LOW CARBON HEATING FOR COMMERCIAL BUILDINGS USING GRID SUPPLIED ELECTRICITY DURING-OFF PEAK PERIODS


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Abstract
The concept of a lower carbon heating system for buildings in this study is based on using lower carbon energy from the electricity grid to meet the heating needs of a commercial building in a heating dominated climate. The lowest carbon option for heating commercial buildings using utility supplied energy in Ontario is through the use of off-peak electricity.

This study demonstrates how the GHG impact from building heating systems can be reduced by almost 90% through design strategies and the use of low carbon energy from the electricity grid. The model for a low carbon electricity supply is in Ontario where the average winter off-peak GHG intensity is 20-42 g/kWh as compared to 179 g/kWh for combustion of natural gas.

To capitalize on the low carbon energy, thermal storage is required. The proposed strategy utilizes water/mass storage in combination with the building mass to serve daily heating needs.

The study building is a two-story office building with a gross area of 2,323 m². The proposed design strategies for the building’s thermal and ventilation performance results in a heating energy reduction of 57%, compared to a “Code” building. The passive load reduction process minimizes the building’s heating requirements which further minimizes the amount of daily thermal storage.

The indirect, but much more significant impacts from the advanced design is the improved occupant comfort, satisfaction and a potential for higher productivity delivering financial benefits well beyond those realized by the more energy efficient building.
1 INTRODUCTION
The most challenging component in developing buildings with a low, or net-zero carbon emission footprint is with the heating. On average, the heating energy is 45% of an Ontario commercial office building’s total consumption.[1] Natural gas is the dominant source of heating energy in Canada due to its low cost and extensive distribution. The Ontario electricity grid offers significantly lower GHG emissions as an energy supply than natural gas, especially during off-peak hours. This paper will demonstrate the strategies for and feasibility of heating building using off-peak electricity.

2 BUILDING HEATING SYSTEMS & CARBON INTENSITIES
The graph shown in figure 1 illustrates the relationship between the utility-supplied fuel source for building heating systems and the CO₂e intensity\(^1\). The goal is to utilize the lowest GHG energy source, which is the off-peak hours during the heating season. The following sections address the design criteria and heating technology that will satisfy the heating needs during peak periods through the use of off-peak electricity on a daily basis.

![Graph showing CO₂e Intensity](image)

*Figure 1: CO₂e Intensity.*

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\(^1\) Based on GHG intensity of the energy source, only. Combustion or coefficient of performance of the heating equipment is not factored.
3 THE ONTARIO ELECTRICITY GRID

The Ontario electricity grid uses a mix of generation including hydroelectric, nuclear, natural gas combustion, wind power, solar power and bio-gas. Natural gas is used mostly to satisfy peak demand periods and has the highest CO₂e intensity of the generation sources. Ontario has been moving away from fossil fuel generation to no-emission and renewable energy sources as a commitment to addressing pollution and climate change. The Ontario electricity grid serves as a model for other jurisdictions that will be decarbonizing their electricity supply.

In 2015, Ontario’s CO₂e emission intensity for electricity generation was 42 g/kWh.[2] Natural gas delivered to Ontario carries a CO₂e intensity of 179 g/kWh². During off peak periods (1900-0700 hrs), the electricity generation mix has the lowest CO₂e intensity due to the lower use of natural gas generation, compared to mid- and on-peak periods (0700-1900 hrs). During the study period, the authors observed an average of 20-25g/kWh during off peak periods during the heating months.

The electricity grid CO₂e intensity was monitored using the mobile app, “Gridwatch”. A screen shot of the app is shown in figure 2.

The relatively low carbon intensity of the electricity power supply from the provincial grid forms the basis for this thesis. The result is a reduction in carbon intensity from 179g/kWh when combusting natural gas, compared to 2U-42g/kWh when heating with electricity.

This paper does not cover the cost of the energy sources, because they differ by jurisdiction and fluctuate in commodity price.

4 TEST BUILDING DESCRIPTION

The values used in this study are based on a two-story office building located in Ottawa, similar to the NECB Archetype, “Small Office”. Table 1 and table 2 describe the details of the building as it was modeled in eQUEST. The baseline values are represented by the Code building.

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2 Canada’s 2015 UNFCCC Submission
Table 1 - Office Building Specifications.

<table>
<thead>
<tr>
<th></th>
<th>O/A Design Temp</th>
<th></th>
<th>Interior Temp</th>
<th></th>
<th>Building Width</th>
<th></th>
<th>Building Depth</th>
<th></th>
<th>Total Floor Area</th>
<th></th>
<th>Radiant Water Delta T</th>
<th></th>
<th>Heated Floor Area</th>
<th></th>
<th>Window to Wall Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-25°C</td>
<td>-13°F</td>
<td>22°C</td>
<td>72°F</td>
<td>50m</td>
<td>164ft</td>
<td>33.5m</td>
<td>110ft</td>
<td>3326m²</td>
<td>35,800ft²</td>
<td>8.3°C</td>
<td>15°F</td>
<td>2,323m²</td>
<td>25,000ft²</td>
<td>40%</td>
</tr>
</tbody>
</table>

Table 2 - Office Building U-values.

<table>
<thead>
<tr>
<th></th>
<th>Wall U-value</th>
<th>Roof U-Value</th>
<th>Window U-value</th>
<th>Ground U-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
<td>Btu/ (hr-F-ft²)</td>
<td>W/ (m²-C)</td>
<td>Btu/ (hr-F-ft²)</td>
<td>W/ (m²-C)</td>
</tr>
<tr>
<td></td>
<td>0.050</td>
<td>0.284</td>
<td>0.033</td>
<td>0.187</td>
</tr>
<tr>
<td>Improved</td>
<td>0.033</td>
<td>0.187</td>
<td>0.025</td>
<td>0.142</td>
</tr>
</tbody>
</table>

5 BUILDING ENVELOPE

The main performance feature of any building is the envelope. A higher performing envelope will result in lower heating costs and associated GHG emissions. The corresponding heating load for both construction types is a function of the upgraded insulation values in combination with a 40% decrease in the infiltration rate. The u-values for Code and Improved construction closely match the NECB³ building envelope values for zone 6 and zone 8 respectively. **Improving the building envelope from Code to Improved results in a 21.7% (9.61 t) reduction in GHG emissions** and represents the first step in achieving the “Model” building for this thesis. An added benefit to the Improved envelope is a reduction in equipment size from the peak heating load reduction.

³ National Energy Code for Buildings 2011
Table 3 – Heating Load for two-storey office building (Ottawa, Ont).

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Building Overall U-Value</th>
<th>Heating Load per Year</th>
<th>Natural Gas non condensing, 70% sessional efficiency</th>
<th>GHG @ 5.025x10^-11 metric tons CO2/Joule[3]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Btu/ (hr-F-t^2)</td>
<td>W/ (m^2·C)</td>
<td>MBtu</td>
<td>MWh</td>
</tr>
<tr>
<td>Code</td>
<td>0.1036</td>
<td>0.588</td>
<td>837</td>
<td>245.3</td>
</tr>
<tr>
<td>Improved *</td>
<td>0.091</td>
<td>0.517</td>
<td>655.7</td>
<td>192.1</td>
</tr>
</tbody>
</table>

5.1 Thermal Comfort Benefits of the Improved Envelope

Improving the thermal performance of the envelope delivers thermal comfort benefits for the occupants. Figure 4 shows how radiant temperature asymmetry affects occupant satisfaction. Occupants will feel less asymmetric thermal radiation differences due to the improved thermal performance of the envelope.

![Figure 4: Percent of People Expressing Discomfort due to Asymmetric Radiation. [4]](image)

6 LOW TEMPERATURE HEATING

The downstream design benefit from the higher thermal performance of the envelope is the ability to use low temperature water to deliver the required heating needs and occupant comfort. Low temperature heating systems allow for the highest efficiency heating options to be used. This is accomplished by using
condensing boilers in combination with radiant floors. This combination of systems results in more energy savings and GHG reductions.

6.1 Hydronic Heating

Hydronic heating uses conduction and radiation to heat the surroundings. These two modes of heat transfer are more efficient than using a forced air convective system due to the poor thermodynamic properties of air. Hydronic heating systems include baseboard heaters, radiant wall panels or radiant floors. These heating systems all require different average water temperatures to satisfy the required heating load. Baseboard heaters and radiant panels require higher average water temperatures >54.4 °C (130 °F) due to the smaller surface area available for transferring heat. Lower average water temperatures <48.8 °C (120°F) can be used with radiant floors because of the larger surface area available for heat transfer. Figure 5 illustrates how envelope thermal performance, combined with radiant floor heating, can lower the average water temperature required for heating.

![Figure 5: Average water temperature for hydronic heating systems (Ottawa test building).](image)

6.2 Condensing Boilers

Low water temperatures are ideal for optimizing the performance of condensing boilers. Condensing boilers have the highest efficiency in natural gas heating as shown in Figure 6. This high efficiency is achieved by condensing the water vapour in the flue gas. The boiler then captures the latent heat that was trapped in the vapour. In order for condensing to occur, the return water temperature to the boiler must be below 54.4 °C (130 °F). As the return water temperature drops below 54.4 °C (130 °F), the boiler enters
condensing mode. Table 4 shows the efficiency increase that condensing boilers can provide over the standard non-condensing boiler.

![Diagram showing temperature range for condensing boilers.](figure6.png)

**Figure 6: Temperature range for condensing boilers. [5]**

Table 4 - Heating load for two-storey office building, radiant floor, 6.4 mm (¼") carpet, 152 mm (6") pipe spacing. Ottawa ON

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Building U-Value</th>
<th>Heating Load per Year</th>
<th>Condensing boiler efficiency</th>
<th>Natural Gas</th>
<th>GHG @ 5.025x10⁻¹¹ metric tons CO2/Joule[3]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Btu/ (hr-F-ft²)</td>
<td>W/ (m²-C)</td>
<td>MBtu</td>
<td>MWh</td>
<td>%</td>
</tr>
<tr>
<td>Code</td>
<td>0.1036</td>
<td>0.588</td>
<td>837</td>
<td>245.3</td>
<td>96</td>
</tr>
<tr>
<td>Improved</td>
<td>0.091</td>
<td>0.517</td>
<td>655.7</td>
<td>192.1</td>
<td>96.5</td>
</tr>
</tbody>
</table>

Combining envelope improvements with low temperature radiant heating using condensing boilers, results in a 43% reduction (19.06 t) in GHG emissions.

6.3 Thermal Comfort

Thermal comfort is affected by many factors that low temperature radiant heating can mitigate. To understand more on this topic, the operative temperature must be defined. This is the temperature that occupants will feel in a conditioned space. The physical benefit of radiant heating is the ability to increase surface temperatures in a building and then radiate that heat. These surface temperatures influence the
mean radiant temperature (MRT). This is important because the operative temperature is a function of both the MRT and the air temperature. Radiant floor heating minimizes the radiation losses by the human body by maintaining surfaces close to the human body temperature.[6] Therefore, if the surfaces in the occupied zone are maintained close to body temperature, the occupants will feel more comfortable.

7 VENTILATION

The ventilation requirements for the occupants represent the largest energy component of the building heating requirements. A Dedicated Outdoor Air System (DOAS) significantly reduces the amount of supply air, compared to a standard mixed air system. Furthermore, the system offers higher ventilation effectiveness and is the best ventilation companion for radiant floor.

The benefits of combining these systems are controlled outdoor air (OA) delivery, air volume reduction, reduced air conditioning, decreased fan power and reduced draft. Combining all of these benefits will help reduce the energy required by the building during the heating season.

DOAS systems reduce the total air-flow requirements by decoupling sensible loads from the latent loads. The total airflow to the building is reduced from approximately 20,000cfm to 2,700cfm. As a result, the supply ducts to each zone will be smaller.

7.1 Air Delivery

Additional to the overall reduction in total air-flow, DOAS has the ability to modulate the amount of OA delivered to a building according to the varying occupant load. The air required in the occupied zone depends on the number of occupants in the zone. CO₂ serves as a suitable proxy for the number of occupants, measured at the return duct and/or occupant zones provide feedback to the supply air control, modulating the volume of OA delivered. For example, if there is half of the number of occupants in the building, the OA requirement would drop from 2,315 CFM to 1,157 CFM. Use of CO₂ sensors also allows the OA to be shut off during unoccupied hours.

![Diagram of Air Handling Unit, AHU](image)

*Figure 7 - Conventional Mixed Air System.[7]*
Figure 8 – Direct Outdoor Air System. [7]

7.2 Ventilation Effectiveness

With a traditional mixed air system, the OA is mixed with space heating air and sent to the zones to be heated. The effectiveness of the OA delivery system plays a role in reducing energy use. The effectiveness refers to how much outdoor air enters the breathing zone. A typical mixed air system will deliver a "ceiling supply of warm air 8°C (15°F) or more above space temperature and ceiling return."[8] This results in an effectiveness of 0.8.

Low temperature systems de-couple the latent and sensible heating loads in the building. This allows for the DOAS system to provide outdoor, latent conditioned, air at a temperature equal to the space temperature. This increases the effectiveness from 0.8 to 1.0 and reduces the maximum OA requirement by 694 CFM; further reducing heating requirements and fan power^4.

Figure 9: Outdoor air requirements for two-storey office building.

7.3 Heat Recovery

Heat recovery, both latent and sensible, are ideally paired with DOAS systems to reduce the energy required to condition outdoor air. Depending on the outdoor air temperature and humidity, the DOAS system can operate in heat recovery mode or economizer mode. Energy wheels represent the lowest cost / highest performing heat recovery option for the test building. An energy wheel with recovery efficiencies of 75% sensible and 72% latent have been selected for the model building.
7.4 Resulting Savings

The DOAS in combination with heat recovery saves an additional 14.5% (6.4 t) of GHGs. Combining envelope improvements with low temperature radiant heating using condensing boilers and DOAS+H/R, results in a 57.3% reduction (25.4 t) in GHG emissions.

7.5 Occupant Comfort: Draft & Indoor Air Quality

Conventional convective heating systems need an air speed of 0.8 m/s (150 fpm) to reach a ventilation effectiveness of 1.0. However 0.8 m/s jet of air will feel like an uncomfortable draft and a high percentage of occupants will be dissatisfied.[9]

With a DOAS system, the supply air is delivered at room temperature and the radiant floor provides space heating. This increases the effectiveness of outdoor air delivery by avoiding the problem of warm air stratification. Outdoor air can now be delivered at more comfortable levels. The actual velocity will depend on the designer’s layout of the DOAS system.

7.6 Occupant and Building Owner Benefits

DOAS reduces the supply air velocity, while delivering fresh air to the breathing zone and reduces contaminants that are present in the recirculated air; contributing to a high indoor air quality (IAQ). The owner receives additional benefit because the ceiling space requirements are shallower that can result in a lower height building for the same area; saving capital cost for the building construction.

8 OFF-PEAK ELECTRIC STORAGE

8.1 Introduction

Off-peak electric energy represents the lowest carbon source of energy (except for 100% renewable sources). However, solar thermal energy is not practical in meeting the heating requirements of our model building due to the reduced energy available during the winter months. In order to use off-peak electrical energy as a heating source, it must be stored as thermal energy. Combining water/thermal mass storage with storage in the floor mass and radiant floor control strategies will minimize the energy required to meet the following day’s on-peak heating demand.

8.2 Thermal Storage

Two options were looked at for storing thermal energy; water and thermal mass (bricks). Both technologies use the proposed shared thermal storage with the floor slab. In order to “match” the amount of stored energy to heating demand of the following day, the storage media needs to be modular & staged, such that only the required volume gets heated. This is accomplished by having multiple tanks. The commercially available thermal mass boilers selected for the study have an output capacity of 80kW.[10] Three of these units are adequate to supply the total heating needs under peak design conditions.

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5 “Ceiling supply of warm air less than 15°F (8°C) above space temperature and ceiling return provided that the 150 fpm (0.8 m/s) supply air jet reaches to within 4.5 ft (1.4 m) of floor level. **Note:** For lower velocity supply air, Ez = 0.8.” [8]

6 Steffes Model 9180
Water storage: The water in the storage tanks is heated to the supply temperature for the radiant floor. The total volume required is 100 m³ (3550 ft³) @ ΔT = 9.4 °C (15°F). This will supply the design heating load for the building for a 12-hour period.

Thermal mass: The thermal mass can be heated to a much higher temperature than water. This results in an overall storage volume, requiring only 8.3 m³ (294.4 ft³) of storage to meet the design heating load of the following day.

Figure 10 - Thermal Storage Discharge Profile. [10]

Figure 11: Control strategies for off-peak heating.
8.3 Thermal Control Strategies

Having control over the amount of thermal storage can also reduce the energy required for heating. Storage modulation uses the weather forecast to store only the required amount of thermal energy required for the next day. Figure 11 illustrates how the storage would be charged and discharged during on and off-peak periods.

Slab temperature control requires an understanding of the comfort requirements of the occupants. Occupants arriving to work have a slightly elevated body temperature from the act of walking and traveling to work. The amount of metabolic heat generated by walking is 150W/m². Compare this to 55W/m² while seated and typing.[12] Figure 12 illustrates how temperatures upon arrival can vary with fewer complaints than complaints received during operational hours with varied temperatures. This difference allows the temperature of the radiant floor to be slightly cooler upon initial arrival and warm up to the daytime setpoint in the first hour, reducing energy delivered.

![Figure 12: Predicted rate of unsolicited thermal operating complaints.[11]](image)

The slab also has the ability to radiate heat as it cools. We see in Figure 11 how heating can be removed from the slab just before occupants are leaving. Because of the thermal mass of the slab, the operative temperature will drop much slower than with a convection based system.

The actual temperature difference for morning heating and evening slab storage release would depend on the response time of the specific radiant floor slab and performance testing after installation. A study of occupants’ arrival complaints can be done to determine the optimal temperature for arrival and during the workday. Figure 12 shows an example of the type of study that can be done to optimize comfort and energy use.

8.4 Greenhouse Gas Impact

Switching from natural gas heating to off-peak electricity combined with thermal storage reduces the GHG emissions by an additional 32.4% for the model building. The use of thermal control strategies has the possibility to further reduce GHG’s and increase occupant comfort.
9 OCCUPANT COMFORT AND PRODUCTIVITY GAINS

The thermal comfort described in previous sections is a component of Indoor Environmental Quality (IEQ); the ultimate measure of the building’s design features that influence the comfort & satisfaction of the occupants. Numerous studies have shown that buildings with high IEQ have a positive impact on occupant wellbeing, as well as productivity.

To examine the value of productivity as it compares with the other costs of operating a business, a 100:10:1 ratio has been generally accepted. This refers to the cost of salary, building costs and energy cost. Therefore, maximizing the productivity of employees is the best way to reduce operating costs. Thermal comfort combined with improved outdoor air delivery, through the proposed strategies will improve the occupant comfort and potential for productivity gains and reduction in absenteeism.

![Cost per Year per Square Foot](image)

*Figure 13: Typical costs for a commercial office building. [13]*

To demonstrate the relative impact of modest productivity gains compared to significant energy savings for the model building, the following simplified analysis is offered. With an employee cost of $10,790,000\(^7\), building cost of $1,079,000 and energy cost of $107,900, a 1% productivity gain would result in an economic gain of $107,900, while a 25% energy saving would yield $26,975. This demonstrates how focusing exclusively on energy savings misses the more significant economic benefits resulting from improved IEQ\(^8\).

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\(^7\) Salary cost is based on occupancy of 166 employees (@14m\(^2\)/person) with an average salary of $65,000/year.

\(^8\) Recommended reading: REHVA Guidebook No. 6; Indoor Environment and Productivity in the Office Environment.
10 CONCLUSION
The staged load reduction strategy reduces the heating energy by 57.3%, minimizing the system capacity and cost impact of switching to electricity as the heating energy source. The summary of strategies with their respective load reduction and greenhouse gas savings is tabled below. The results illustrate the potential to reduce carbon emissions by approximately 90% through the use of off-peak electricity in Ontario. Capital cost reductions resulting from smaller heating and ventilating equipment offset investments in the high performance envelope and radiant heating. Low heating water temperatures have the added benefit for the integration of other, renewable sources of energy, such as solar thermal, and refrigeration heat recovery, to further reduce GHG emissions and “future-proof” the building for new energy systems.

Table 5 – Summary of Results.

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>GHG Emissions</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heat Load (kWh)</td>
<td>CO₂e (t)</td>
<td>CO₂e (t)</td>
</tr>
<tr>
<td>Baseline</td>
<td>Code Building</td>
<td>245,300</td>
<td>44.38</td>
</tr>
<tr>
<td>Load Reduction Measures</td>
<td>High Performance Envelope</td>
<td>192,166</td>
<td>34.77</td>
</tr>
<tr>
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<td>Low Temp Water Heating</td>
<td>139,384</td>
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<tr>
<td></td>
<td>DOAS + H/R</td>
<td>103,900</td>
<td>18.82</td>
</tr>
<tr>
<td>Total Measures</td>
<td>103,900</td>
<td>18.82</td>
<td>25.4</td>
</tr>
<tr>
<td>Conversion electricity to off-peak</td>
<td>103,900</td>
<td>4.4</td>
<td>39.86</td>
</tr>
</tbody>
</table>

In an owner-occupied building, the business owner receives a double benefit of energy savings and enhanced indoor environmental quality, yielding significant financial rewards from increased employee productivity.

Figure 14 - Energy Savings & Occupant Comfort Benefits.
11 REFERENCES
5. ASHRAE. (2012). Systems and Equipment. P. 32.4