CHARACTERIZATION OF SPACE HEATING BOILER OPERATION IN POST-WAR MULTI-UNIT RESIDENTIAL BUILDINGS

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ABSTRACT

In Ontario, residential building operation produces a significant portion of the province's greenhouse gas (GHG) emissions. In the Greater Toronto Area (GTA), a significant portion of all multi-unit residential buildings (MURBs) were constructed in the post-war period during the 1960s and 1970s. Typically, heating loads in these buildings represent approximately half of total building energy consumption, so reducing space heating energy use in this building typology can greatly contribute to GHG emissions reduction. Literature suggests that oversized boiler equipment can reduce the operational efficiency of the heating plant leading to greater than necessary energy consumption. There is no current inventory of installed system capacity in Ontario's post-war MURBs nor information on the operational characteristics of these systems. This information is key to understanding when heating plant retrofits should occur, predicting the true energy reduction from envelope retrofits, and how new heating systems should be designed. Field data was collected from two post-war MURBs with hot water boiler systems. Building 1 has a modular boiler arrangement with 10 space heating boilers whereas Building 2 has a typical four-boiler system. Building 1 exhibited longer average boiler cycle times, with a minimum monthly average cycle time of 123 and a maximum of 285 minutes. In Building 2, the monthly average cycle time ranged between 12 and 34 minutes. An analysis of space heating demands in Building 1, based on the temperature difference between the supply and return for the building supply loop, showed a decrease in system efficiency for low loads. The preliminary analysis suggests that modular boiler systems may offer performance improvements over traditional boiler configurations in MURBs. The analysis also indicates that installed boiler capacity, in relation to the heating demand of the building, affects heat plant performance. Envelope retrofits that reduce space heating demands are likely to reduce building heat plant efficiencies as equipment will spend more time operating in lower load scenarios.

INTRODUCTION

In Ontario, building operation produces approximately 24% of the province's GHG emissions, with over half of this produced by residential buildings in the province (Ontario Ministry of Environment and Climate Change, 2015). A key component of Ontario's Climate Change Strategy is to reduce GHG emissions from both new and existing buildings through energy conservation strategies and the increased use of renewable fuels (Ontario Ministry of Environment and Climate Change, 2015).

In the Greater Toronto Area (GTA), the largest urban region in the province, 38% of all residential

dwellings are in multi-unit residential buildings (MURBs) (Statistics Canada, 2012). In the 1960s and 1970s, the GTHA experienced a boom in MURB construction. In 2009, it was estimated that almost 50% of all Toronto MURBs were constructed during these two decades (Kesik and Saleff, 2009). Space heating energy use in these buildings typically represents over half of a building's total energy use. Given the sheer number and energy intensity of these buildings, understanding where opportunities lie to improve energy efficiency through retrofitting and operational changes is key to reducing GHG emissions in Ontario. Additionally, MURBs constructed in the 1960s and 1970s are frequently undergoing renewal and retrofit projects due to their aging infrastructure. Understanding how changes in building heating demand due to envelope improvements impact heat plant operation is important to ensure retrofit strategies are designed to truly minimize energy use.

MURB heating system design in industry traditionally has been geared towards providing sufficient system capacity for worst-case heating loads. Previous studies by Cholewa et. al (2011), Butcher (2007) and Underwood (1992) have indicated that central boiler systems in MURBs may operate at lower system efficiencies for loads below the system capacity. Industry professionals are beginning to advocate for more conservative system sizing and part-load design considerations, however, a lack of regulation of installed system efficiency, the designer's professional liability for under-capacity systems, and the division of design and operational costs between different stakeholders has meant that system oversizing is still prevalent. Furthermore, given the long service life and high capital cost of central heating systems, older MURBs often still have the originally installed central heating plant.

There is no current inventory of installed system capacity in Ontario's post-war MURBs nor information on the operational characteristics of these systems. This information is essential to understanding where central heating plant retrofits may be economical as well as to understanding the true energy savings potential of proposed building envelope retrofits. Retrofit strategies that greatly reduce building heating loads may result in or increase equipment oversizing in building heat plants and reduce equipment efficiency. As a result, envelope retrofits may realize significantly lower reductions in natural gas demand than anticipated from the building heating demand reductions. Envelope retrofits should be coupled with heating plant retrofits or operational changes to maximize reductions in building energy use.

Understanding the performance characteristics of heating plants in existing MURBs is also important in informing heating plant design in new construction. Traditional configurations of two to four single stage atmospheric boilers, with a capacity far beyond typical building demand, are still installed to provide space heating in many newly constructed buildings. In Ontario, the Building Code includes requirements for the efficiency of individual boiler units, however, no requirements are included with respect to the realized installed system efficiency. As the sizing of heating plant systems has been shown to affect the realized system efficiency in other building types, understanding how system sizing and configuration affects efficiency in the MURB sector is essential to informing future code provisions which will reduce building energy use.

This paper characterizes the performance of the heating plants in two MURBs in the Greater Golden Horseshoe Area (GGHA) using data collected from their building automation systems (BAS). Natural gas consumption, runtime and cycle length profiles are developed for each of the buildings. A preliminary assessment of changes in boiler system efficiency for different building space heating demands is also performed. This characterization is intended to showcase the differences in the operational characteristics

of more modular boiler systems and traditional two to four boiler space heating systems.

BACKGROUND

While some research has been done to characterize suite-level energy consumption in MURBs in Toronto, there has been limited characterization of the operation of installed heating plants in existing building stock. Previous studies have characterized performance of heating plants in relatively small MURBs in other geographical areas. In a 1993 field study, Landrey et. al (1993) found the in-situ efficiency of a hot water boiler in a 17-unit MURB to be significantly lower than the stack efficiency of the boiler (66% versus 81.5%). Cholewa et. al (2011) found the input-output efficiency of a centralized space heating and domestic hot water (DHW) system for a four-storey building in Poland was lower when the system was only used for DHW production, with an annual efficiency of 56.9%. A laboratory study of boiler operation under various loading conditions found that oversizing of atmospheric boilers reduced efficiency – an oversizing factor of three reduced efficiency by approximately 10% (Butcher, 2007). Underwood (1992) reported lowered condensing boiler efficiency at low and high demands in a United Kingdom 30-unit residential complex. The lowered efficiency for high demands was attributed to the need for the lag boiler to supply heat in high load conditions.

Outside of the MURB sector, Orr et al. (2009) reported that the efficiency of condensing boilers was independent of the load factor for factors greater than 5% in single family residential buildings, which is different from the results of the other studies outlined above

Studies in commercial and institutional buildings have generally demonstrated that many buildings have boilers with capacities greater than the peak demand and that a decrease in boiler efficiency tends to occur as load decreases. An assessment of condensing boiler performance in a 31-storey federal office building in Georgia reported a 93% input-output (IO) efficiency at full load for a boiler sized closely to peak building demand (Parker and Blanchard, 2012). The report mentioned that cycling affected boiler efficiency but did not quantify this effect. Gestwick et al. (2014) measured IO efficiency for heating plants with condensing boilers in a school and a university building in Alberta. The school building had low variation in efficiency with load, while the university building IO efficiency increased with load. In a 2012 study, Lazzarin reported a decrease in IO efficiency during the summer months for a 105kW (358,275 BTU/hr) condensing boiler with variable water flow (Lazzarin, 2012). Similarly, a simulation study by Riise and Sorensenn (2013) demonstrated a decrease in heat plant efficiency for oversized oil and electric boilers. A 2014 assessment of field measurements in 12 retails stores showed heat equipment oversizing between 166% and 631% and estimated an associated energy penalty of 25 - 1375 kW (85,300 – 4,691,695 BTU/hr) for heating equipment during low load periods (Woradechjumroen et al., 2014).

Generally, previous studies have found that heating plants using hot water boilers tend to experience lower efficiencies when loads are significantly below capacity. In addition to reduced system efficiency, short runtimes and the associated frequent cycling of heat plant equipment may reduce equipment lifespan and increase maintenance requirements.

The study characterizes the performance of two hot water space heating boiler systems in the Greater Golden Horseshoe Area (GGHA). The buildings analyzed in this study are larger than those examined in previous studies of multi-unit residential buildings and provide an opportunity to understand heating plant

performance characteristics specific to the GGHA. Improving heating plant operation in MURBs in this area may provide opportunities for significant reductions in building energy use and associated GHG emissions.

This study can also be viewed as a pilot of a methodology using readily available BAS data to characterize heat plant performance. BAS data can provide an affordable option for the assessment of heating system performance in MURBs as it does not require substantial financial investment for additional equipment.

BUILDING TYPOLOGIES AND MONITORING SET-UP

Building 1

Building 1 is a multi-unit residential building in the GGHA. It is comprised of 94 suites on 12 floors with a gross floor area of approximately 7,800 m^2. The exact age of construction is unknown, however it was likely built in the 1970s. No suite-level heating control is available to building residents.

Building 1 uses a hyper-modular boiler configuration in its heating plant. Thirteen, single stage atmospheric boiler modules provide hot water for space heating and domestic hot water. The boilers have a rated input of 300,000 BTU/hr (88 kW) per module and a nameplate efficiency of 80%. Ten of the 13 are used for space heating. The remaining three boilers are used for domestic hot water production. The space heating boilers are sequenced in a rotating pattern to maintain the primary loop setpoint at the maximum of the building hot water supply setpoint plus 2°C or 58°C (136.4°F). A Proportional-Integral-Derivative (PID) controller is used to maintain the primary loop setpoint. The temperature of the building loop is controlled through the use of a three-way valve which is modulated to maintain the supply at the temperature setpoint. Single speed pumps are used for the primary loop circulation and the building supply loop circulation. While Building 1 does have a make-up air unit, the make-up air is unheated.

Natural gas consumption was recorded hourly to the 10th of a cubic foot between late June 2016 and March 2017. Natural gas measurements were taken through the gas provider's revenue meter which can be assumed to be accurate to at least 1% due to strict revenue meter requirements. Outdoor air temperature (OAT) at the site was recorded at five minute intervals to 0.1 ± 0.2℃. Sensor accuracy at temperatures below 0 ° C is reduced, with a maximum error of ±0.6 ° C at -50 ° C. Hot water supply and return temperatures were recorded to 0.1 ± 0.2℃ at five minute intervals between December 2016 and March 2017. Boiler status was recorded as a binary state change (on/off) between June 2016 and March 2017. Flow rates were not measured. As a result, demand and system efficiency cannot be determined for the building as an actual building demand cannot be calculated without flow rate measurements. However, relative space heating demands can be compared using the temperatures of supply and return water as the installed building pumps do not have variable outputs.

Building 2

Building 2 is a mid-rise multi-unit residential building in the Greater Toronto Area (GTA). It has 92 suites on seven floors and was constructed in 1966. The boiler plant in this building provides domestic hot water

and hot water for space heating to the seven-storey tower as well as one row of townhouses, which are heated using two separate hot water supply loops. Similar to Building 1, the suites in Building 2 do not have individual heating controls. The building temperature is entirely controlled by the heating plant operation.

Domestic hot water is supplied by two single stage atmospheric natural gas boilers with an input of 631,000 BTU/hr (185 kW) per boiler. Due to the age of the boilers, specification sheets were not available to determine the nameplate efficiency but is expected to be around 75%.

Space heating in the building is supplied by four two-stage boilers. Two forced convection boilers are designated as the primary boilers, which are first to be signaled on when a call for heat occurs. Of the two primary boilers, the boiler with the lowest runtime in the previous week is designated as the lead boiler (i.e. the first of the two boilers to be activated when a call for heat occurs) for the following week. The boilers have an input capacity of 750,000 BTUs/hr (220 kW) each and a rated efficiency of 85%. Two atmospheric boilers with a capacity of 2,000,000 BTU/hr (586 kW) act as the secondary boilers and supply required heat beyond the capacity of the two primary boilers. Due to the age of these boilers, the nameplate efficiency was not available but is expected to be around 75%. Boilers are sequenced to maintain the primary hot water loop at the maximum of the building hot water loops setpoints plus 5˚C. A PID controller is used to maintain the primary loop setpoint. A three-way valve is used to maintain the setpoints of the two building hot water loops supplies.

In addition to supplying the suite-level radiators, the space heating boilers supply hot water to a make-up air unit. The make-up air unit is designed to be operational at all times and uses heated water to preheat the inlet air when outside air temperatures are below 14˚C (57˚F).

Natural gas consumption was recorded hourly to the 10th of a cubic foot between May 2016 and May 2017. Natural gas measurements were taken through the gas provider's revenue meter which can be assumed to be accurate to 1%. Daily total runtime in seconds was recorded for each boiler from December 2015 to May 2017. Hot water supply and return temperatures were measured to 0.1˚± 0.2 C and recorded for a one month period between April and May. Boiler status (on/off) was recorded between mid-December 2016 and April 2017, with the exception of one primary space heating boiler. The status for this primary space heating boiler was only recorded for April 2017 as it was operating as the lead boiler during April and high cycle rates during this period meant that data storage capacities were quickly filled. Average performance characteristics for this boiler were assumed to be similar to the other primary boiler as they alternate as the lead boiler based on total runtime.

Outdoor air temperature was not recorded for the site for the entire monitoring period. Air temperatures from a nearby weather station have been used to estimate the air temperatures at the site.

BUILDING OPERATIONAL PROFILES

Daily and annual natural gas consumption and boiler operational profiles were developed for each of the two buildings based on the collected data. Natural gas data represents the total of the natural gas usage for both space heating and domestic hot water. Summer profiles represent domestic hot water use only as space heating is not required in the summer months.

Profiles of the average Operating Boiler Utilization (OBU), Total Capacity Utilization (TCU), and cycle length were also developed for each building.

In the context of this paper, average Operating Boiler Utilization (OBU) is defined in Equation 1.

$$OBU = \frac{\sum_{i=1}^{n} RT_{i,j}}{nt_j} \quad (1)$$

where $RT_{i,j}$ is the runtime for boiler i during interval j, n is the number of boilers with non-zero runtime in interval j, and t_j is the time duration of interval j. Average OBU is used to exclude boilers when they are not signaled on during an hourly or daily period, given that these boilers would not contribute as significantly to an energy penalty associated with oversizing or cycling. However, boilers not signaled on during an hourly period can still reduce overall system efficiency through losses at the end of operation in a previous period.

Total Capacity Utilization (TCU) is defined in Equation 2.

$$TCU = \frac{\sum_{i=1}^{m} RT_{i,j}}{mt_j} \quad (2)$$

where m is the number of boilers installed.

Building 1

Figure 1 shows the average hourly percentage of daily consumption of natural gas in the building over a

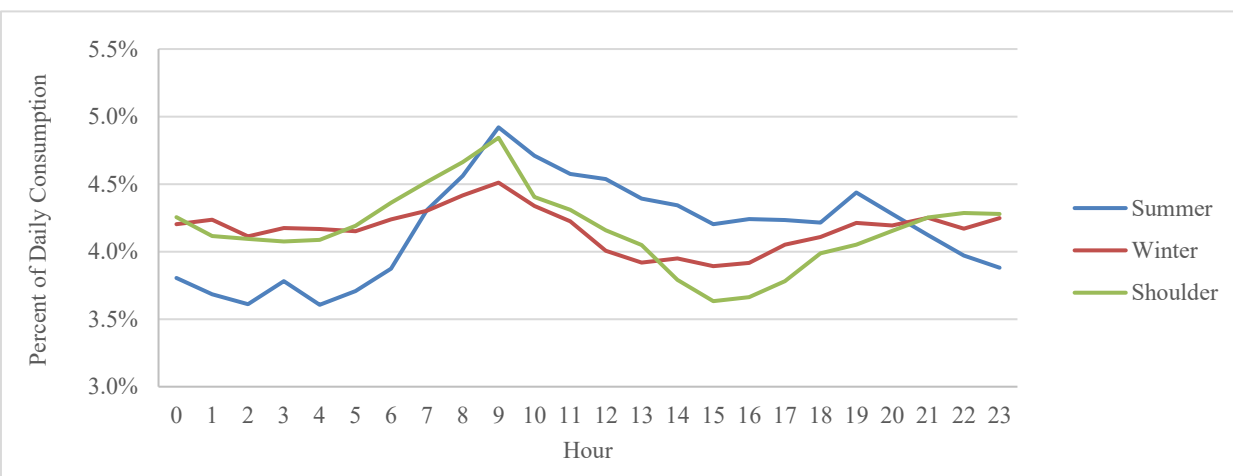

Figure 1: Building 1 percentage of daily natural gas consumption (space heating and domestic hot water) by hour for summer, winter and shoulder seasons.

24-hour period for the summer (June – August), winter (December – February) and shoulder seasons. Summer and winter percent consumptions had similar standard deviations which ranged between 0.4% and 0.8% depending on the hourly period, while shoulder season percent consumptions were more varied, with a standard deviation between 0.6% and 1.2% for each hourly period. In all seasons, natural gas consumption peaked at 9:00am likely due to the increased domestic hot water consumption immediately before this time period. Summer natural gas consumption, which represents only domestic hot water use, tends to be lowest between midnight and 5:00am. In the winter and shoulder seasons, natural gas consumption tends to be lowest between noon and 5:00pm, which may result from warmer afternoon temperatures or solar gains reducing space heating needs.

During the monitoring period, average daily natural gas consumption for the building ranged from 75 m^3/day (2648 ft^3/day) to 824 m^3/day (29,099 ft^3/day) and was well correlated with outdoor air temperature (OAT) at the site ($R^2 = 0.9$). Daily average consumption and standard deviation for natural gas is shown by month in Table 1.

Table 1: Daily average natural gas consumption and standard deviation (space heating and domestic hot water) for Building 1 by month.

Month *	**1**	**2**	**3**	**7**	**8**	**9**	**10**	**11**	**12**
Daily Average Consumption (m^3)	760 ± 174	620 ± 188	824 ± 246	82 ± 4	75 ± 7	94 ± 27	242 ± 140	407 ± 149	710 ± 139
Daily Average OAT (℃)	0.6	4.6	-0.1	23.8	24.2	16.9	13.6	8.9	0.8

*** Months of April – June missing due to lack of data.**

Total runtime as well as average hourly period OBU of the ten space heating boilers during months of December, January, February and March is shown in Table 2. Space heating boiler runtime and OBU fluctuated with the average monthly outdoor air temperature. The maximum TCU for space heating was 74% over the monitoring period. In some periods, OBU was 100% meaning that all boilers operating during the hourly period were on continuously for the entire hour.

Table 2: Building 1 average space heating boiler runtimes and utilization.

Month	**Average OAT (˚C)**	**Average Daily Space Heating Boiler Runtime (hr) ***	**Average Space Heating OBU**	**Average Space Heating TCU**
12	0.8	93 ± 24	72%	39%
1	0.6	96 ± 32	71%	40%
2	4.6	72 ± 32	54%	30%
3	-0.1	108 ± 42	78%	45%

*** Average daily space heating boiler runtime is the combined runtime for all 10 space heating boilers.**

Building 1 average cycle times for the hyper-modular space heating boilers are shown in Figure 2. In Building 1, the space heating boilers had average cycle lengths ranging from 123 minutes (approximately 2 hours) in the shoulder season to 285 minutes (just under 5 hours) in the winter months. Of course, cycle length was highly variable likely due to changing weather conditions and if the boiler was currently classified as a lead or lag boiler. The time the boiler was on per cycle was lower during the shoulder seasons, whereas during the winter season, the boilers tended to be on for approximately half of the total

cycle length.

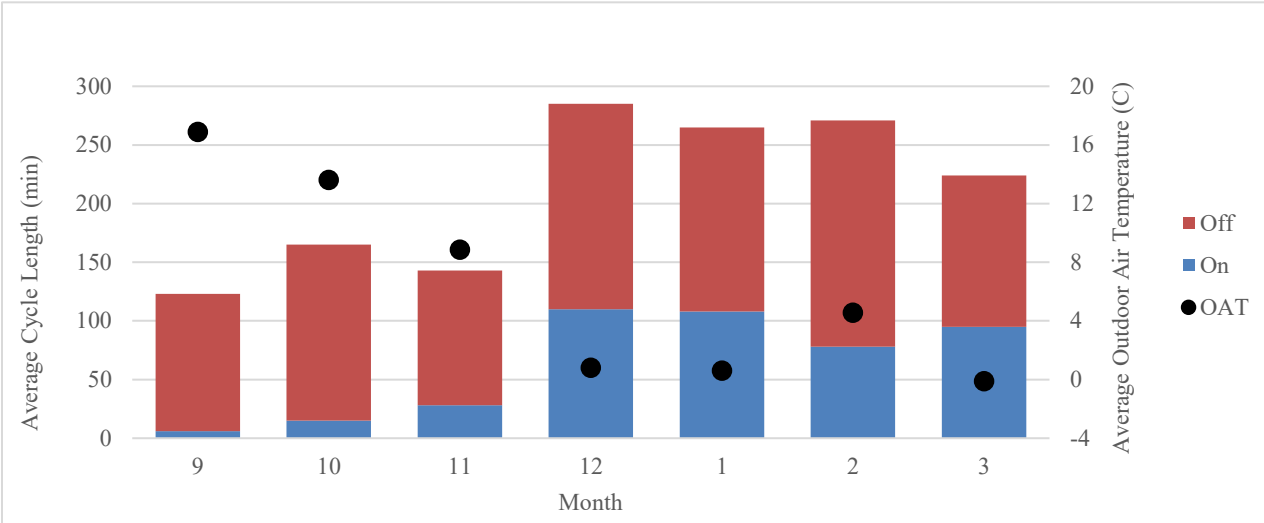

Figure 2: Monthly average boiler cycle lengths and On/Off duration for Building 1.

The average cycle length tended to increase for lower outdoor air temperatures as shown in Figure 3, likely due to increases in building space heating demand, requiring more of the modular boiler units to be on for a longer period of time. The few data points showing high cycle lengths for higher temperatures occurred due to long periods in the cycle where the boiler was off.

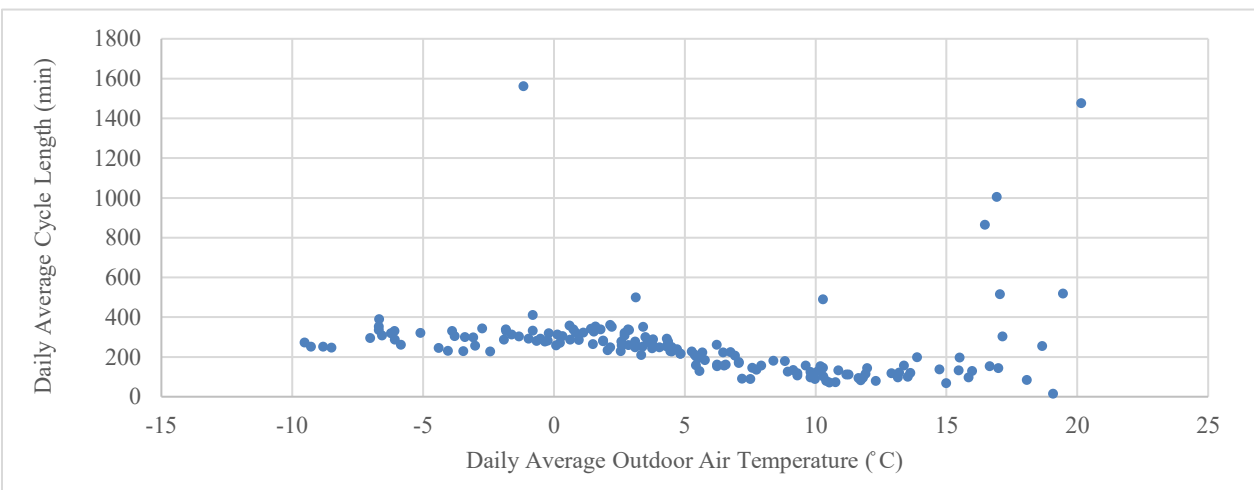

Figure 3: Building 1 average daily boiler space heating cycle length versus average daily outdoor air temperature.

Building 2

The average profile of natural gas consumption in Building 2 over the course of one day for the summer (June – August), winter (December – February) and shoulder seasons is shown in Figure 4. Hourly variation in demand was high in the summer, with hourly standard deviations ranging between 2.2% and 5%. Winter and shoulder season profiles had standard deviations of 0.6 – 1.4% and 1.8 – 3.3% respectively. Summer

natural gas consumption, which represents only domestic hot water uses, tends to be lowest between 1:00 am and 7:00 am (when residents are more likely to be sleeping and require less domestic hot water). In the winter and shoulder seasons, natural gas consumption tends to be fairly consistent over the day, with a slight dip during the early morning period and peak around 10:00 pm. This may indicate that there is less temperature variability across the daytime hours at the site, that the solar gains at the building are small or that the building has a relatively high thermal mass.

Average daily natural gas consumption is shown in Table 3 and ranged between a low of 151 m^3/day (5333 ft^3/day) in the summer months and a high of 880 m^3/day (31,077 ft^3/day) in the winter months. Average consumption was well correlated with the monthly average outdoor air temperature ($R^2 = 0.95$).

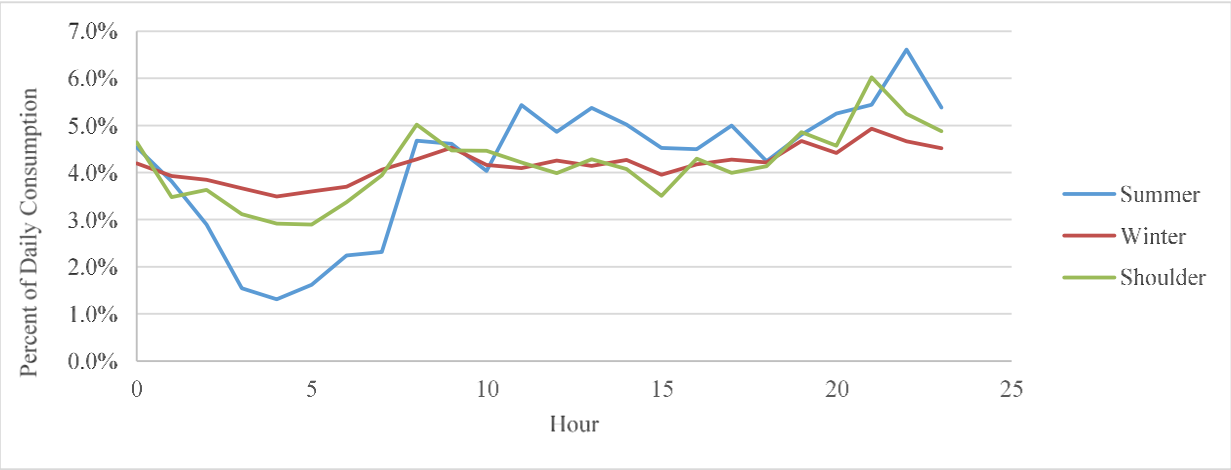

Figure 4: Profiles of summer, winter, and shoulder season hourly percentage of daily natural gas consumption (space heating and domestic hot water) for Building 2.

Table 3: Daily average natural gas consumption (space heating and domestic hot water) by month for Building 2.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Daily Average Consumption (m^3)	793 ± 138	728 ± 152	739 ± 183	446 ± 92	335 ± 99	197 ±13	171 ± 14	151 ±11	153 ± 17	355 ±219	562 ± 155	880 ± 113
Daily Average Outdoor Air Temperature (°C)	-1.4	1.1	-0.7	8.4	12.0	18.5	22.1	23.7	19.5	13.1	7.6	0.3

Table 4 shows the daily average runtime, OBU, and TCU for the space heating boilers. Note that space heating was not operating during the months of June to September so these months are not included. The average OBU is based on potential runtime from the number of boilers that were operating during a daily period. As the OBU for Building 2 was determined over a daily period (instead of an hourly period as was used for Building 1), the operating boiler utilizations for Building 2 will tend to be lower. Space heating runtime and utilization generally varied with outdoor air temperature. The maximum operating boiler utilization was 100% for the space heating boilers and the maximum space heating capacity utilization was 50%.

Table 4: Daily average space heating boiler runtimes and utilization for Building 2.

Month	Average OAT (˚C)	Average Daily Space Heating Boiler Runtime (hr)	Average OBU	Average TCU
1	-1.4	36 ± 8	75%	37%
2	1.1	33 ± 10	68%	34%
3	-0.7	32 ± 13	67%	33%
4	8.4	15 ± 6	31%	16%
5	12.0	8 ± 6	18%	9%
10	13.1	11 ± 13	24%	12%
11	7.6	21 ± 10	22%	22%
12	0.3	41 ± 6	86%	43%

Figure 5 shows the average cycle times for the primary space heating boilers. The secondary space heating boilers were rarely in operation and their associated cycle lengths are not significant. The primary boilers had an average cycle time which ranged between a low of 12 minutes in May and a high of 34 minutes in March. Short cycle lengths are expected for non-modular boiler systems that are oversized as compared to building demand. Short cycle lengths tend to occur when a boiler with a capacity that greatly exceeds the heating demand quickly brings the primary loop water (and as a result the building loop water) up to or slightly above the setpoint temperature and then turns off. After, as the primary loop water gradually falls below the setpoint temperature, the boiler turns on again, quickly heats up the primary loop's water and is turned off. Note that, while Building 2 has two-stage boilers, the minimum output at the first stage may still provide too much capacity for the building demand or the controller's delay in switching from the first stage to the second stage may be too low. Time on versus time off tended to be fair evenly split throughout the months. Cycle time varied greatly likely based on variation in site weather conditions.

As shown in Figure 6, the boiler cycle length tended to increase for lower outdoor air temperatures. This is likely due to the higher space heating demands caused by lower outdoor air temperatures. The cycle length also tended to increase for outdoor air temperatures greater than 4˚C (39˚F). This is likely due to one of the two primary space heating boilers being off for long periods of time during days with higher outdoor temperatures.

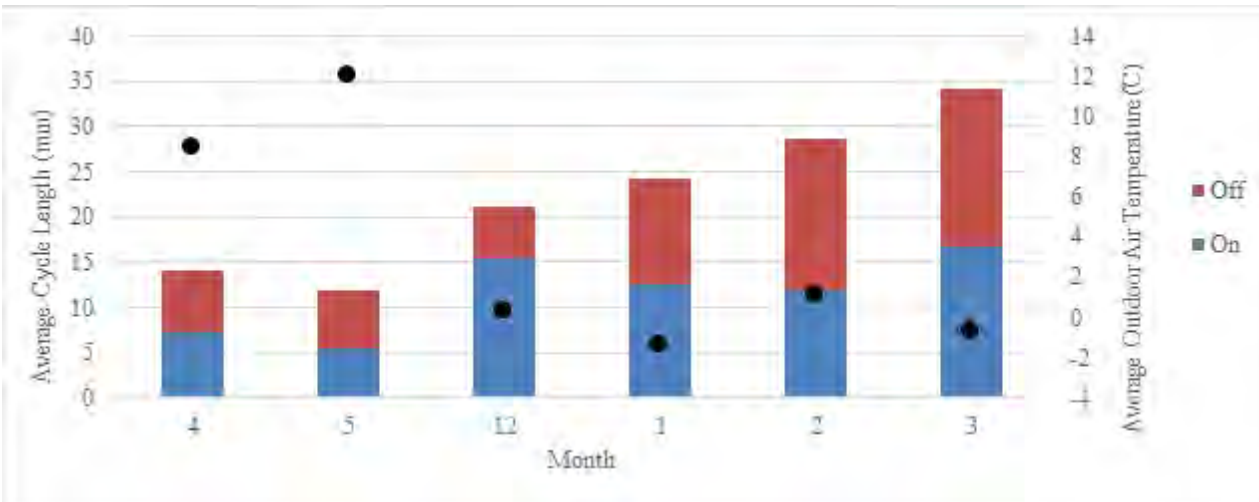

Figure 5: Average boiler cycle length and on/off duration by month for Building 2.

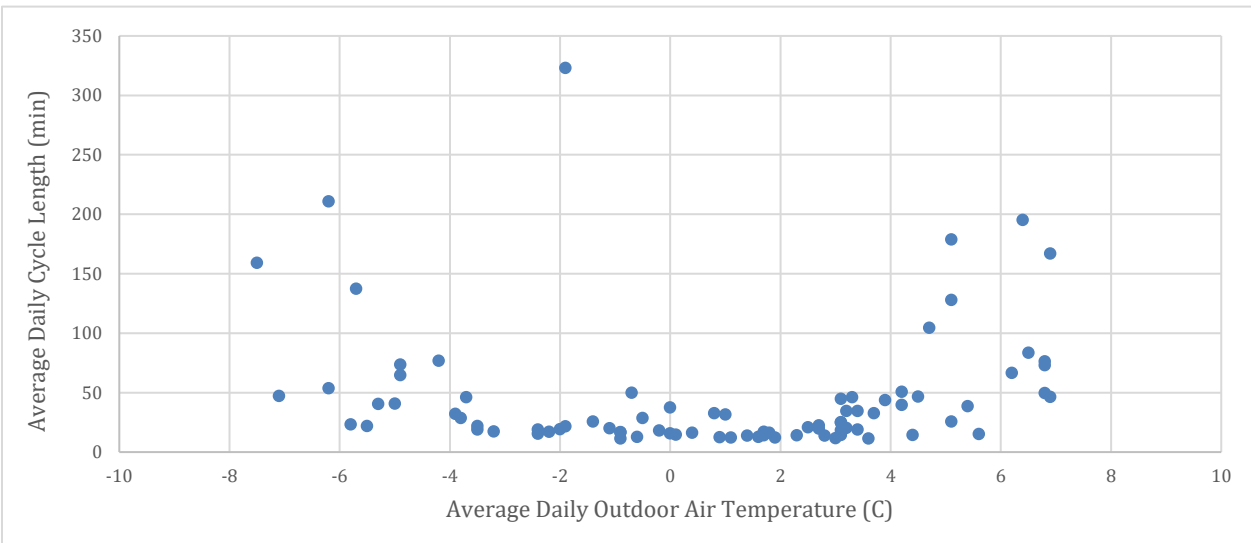

Figure 6: Average daily boiler cycle length versus average daily outdoor air temperature for Building 2.

Operational Profile Comparison

The natural gas profiles varied slightly between the two buildings. In Building 1, a clear peak in consumption occurred at 9:00am, while in Building 2 natural gas consumption was fairly consistent from 8:00am until 9:00pm. This difference is likely a result of different occupant behaviour as well as differences in regional air temperature variations, domestic hot water equipment configuration, and/or building envelope structure.

It is interesting to note that while Building 1 and Building 2 had similar average daily natural gas consumption during the winter months (710 m^3 vs. 880 m^3 in December, 760 m^3 vs. 793 m^3 in January, and 620 m^3 vs. 728 m^3 in February), Building 2 consumed 1.5 to 2 times the amount of natural gas in July, August and September as compared to Building 1. There are two possibilities for this difference: 1) the

residents in Building 2 have a higher demand for domestic hot water or 2) the DHW supply system in Building 2 is significantly less efficient than the system in Building 1. Insufficient data is available to determine which possibility is more likely.

The modular space heating boiler arrangement in Building 1 resulted in higher average OBU and longer cycle times than the four-boiler configuration in Building 2. The difference in average cycle time between the two system configurations was particularly significant – for the hyper-modular system in Building 1, the longest monthly average cycle length was almost five hours, while the traditional four-boiler system in Building 2 had a maximum monthly average cycle length of only 34 minutes. The two buildings use similar PID controls to maintain the desired primary and building loop setpoint temperatures which suggests that the control mechanism itself is not responsible for the difference in cycle length. Rather, it appears that the lack of heating plant controllability resulting from large boiler sizing and low turndown ratios (i.e. the difference between the second stage maximum output and first stage minimum output) is likely responsible.

INDIRECT PEROFRMANCE ASSESSMENT USING DEMAND DATA: BUILDING 1

In general, building space heating demand can be calculated using Equation 3.

$$Space\ Heating\ Demand = \dot{m}_{supply} c T_{supply} - \dot{m}_{return} c T_{return} \quad (3)$$

where $\dot{m}$ is the mass flow rate of the supply or return water, T is the temperature of the supply or return water and c is the heat capacity of water. As no variable speed pumping equipment is installed in Building 1 and the building hot water supply loop pump is always running, the flow rate of the building hot water supply and return should be relatively constant. As a result, the temperature difference between the supply and return temperatures can be used to establish relative heating demands for various time intervals. In this paper, Relative Demand is defined as the difference in supply and return temperature for the building hot water supply loop, measured in degrees Celsius. A small difference between the supply and return water temperature indicates a low building demand for space heating which results in a low boiler load.

For the data presented in Figures 7 and 8, the space heating natural gas demand has been separated from the domestic hot water natural gas demand. This has been done by using the average natural gas consumption per boiler runtime from the entire data set ($0.0026 \pm 0.00005\ m^3/s_{\ Runtime}$).

In Building 1, the temperature difference between building hot water supply and return was used to calculate the Relative Demand in degrees Celsius. Then, natural gas consumption in cubic metres was normalized by the change in temperature per degree Celsius for that period. This normalization was used to illustrate how system efficiency changes for different levels of building demand. The natural gas consumed per degree Celsius of water temperature tended to increase at low Relative Demands as shown in Figure 7, which indicates a lower system efficiency for these scenarios. One possible reason for the apparent decrease in efficiency is the decrease in cycle length that tended to occur at higher OATs (which generally correspond to lower boiler loads).

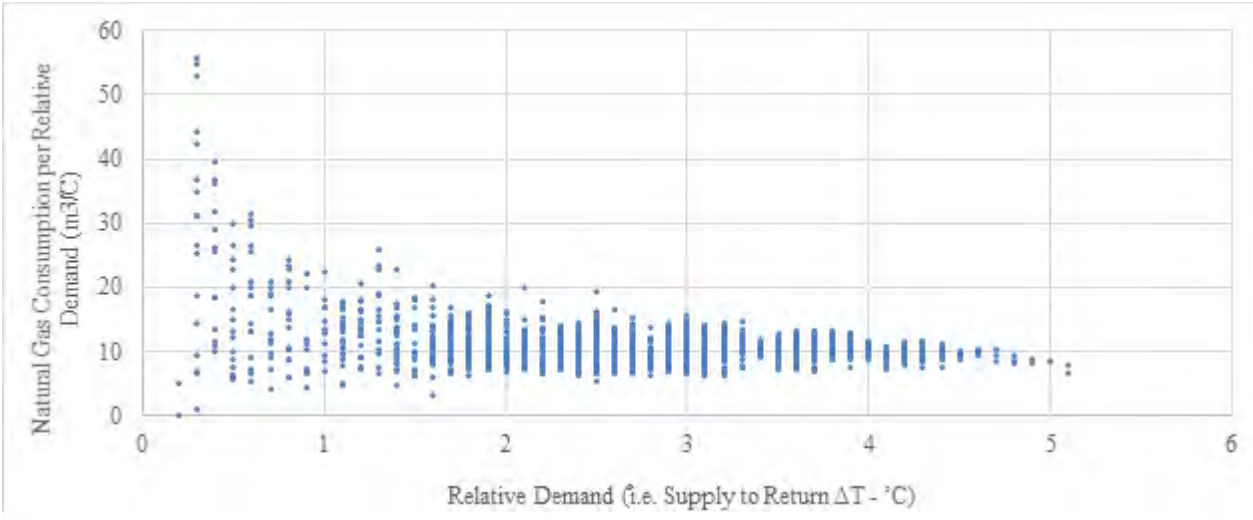

Figure 7: Natural gas consumption per degree relative demand for various levels of relative demands in Building 1.

Hourly periods with low OBUs exhibit a large variation in natural gas demand per degree relative building demand, while periods with higher OBUs tend to be more consistent (Figure 8). Based on the available data, this variance could not be explained – natural gas consumption per Relative Demand for OBU values less than 40% did not appear to have any additional sensitivity to the outdoor air temperature or average time off per cycle as compared to higher OBU values. Further investigation and additional data collection is required to determine the cause of this increase.

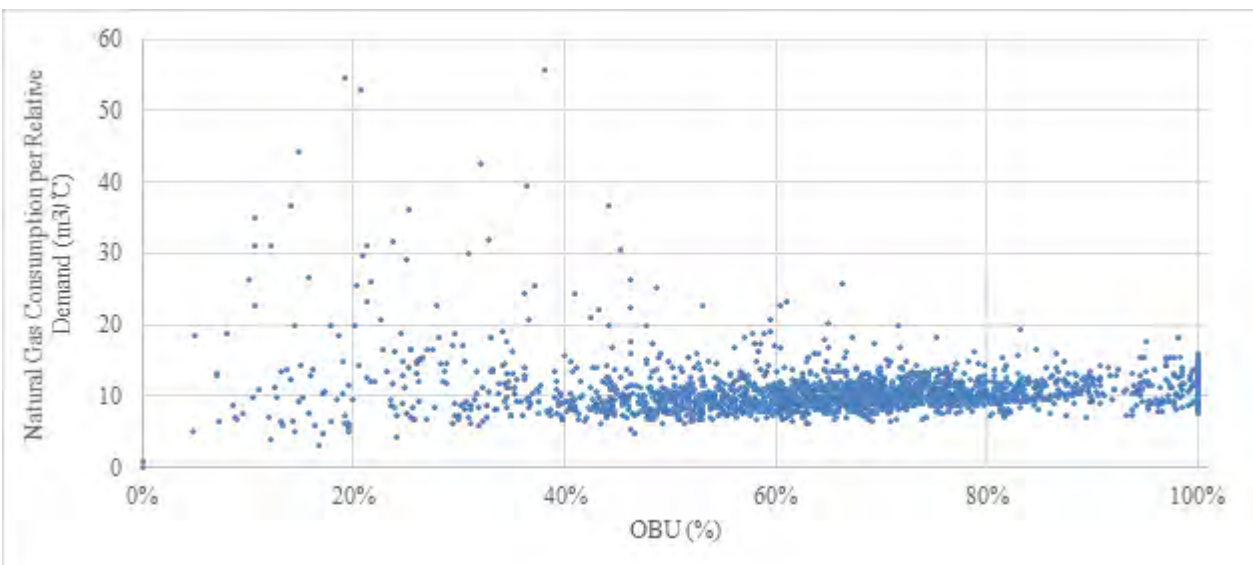

Figure 8: Natural gas consumption per Degree Relative demand for various OBUs in Building 1.

Figures 7 and 8 suggest that, in Building 1, lower space heating demand levels (and associated low OBUs) influenced space heating system performance. Figure 7, in particular, shows that for lower levels of demand, system efficiency tended to decrease in many cases. More granular data collection and analysis is required to investigate what specific operational conditions, in combination with low-demand scenarios, are motivating reduction in system efficiency. Additionally, flow rate data would help to further quantify actual energy efficiencies.

Envelope retrofits or new systems that are oversized for building demand would increase the time the system spends operating in the low loading region that seems to be associated with reduced system efficiency in many scenarios. As a result, an oversized system is likely to have higher operational costs than a more appropriate sized or modular system.

Unfortunately, sufficient data was not available to perform a complementary analysis for Building 2. It is expected that Building 2 would exhibit similar trends and that decreases in system efficiency would be aggravated by the less modular equipment, given the decrease in efficiency shown to occur at low-load scenarios for traditional equipment configurations in different building typologies.

CONCLUSION

Modular arrangements of boilers may provide reductions in cycling rates for space heating boilers in MURBs. Building 1, which had a modular heating plant, had longer boiler cycle times compared to Building 2, which had a more typical four-boiler space heating system. Building 1 average cycle lengths were between 123 minutes in shoulder season and 285 minutes in winter while Building 2 average cycle lengths varied between 12 minutes in shoulder season and 34 minutes in March (the coldest month monitored at the site).

An analysis of natural gas consumption for Relative Demands in Building 1 revealed that system efficiency tended to decrease at low demands. However, this study was unable to provide a basis for assessing the extent of this reduction. Unfortunately, sufficient demand data was not available to complete the analysis for Building 2.

The preliminary analysis presented in this paper suggests that the size and configuration of heating plants has a significant affect on the operational characteristics of equipment (e.g. cycle time, boiler utilisation) and likely affects the efficiency of the system for low-load scenarios. As a result, envelope retrofits that significantly reduce building space heating demand and increase the amount of time heating plant equipment spends operating in relatively low-load conditions likely will result in reduced heating system performance. This should be factored into the assessment of planned envelope upgrades. In new MURB construction and for heating plant retrofits, modular systems, with appropriately sized modules, may provide long-term energy and cost savings through improving operational performance, despite the potential for increased design and capital costs. In conjunction or independently of envelope retrofits, heating plant retrofits should be explored in post-wars buildings as measures to increase the controllability of the system can help to reduce energy consumption. These measures may include installation of a BAS system, changes to a boiler's turn-ratio, or, where equipment replacement is already required, the use of a modularly designed boiler equipment.

The analysis in the study has shown that data from existing BAS systems can be used to perform a rudimentary assessment of heating plant performance in MURBs without variable speed pumps. This analysis can be applied in the future to identify opportunities for energy savings through operational changes (e.g. control or modulation changes) or capital retrofits (e.g. boiler replacement). Augmenting this approach with spot flow rate measurements using ultrasonic flow meters can allow for the direct assessment of system efficiency.

Extensions of this work would include: taking water flow measurements at the sites to determine actual demand values as opposed to the relative values used, collection of boiler status data over a longer period of time and collection of more granular natural gas consumption data to investigate if a cycle rate penalty exists and if it can be quantified. In particular, collection of building demand data for Building 2 would be helpful to investigate the efficiency differences between it's traditional four-boiler systems and the more modular system used in Building 1.

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