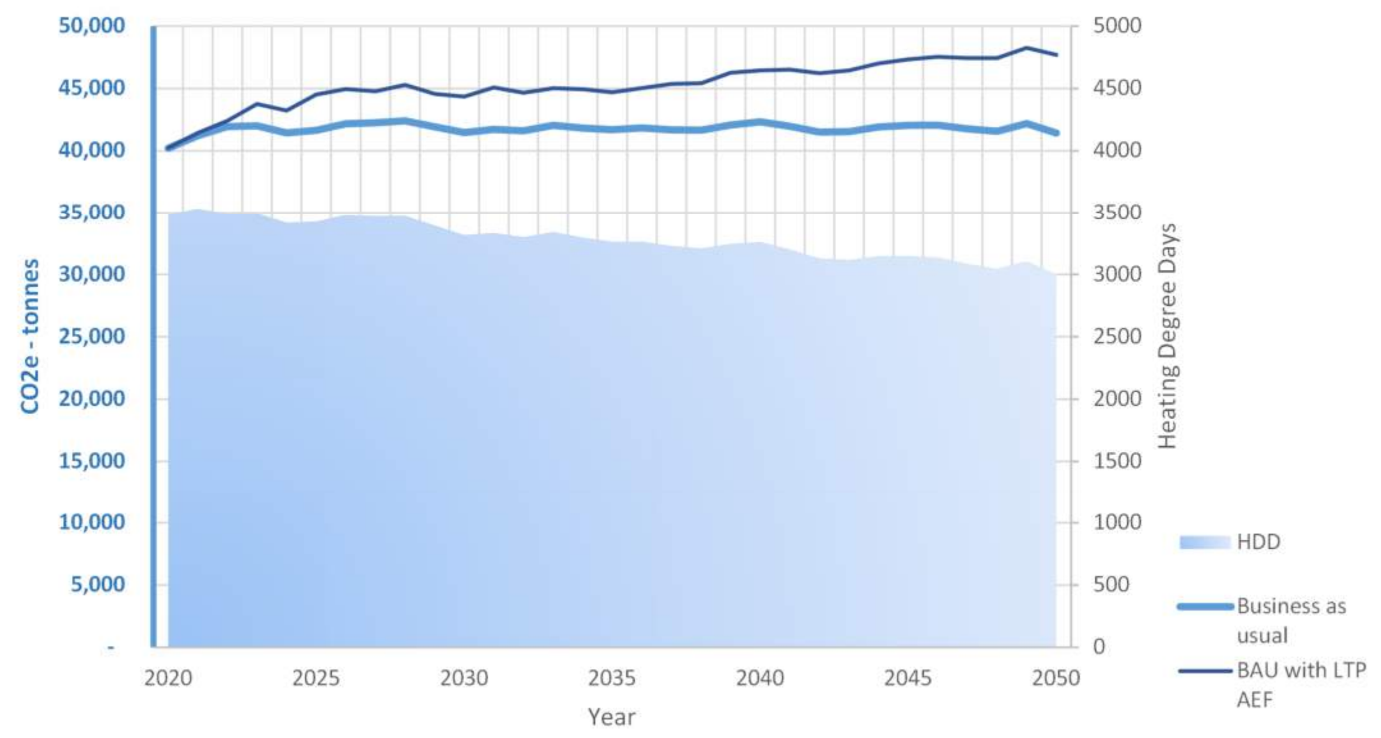


Figure 15A: Baseline Emissions Forecast with Indirect Emissions Factor Growth

Figure 15A adds the variable for the forecast increase in the indirect emissions factor for electricity as shown in figure 12A above.

Two figures are presented below. The first shows the Campus utility cost forecast for the 'business and usual' scenario with a 2% escalation applied to current utility rates and the known increase in carbon pricing to $50/tonne by 2022. The second shows the utility cost projection for the 'business as usual scenario' with potential carbon pricing included and the 2% per year uniform rate escalation. This projection has carbon pricing increasing at $10/tonne to 2030 and $5/tonne subsequently. Currently natural gas is 34% of the campus utility cost. Under this carbon pricing scenario, natural gas cost increases to 54% by 2050. There is no certainty on carbon pricing beyond 2022.

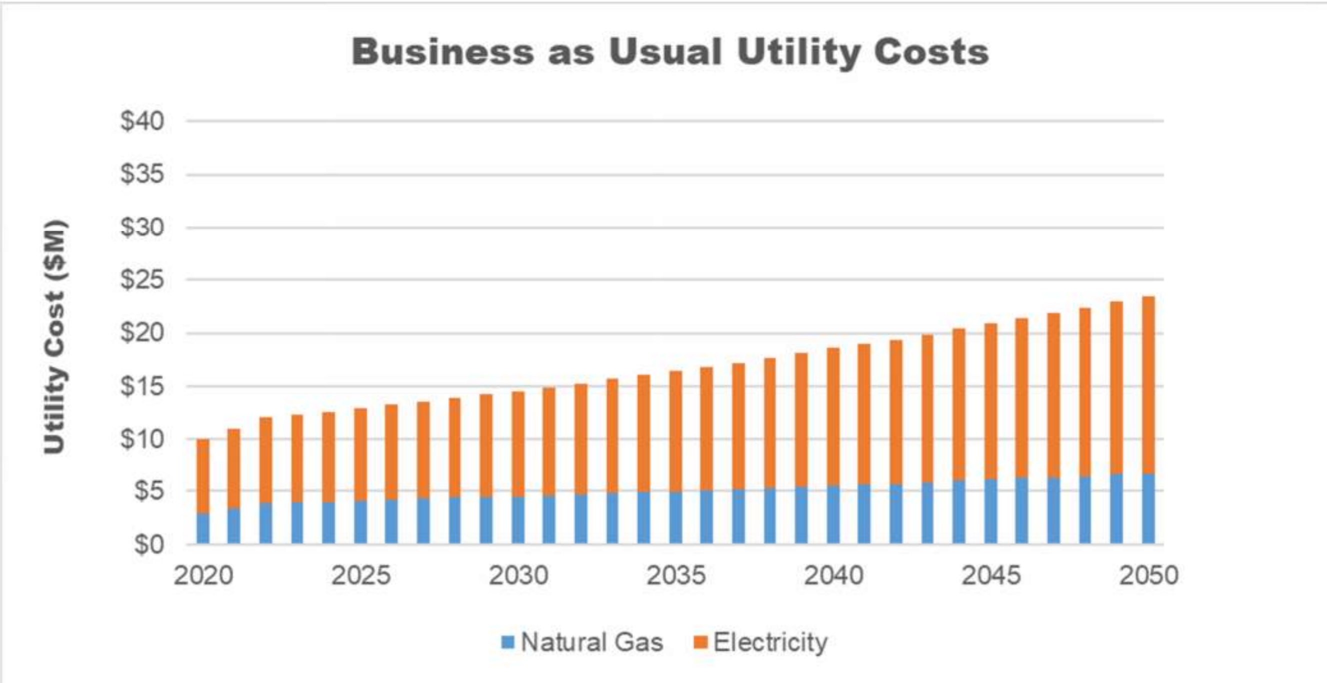


Figure 16: Business As Usual Utility Costs

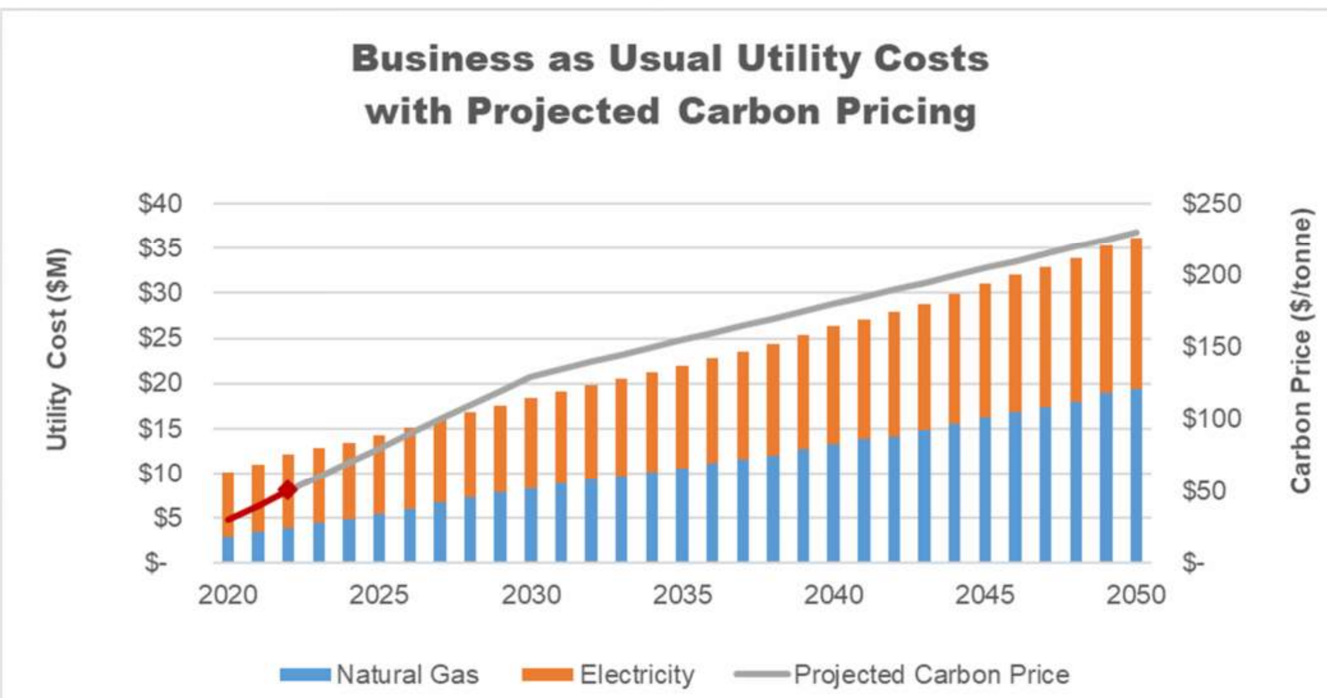


Figure 17: Business As Usual Utility Costs with Projected Carbon Pricing

Building Energy Conservation

This section of the report summarizes strategies, also termed energy conservation measures (ECMs), for carbon reduction at the building level and at the district energy system level. The ECMs included in this summary provide both ways to reduce steam and electricity demand within individual buildings and strategies to eventually eliminate carbon emissions. Appendix C provides a detailed overview of each of the ECMs included.

BUILDING ENERGY CONSERVATION MEASURES

Ninety-five percent of the campus's carbon emissions are from the combustion of natural gas to supply steam to the district energy system. Reducing the steam demand of each building serviced by the district energy system is a critical step towards reducing campus-wide carbon emissions. Similarly, the chilled water network accounts for a large portion of the electricity the campus consumes, and therefore accounts for a major portion of the campus' indirect emissions. Reducing the cooling demand of the buildings serviced by the chilled water district energy system is another critical step to reducing campus-wide carbon emissions.

Reducing the steam and chilled water demand of the buildings across campus will:

- Reduce the amount of fuel the district energy heating plant has to burn to meet the steam demand;
- Reduce electricity required by the district energy cooling plant to meet the chilled water demand;
- Reduce pumping energy required to distribute the steam and chilled water;
- Reduce pumping energy required within each building;
- Reduce fan energy within the buildings in certain cases.

The energy conservation measures explored below focus on reducing the building energy consumption. By reducing the energy demand of the buildings, the demand on the district energy system is reduced. Measures to reduce building energy demand can be implemented more easily across a portfolio of buildings compared to substantial upgrades at the district energy system level.

The four measures below represent the ECMs that are recommended for implementation. Appendix D provides a detailed overview and associated energy modelling results of the full list of ECMs that are included in the energy modelling analysis.

Demand Control Ventilation

Demand control ventilation (DCV) is a ventilation air control strategy where the amount of outdoor air brought into a building is controlled by indirectly measuring the occupancy level of the space. Methods to control ventilation air based on occupancy include counting occupants (for example, using a turnstile) or by measuring the difference in carbon dioxide between the outdoor air and the space. Reducing the amount of outdoor air brought into a space results in heating, cooling, pumping and fan energy savings.

Energy and Heat Recovery

Energy or heat recovery is a process where energy or heat is transferred from the building's exhaust air stream to the incoming outdoor air. Energy recovery includes the transfer of both heat and humidity while heat recovery transfers only heat. Energy and heat recovery systems work in all seasons, either pre-heating or pre-cooling outside air depending on the temperature differential between the outdoor and indoor space conditions. Recovering heat and humidity from the exhaust air stream and transferring to the incoming airstream reduces the need for mechanical heating and cooling and the associated utility costs.

Building Automation Optimization

Building automation systems represent opportunities for energy savings and carbon emissions reductions through optimization, analytics and monitoring. The available savings depend on how far current operation is from optimal operation. However, energy savings and emissions reductions of this magnitude from a measure that does not require any significant changes to the equipment itself is significant.

Low Flow Plumbing Fixtures and Instantaneous Point-of-Use Electric Domestic Hot Water Heaters

Plumbing fixture flow rates control the rate at which domestic hot water is consumed in the building and represent the primary opportunity for reducing unnecessary domestic hot water consumption. Retrofit or replacement of fixtures to lower the maximum water flow rate delivered to the user reduces the amount of domestic hot water the fixture needs to provide to fulfill its purpose, which reduces steam and resultant natural gas consumption.

An alternative to providing centralized domestic hot water generation with distribution and recirculation networks throughout a building is to instead provide localized instantaneous hot water generation units that provide on-demand hot water to the group of fixtures nearby. This eliminates the need for lengthy piping networks and the inevitable thermal losses of water travelling and standing in a piping network as well as the need for recirculation pumps.

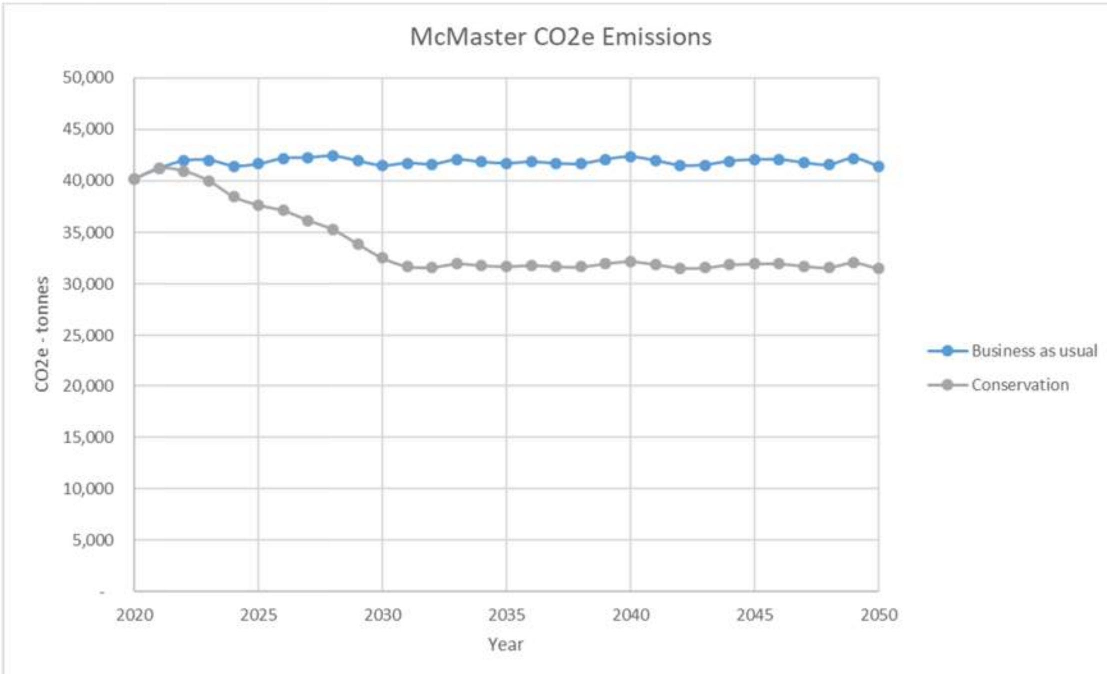


Figure 18: Carbon Reduction Path - Building Energy Conservation

The investment in energy conservation measures is envisioned to start in 2021 as detailed in the campus energy management plan. Measures are envisioned being phased in over 10 years. Energy savings of 24% of the heating and DHW loads are targeted.

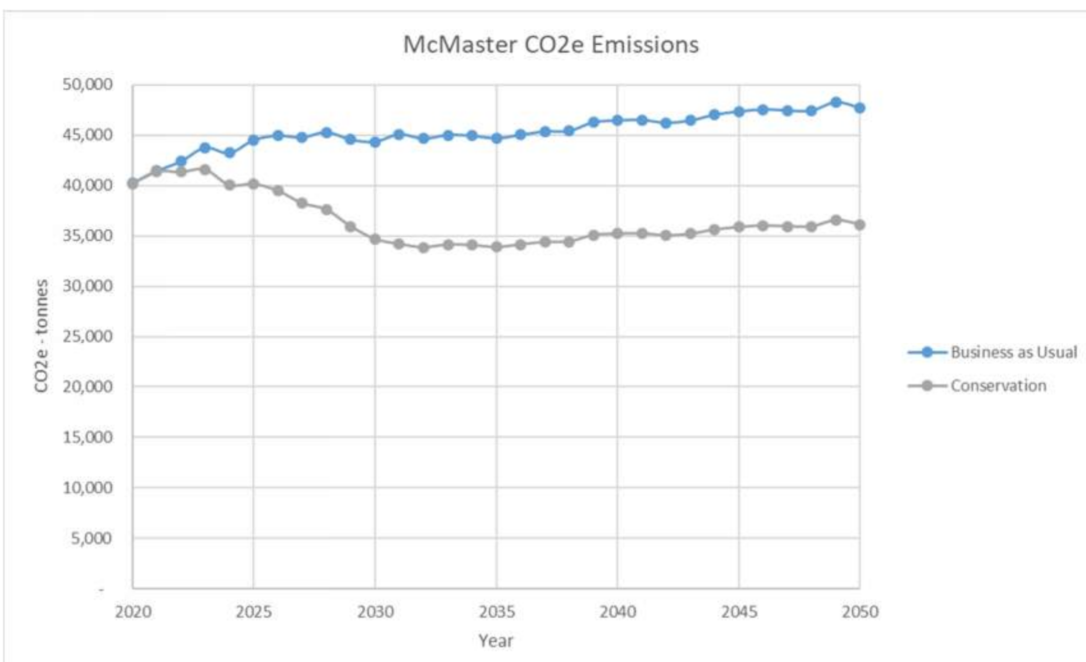


Figure 18A: Carbon Reduction Path - Building Energy Conservation with Indirect Emissions Factor Growth

Campus Electrification

In seeking to reduce carbon emissions, the case for electrification is twofold. Firstly, the electrical grid in Ontario currently has a low emissions factor at 30 g-CO2e/kWh generated. Secondly, energy from renewables – either on-site or off-site, is generated in the form of electricity. By transferring the campus energy from fossil fuel fired to an electrical source it is better situated to utilize energy from renewable sources.

DISTRICT ENERGY MEASURES

From a carbon emissions reduction perspective, the district energy system represents the single greatest opportunity for campus emissions reductions. Producing approximately 95% of the campus's overall emissions and essentially all of the direct emission, reducing and eventually eliminating the carbon emissions produced by the district energy system is essential to overall campus reductions and driving toward a net-zero campus.

The Electrifying Steam Production, Heat Pump Transition and Ground Source Heat Exchanger measures are related to the overall investment path McMaster chooses with their district energy system upgrades. The Reactor Heat Recovery and Wastewater Heat Recovery measures are decoupled from the overall investment path and represent zero carbon sources of thermal energy which are recommended regardless of which other measures are implemented.

PROPOSED PEAK SHAVING PROJECT

McMaster is planning to install 10 MW of natural gas fired peak shaving generation capacity to reduce the campus peak electrical demand during grid peak events. This will supplement the 5.7 MW generation capacity of the cogeneration unit and will allow the campus peak demand to near zero during the provincial peaks.

In 2019, 87% of the campus electrical rate went to global adjustment totalling $6.8M. If the campus switches from class B to class A and actively engages in peak shaving, it can dramatically reduce its peak demand factor and thereby the global adjustment is pays.

It is estimated that the generators will be required to operate for an estimated 60 - 100 hours per year in order to ensure that the campus demand is reduced during the provincial peaks. Additional runtime may be required as more class A customers take steps to peak shave, predicting the occurrences of the provincial peaks becomes increasingly challenging. Clearly, peak shaving in of itself is not a carbon reduction measure. Running the natural gas peak shaving generators plus the cogeneration unit to generate electricity adds to the campus direct emissions. Approximately 415 tonnes of additional CO_2e emissions will result from 60 hours of generator operation. It is worth noting that at the occurrence of the provincial peaks, the peaking gas fired generators will be online and supplying the grid. The run time for the generators should be minimized but not to the point of risking missing a provincial peak.

Much of the reduction of GHG emissions on the McMaster campus involves fuel switching from natural gas to electricity as an energy source. In order to achieve this transition without significant increases in utility costs, the campus needs to reduce the electrical rate it pays. By successfully peak shaving as a Class A customer, McMaster will reduce their electrical rate and thereby enable cost effective fuel switching to electricity on the campus.

REDUCED COGENERATION OPERATION

Aside from downtime for maintenance, the cogeneration unit currently operates continuously to generate electricity to offset the campus electrical draw from the Ontario electricity grid. Steam produced from the cogeneration exhaust is fed into the campus steam network supplementing the district energy steam boiler plant. When the cogeneration system is running at full capacity it produces 30,000 pounds of steam per hour (lbs/hr) from the hot turbine exhaust stream. Additionally, there is a burner section in the exhaust stream capable of increasing the steam production to 100,000 lbs/hr.

Operating the cogeneration unit has resulted in a significant increase in the campus natural gas consumption and related carbon emissions. From a greenhouse gas emissions standpoint, the cogeneration unit is detrimental to campus carbon reduction strategies. The Ontario electrical grid has a relatively low emissions factor as with overall average at 30 grams of CO_2e/kWh. When running the cogeneration unit, electricity is produced at approximately a 40% efficiency while burning natural gas in the turbine. The effective emissions factor for electricity produced by the cogeneration system is approximately 450g of CO_2/kWh.

The recommendation for operation of the cogeneration unit is not straightforward. Firstly, it generates electricity at about $0.033/kWh of energy costs in contrast with the current campus electrical rate of $0.115/kWh, not factoring maintenance. Maintenance costs for the cogeneration are a fixed cost of $600k/year. Further, each kWh of electricity produced has a further production of 3.2 pounds of steam at a value of about $0.019. Therefore, from a economics standpoint it would be beneficial to run the cogeneration unit if today's pricing remained in place, but with the incoming carbon tax, the financial model becomes less appealing as carbon prices increase through to 2022 and beyond.. At a natural gas rate of $0.47/m³ the cogeneration operation becomes break-even on an energy cost alone basis.

Secondly, while the carbon comparison to the average generation emissions factor of the Ontario grid reflects poorly on the cogeneration unit, the margin production (the last kWh onto the grid) is generated by natural gas fired generators. Moreover most of the gas fired generators feeding the Ontario grid do not have the ability or available thermal demand to use the waste heat as the McMaster unit does at all times of the year. Thus, the McMaster cogeneration unit is considerably more efficient than the natural gas plants operated to generate electricity during a grid wide peak event

From a campus carbon emissions standpoint, it would be best to not operate the cogeneration unit. From a financial perspective at current utility rates, it should be the first piece of equipment run to generate steam. At times when the provincial electrical grid is nearing peak, the cogeneration unit should definitely be operating – both from the standpoint of reducing the campus peak demand factor to reduce global adjustment electrical costs and from the broader viewpoint of reducing greenhouse gas emissions if the cogeneration unit is producing steam offsetting boiler use.

The cogeneration unit is currently operating near continuously. While this reduces the cost of electricity to the campus it does increase the campus greenhouse gas emissions. Each hour the cogeneration unit runs, there is an incremental increase to the campus CO_2 emissions of about 1.05 tonnes.

From a carbon standpoint, it is recommended to reduce the operating hours of the cogeneration unit. The emissions targets in the recommended path have been set with the cogeneration unit running only 500 hours per year at an average load of 4,000 kWh per hour. It is recommended that the cogeneration unit be operated during the peak grid demand times when it is offsetting natural gas fired electric plants.

It can be seen in the figure below that as the cogeneration unit operation is scaled back in 2022, the steam that is no longer coming from the unit must be supplied by the boilers instead. Similarly, the indirect emissions for electricity purchased from the Ontario grid also increase – but with a 12% reduction in overall campus GHG emissions.

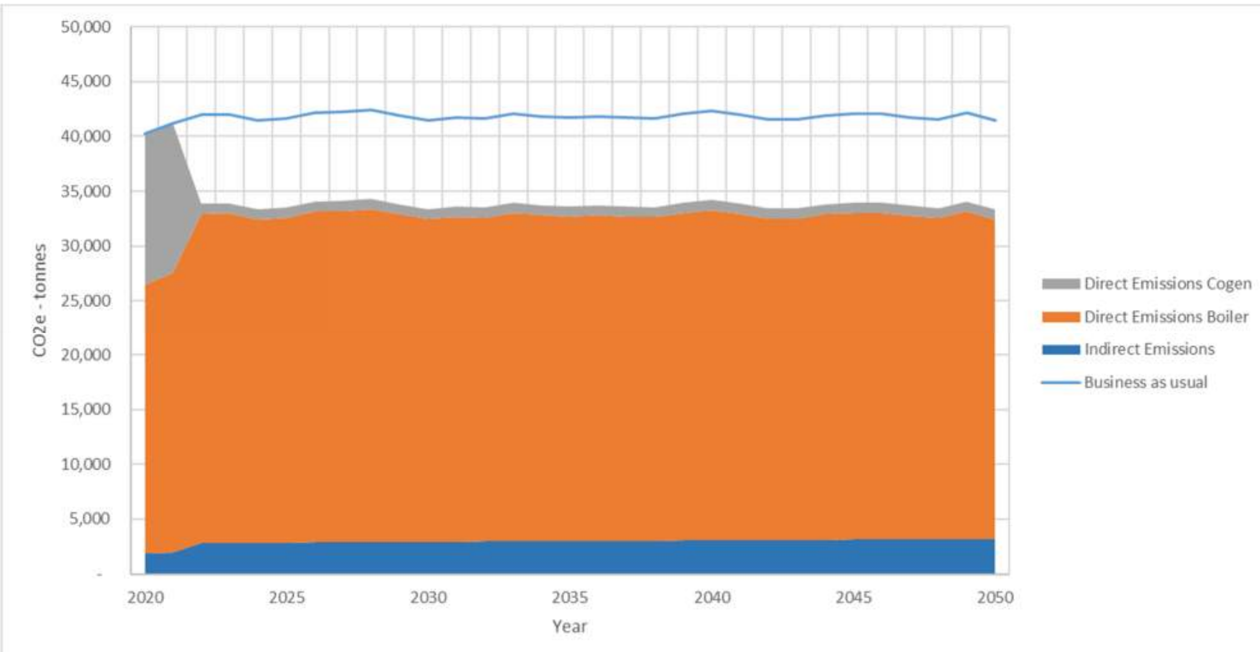


Figure 19: McMaster Campus Emissions with Reduced Cogeneration Operation

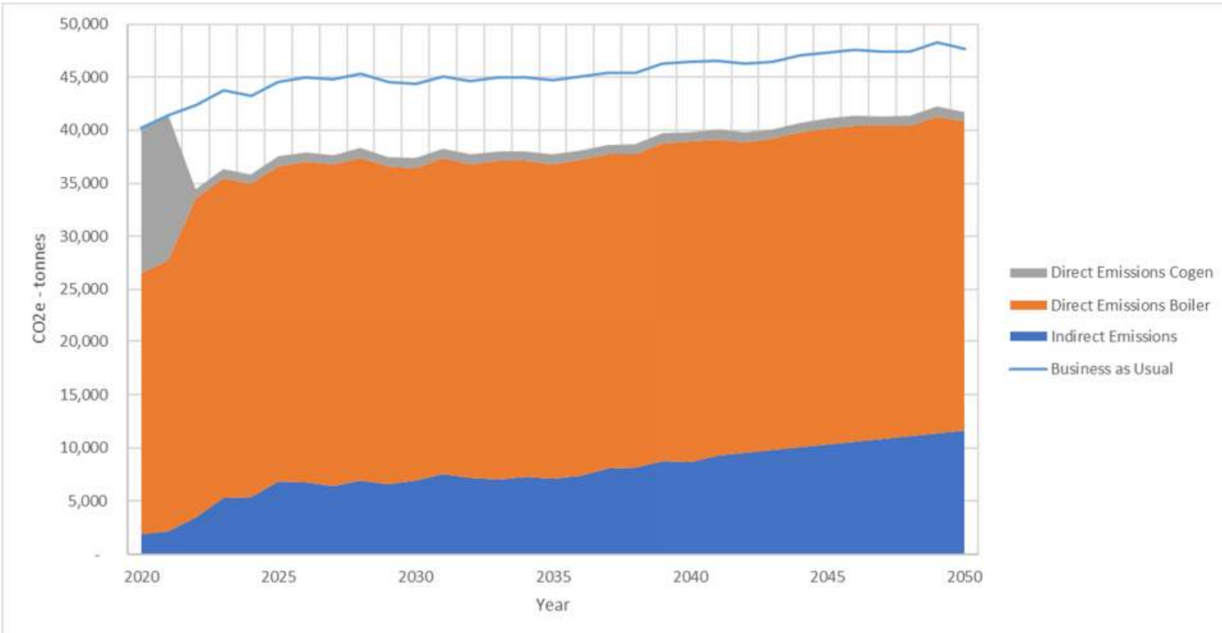


Figure 19A: McMaster Campus Emissions with Reduced Cogeneration Operation with Indirect Emissions Factor Growth

Figure 19A above adds the impact of the forecast growth of the Ontario average emissions factor per figure 12A above to Figure 19.Given that the cost of generation electricity from the cogeneration unit (without maintenance considerations) is about $0.033/kWh, reducing its operation would have a negative effect on the campus utility costs. It is therefore recommended that the reduced operation of the cogeneration unit be done in conjunction with the planned campus peak shaving implementation and resulting electrical cost reduction. Without peak shaving and class A, reducing the cogeneration operation would result in increased campus utility costs of approximately $3.1M per year.

ELECTRIFYING STEAM PRODUCTION

Currently the steam used on the McMaster campus is produced by natural gas-fired boilers housed within the E.T. Clarke Center. It is the natural gas combustion in these boilers that account for approximately ninety-five percent (95%) of the campus's carbon emissions.

Installation of an electric boiler allows for the continued use of the existing steam network infrastructure while reducing the campus fossil fuel consumption and resulting GHG emissions. It makes this a good first step in the path to a net zero carbon campus.

Based upon the daily log and steam consumption provided by Facility Services, it is estimated that a boiler with a steam production capacity 30,000 lb/hour would supply half of the current campus annual heating requirements. It would meet all summer consumption and 25 – 35% of the winter steam load. The 2020 McMaster Energy

Management Plan recommends the installation of a 40,000 lb/hr boiler as part of the campus decarbonisation plan at a budget price of $4M. This well matches our investigation into budget pricing and proposed sizing.

The electric boiler would be operated as the lead boiler followed by the cogeneration unit and finally the subsequent natural gas fired boilers should the load require. The operating cost implication of operating the electric boiler depends on the electric rate the campus can achieve which relates how and how much global adjustment is paid. With the natural gas rate of 0.14/m³ ($0.013 / equivalent kWh), every 1000 pounds of steam costs approximately $6.02 in natural gas costs. If the campus installs additional peak shaving generator capacity, adopts class A rate and is successful in removing the campus from the grid during all five provincial peaks, it will be only paying the HOEP for electricity. This reduces the electrical rate to approximately $0.02/kWh. In this case the cost of steam production would only decrease slightly to $5.24 per thousand pounds produced. At current rates without class A and peak shaving, the cost of steam production from an electrical boiler would be $30.13 per thousand pounds of steam. The electric boiler installation requires the peak shaving generator installation and operation along with careful consideration of current and forecast electrical rates to be economically viable.

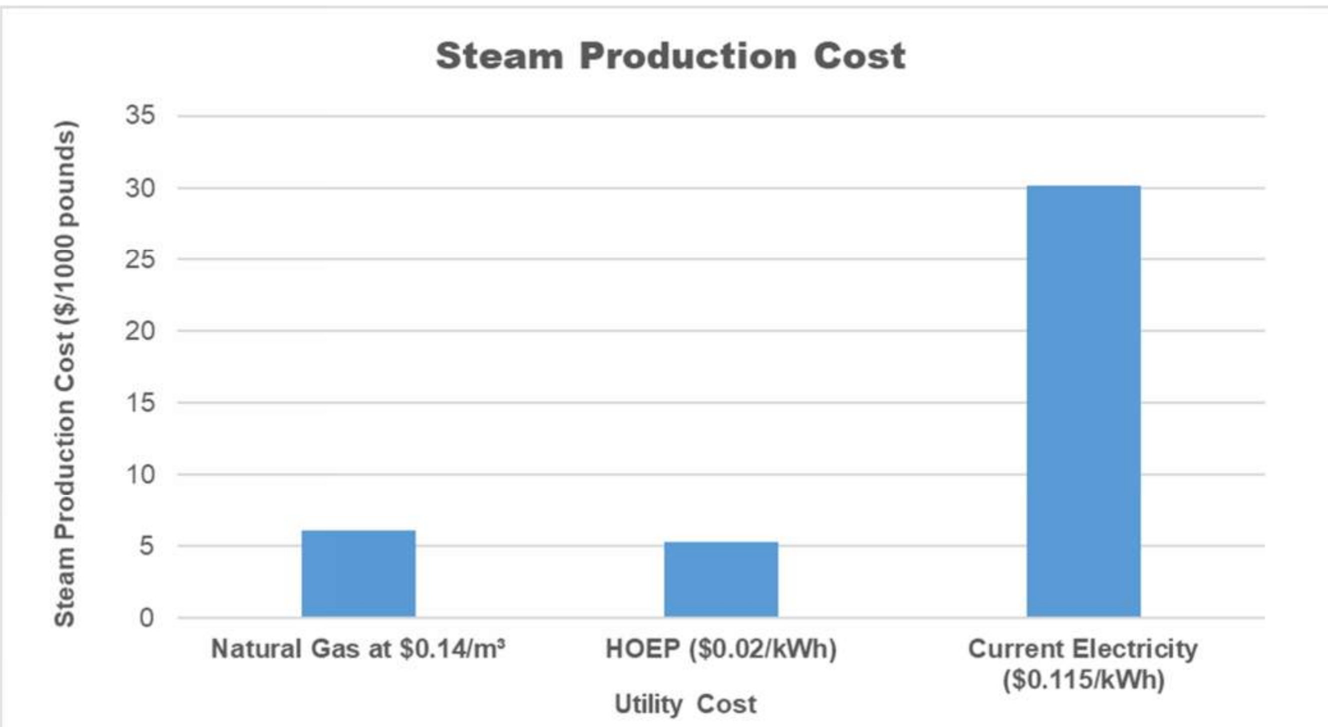


Figure 20: McMaster Campus Emissions

A 30,000 lb/hour electric steam power would have a peak power draw of approximately 10 MW. In order to avoid increasing the campus peak demand factor and global adjustment costs under class A, it is imperative that the electric boiler is not operated during periods that could set a provincial peak. The first peak shaving strategy will be to cycle off the electric boiler and operate the steam plant first on the cogeneration system and subsequently on the natural gas fired boilers.

The pathway of fuel-switching some of the capacity of the district energy steam plant from natural gas to electricity provides a method of addressing the emissions associated with combustion.

The graph below shows the impact on the campus emissions of running a 30,000 lb/hr electric boiler as the lead boiler to provide steam to the campus. A 30,000 lb/hr boiler as the lead boiler can produce 63% of the current annual steam and reduce the campus emissions by about 35%. Used in conjunction with a heat pump installation, a 30,000 lb/hr boiler could provide all of the required steam by the implementation of the 3rd of 7 phases of the heat pump installation. It would require a 9 MW power feed.

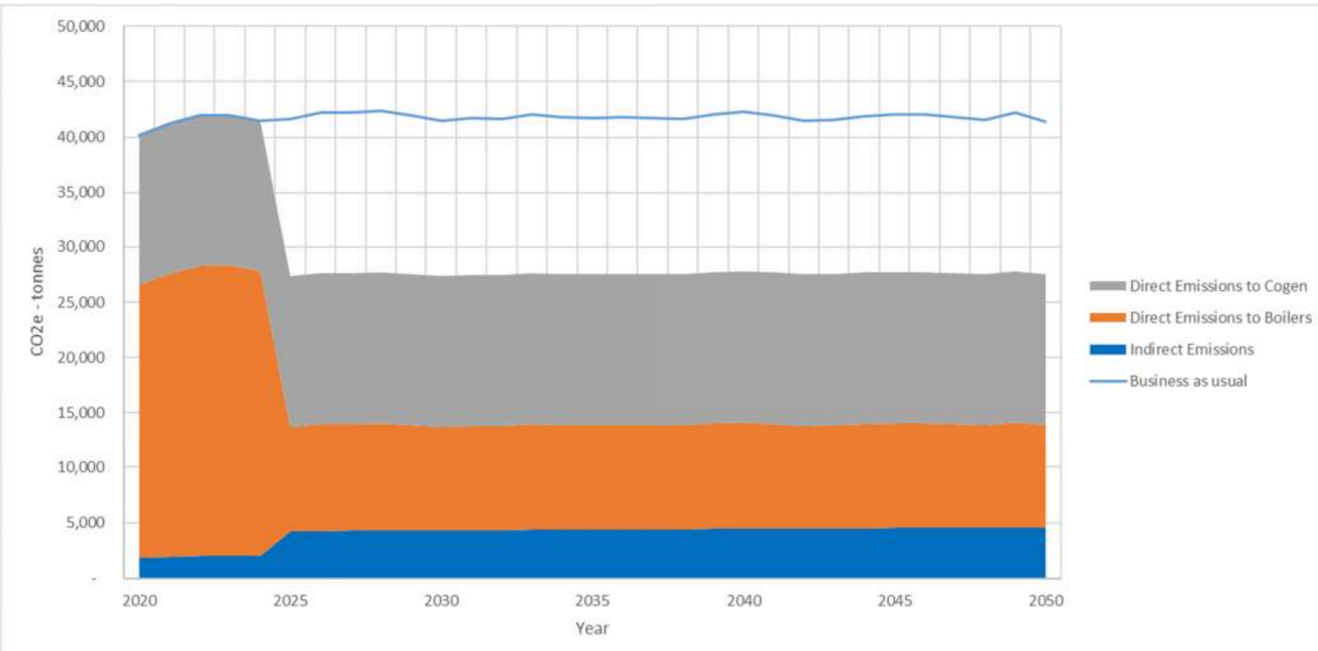


Figure 21: Carbon Reduction Path – Steam Plant Electrification – 30,000 lb/hr boiler

By contrast, the next figure shows the installation of a 20,000 lb/hr electric boiler. This smaller boiler operated continuously would reduce campus emissions by 22% and producing 42% of the campus steam. It would still meet all the campus steam requirements by the 5th phase of the proposed heat pump installation. This smaller boiler would require a 6MW power feed.

As discussed above, at current rates as a Class B customer, generating steam from an electrical boiler has five times the input utility cost of a natural gas fired boiler. To make it economical, this measure should be implemented after the campus peak shaving plan is complete. It is imperative from a utility cost perspective that the electric boiler not be run during the provincial peaks once the campus has changed their electrical rate to class A.

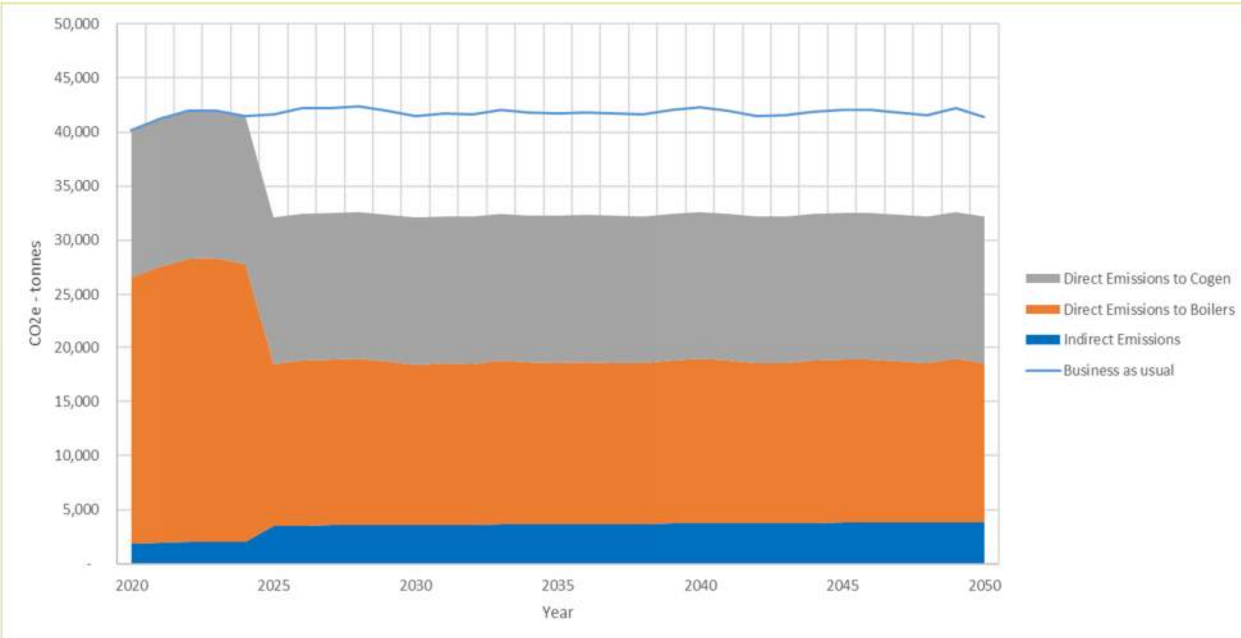


Figure 22: Carbon Reduction Path – Steam Plant Electrification – 20,000 lb/hr boiler

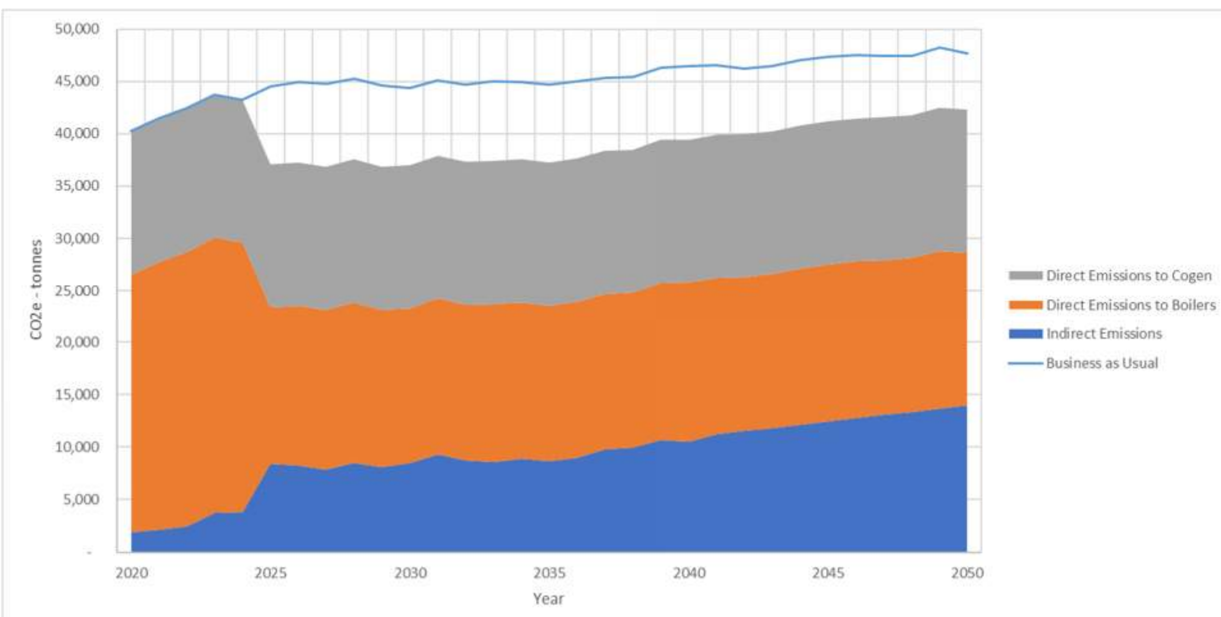


Figure 22A: Carbon Reduction Path – Steam Plant Electrification – 20,000 lb/hr boiler with Indirect Emissions Factor Growth

Future Project Considerations

The measures described above provide for substantial carbon emission reductions for the McMaster campus. They reflect the significant investment and residual life in the district energy system infrastructure. For further, cost effective emissions reductions fundamental changes to some of the campus energy transfer systems must be considered. It is expected that there will be technological development in the area of heat pump and non-fossil fuel heating technologies. Currently installation of heat pumps to provide heating for the campus buildings appears to be the most effective and commercially viable solution for the campus. There are a number of avenues that will result in the targeted significant emissions reductions The University can choose from these in time.

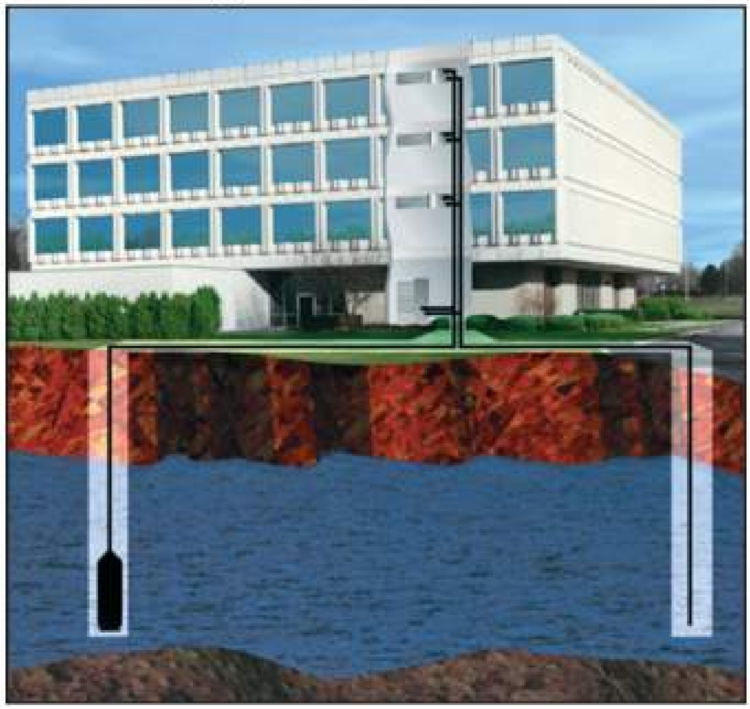
HEAT PUMP TRANSITION

An alternative to continuing to rely on the district energy steam boilers and heating network is to phase in the use of heat-pump chillers to provide heating. Heat pumps transfer heat by way of a refrigeration cycle. Because the electricity is being used to run a compressor in the refrigeration cycle rather than as a source for the heat, more heat is transferred than the electrical input. The ratio of the heat transferred to the input electricity is the coefficient of performance or COP and for heating cycles it is typically in the range of 2.5 to 4. From an economic standpoint, the introduction of heating with heat pumps means the higher cost of electricity is mitigated by the coefficient of performance of the heat pumps. In this way, the production of heating using electricity is more cost effective that the electric steam boiler or resistance heating where the ratio of heat out to electrical energy in is essentially 1. Heat pump solutions range in scale from residential to district energy scale.

HEAT PUMPS – GROUND SOURCE

Ground source heat pumps use the stable ground temperature as the source for building heating as well as the sink for heat rejected from cooling. The heat transfer to the ground can be accomplished by either an open loop or a closed loop.

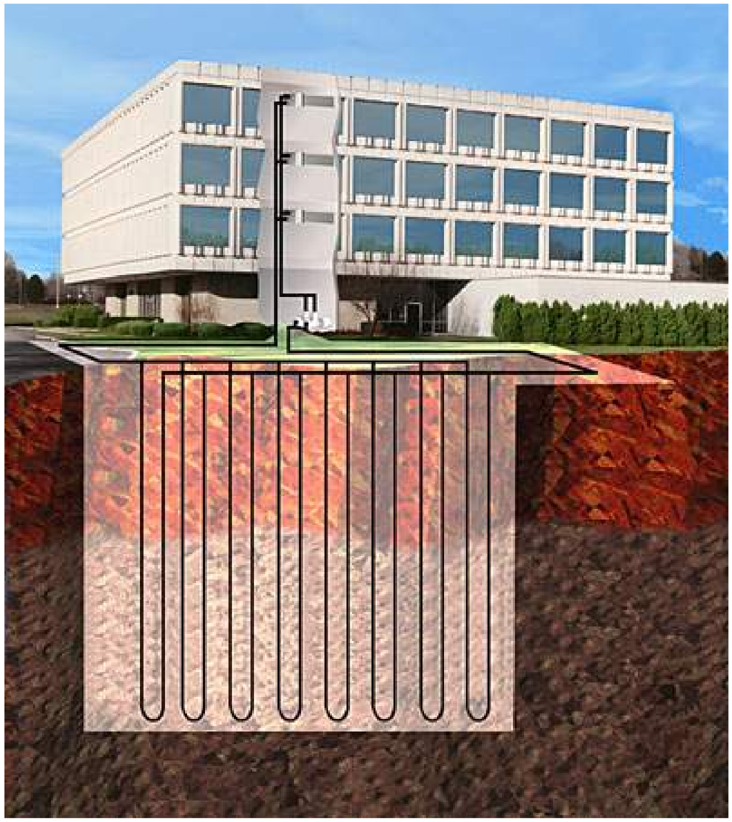
Open loops systems draw ground water directly from a well or series of wells and transfer heat to or from the ground water stream as condenser water in the heat pump before returning it to the ground.



Source: http://www.americancoolingandheating.com/wp-content/uploads/2012/06/022-1850-01.pdf

Figure 23: Open Loop Ground Source System

Closed loop ground source systems use the ground as a heat source by passing the condenser water through a large number of u-tube wells drilled to a depth of between 150m and 250m (500 – 800 ft). It is estimated that a wellfield consisting of 3,000 wells to a depth of 600 ft would be required to act as a closed loop heat pump source for the entire McMaster Campus. At a 6m (20 ft) spacing – that wellfield would cover and estimated area of 109,000 m².



Source: http://www.winslowpumpandwell.com/commercial.html

Figure 24: Closed Loop Ground Source System

Given this very large wellfield size required to satisfy the heating and cooling requirements of the McMaster Campus with a closed loop, a series of open loops is seen to be the preferred option as long as the water table and campus geology will support this option. The existing chilled water network would be reused as a low temperature condenser loop.

Implementation of a heat pump solution centered on the E.T. Clarke Centre is technically challenging. The introduction of a low temperature hot water heating loop to the campus is both expensive and the long distribution runs would impose excessive heat loss on the hot water distribution system.

Conversely, it is challenging to find space in each campus building to install heat pumps were a building-by-building system considered.

The suggested path for the implementation heat pump solution is to locate the heat pump chillers to serve low temperature hot water and chilled water to clusters of campus buildings. We have envisioned seven heat pump chiller installations serving clusters of buildings. The building clusters have been determined based upon the chilled water distribution network for the campus with each cluster currently being served by a main branch.

GROUND SOURCE HEAT PUMP TRANSITION

The heat pump system could be phased in with each cluster being installed. Open loop wells supporting the heat pumps of each phase would be drilled as each project was undertaken, allowing for modular projects phases that can be performed separately and added to the network as funding becomes available. The image below shows the suggested clustering of the campus buildings.

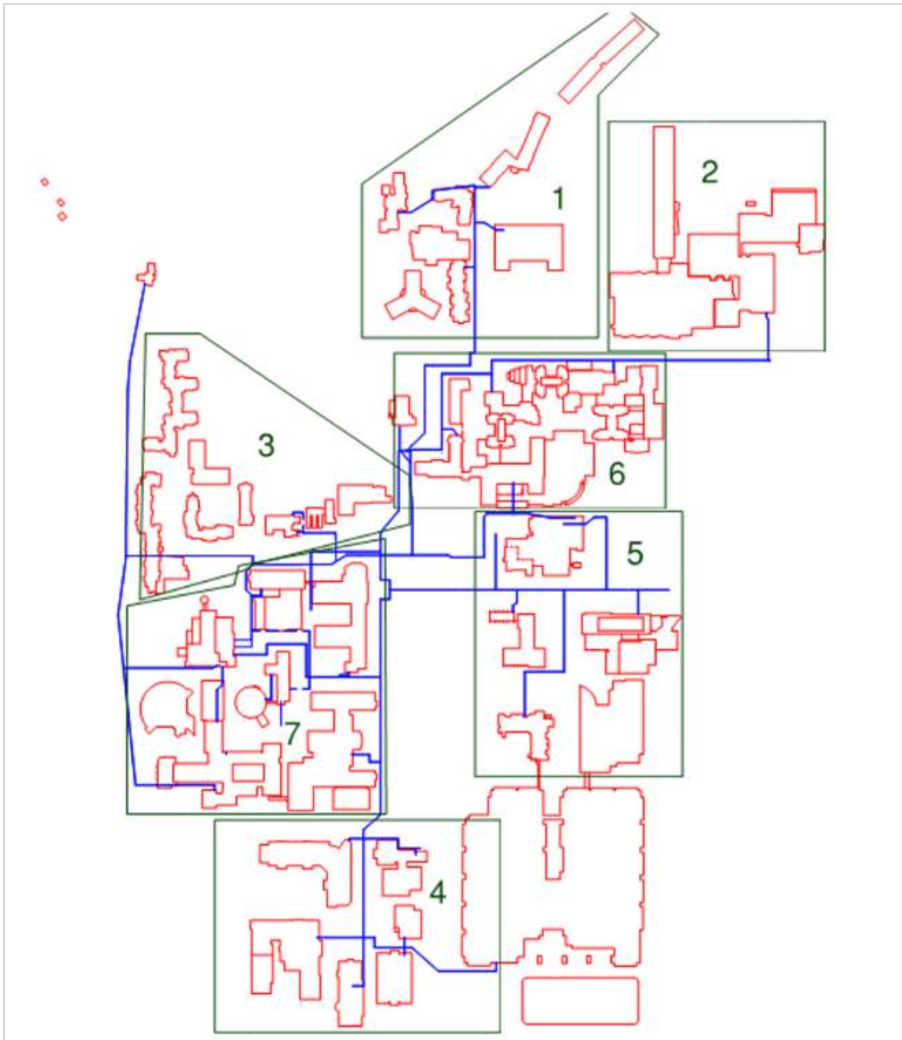


Figure 25: Proposed Heat Pump Clusters

Table 7: Proposed Heat Pump Clusters

Cluster	Estimated Heat Pump Capacity (Tons)	Number of Buildings
1	1,500	8
2	700	3
3	1,200	9
4	800	5
5	1,250	5
6	1,150	9
7	2,550	11
Total	**9,150**	**50**

It is recommended that McMaster consider a future installation of a ground source heat pump system to provide primary heating and cooling to the campus buildings. We estimate a heat pump capacity of 9,150 tons-refrigerant is required after the load reductions from the energy conservation measures.

From a capital cost perspective, an open loop system would be less expensive to install than a closed loop system. Geotechnical surveys will be required to determine whether there is sufficient ground water flow to support the heating and cooling requirements of the building groupings that are adopted. However, it is likely that a closed loop system will be required for many of the building clusters.

The implementation of a campus wide ground source heat pump solution would reduce the McMaster emissions by 52% on its own.

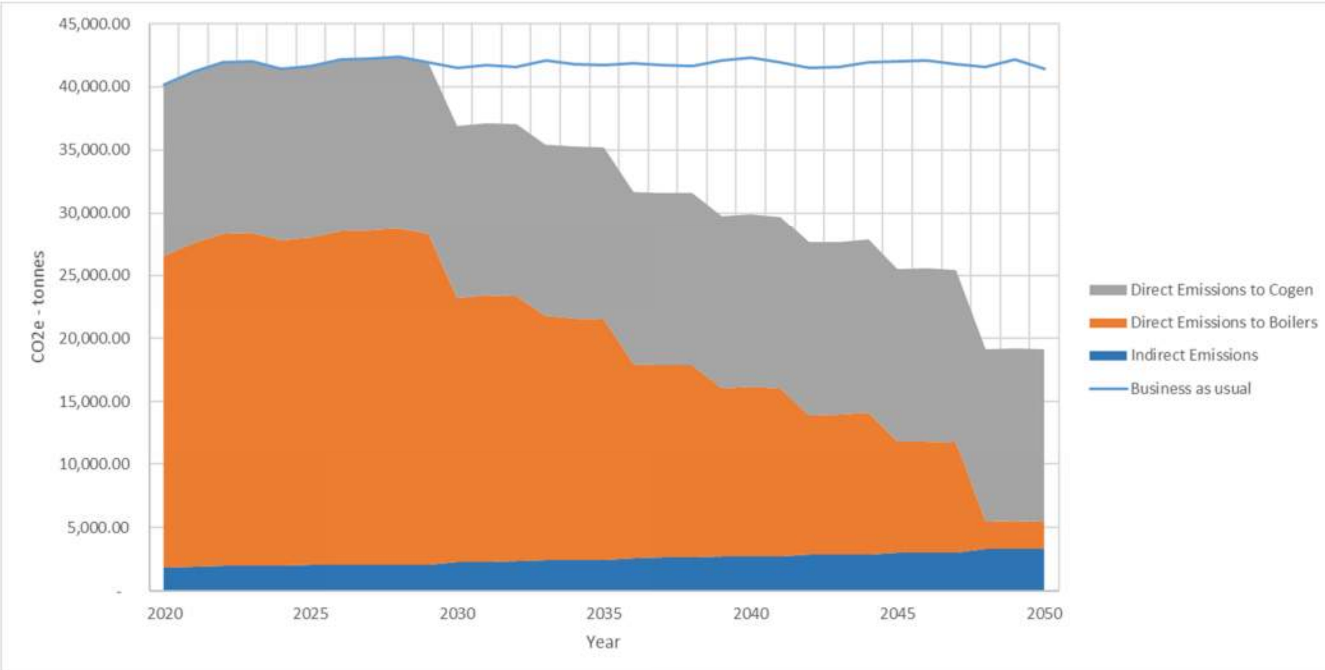


Figure 26: Carbon Reduction Path – Ground Source Heat Pump Transition

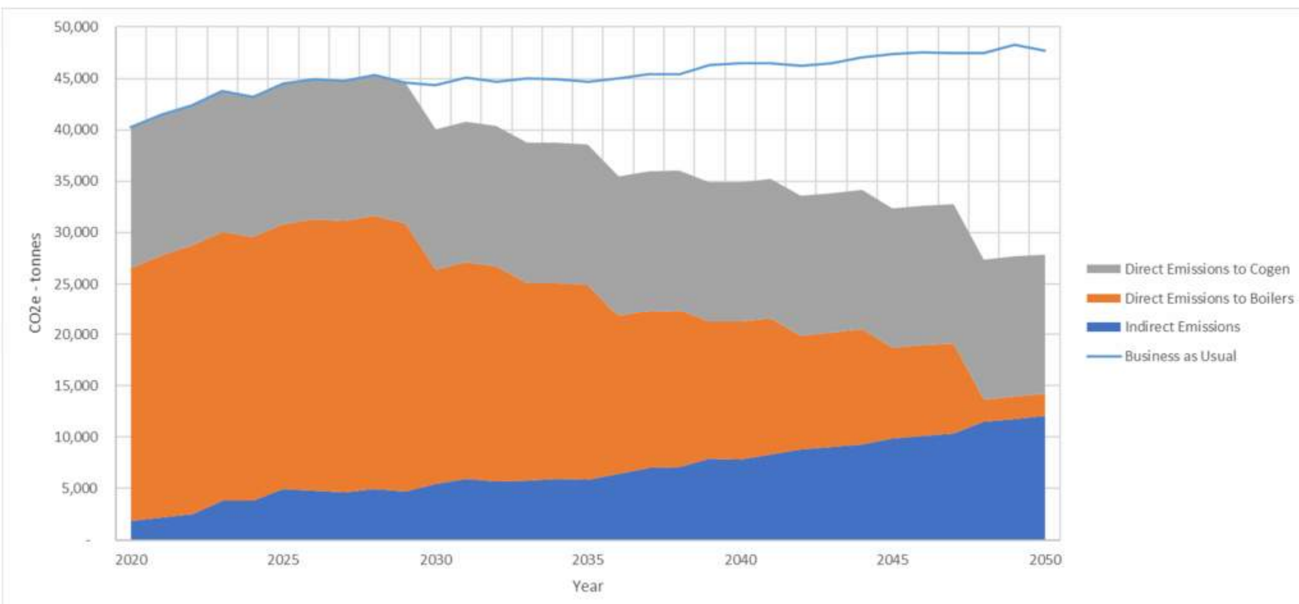


Figure 26A: Carbon Reduction Path – Ground Source Heat Pump Transition with Indirect Emissions Factor Growth

Heat pump efficiency is inversely proportional to the hot water temperature they produce. They are not efficiently capable of producing the 80°C (180 °F) high temperature hot water currently used in the campus buildings. This is true of both air source and water source heat pump technologies. It is recommended to retrofit the buildings such that the majority of the heating loads can be served by lower temperature hot water – supplied at approximately 50°C (120°F). This includes replacing the steam heating coils in the ventilation units with hot water (glycol) coils. The lower temperature hot water will be supplied to the buildings from heat pump chillers.

Figure 26 above shows the impact in campus carbon emissions in transitioning heating to heat pumps. Figure 26A adds the impact of the forecast growth of the emissions factor for electricity for Ontario per figure 12A

HEAT PUMPS – AIR SOURCE

Air source heat pumps take heat from the ambient air. They are convenient in that no infrastructure is required for the heat source. While they can operate when the ambient air goes all the way down to -15°C, both their efficiency and capacity diminishes with reduced outdoor air temperature.

The largest component of the capital cost of a ground source heat pumps solution is the cost of the installation of the wellfield. The alternate heat pump technology, which can be applied on the McMaster campus, is air source heat pumps. Large capacity air-to-water heat pump chillers are commercially available up to 350 ton-refrigerant capacity units.

Air source heat pump chillers could be installed in groups to serve clusters of buildings on the McMaster campus in a similar scenario to the ground source heat pumps solution proposed above. In the case of the air source heat pumps there is no requirement or advantage to converting the district energy chilled water distribution system to be a condenser system. The existing chilled water infrastructure could remain with the air source heat pumps solely providing low temperature hot water to the campus buildings.

The disadvantage of air source heat pumps is that both their heating capacity and their efficiency diminish as the outdoor air temperature decreases. At outdoor air temperatures below approximately -10°C to -15°C, the heating coefficient of performance drops to 1 – equivalent to electric boiler or electric resistance heating. The means that there are more hours of the year where supplementary heating from the district energy steam system would be required.

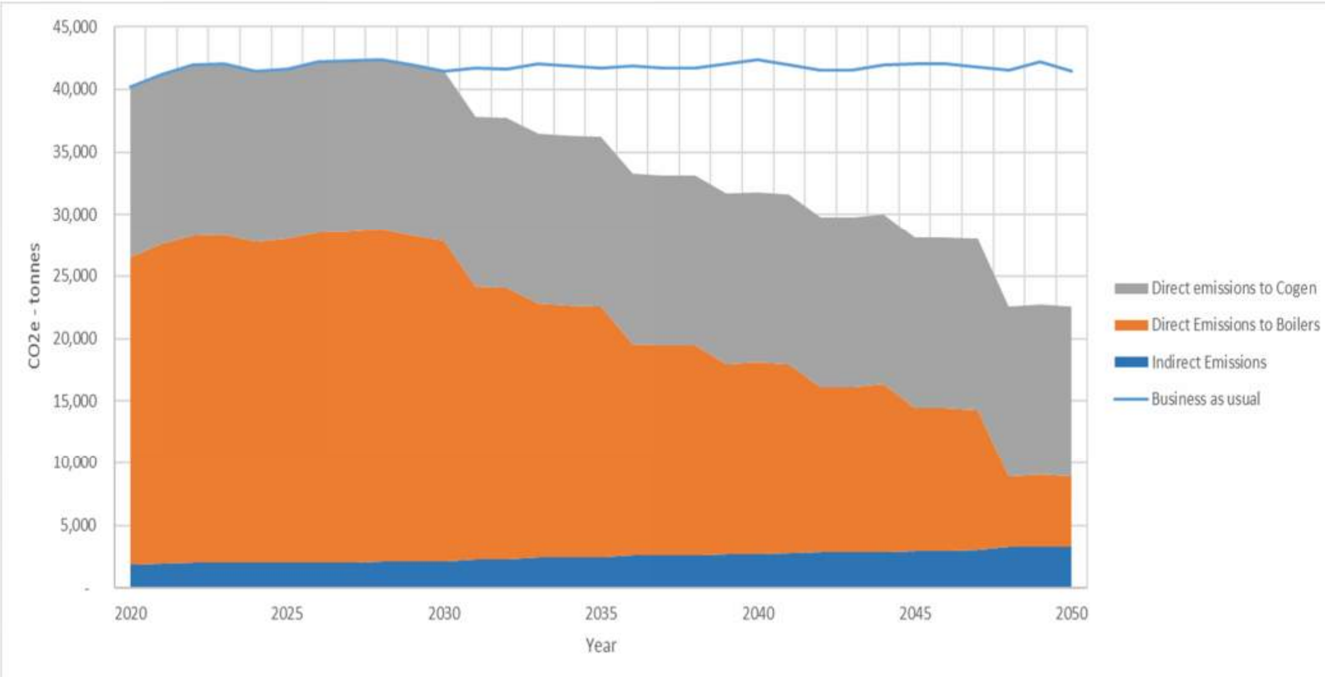


Figure 27: Carbon Reduction Path – Air Source Heat Pump Transition

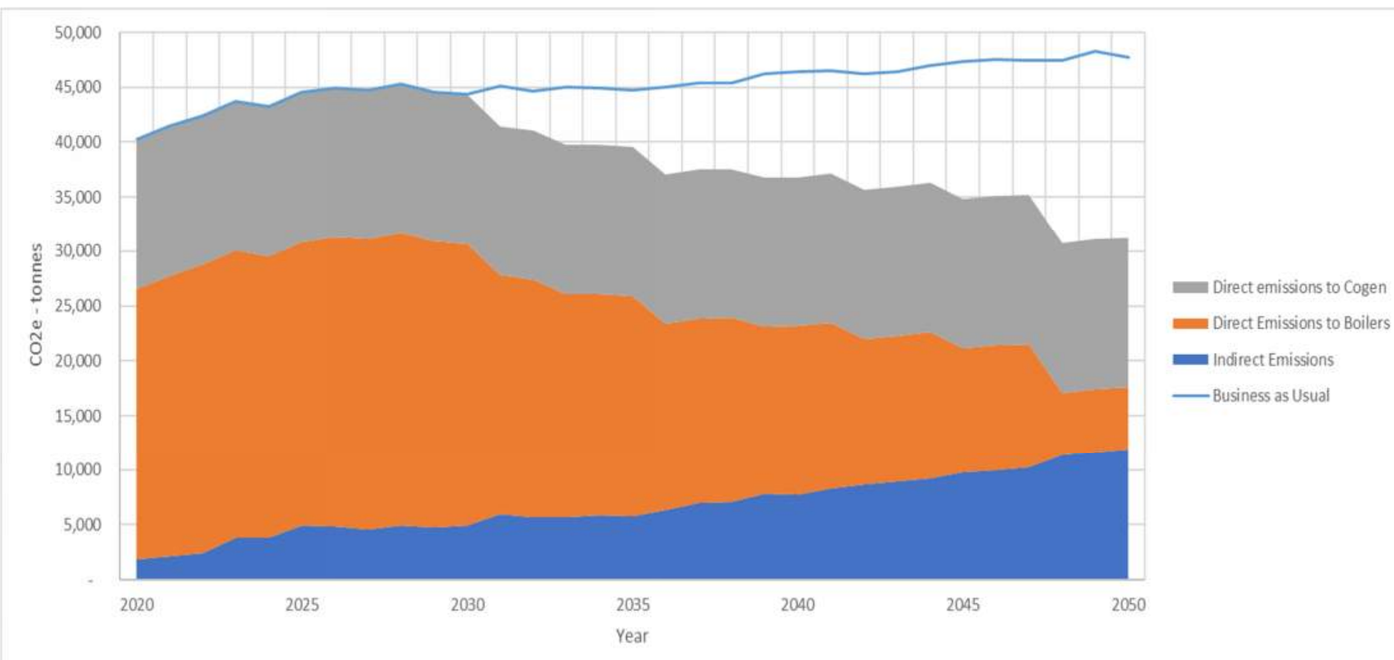


Figure 27A: Carbon Reduction Path – Air Source Heat Pump Transition with Indirect Emissions Factor Growth

Figure 27A adds the impact of the forecast growth of the Ontario average electrical emission factor per Figure 12A.

REACTOR HEAT RECOVERY

The nuclear reactor on campus used for nuclear research and isotope production creates useful heat as part of the reaction process. This heat can be harnessed for use in the campus heating network through the installation of a heat exchange system capable of transferring the heat recovered from the reaction process into heating water for building heating. More specifically, if the campus adopts a ground source heat pump solution, the heat recovered from the reactor can be supplied to the condenser loop as a heat source.

In 2009, Atkinson Engineering performed a feasibility study on methods for usable heat recovery from the nuclear reactor. They analyzed two methods of heat recovery including using either a heat pump or heat exchanger based system. The system parameters from the Atkinson Engineering report are summarized below, assuming the nuclear reactor is operating at the higher capacity scenario of 5MW for 160 hours per week.

The McMaster nuclear reactor generates an estimated 5MW (1,400 tons) of low grade heat when operating. This heat is currently rejected via a cooling tower. This would be an ideal heat source to add to the heat pump condenser loop. It represents about 15% of the estimated heat pump heating capacity.

Table 8: Reactor Heat Recovery Potential

System	Production Temp	Heat Recovered
Heat Exchanger	30°C	14,018 MWh
Heat Pump	71°C	20,995 MWh

It is recommended to use the heat from the reactor to supplement the ground water heat pump source. The reactor provides approximately 1,000 tons of low temperature heat which would supplement heat recovered from the ground improving the temperature and operation of the heating dominated heat pump system.

WASTE WATER HEAT RECOVERY

A new technology in the building industry, adapted from mature technology used in the paper and pulp industry, is to utilize the waste water as either a heat source or sink depending on energy production requirements. The system uses heat exchangers and heat pumps to extract or expel heat from or to the wastewater stream, either converting it into higher grade usable heat which is then transferred into the heating network (heating mode), or receiving heat from the condenser water network and using the heat pump to convert it to temperatures that can then be expelled into the waste water stream (cooling mode). Overall this is quite a useful technology as it harnesses a heat source/sink which is constant, not created using an environmentally harmful fuel source and remains untapped until such a system is installed.

McMaster campus is fortunate that there is a main sanitary sewer running beneath the campus grounds which would be suitable for installation of a wastewater heat recovery system estimated to be capable of extracting / expelling approximately 4MW (~1,000 tons) adjacent to the Wilson Building.

Table 9: Waste Water Heat Recovery Potential

Mode	Wastewater Heat	HP Chiller Heating / Cooling
Heating	4 MW (extracted)	4.8 MW – 6.0 MW
Cooling	-4 MW (rejected)	2.8 MW – 3.2 MW

Budget level quoting was gathered for a 4 MW wastewater heat recovery system with the overall system cost estimated at $1,000,000, including macerator, sump pumps and heat exchanger pictured on the pink side of schematic in Figure 4 below.

As with the reactor heat recovery, we envision the waste water heat recovery system to integrate with the condenser loop for the heat pumps providing additional heat to the heat pump system.

Figure 28 below illustrates how a wastewater heat recovery system can be integrated into a district system utilizing heat pumps.

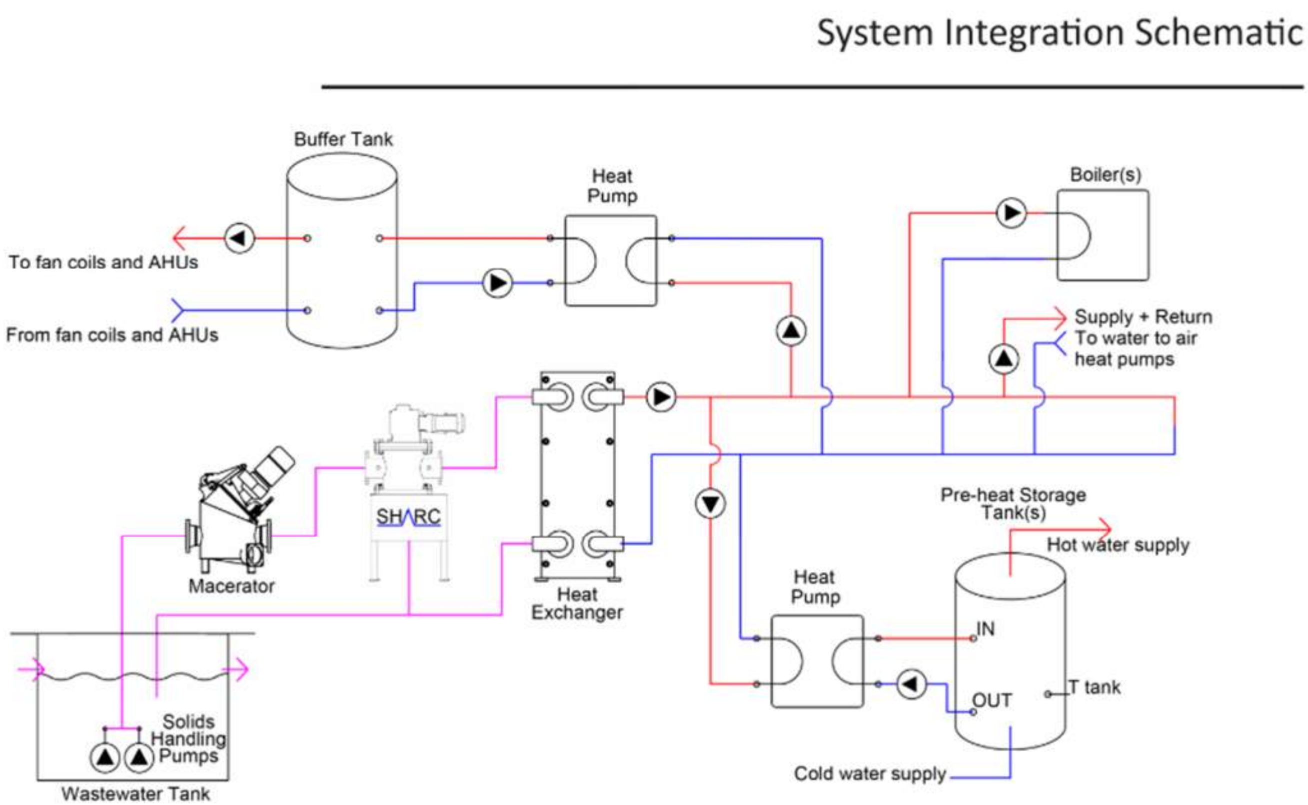


Figure 28: Example Wastewater Heat Recovery Schematic

Recommended Existing Campus Emissions Reductions

It is recommended that McMaster adopt a multi-faceted approach to GHG emissions reductions on the main campus. The graph below summarizes the anticipated carbon emissions based on in the recommended measures along each pathway from now to 2050. The forecasts presented include the impact of a projected reduction in heating energy demand due to forecast heating degree day changes and assumptions for campus growth.

Figure 29: Carbon Reduction Pathways

The recommended McMaster carbon emissions reduction path includes the following steps:

1. Energy conservation – starting in 2021 over 10 years focused on demand control ventilation, ventilation heat recovery, BAS optimization and DHW reduction and electrification
2. Implement peak shaving and transfer to class A electrical rate – to facilitate the cost effective transition to a more electrified campus
3. Cogeneration operation reduction to reduce GHG emissions and also provide additional peak shaving capability to further lower the peak demand factor to close to 0.
4. Electric boiler installation – 20,000 lbs/hr electric boiler - starting in 2024 once peak shaving is operational
5. *Future consideration: Heat pump chiller/heater installation – starting in 2030 and phased in in 7 clusters over 20 years – with a decision on open loop vs closed loop being based upon geotechnical investigations and a decision between ground source and air source heat pumps being based on capital considerations.*

In following this plan, the campus CO_2 emissions will be reduced by 75% in 2030 and by 90% by 2050 with a net reduction of 37,000 tonnes of CO_2 per year.

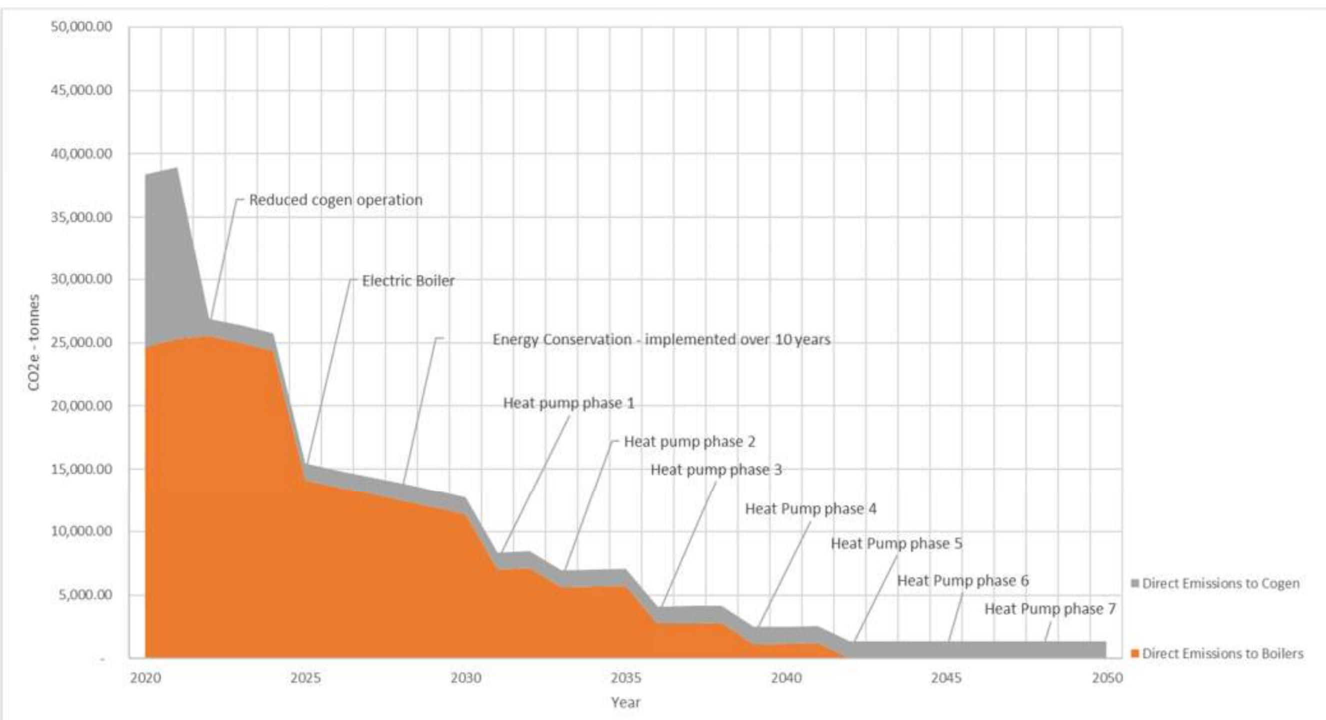


Figure 30B: Direct On Site Carbon Emissions Reduction

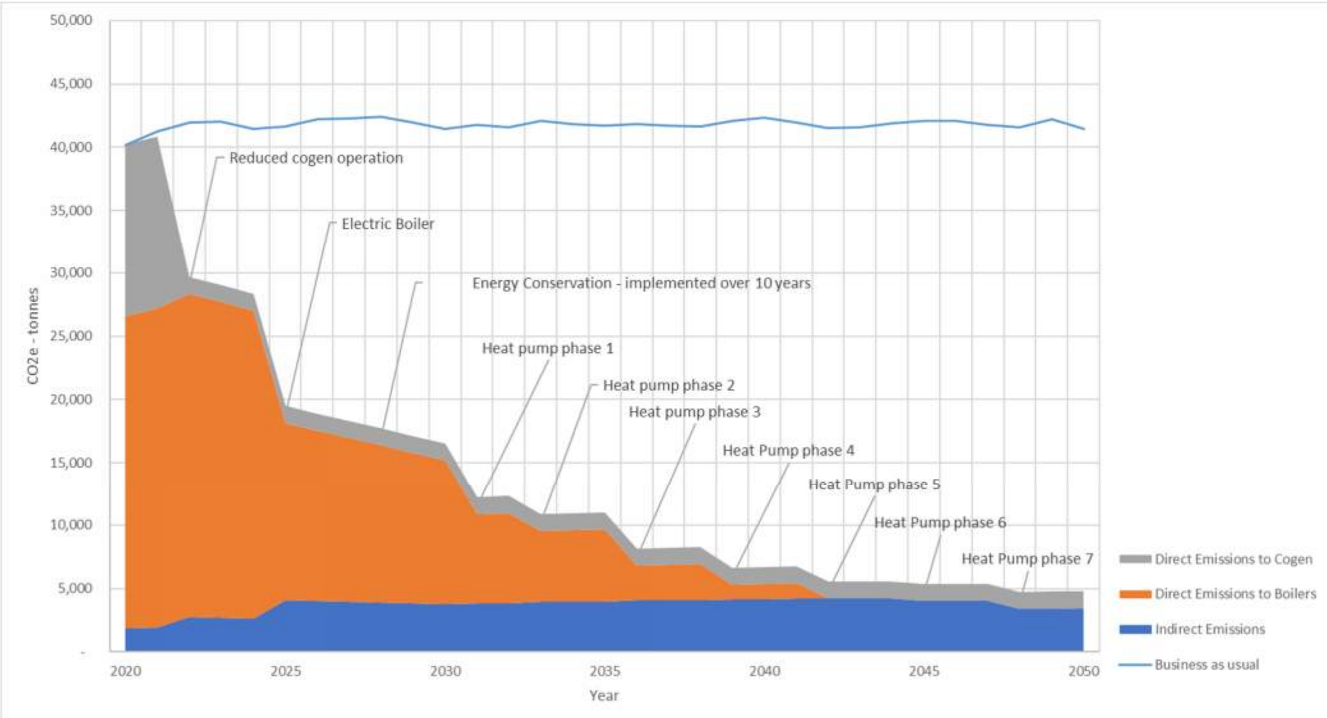


Figure 30: Carbon Emissions Reduction – by Phase from Recommended Path

Figure 30 was generated without factoring in the growth in the indirect emissions factor for Ontario.

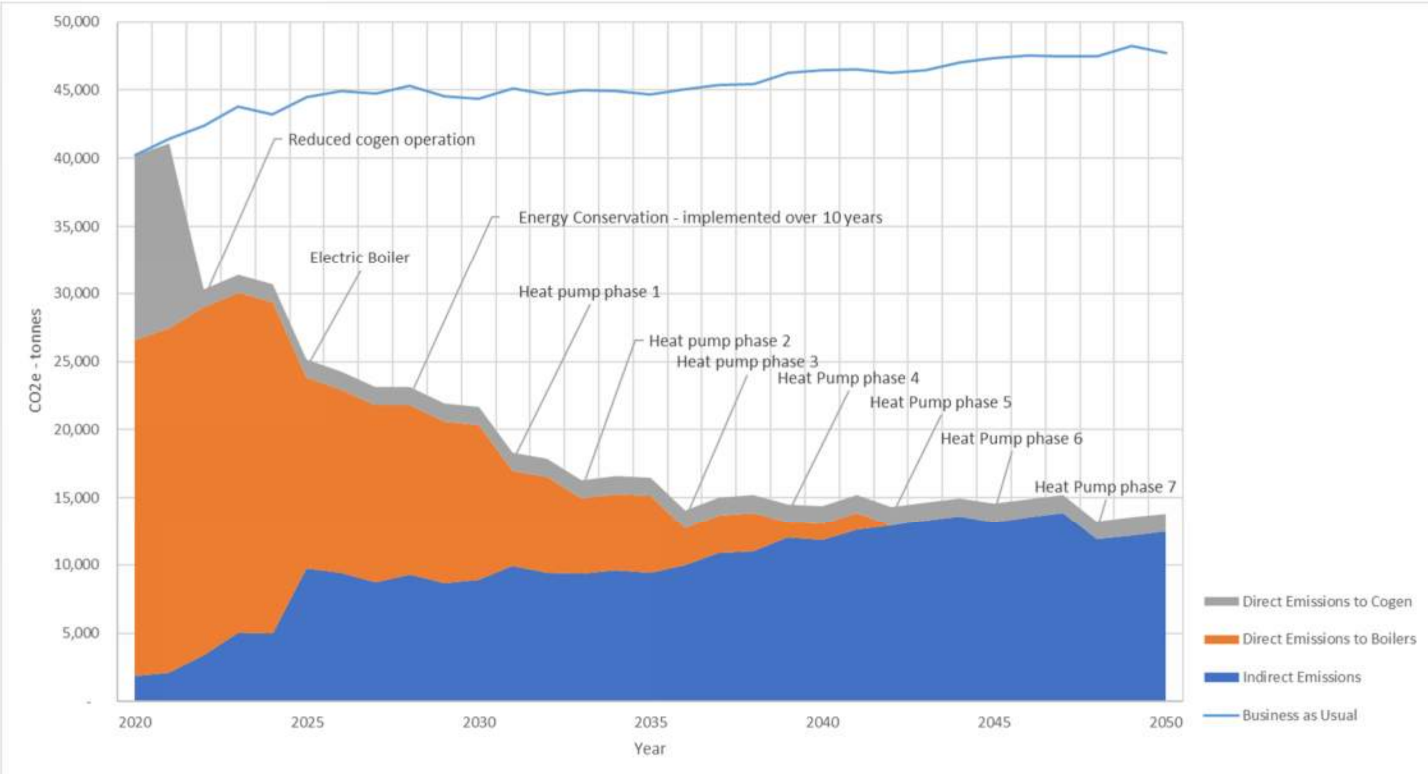


Figure 30A: Carbon Reduction Pathways – by Phase with Indirect Emissions Factor Growth

Figure 30A incorporates the impact of the forecast growth of the Ontario emissions factor for electricity as shown in figure 12A above.

High level cost estimates has been developed for each proposed solution within the campus carbon reduction roadmap. The cost estimates are based on supplier pricing information and scaled pricing from comparable projects. Pricing includes materials, installation, contractor general requirements, overhead and profit, design fees and contingencies. The pricing presented does not include taxes or servicing and maintenance costs.

Table 10: Carbon Emissions Reduction Path

Plan Component	Budget Cost in millions	Utility Cost Impact without Class A and Peak Shaving	Utility Cost Impact with Class A and Peak Shaving	Emissions Savings Tonnes CO_2e[1]
	Near Term Projects			
Energy Conservation Measures	$17.4	Decrease $1.1M/year	Decrease $0.8M/year	9,900
Reduced Cogeneration Operation	-	Increase $3.1M/year	Increase $129k/year	8,300
Electric Boiler Installation	$4.0	Increase $6.1M/year	Decrease $127k/year	9,200
	Future Projects			
Ground Source Heat Pump - Closed Loop	$86.7	Increase $1.9M/year	Neutral	22,300
Waste Water Heat Recovery	$3.7	Included above	Included above	Included in GSHP
Reactor Heat Recovery	$4.2	Included above	Included above	Included in GSHP
	Alternate Heat Pump Solutions			
Ground Source Heat Pump - Open Loop	$65.4	Increase $1.9M/year	Neutral	22,300
Air Source Heat Pump Chiller/Heaters	$29.6	Increase $2.1M/year	Increase $300k	-

1 – Note that interaction between measures means the savings from individual measures do not total to the cumulative plan reduction

The figure below shows the impact on operating utility costs of the proposed plan with and without reducing the electrical rate paid by the campus by peak shaving. This highlights the importance of the successful implementation of the global adjustment reduction plan through peak shaving. This curve is using current utility rates without carbon pricing or escalation.

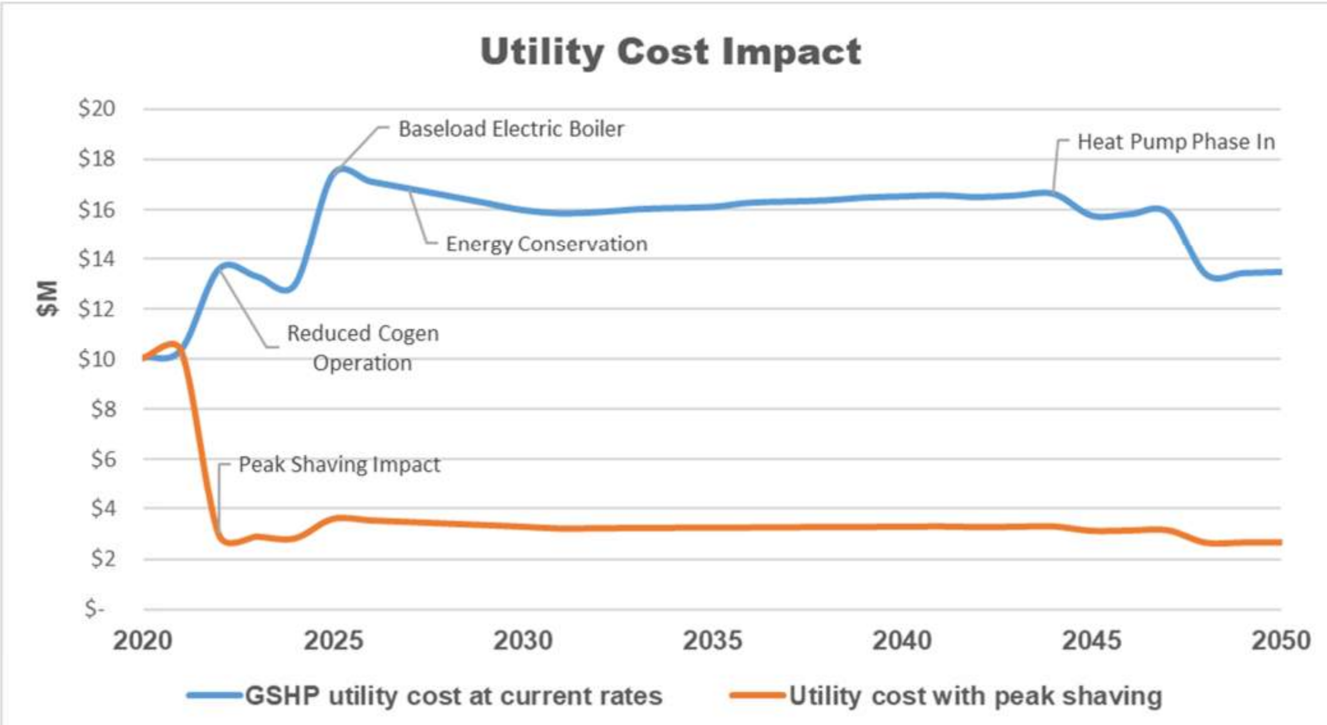


Figure 31: Utility Cost Scenarios

Supplemental note – the November 2020 Ontario Budget forecast a 15% reduction in global adjustment. The impact of this will be to reduce the savings associated with the peak shaving initiative and to reduce the operational cost of electricity correspondingly.

The following graph contrasts the total cost of electricity and natural gas with the carbon pricing and rate escalation included with the operational utility costs for the recommended path both with the current rates escalated at 2% per year (blue) and with class A and successful implementation of peak shaving such that global adjustment is eliminated. Implicit in the orange curve is that the global adjustment remains the primary component of the electrical rate and the class A rate structure remains unchanged. The expected trajectory lies between the orange and blue extremes.

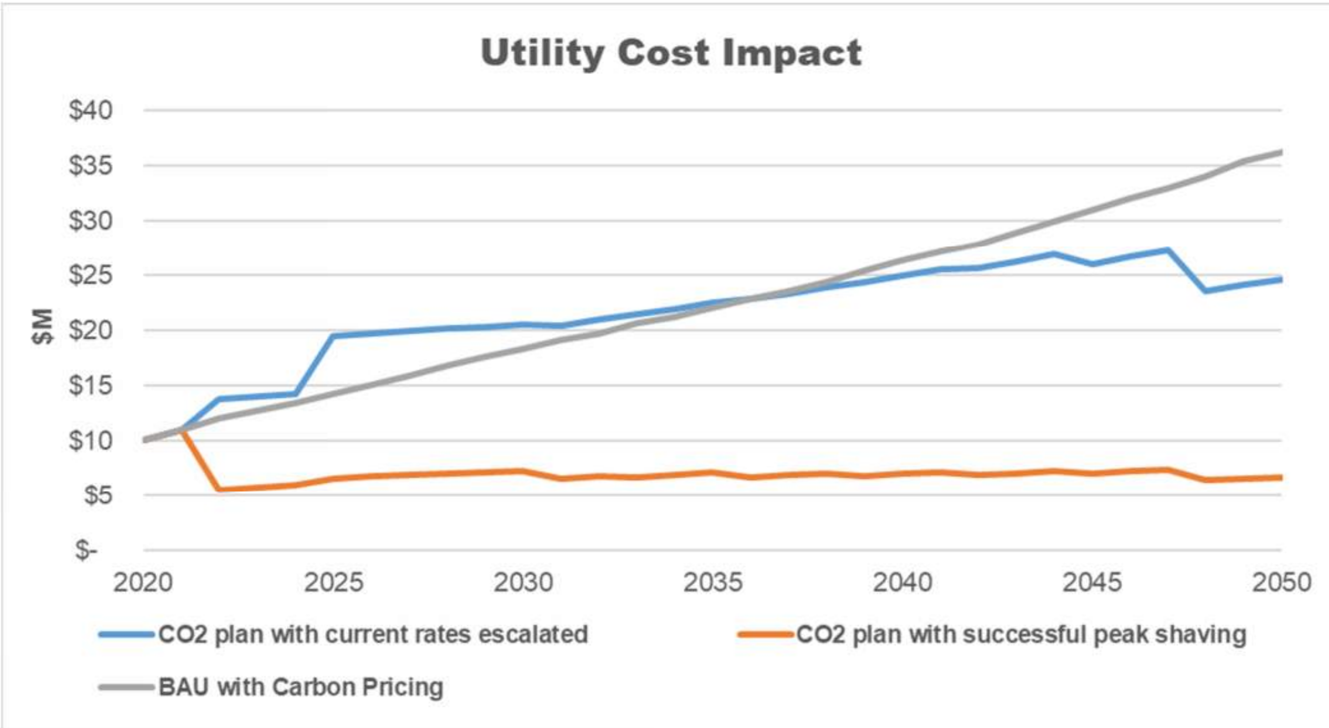


Figure 32: Utility Cost Scenarios

ALTERNATE AIR SOURCE HEAT PUMP TRANSITION

The curve below shows the alternate recommended path including energy conservation, cogeneration unit reduced operation, a 20,000 lb/hr electric boiler in combination with air source heat pumps. Under this scenario, the campus emissions are reduced by 89% by 2050.

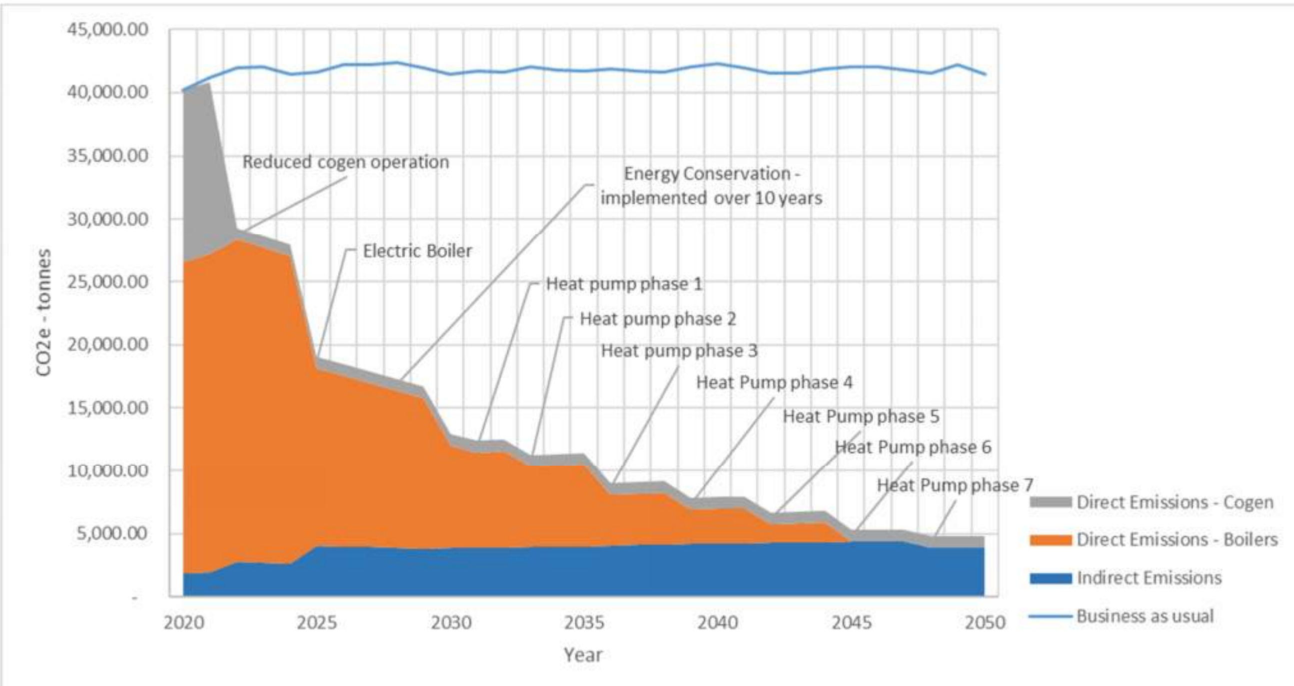


Figure 33: Alternate Carbon Reduction Pathway with Air Source Heat Pump – by Phase

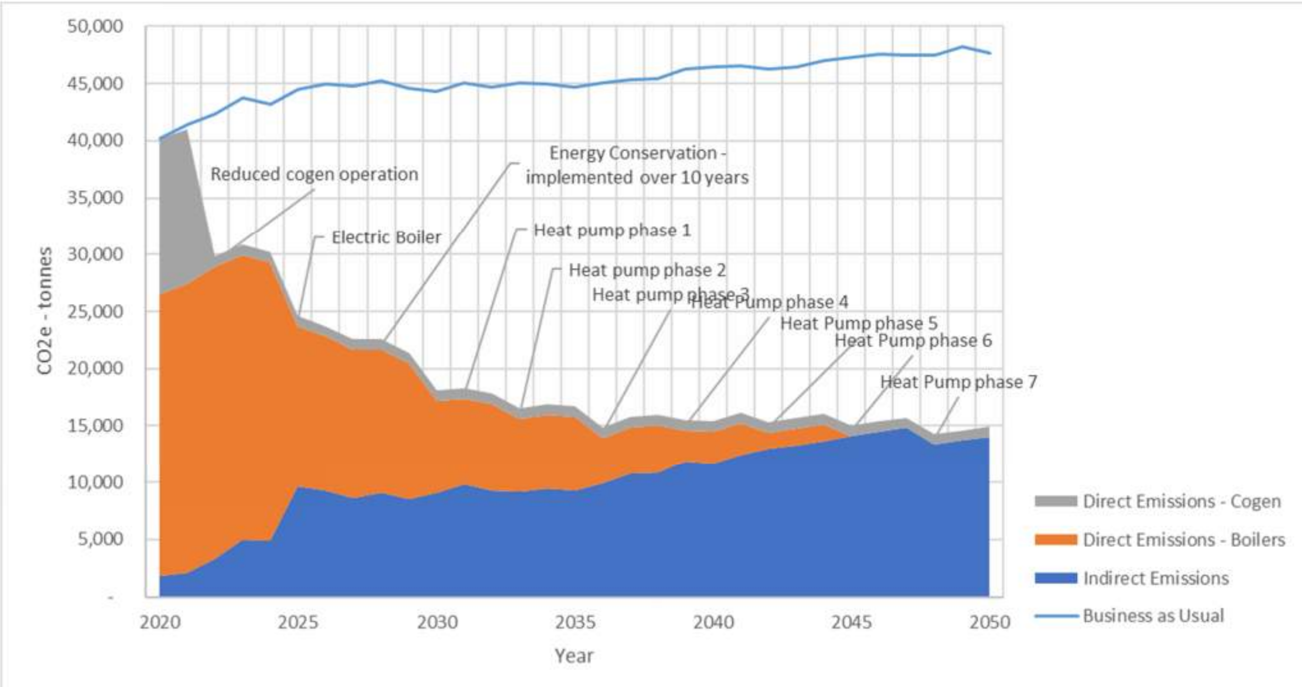


Figure 33A: Alternate Carbon Reduction Pathway with Air Source Heat Pump with Indirect Emissions Factor Growth

The figure below compares the air source and ground source heat pumps from the perspective of utility cost under both the current and HOEP only rates.

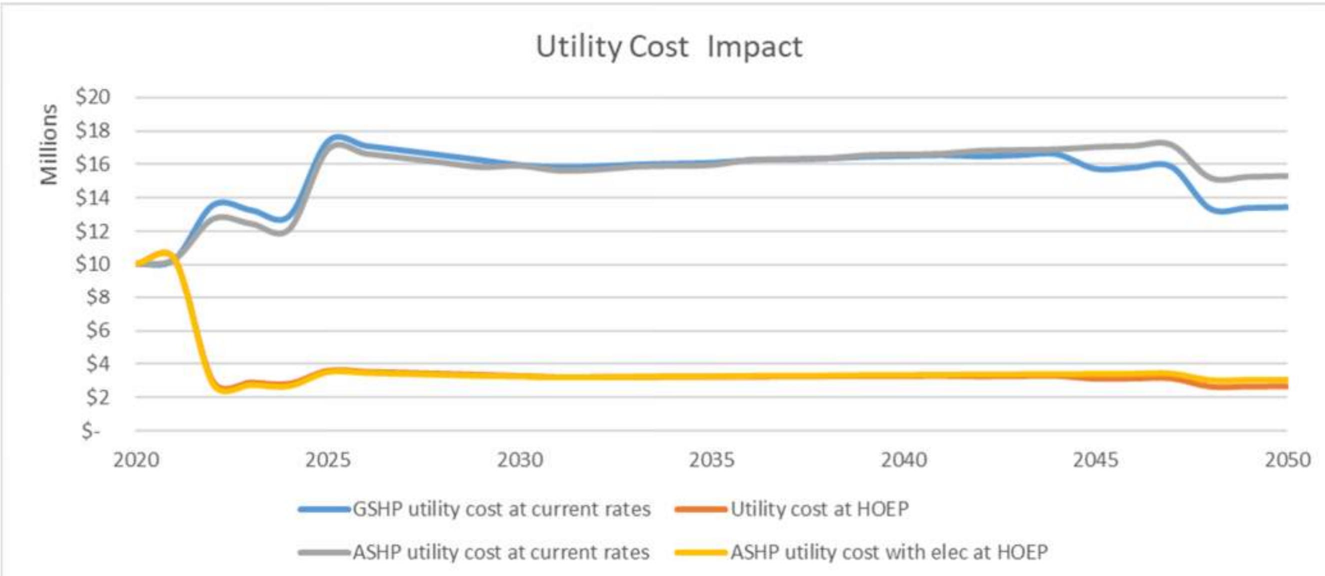


Figure 34: Estimated Utility Costs – Current and HOEP Only

The final solution for the campus may be a hybrid where several of the clusters are served by ground source heat pumps while others have air source heat pumps installed.

Carbon Reduction Roadmap – New Construction

A critical component of achieving a carbon neutral campus is the adoption of design and construction practices, which will allow the campus to continue to grow without increasing carbon emissions from the new construction projects.

Designing each new construction project to achieve net-zero carbon will allow the campus to reduce its carbon emissions while not limiting its growth potential.

The measures below represent a “recipe-book” of design elements, which are effective in achieving net-zero carbon for new construction project. Every building is unique and it is recommended that a professional design team evaluate which measures fit best and will compliment each other on a building specific basis.

NET ZERO STRATEGIES FOR NEW CONSTRUCTION

High Performance Building Envelope

Like most of the built environment in Canada, the buildings on campus have significant heating loads to be met through the winter and shoulder seasons, which is typically met with natural-gas burning equipment. Although there are ways to integrate efficient heating, ventilation and air-conditioning systems that are able to meet the heating load in an efficient manner, the ultimate solution to reducing the heating loads themselves is to increase the thermal performance of the building envelope. The best first step to reducing carbon emissions is to reduce the building loads as much as is feasible. A high-performance building envelope should include:

- Improved roof and wall thermal resistance – recommended roof insulation to RSI-8.8 (R-50) for all new construction – recommended wall insulation to RSI-4.4 (R-25) with all thermal bridging included in the effective performance
- Increased airtightness: design for an airtight building including reducing mechanical and electrical envelope penetrations, assigning an airtightness champion during construction who is responsible for maintaining the integrity of the air barrier on site. – recommended target tested air tightness of 1 litre/second per m^2 of exterior envelope area at 75Pa
- Reasonable window-to-wall ratio: aim for window-to-wall ratio not exceeding 40%. This value generally represents a balance between providing natural daylighting and thermal performance
- High-performance glazing systems: include low-e coatings, non-metal spacers and increased thermal breaks in window specifications to increase the thermal performance of the glazing system – Recommended fenestration overall thermal performance (including glass, edge of glass and frame) of 1.4 W/m^2K (0.25 $BTU/hr\text{-}ft^2\text{-}°F$) – this would typically require triple glazed windows or thermally excellent double glazing.

Green Roofs

Green roofs provide accessible green space for the building occupants. They also provide solar shading to the roof surface. This reduces building summer cooling load. Green roofs also reduce the heat island effect, which will help reduce the temperature around the buildings on campus.

Avoid Steam Network Expansion

As the steam plant is the primary source of carbon emissions and the district energy strategies for carbon reduction involve either electrifying or reducing the steam demand, it is recommended that new construction projects be designed without drawing from the steam network.

This can be accomplished by adopting a heat pump technology into the design and incorporating design measures like heat recovery and high performance envelopes so that the heat demand is optimally low and met by an electrified local source.

Heat Pump Integration

Heat pump technology has improved to the point where they can provide heating even during a Canadian winter, and as a result are becoming a widely adopted method of electrifying both the cooling and heating sources for a building. This makes them an attractive solution for a net-zero carbon design, allowing the only emissions attributable to the building to be indirect emissions from the grid if no gas-burning technologies are included in the building's systems.

It is recommended that primary heating for future buildings be delivered through either air source or ground source heat pumps systems including variable flow refrigerant systems.

Ventilation Energy Recovery

As discussed above, recovering heat from the exhaust air stream leaving the building and transferring it to the incoming outdoor air stream can be an effective way to reduce the large amount of energy required to condition incoming outdoor air.

It is recommended that for all new construction projects, ventilation air energy recovery is integrated into the mechanical system design. Consider systems that recovery both latent and sensible energy with high energy recovery effectiveness.

Demand Control Ventilation

As discussed above, demand control ventilation is an effective method of minimizing the amount of excess outdoor air that is brought into the building. This reduces the overall amount of energy required to ventilate the space by reducing the amount of outdoor air required and the associated heating, cooling and fan energy.

It is recommended all new construction projects integrate demand control ventilation systems to minimize the energy required to ventilate the facilities.

Return Air Scrubbers

Implementing technology capable of “scrubbing” the return air of carbon dioxide (CO_2) and other by-products allows outdoor air amounts to be reduced as the scrubbers increase the quality and usefulness of the returned air from occupant zones. These technologies are now officially recognized by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) as an acceptable method of reducing the required outdoor air amounts, resulting in energy savings, when properly integrated into the systems designs and passing an ASHRAE design review. This technology is recommended for all new construction projects where it will meet ASHRAE requirements.

BAS systems equipped with analytics and trending

Advances in software solutions available for building analytics have resulted in a growing market of companies providing solutions for monitoring a building’s operation in real time. These systems provide the operators with insight into the building’s performance through analysis and visualisations. Without building analytics, staff must review trends and energy consumption data manually, which can be labour intensive and not necessarily identify operational issues that lead to increased energy consumption and emissions.

Building analytics systems can:

- Save building operators time in evaluating the building’s energy performance by providing analysis and visualizations;
- Alert the staff to potential maintenance issues;
- Provide the operator opportunities for energy consumption and emissions reductions.

Photovoltaic (PV) Integration

During the design phase of new buildings, it is recommended that the design evaluate the integration of photovoltaic elements. Making designs “solar ready” involves ensuring the roofs are designed with the ballasting load for PV racking considered and ensuring electrical system designs allow room and capacity for PV array inverters.

Electric Vehicle (EV) Charging Stations

There are a small number of electric vehicle charging stations on campus. Increasing the amount of available stations and implementing EV specific parking spots will promote electric vehicle use by faculty and visitors. It also provides excellent visibility to McMaster’s dedication to sustainability. The dedicated electric vehicle parking spots should be placed in locations that will promote the use of electric vehicles. These can be located near important buildings and in high traffic areas around campus.

ENERGY PERFORMANCE TARGETS FOR NEW CONSTRUCTION

It is recommended that the University adopt energy performance targets for the new buildings being designed for the campus. The table below proposes energy use and greenhouse gas targets for various program elements of new construction. These targets are based in part on achieving Tier 3 level of the Toronto Green Standard.

Table 11: Energy Performance Targets

Program Element	Energy Use Intensity Target kWh/m²	GHG Intensity Target kg/m²
Classrooms	100	10
Labs	500	50
Office	100	8
Residential	100	10

Carbon Reduction Roadmap – Vehicle Fleet

Currently, the Special Constable's operate hybrid vehicles for their operations. The rest of McMaster's vehicle fleet uses a combination of gasoline and diesel powered vehicles. The total greenhouse gas emissions from the vehicles has been calculated based on gasoline and diesel invoices. The annual greenhouse gas emissions from vehicles is estimated to be 47. 7 tons CO_2e. Although emissions from fleet vehicles represents a small portion of the overall campus emissions, they can also be eliminated.

FLEET TRANSITION TO ELECTRIC VEHICLES

In order to eliminate the greenhouse gas emissions from the current vehicle fleet, the vehicles will need to be replaced with electric vehicles. There are currently eight (8) fully electric passenger vehicles available in Canada (not considered luxury models). These models can replace any of the passenger vehicles currently used by McMaster. There are also new vehicles coming to market as fully electric vehicles become more popular. At the moment, there are no fully electric vehicles to replace the pickup trucks, vans, or shuttle bus fleets. However, hybrid and fully electric pickup trucks and cargo vans will be commercially available in the near future. It is expected that a full variety of electric vehicles meeting all of the McMaster's fleet needs will be commercially available before 2050. Although the total greenhouse gas emissions from vehicles is relatively low, transitioning to a fully electric fleet is a highly visible solution that can be used to demonstrate McMaster's dedication to achieving a net-zero carbon campus.

Resolving Indirect Emissions

In order for McMaster to completely reach net-zero carbon emissions, there will be a need to offset the indirect emissions the campus is still responsible for from the electricity it consumes from the grid. This is after reducing to a minimum or eliminating direct carbon emissions produced on campus.

The main methods of offsetting indirect carbon emissions are:

- Produce and supply to the grid enough renewable energy to displace the amount consumed that came from emitting sources, on an annual basis;
- Purchase sufficient Carbon Offset Credits.

RENEWABLE ENERGY

Energy produced from a renewable source owned by the University which is then fed into the electricity grid for consumption by other grid participants can successfully offset the carbon emissions produced by the grid during production and supply of the electricity the University uses.

This approach actually turns the University campus itself into a node of renewable energy production that is progressing the Ontario grid as a whole towards lower carbon emissions. A good example of this would be installations of PV arrays in various places around the campus. The largest areas of available land on campus are the parking lots. Raised PV arrays can capture the sunlight while still allowing cars to park underneath. Ideal lots for these arrays are Lots I, M, and P as these are the largest on campus. Parking Lot I has the added advantage of being highly visible to faculty, students, and visitors – underlining McMaster’s commitment to being a net zero campus.

There are net metering programs in Ontario so institutions can generate their own electricity and use it to power their operations. In order to achieve this through covered parking, all of the available outdoor parking spaces will need to be covered with PV shades. The areas outlined below were used to calculate the area that will be covered by PV shading. That includes areas that may receive shade from trees or buildings. There may be an additional need for PV. A feasibility study was done for the possibility of a solar array to be placed atop the new multi-level parking lot in Lot K. While that study was specific for a solar array to be on the roof of a proposed parking garage, similar analysis could be done to determine the feasibility of installing solar array parking covers in the rest of the parking lots.

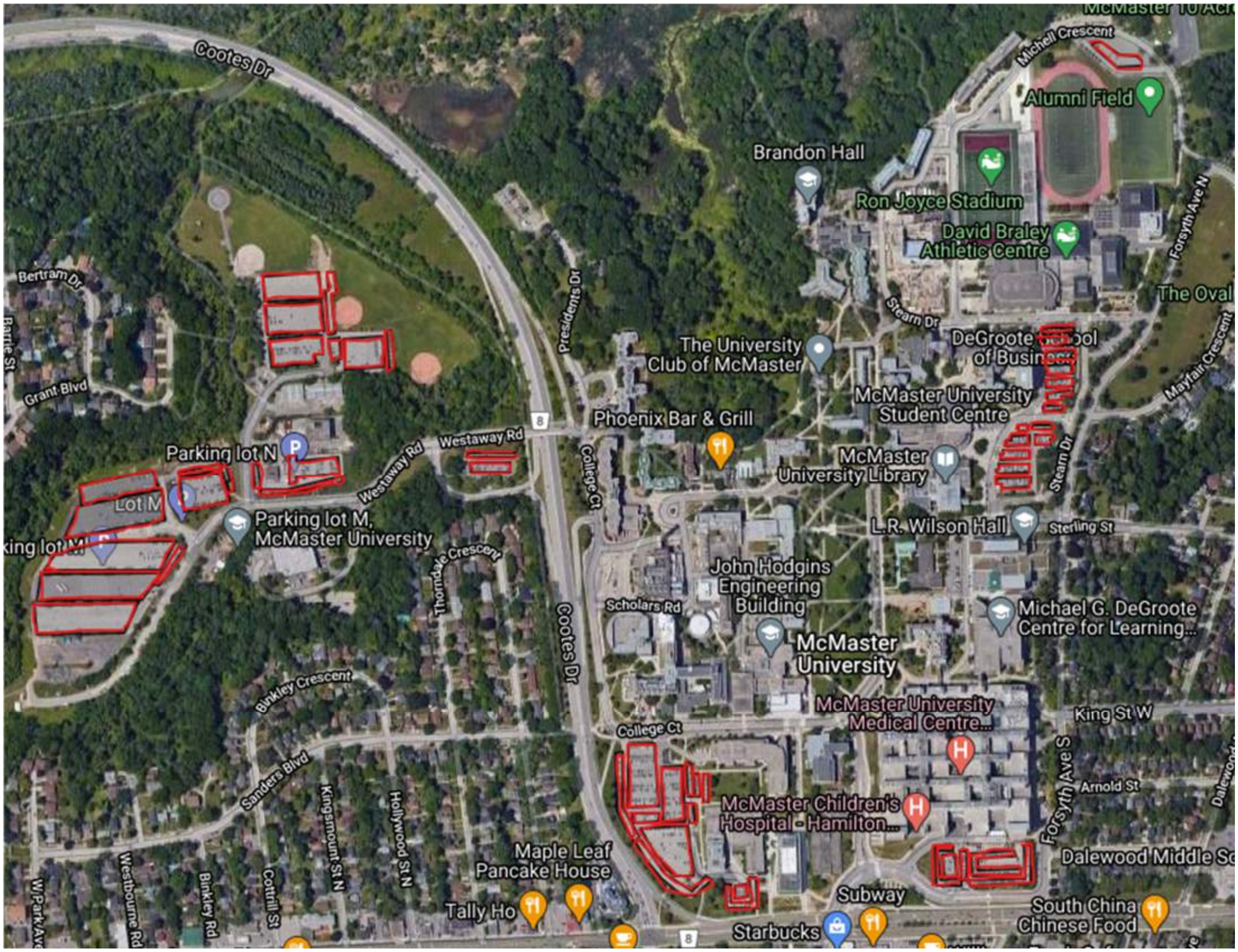


Figure 35: Potential PV Area

Using the Ontario grid emissions factor of 30g/kWh, the campus would need to generate 142,000 MWh/year to offset the remaining 4,300 tonnes of emissions after the full implementation of the carbon reduction plan. This would require a PV array of capacity 135 MW or PV panel area of approximately 750,000 m².

The CaGBC Zero Carbon Building (ZCB) Performance path recommends using the marginal emissions factor for the calculation of carbon offsets. The Ontario Marginal Emissions Factor per the Toronto Atmospheric Fund report “A Clearer View on Ontario’s Emissions” 2019 Edition is 134 g-CO2e/kWh. Using this factor, the campus would need to generate 32,000 MWh/year to offset 4,300 tonnes of residual emissions. This would require a PV array of capacity 30 MW of area approximately 170,000 m².

CARBON OFFSETS

An alternative to actually becoming a production node of renewable energy in order to offset indirect carbon emissions from the grid is to purchase carbon offsets from another party who has essentially turned themselves into a large node of renewable energy production. These companies sell portions of the carbon they have reduced by lowering the amount of energy the grid needs to supply to parties that would rather support the larger producers than produce renewable energy themselves.

In order for a Carbon Offset Credit to meet the requirements of the CaGBC's Zero Carbon Building Standard it must meet one of the following criteria:

- Certified by Green-e Climate or equivalent; or
- Derived from carbon offset projects certified under one of the following high-quality international programs:
  - Gold Standard
  - Verified Carbon Standard
  - The Climate Action Reserve
  - American Carbon Registry

Offsets may come from anywhere in the world and any project type that meets the requirements of the programs listed above.

Quotes for Carbon Offset Credits were obtained from Schneider Electric for two quantities of carbon using the product "Carbon Offsets – Green-e Climate -Ecomix", summarized in the table below:

Table 12: Estimated Cost of Carbon Offsets

Carbon Quantity (Tonnes CO_2e)	Product Price	Quantity Logic
4,000	$9,000	Offsets remaining Indirect Emissions after complete heat-pump + electric boiler transition
14,000	$31,000	Offsets direct and indirect emissions after energy conservation measures, electric boiler transition and reduced cogeneration operation.

These prices reflect current market conditions and the cost of purchasing enough of the Carbon Offset Credit product to offset a single instance of each quantity of carbon. Offset credits would need to continue to be purchased on an ongoing basis to continually offset the carbon produced on campus and future product prices are subject to market forces and are not able to be forecasted at this time.

Carbon Capture and Reuse

With 95% of the greenhouse gas emissions of the McMaster campus concentrated at a single point – the flue of the ET Clarke Centre -- Carbon capture would be an attractive solution to apply at the McMaster campus. In this way, the district energy system could continue to operate on natural gas fired boilers producing steam for the campus with the CO_2 being removed from the exhaust air stream.

Carbon capture projects typically pass the flue gas through a solvent to capture the CO_2. The Quest carbon capture project in Fort Saskatchewan uses an amine solution to capture the carbon dioxide from a flue stream. In that project, the CO_2 is sequestered back into and underground storage facility. A preferred solution for McMaster would be the reuse of the captured CO_2. Several industrial processes require CO_2 and could use the recovered gas as an input stream including the manufacture of cement. While there are industrial areas within Hamilton and significant cement making operations in Halton region, there is nothing immediately adjacent to the campus. An effective carbon capture and reuse program would require the transportation of an average of 100 tonnes per day of CO_2 to an offsite reuse facility. This would required either a significant trucking effort or the installation of a pipeline for CO_2 transportation.

While several pilot carbon capture plants have been developed, only a handful of full scale plants are operational with only one in Canada. It was our view that this is a technological solution to watch but that it was not sufficiently commercially mature to be recommended for the McMaster campus at this time.

Appendix A: Emissions Factors

Table A1: Emissions Factors

Global Warming Potential	CO_2e		CO_2		CH_4		N_2O	
			1		25		298	
Electricity	**30**	g/kWh	29	g/kWh	0.01	g/kWh	0.001	g/kWh
Natural Gas	**1,899**	g/m^3	1,888	g/m^3	0.037	g/m^3	0.035	g/m^3
Diesel Fuel	**2,690**	g/litre	2,681	g/litre	0.078	g/litre	0.022	g/litre
Gasoline	**2,315**	g/litre	2,307	g/litre	0.1	g/litre	0.02	g/litre

Source: National Inventory Report 1990 – 2018: Greenhouse Gas Sources and Sinks in Canada

Appendix B: Energy Modelling Input Summary

Table B1: Simulation Input Assumptions per Building Type – Loads and Opaque Envelope

Building Type	LPD (W/m^2)	Occupancy (m^2/person)	Equipment (W/m^2)	Exterior Wall	Roof
Residence	5.5	25	6	R-5	R-20
Classroom	15.5	7.5	14.5	R-10	R-12
Lab	16.5	20	15	R-10	R-12
Exhibition	17	10	12	R-10	R-12
Office	12	20	11.5	R-10	R-12
Dining	9.5	10	7.5	R-10	R-12
Gym	9	5	5	R-10	R-12
Library	12.5	20	18	R-10	R-12

Table B2: Simulation Input Assumptions per Building Type – Glazing, Ventilation and Schedule

Building Type	Glazing	OA Ventilation Rate (L/s/person)	Operation Schedule
Residence	U-0.5 | SHGC-0.7	14.5	NECB G
Classroom	U-0.5 | SHGC-0.42	5	NECB D
Lab	U-0.5 | SHGC-0.42	1~8 ACH	NECB D
Exhibition	U-0.5 | SHGC-0.42	10~12 ACH (Nuclear Research)	NECB D & ASHRAE Assembly
Office	U-0.5 | SHGC-0.42	7.5	NECB D
Dining	U-0.5 | SHGC-0.42	8.5	NECB D
Gym	U-0.5 | SHGC-0.42	6	NECB B
Library	U-0.5 | SHGC-0.42	11	NECB C

Appendix C: Energy Modelling Results

Table C1: Detailed Energy Modelling Results

Building	Total Energy (kWh)	Total Steam (kWh)	Total Electricity (kWh)	EUI (kWh/m²)	Total Carbon (kg CO_2)	GHGI (kg CO_2 /m²)
Michael G. DeGroote Centre for Learning and Discovery	12,854,636	7,330,696	5,523,941	514.7	1,482,869	59.4
Burke Science Building	12,422,690	7,663,559	4,759,131	807.8	1,520,191	98.8
John Hodgins Engineering Building	13,841,772	8,709,639	5,132,133	674.5	1,719,524	83.8
General Sciences Building	4,676,479	3,268,127	1,408,352	978.8	629,931	131.8
H. G. Thode Library of Science & Engineering	3,971,564	1,249,810	2,721,754	512.3	305,409	39.4
Mohawk/McMaster Institute for Applied Health Sciences	5,113,966	2,547,980	2,565,986	573.7	534,499	60.0
Alumni House	287,124	199,837	87,287	589.6	38,553	79.2
Greenhouse	502,460	352,869	149,591	715.8	67,942	96.8
David Braley Athletic Centre	7,163,352	4,140,264	3,023,088	554.5	834,643	64.6
Hedden Hall	3,552,054	2,800,359	751,696	426.6	526,322	63.2
Les Prince Hall	4,121,183	3,374,404	746,779	500.2	629,515	76.4
Mary E. Keyes Residence	9,202,251	7,436,429	1,765,822	817.8	1,390,857	123.6
McKay Hall	2,508,587	1,996,238	512,349	417.9	374,495	62.4
McMaster Museum of Art	1,984,125	719,995	1,264,130	429.5	166,964	36.1
Refectory	789,142	491,350	297,792	520.5	97,250	64.1
Tandem Accelerator Building	**2,255,723**	**1,284,071**	**971,652**	**797.9**	**259,865**	**91.9**
Engineering Technology Building	7,676,518	4,479,774	3,196,744	625.1	900,891	73.4
Chester New Hall	4,259,536	2,362,575	1,896,961	616.2	481,354	69.6
DeGroote School of Business	3,516,191	1,966,588	1,549,604	512.9	399,806	58.3
Kenneth Taylor Hall	5,542,609	2,907,971	2,634,638	552.7	601,331	60.0
University Hall	2,058,060	1,341,969	716,091	560.9	262,736	71.6

Building	Total Energy (kWh)	Total Steam (kWh)	Total Electricity (kWh)	EUI (kWh/m²)	Total Carbon (kg CO_2)	GHGI (kg CO_2 /m²)
Nuclear Research Building	3,221,259	1,926,213	1,295,046	641.7	385,016	76.7
Commons Building	2,669,004	1,433,982	1,235,022	572.9	294,633	63.2
Gilmour Hall	3,106,541	1,496,255	1,610,287	416.0	316,931	42.4
Ivor Wynne Centre	9,474,279	5,538,968	3,935,311	538.4	1,113,387	63.3
McMaster University Student Centre	5,675,800	2,712,645	2,963,155	458.2	575,877	46.5
Togo Salmon Hall	6,657,605	3,825,362	2,832,243	571.3	772,316	66.3
Life Sciences Building	7,393,738	4,888,815	2,504,924	843.2	954,084	108.8
Divinity College	1,826,564	1,200,624	625,941	608.4	234,628	78.2
Mills Memorial Library	6,846,019	1,384,354	5,461,665	456.4	410,588	27.4
Psychology Building	5,055,623	2,784,679	2,270,943	504.2	568,390	56.7
Bates Residence	6,062,190	4,419,746	1,642,444	448.6	844,159	62.5
Hamilton Hall	2,191,459	1,254,921	936,538	583.1	253,580	67.5
Matthews Hall	2,247,870	1,736,903	510,967	461.9	327,770	67.3
Whidden Hall	2,424,339	1,944,589	479,750	433.4	364,234	65.1
Building T-13	925,688	430,209	495,479	459.4	92,085	45.7
Security & Parking Services	1,047,046	288,573	758,473	226.7	74,359	16.1
Edwards Hall	**1,002,989**	**834,393**	**168,596**	**519.7**	**155,186**	**80.4**
Communications Research Laboratory	1,121,592	495,355	626,237	452.3	107,676	43.4
Wallingford Hall	1,067,523	967,815	99,707	581.8	177,169	96.5
Moulton Hall	2,152,521	1,671,220	481,301	447.8	315,069	65.5
Woodstock Hall	2,158,486	1,714,184	444,302	428.4	321,710	63.8
Alumni Memorial Hall	621,464	438,907	182,557	580.3	84,405	78.8

Building	Total Energy (kWh)	Total Steam (kWh)	Total Electricity (kWh)	EUI (kWh/m²)	Total Carbon (kg CO_2)	GHGI (kg CO_2 /m²)
Information Technology Building	4,904,661	2,482,393	2,422,268	475.7	518,445	50.3
Brandon Hall	4,177,525	3,344,624	832,901	453.8	626,699	68.1
L.R. Wilson Hall, Faculty of Social Sciences	6,904,450	3,749,240	3,155,211	486.4	768,156	54.1
Peter George Centre for Living and Learning	12,409,848	8,304,885	4,104,963	447.9	1,616,311	58.3
Applied Dynamics Laboratory	960,150	428,187	531,964	541.5	92,799	52.3
Arthur Bourns Building	14,309,137	9,446,825	4,862,313	784.9	1,844,257	101.2
McMaster Nuclear Reactor	642,371	440,296	202,075	389.8	85,231	51.7
Campus Service Building Shop	1,407,417	581,378	826,039	351.9	129,066	32.3
Campus Service Building	358,361	265,627	92,734	690.5	50,557	97.4
A.N. Bourns Extension	3,495,762	2,268,374	1,227,388	687.1	444,612	87.4
John Hodgins Extension	1,161,551	584,912	576,639	498.7	122,332	52.5
Ron Joyce Stadium	1,039,364	688,241	351,123	279.5	134,270	36.1
Michael G. DeGroote Centre for Learning and Discovery	12,854,636	7,330,696	5,523,941	514.7	1,482,869	59.4
Burke Science Building	12,422,690	7,663,559	4,759,131	807.8	1,520,191	98.8

Appendix D: Energy Conservation Measures Summary

Demand Control Ventilation

Demand control ventilation (DCV) is a ventilation air control strategy where the amount of outdoor air brought into a building is controlled by indirectly measuring the occupancy level of the space. Methods to control ventilation air based on occupancy include counting occupants (for example, using a turnstile) or by measuring the difference in carbon dioxide between the outdoor air and the space. Reducing the amount of outdoor air brought into a space results in heating, cooling, pumping and fan energy savings.

Retrofitting air handling systems to integrate demand control ventilation involves introducing:

- Variable Air Volume (VAV) terminal units installed for each zone;
- Variable Frequency Drives (VFDs) on air handler fan(s);
- Duct pressure sensor(s) providing feedback for fan speed control;
- Control sequences allowing the VAV units to provide feedback to dictate supply temperature;
- CO_2 sensing equipment.

Certain spaces within several of the University laboratory buildings have been retrofitted to include demand control ventilation by integration of pressure independent venturi valve VAV units and active air particle and contaminant monitoring. Used together, this is a very effective energy saving strategy for a laboratory spaces since these space types typically require very high exhaust and make-up air rates. Conditioning these high rates of make-up air is energy intensive. Introducing VAV and active contaminant monitoring can reduce 100% outdoor air change rates from very high prescriptive levels (10 to 20 air changes per hour) down to as low as four (4) air changes per hour, dramatically reducing energy consumption of the labs.

It is understood that demand control ventilation has been implemented in the physics wing of the Arthur Bourns Building, John Hodgins Engineering and the Michael Degroote Centre for Learning and Discovery and is planned for further integration throughout the campus. It is recommended that VAV and active contaminant monitoring be retrofitted in all existing laboratories and is a standard design requirement for all newly constructed laboratories moving forward, along with retrofitting and implanting in all other applicable spaces. The table below summarizes estimated energy savings from implementing demand control ventilation across the campus.

Energy and Heat Recovery

Energy or heat recovery is a process where energy or heat is transferred from the building’s exhaust air stream to the incoming outdoor air. Energy recovery includes the transfer of both heat and humidity while heat recovery transfers only heat. Energy and heat recovery systems work in all seasons, either pre-heating or pre-cooling outside air depending on the temperature differential between the outdoor and indoor space conditions.

In some locations on campus, the exhaust air and incoming outdoor air ductwork are physically close enough to each other, within mechanical spaces or on rooftops, that it is feasible to install energy or heat recovery equipment in the air streams to transfer heat from the exhaust air stream to the incoming outdoor air.

There are numerous energy and heat recovery systems available, including:

- Heat Recovery Ventilators (HRVs): transfers sensible energy only, can be stand-alone or integrated into air handling system;
- Enthalpy Recovery Ventilators (ERVs): transfers sensible and latent energy, can be stand-alone or integrated into air handling system;
- Dual-Core Energy Recovery: transfers sensible and latent energy, can be stand-alone or integrated into air handling system, high energy transfer effectiveness (+90%);
- Glycol Run-Around Loop: transfers sensible energy only, lower heat transfer effectiveness than other systems but useful when outdoor and exhaust airstreams are not immediately adjacent;
- Refrigerant or “heat pipe” Heat Recovery Coils in both air streams connected with piping.

Building that are suitable for adding energy or heat recovery include:

- All buildings where exhaust and outdoor air ducts are physically close enough that a heat recovery system can be installed with reasonable cost and complexity. During the decision making process for a specific building, the feasibility of energy or heat recovery should be analyzed including a simple payback analysis.
- Laboratories where, based on the =exhaust air stream contaminants present are allowed to have energy or heat recovery systems as per the local Authority Having Jurisdiction (AHJ).

Building Automation Optimization

Building automation systems represent opportunity for energy savings and carbon emissions reductions through:

- Refining current operational sequences;
- Optimize supply water and air temperature set points and flow to maintain space comfort based on space temperature sensor feedback;
- Incorporating advanced monitoring and analytics packages that can detect sequence inefficiencies and notify operators of calculated improvements or simply alter the operating sequences automatically;
- Calculate and visualize available energy savings using methods that would take operators much longer to perform;
- Monitor systems simultaneously allowing the operations team to have time for other activities beyond just monitoring systems.

Energy savings and emission reductions resulting from implementing an analytics package typically range from 5%-20% of heating, ventilation and air-conditioning (HVAC) energy. Each building has a unique combination of structure, mechanical systems, control systems, operator practices and sequences of operations currently in place. The available savings depend on how far current operation is from optimal operation. However, energy savings and emissions reductions of this magnitude from a measure that does not require any significant changes to the equipment itself is significant.

Below is a list of providers:

- Switch Analytics

- Coppertree Analytics
- Peak Power – Building Insights Platform
- BrainBox AI

Buildings that are suitable for implementing an analytics package include:

- Offices
- Residences
- Classrooms
- Athletics

Envelope Improvements

For most building types, the envelope has a large impact on cooling and heating loads and associated energy requirements. As with mechanical and electrical equipment, a building's envelope requires maintenance and eventually reaches the end of its useful life and requires replacement due to degradation or envelope failure.

Heating energy is McMaster's largest source of campus carbon emissions. Improving the envelopes of campus buildings will reduce overall heating energy demand in turn reducing carbon emissions. Building envelope improvements will generally also reduce cooling demand thereby reducing the indirect emissions associated with electricity consumption from the campus district energy cooling system.

Window, wall and roof upgrade and replacement project are costly compared to the energy cost savings realized and generally have a longer payback than mechanical or electrical system upgrades. These upgrades are typically only financially feasible at end of system life when system replacement is necessary to maintain building integrity. Building specific energy modelling should be used to optimize the energy performance of envelope upgrade projects.

Steam energy savings have been estimated for four envelope improvements:

- Air sealing: reduce infiltration by adding or replacing sealing;
- Window upgrades: replace windows with higher performance systems for improve thermal performance;
- Roof upgrades: increase thermal performance of roofs;
- Wall upgrades: increase thermal performance of walls;

Any building where envelope components have reached the end of service life are suitable to for envelope upgrade and replacement projects.

Unintentional air leakage in buildings affects durability, occupant comfort, indoor air quality and energy consumption. A 2015 study of Part 3 Building Air Tightness by RDH Building Science for the National Research Council of Canada found that 16% of office and 24% of multi-residential energy consumption directly results from air leakage. While many aspects of the building envelope air barrier are inaccessible without major envelope rehabilitation, door and window seals and mechanical penetrations can generally be replaced with minimal disruption. Door and window seals and mechanical penetrations, should be inspected regularly, replacing seals where required.

Air tightness testing is recommended in taller buildings that are experiencing problems that are likely to be caused by air leakage.

Advancing energy codes have resulted in significant improvements in window technology, with improvements in glass coatings, seals, and frames. Even replacing a decade-old double-glazed window with a new double-glazed window, will result in notable energy savings. Window replacement is unfortunately expensive and the energy savings will not rationalize replacement costs. Several buildings do have single glazed windows that are candidates for replacement. All windows should be inspected for signs of window failure yearly including frame damage, cracked panes, water damage, condensation between panes and drafts. Regular inspections and maintenance can help to increase service life and reduce energy consumption.

Roofs typically last 20 to 40 years. When roofing replacements are required, insulation should be part of the project. A building science consultant is recommended to confirm the condition of the existing insulation and air barrier and, in conjunction with energy modelling, determine the optimal upgrade.

Building walls often last the full service life of the building. If wall rehabilitation or replacement is required, similar to roofing projects, a building science consultant is recommended to confirm the condition of the existing insulation and air barrier and, in conjunction with energy modelling, determine the optimal upgrade.

Low Flow Plumbing Fixtures

Plumbing fixture flow rates control the rate at which domestic hot water is consumed in the building and represent the primary opportunity for reducing unnecessary domestic hot water consumption. Retrofit or replacement of fixtures to lower the maximum water flow rate delivered to the user reduces the amount of domestic hot water the fixture needs to provide to fulfill its purpose, which in McMaster’s case reduces steam and resultant natural gas consumption.

Lowering the overall flow rate of the fixture reduces hot water consumption when the fixture is providing any temperature of water besides completely cold and therefore is generally applicable to all faucets, showers and wash-up sinks or tubs.

The table below summarizes estimated steam energy reductions from converting existing faucets on campus to industry standard low flow fixtures, per building type.

Instantaneous Point-of-Use Electric Domestic Hot Water Heaters

An alternative to providing centralized domestic hot water generation with distribution and recirculation networks throughout a building is to instead provide localized instantaneous hot water generation units that provide on-demand hot water to the group of fixtures nearby. This eliminates the need for lengthy piping networks and the inevitable thermal losses of water travelling and standing in a piping network as well as the need for recirculation pumps

Introducing these systems within the campus would result in direct emissions reductions from eliminating the domestic hot water steam load in the buildings targeted, and potentially indirect emissions through eliminating the recirculation pumps.

The table below summarizes steam energy reductions estimated for each building type from installing instantaneous point-of-use domestic hot water heaters.

Steam Traps

It is understood there is a steam trap replacement and maintenance program that implements steam guard orifice traps which require very little maintenance over their life in order to maintain efficiency. It is unknown the extent of how many traps have been replaced but it is recommended this replacement program is continued along with trap monitoring and maintenance. This is an effective measure for minimizing carbon emissions because steam distribution losses due to traps out of maintenance and resulting in inefficient steam system operation can represent 10%-15% of the steam system load.

Schedule Optimization

Scheduling building operation is a challenge for any building operator even when they have full control over all systems within the portfolio. The McMaster’s organizational structure separates certain buildings into groups which are then billed by the University for utilities (electricity, chilled water, steam), adding another layer of complexity when attempting to optimize system scheduling campus wide.

Building operators typically will use occupant complaints and system alarms as indicators for when the system operations requires modifications. Owners and operators often use utility bills as longer-term building performance indicators. This approach leaves room for improvement that may not be visible when using only complaints, alarms and utility bills as feedback on system performance. Occupants will complain when they are hot or cold; however, conditioning unoccupied spaces will likely not trigger any occupant complaints and an evaluation of utility bills may not illustrate anything of concern, especially if the buildings have been operated this way for multiple cooling seasons. There may be more similar opportunities for “hidden” energy reductions requiring no physical system changes. Analytics providers or specialized consultants can provide services to review BAS trends and provide actionable recommendations on such opportunities for energy savings.

Quantification of cost savings and emissions reductions of this measure requires detailed analysis of operational sequences and trends available for each building individually therefore calculation was not possible within the bounds of this study, but it is realistic that carbon savings are possible.

All buildings with operational sequences and trend data available are suitable for further investigation.

LED Lighting & Occupancy Sensors

Lighting energy consumption can be significantly reduced with LED lighting retrofits and occupancy sensing lighting control.

Advancements in LED lighting technology and supply in the last few years has resulted in increased market penetration and availability of LED retrofits at price points which result in a favourable return on investment. A lighting designer should review the retrofit to confirm that the resulting light levels are aligned with the Illuminating Engineering Society recommendations and current Building Code requirements.

Occupancy based lighting control allows for further reduction of energy consumption. According to the Lawrence Berkeley National Laboratory, occupancy-based strategies can produce average lighting energy savings of 24%. Due to their relative simplicity and high energy-savings potential, coupled with energy code mandates, these sensors are a staple in new construction.

Occupancy and vacancy sensors both turn off or dim lighting after detecting when a space is unoccupied. Occupancy sensors also turn the lights on automatically when detecting occupancy, providing convenience and a potential security aid. Vacancy sensors or Manual-ON sensors are typically wall mount switches with integral sensors that require the occupant to turn the lights on. Partial-ON sensors are similar to Manual-ON sensors; however, upon motion detection they automatically set the lights to a designated level such as 50%, requiring the occupant to manually switch the lights to 100% on. Manual- and partial-ON sensors tend to save more energy because the occupant may want to leave the lights OFF or at a lower level. Generally, manual-ON sensors are well suited to smaller daylit spaces such as meeting rooms and classrooms and private offices. Partial-ON sensors are common in larger class rooms. Occupancy sensors (full-ON) are appropriate for washrooms, storage rooms and other common spaces where variable levels of light are not appropriate.

Energy savings and emissions reduction from LED retrofits are dependant on the number of bulbs or fixtures replaced and their operating schedules; however, lighting electricity consumption and demand savings are typically in the range of 40% to 75%. Install costs for LED bulbs have dropped often resulting in a one to two year simple payback for LED replacement projects with current pricing.

Occupancy sensing lighting control energy savings depend on the space type involved, but generally yield savings listed in Table 3 below.

Table D1: Occupancy Sensing Lighting Typical Energy Savings

Room Type	Occupancy Sensing Lighting Energy Savings
Breakroom	29%
Classroom	40%
Conference Room	45%
Corridor	30%
Office – Private	13%
Office – Open	10%
Restroom	30%
Storage Area	45%

Emissions reductions from LED lighting and occupancy control upgrades result from reducing the amount of electricity required for lighting thereby reducing the associated indirect emissions.

All buildings that have non-LED lighting and/or do not integrate occupancy controls are suitable for upgrading to LED based systems with occupancy controls.

Variable Frequency Drives – Pumps & Fans

The addition of a variable frequency drive (VFD) to the motor in a pump or fan allows for the motor speed to be controlled and held anywhere between 30% to 100% of full power. This allows equipment, which previously only ON/OFF control, to be turned up or down to suit the current operational requirements. Energy-wise, turning a motor down to a lower setting within its speed range allows for non-linear energy reductions because of the governing “fan laws’. As depicted in Equation 1 below, the energy-speed relationship of a fan or pump is cubic, therefore reducing motor speed by results in the cubic reduction in energy. For example; turning a motor's speed down 20% will result in an 80% reduction in energy consumption.

$$kW_1 = kW_2 \left(\frac{S_1}{S_2}\right)^3$$

Equation 1: Motor Power Law

It is understood that most of the newer major pumps and fans have VFDs, but some equipment are currently constant volume operating in an "ON/OFF" fashion without VFD control. This represents opportunity for energy savings through installation of VFDs and integration of variable flow operational sequences.

Calculating energy savings and emissions reduction potential from VFD integration involves holistically looking at the system the pump or fan serves to establish how far the motor may be turned down during times of low service demand and reviewing trends or applying reasonable assumptions for how long the motor will operate in different load conditions. Energy modelling is also well suited to evaluate savings. Often VFDs are part of a bigger system upgrade to a demand control based system where control devices are incorporated allowing water or air flow to each device the motor serves to be modulated to suit the actual space demands and result in a variable demand. Typical examples include:

Hydronic System

- Integrating direct digital control (DDC) valves at each terminal device and VFDs on the pumps serving the loop;
- The BAS modulates control valves to suit space demands and pump to suit combined flow demand of all terminal devices.

Air System

- Variable Air Volume (VAV) terminal devices incorporated in each space;
- VFD on fan and DDC devices on the cooling and heating services provided to the unit;
- The BAS modulates VAVs to suit space needs and fan VFD and cooling/heating to meet combined VAV air and temperature demand.

In addition to the electricity savings from operating motors at a lower speed, it is typical that heating and cooling energy consumption will also be reduced with a corresponding reduction in direct and indirect carbon emissions associated with reduced steam and chilled water use.

All buildings that have constant volume pumps and fans should be considered for VFD upgrades.

As the addition of a VFD to a fan or pump motor is not a measure on it's own, but an integral part of a larger mechanical system upgrade, estimates have not been developed explicitly for VFD upgrade but they are recommended to be retrofitted on all constant volume systems and specified for all future systems.

Building	Heating Energy	DHW Energy	Total Steam Energy Required	Heating Energy - Ventilation	Heating Energy - Non-Ventilation	Heat Recovery - Steam Energy Reduction	DCV - Steam Energy Reduction	BAS - Steam Energy Reduction	Air Sealing - Steam Energy Reduction	Windows Upgrade - Steam Energy Reduction	Roof to R35 htg savings - Steam Energy Reduction	Walls - Steam Energy Reduction	Low Flow Fixtures/Heat Pump DHW - Steam Energy Reduction	Instantaneous DHW - Steam Energy Reduction	Post Retrofit - Total Steam Energy Required	Post Retrofit - Total Steam Energy Reduction
Arthur Bourns Building	20,406,982	700,976	21,107,957	15,305,236	5,101,745		3,826,309	1,020,349	267,842	446,403	235,949	95,665		700,976	14,514,466	6,593,491
Mary E. Keyes Residence	7,360,143	76,286	7,436,429	3,312,065	4,048,079	1,821,635		368,007	212,524	354,207	130,493	132,632		76,286	4,340,645	3,095,784
Michael G. DeGroote Centre for Learning and Discovery	6,797,120	1,151,496	7,948,616	4,418,128	2,378,992			339,856	124,897	208,162	45,431		287,874		6,942,396	1,006,220
John Hodgins Engineering Building	5,974,157	1,407,891	7,382,048	3,883,202	2,090,955	2,135,761		298,708	109,775	182,959	58,530	77,382		1,407,891	3,111,042	4,271,006
Peter George Centre for Living and Learning	5,850,096	2,454,789	8,304,885	2,632,543	3,217,553			292,505	168,922	281,536	31,087	178,053			7,352,782	952,103
Burke Science Building	5,566,867	859,610	6,426,477	3,618,463	1,948,403	1,990,155		278,343	102,291	170,485	37,524	89,123		859,610	2,898,946	3,527,531
Ivor Wynne Centre	5,017,039	521,930	5,538,968	3,261,075	1,755,963	1,793,591		250,852	92,188	153,647	67,661	46,477		521,930	2,612,623	2,926,345
Life Sciences Building	4,525,374	601,618	5,126,992	2,941,493	1,583,881	1,617,821		226,269	83,154	138,590	17,910	85,043		601,618	2,356,589	2,770,404
A.N. Bourns Extension	4,383,035	164,517	4,547,552	3,287,276	1,095,759			219,152	57,527	95,879	21,851	49,374		164,517	3,939,253	608,300
Bates Residence	4,309,755	109,990	4,419,746	1,939,390	2,370,365	1,066,664		215,488	124,444	207,407	46,676	107,398	27,498		2,624,171	1,795,575
Engineering Technology Building	3,794,219	685,554	4,479,774	2,845,665	948,555		711,416	189,711	49,799	82,999	15,634	46,022		685,554	2,698,639	1,781,135
Nuclear Research Building	3,776,452	37,987	3,814,439	2,832,339	944,113		708,085	188,823	49,566	82,610	16,923	44,444		37,987	2,686,001	1,128,438
David Braley Athletic Centre	3,754,747	385,517	4,140,264	2,440,586	1,314,162			187,737	68,993		26,828	58,592		385,517	3,412,596	727,668
Les Prince Hall	3,337,159	37,244	3,374,404	1,501,722	1,835,438			166,858	96,360	160,601	34,663		9,311		2,906,610	467,794
Brandon Hall	3,272,826	71,798	3,344,624	1,472,771	1,800,054	810,024		163,641	94,503	157,505	34,274	82,730	17,950		1,983,998	1,360,626
Togo Salmon Hall	3,127,867	697,495	3,825,362	2,033,113	1,094,753	1,118,212		156,393	57,475	95,791	23,469	47,689		697,495	1,628,837	2,196,525
General Sciences Building	2,976,957	291,169	3,268,127	1,935,022	1,041,935	1,064,262		148,848	54,702	91,169	15,698	52,028		291,169	1,550,251	1,717,876
L.R. Wilson Hall, Faculty of Social Sciences	2,825,645	923,595	3,749,240	1,836,669	988,976	1,010,168		141,282	51,921	86,535	19,810	44,474	230,899		2,164,151	1,585,089
Hedden Hall	2,762,377	37,982	2,800,359	1,243,070	1,519,307	683,688		138,119	79,764	132,939	37,395	61,359	9,495		1,657,598	1,142,761
McMaster University Student Centre	2,575,804	136,841	2,712,645	1,674,272	901,531	920,850		128,790	47,330	78,884	29,774	28,826		136,841	1,341,350	1,371,295
Kenneth Taylor Hall	2,337,742	570,229	2,907,971	1,519,532	818,210	835,743		116,887	42,956	71,593	38,504	14,680		570,229	1,217,379	1,690,592
Mohawk/McMaster Institute for Applied Health Sciences	2,141,473	406,507	2,547,980	1,606,104	535,368		401,526	107,074	28,107	46,845	6,584	28,215		406,507	1,523,122	1,024,857
Psychology Building	2,096,682	687,997	2,784,679	1,362,843	733,839	749,564		104,834	38,527	64,211	12,369	35,331		687,997	1,091,847	1,692,832
McKay Hall	1,960,820	35,417	1,996,238	882,369	1,078,451	485,303		98,041	56,619	94,364	25,715	44,385		35,417	1,156,394	839,844
Whidden Hall	1,920,821	23,769	1,944,589	864,369	1,056,451	475,403		96,041	55,464	92,440	17,468	51,202	5,942		1,150,631	793,959
Chester New Hall	1,888,278	474,297	2,362,575	1,227,381	660,897	675,059		94,414	34,697	57,829	8,500	34,458		474,297	983,321	1,379,254
Information Technology Building	1,774,979	707,414	2,482,393	1,153,736	621,243	634,555		88,749	32,615	54,359	31,099	9,281		707,414	924,320	1,558,073
Matthews Hall	1,710,734	26,169	1,736,903	769,830	940,904	423,407		85,537	49,397	82,329	21,096	40,062	6,542		1,028,532	708,371
Woodstock Hall	1,679,849	34,335	1,714,184	755,932	923,917	415,763		83,992	48,506	80,843	18,525	41,529	8,584		1,016,442	697,742
Moulton Hall	1,645,459	25,760	1,671,220	822,730	822,730	452,501		82,273	43,193	71,989	23,378	30,100	6,440		961,346	709,874
DeGroote School of Business	1,557,197	409,391	1,966,588	1,012,178	545,019	556,698		77,860	28,613	47,689		4,274		409,391	842,062	1,124,525
Gilmour Hall	1,456,059	40,195	1,496,255	728,030	728,030	400,416		72,803	38,222	63,703	9,828	37,493		40,195	833,594	662,661
University Hall	1,322,219	9,875	1,332,094	661,110	661,110	363,610		66,111	34,708		10,971	32,001		9,875	814,818	517,276
Mills Memorial Library	1,306,791	77,563	1,384,354	849,414	457,377	467,178		65,340	24,012	40,020	5,815	23,914		77,563	680,511	703,842
Tandem Accelerator Building	1,262,681	21,390	1,284,071	947,011	315,670	520,856		63,134	16,573	27,621	7,642	12,877		21,390	613,979	670,092
H. G. Thode Library of Science & Engineering	1,209,726	40,083	1,249,810	786,322	423,404	432,477		60,486	22,229	37,048	6,256	21,265		40,083	629,965	619,845
Commons Building	1,208,982	225,000	1,433,982	785,838	423,144	432,211		60,449	22,215	37,025	11,530	15,975	56,250		798,327	635,655

Divinity College	1,024,944	175,680	1,200,624	666,213	358,730	366,417		51,247	18,833	31,389	2,624	20,693		175,680	533,739	666,884
Hamilton Hall	997,093	257,828	1,254,921	648,111	348,983	356,461		49,855	18,322	30,536	8,548	14,136		257,828	519,236	735,685
Wallingford Hall	950,326	17,490	967,815	427,647	522,679	235,206		47,516	27,441	45,734	14,719	19,255	4,372		573,572	394,244
Edwards Hall	819,185	15,208	834,393	368,633	450,552	202,748		40,959	23,654	39,423	12,033	17,253	3,802		494,521	339,873
McMaster Museum of Art	690,866	29,129	719,995	276,346	414,520	151,991		34,543	21,762					29,129	482,570	237,425
Campus Service Building Shop	570,939	10,440	581,378	371,110	199,829	204,111		28,547	10,491	17,485	5,727	7,262		10,440	297,316	284,062
Ron Joyce Stadium	488,241	200,000	688,241	317,357	170,884	174,546		24,412	8,971		3,753	7,354		200,000	269,204	419,037
McMaster Nuclear Reactor	440,296	-	440,296	330,222	110,074			22,015	5,779		5,643	1,511		-	405,347	34,948
Alumni Memorial Hall	433,635	5,272	438,907	281,863	151,772	155,024		21,682	7,968	13,280	5,385	4,480		5,272	225,815	213,091
John Hodgins Extension	432,453	152,459	584,912	281,094	151,359			21,623	7,946	13,244	3,235	6,603		152,459	379,802	205,110
Applied Dynamics Laboratory	419,244	8,943	428,187	314,433	104,811		78,608	20,962	5,503	9,171	4,757	2,056		8,943	298,187	129,999
Building T-13	369,223	60,986	430,209	276,917	92,306			18,461	4,846					60,986	345,915	84,293
Communications Research Laboratory	356,903	138,452	495,355	267,677	89,226		66,919	17,845	4,684		1,647	4,153		138,452	261,654	233,701
Greenhouse	352,869	-	352,869	70,574	282,295			17,643	14,820					-	320,405	32,464
Refectory	341,350	150,000	491,350	221,878	119,473	122,033		17,068	6,272	10,454	2,087	5,679		150,000	177,758	313,592
Security & Parking Services	272,000	16,573	288,573	136,000	136,000			13,600	7,140	11,900	2,802	6,038		16,573	230,520	58,053
Campus Service Building	262,833	2,794	265,627	131,417	131,417	72,279		13,142	6,899	11,499	6,633	1,909		2,794	150,472	115,155
Alumni House	197,216	2,622	199,837	98,608	98,608			9,861	5,177		1,648			2,622	180,530	19,307