Estimating the impact of building retrofit measures on the operational greenhouse emissions of medium office buildings – A case study in Ontario, Canada

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Abstract
A simulation-based approach was used to estimate the operational greenhouse gas (GHG) emission reductions of building retrofit measures in medium-sized office buildings in Ontario, Canada. The study focuses on evaluating the effects of using hourly marginal emission factors (MEFs) for electricity consumption compared to annual average emission factors (AEFs) to estimate operational greenhouse gas (GHG) emissions. Considering the limited availability of MEFs across jurisdictions in Canada, three cities located in different climate zones within the province of Ontario were selected for this study: Toronto (CZ5), Ottawa (CZ6), and Timmins (CZ7A). Operational carbon dioxide equivalent emissions were calculated by multiplying each of the considered emission factors by the annual consumption of each energy source required by the building, as specified in common carbon accounting methods such as the GHG Protocol and ISO 14064. The results for the buildings studied indicate that the annual emissions from electricity use are significantly higher when using MEFs in comparison to when using AEFs reported in the National Inventory Reports published by Environment and Climate Change Canada (ECCC). This means that scope 2 indirect emissions are significantly underestimated when using AEFs compared to MEFs. Additionally, in cases where natural gas is currently used as the primary heating fuel, estimating the emissions change for heating electrification using AEFs overestimates the percentage of GHG emission reduction associated by up to 23% compared to cases where MEFs are used.

Highlights
• Scope 2 indirect emissions are significantly underestimated when using AEFs, compared to MEFs.
• The use of AEFs overestimates the GHG emission reduction associated with switching heating fuels.
• Replacing HVAC systems, replacing windows, and reducing air leakage rate are the most effective retrofit measures to reduce operational GHG emissions in all studied locations.
• Lighting retrofits result in a net GHG emission increase in all locations when AEFs are used.
• The annual MEF in Ontario for the year 2020 is approximately six times higher than the annual AEF.

Introduction
The global buildings sector is responsible for around 27 per cent of global operational related CO₂ emissions (10 GtCO₂) (United Nations Environment Programme (UNEP), 2022), indicating that there is a great potential for GHG emissions reductions by targetting this sector. This study evaluates several strategies aimed at reducing operational GHG emissions through the retrofitting of existing buildings, which represent the majority of the total building stock.

In recent years, there has been a special emphasis not only on reducing energy consumption in buildings but also on reducing GHG emissions. This has been clearly reflected in current green building rating systems and standards, which now require reporting GHG emissions throughout the buildings life cycle (Canada Green Building Council (CAGBC), 2022). Targeting GHG emissions is certainly appropriate, but it requires the use of carbon accounting methods that are accurate, reliable, and reflect true effects in practice.

The most commonly used methodologies for GHG accounting are those proposed by the GHG Protocol (World Business Council for Sustainable Development (WBCSD) & World Resources Institute (WRI), 2004) and ISO 14064 standard (International Organization for Standardization (ISO), 2018, 2019). According to these methodologies, two types of GHG emissions need to be accounted at the operational stage of buildings: direct or scope 1 emissions (i.e., emissions that occur directly at the project site as a result of the combustion of fossil fuels, and fugitive emissions from refrigerants or other chemicals), and indirect or scope 2 emissions (emissions that do not occur directly at the project site, such as emissions from grid purchased electricity). This study specifically focuses on estimating GHG emissions due to energy consumption during the operational stage of buildings. Fugitive emissions such as those due to refrigerant leakage from HVAC equipment have not been considered.

Both direct and indirect GHG emissions are typically calculated by multiplying a GHG emission factor by the annual consumption of each energy source required by a building to meet energy demands. GHG emission factors are thus calculated ratios relating GHG activity data with the GHG emissions. The accuracy of this calculation method depends on the availability of site-specific energy consumption and emission factors.
Several existing studies have used emission factors to estimate the GHG emissions reduction effect of building retrofit measures. Kneifel (2010) investigated the life-cycle GHG emission reductions of retrofit measures in new commercial buildings and employed a state-level annual emission factor of electricity. Niemelä et al. (2017) utilized the average electricity emission factor from the last five years in Finland to determine the cost-effective renovation options for reducing GHG emissions. Garriga et al. (2020) used the average emission factor for electricity in Spain to examine the optimal carbon-neutral retrofitting of residential communities in Barcelona.

Based on the literature review, it is evident that there is insufficient research on estimating the GHG emissions resulting from building retrofit measures using dynamic electricity emission factors. Previous studies have used fixed electricity emission factors, which ignore the variability of electrical grid generating sources. Considering that electricity is one of the main energy sources in buildings, it is essential to calculate GHG emissions related to its use as accurately as possible. Therefore, it is crucial to examine the differences in estimated GHG emissions when utilizing dynamic emissions factors versus fixed annual values.

There are few studies like the one published by Lou et al. (2021), which uses dynamic emission factors. However, these emission factors represent the average carbon intensity of the electricity supply mix. They thus do not consider the sequence by which electricity generation facilities are dispatched to meet the demands called for by the grid. To overcome this limitation, this study uses marginal emission factors (MEF), which represent an estimate of the change in carbon emissions resulting from adding or removing loads from the electric grid.

In this study, hourly MEFs are used to calculate operational GHG emissions from implementing different building retrofit measures. Medium office buildings compliant with the 2020 version of the National Energy Code for Buildings (NECB) are used as a case study. The following sections are organized as follows: In the ‘Methods’ section, the design of the case study is introduced, including the selection of location, building retrofit measures, and the methodology employed to estimate the operational GHG emission reduction effects of each retrofit measure. The ‘Results’ section provides an analysis of the hourly GHG emission reductions achieved by applying individual retrofit measures, using one location as an example. The annual GHG emissions in tonnes of carbon dioxide equivalent (CO₂e) of baseline and retrofit models across all locations are also examined in this section, as well as variations between using MEFs versus AEFs for calculating indirect emissions. The last two sections correspond to the ‘Discussion’ and ‘Conclusions’, which summarize the most significant findings of the study.

**Methods**

A simulation-based approach was used to analyze the effects of building retrofit measures on operational GHG emissions reductions. The following subsections describe the simulation parameters that were considered to generate the baseline model, the retrofit measures that were implemented to reduce GHG emissions, and the GHG accounting methodology that was used to estimate the GHG emission reduction effect of the selected retrofit measures.

**Baseline model and selected locations**

Prototype office building models compliant with the 2020 version of the National Energy Code of Canada for Buildings (NECB) (Canadian Commission on Building and Fire Codes, 2020) are used as a case study. The prototype models are based on the United States Department of Energy (US DOE) reference building prototypes, but with only the geometry and space type information retained. The NECB 2020 ruleset is then applied to these skeleton geometric models to add the correct envelope and HVAC systems depending on the location of the building. This framework is based upon the U.S National Renewable Energy Laboratory’s OpenStudio software development kit (SDK) and allows to quickly generate prototype buildings based on different NECB version rulesets.

Considering the availability of MEFs, three cities located in different climate zones within the province of Ontario were selected for this study, i.e., Toronto, Ottawa, and Timmins. Actual Meteorological Year (AMY) EnergyPlus Weather (EPW) files for the year 2020 for each of these locations were generated with the “diyepw” tool developed by Pacific Northwest National Laboratory (Smith et al., 2021).

The effects of retrofit measures were evaluated using two sets of baseline models with different primary heating fuels (i.e., electricity and natural gas), which result in 42 models [3 locations x 2 models/location x (1 baseline model + 6 retrofit models)]. Table 1 summarizes the main simulation parameters of the baseline medium office models in each of the selected locations.

**Retrofit measures**

The selection of retrofit measures was based on the recommendations of the studies carried out by Lou et al. (2021) and by Ye et al. (2021).

To reduce heat transfer between the interior and exterior of the building through the building envelope, the level of insulation in walls and roofs was increased. This results in a reduction of the overall thermal transmittance (U-value) of these building envelope components compared to the baseline case. The overall thermal transmittance values that are used in the retrofit case correspond with those already included in the NECB 2020 for the coldest Canadian climate zone (i.e., climate zone 8). These values were agreed upon by the experts that develop the technical requirements for NECB, released for public review and ultimately approved by the Canadian Commission on Building and Fire Codes (CCBFC). For this reason, they are all seen as being technically achievable – i.e., it is possible to construct walls and roofs to these requirements (note this is independent of cost).
Airtightness is a critical factor to reduce energy consumption and operational GHG emissions. The airtightness of a building can be improved by using different air sealing techniques. From previous projects and experiments, it was estimated that the implementation of air sealing techniques could help reduce air leakage rates from 1.5 L/(s·m²) @ 75 Pa (which is the air leakage rate of NECB 2020 reference models) to 0.5 L/(s·m²) @ 75 Pa, which corresponds to the infiltration rates of a tight building (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2013). These values were used in the baseline and airtightness retrofit building models, respectively.

Table 1: Simulation parameters of the baseline medium office models in each of the selected locations.

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Toronto (CZ5)</th>
<th>Ottawa (CZ6)</th>
<th>Timmins (CZ7A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total floor area</td>
<td>4982 m² (49.91 m × 33.27 m × 3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of floors</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Window-to-wall ratio</td>
<td>40%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor-to-floor height</td>
<td>3.96 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walls U-value (W/m²·K)</td>
<td>0.265</td>
<td>0.24</td>
<td>0.215</td>
</tr>
<tr>
<td>Roof U-value (W/m²·K)</td>
<td>0.156</td>
<td>0.138</td>
<td>0.121</td>
</tr>
<tr>
<td>Windows U-value</td>
<td>1.9</td>
<td>1.73</td>
<td>1.73</td>
</tr>
<tr>
<td>Windows SHGC</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air leakage rate</td>
<td>1.5 L/(s·m²)@ 75 Pa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>People density (m² per person)</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting Power density (W/m²)</td>
<td>6.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plug load density</td>
<td>7.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HVAC system baseline</td>
<td>System 6: Multi-zone built-up system with baseboard heating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chiller COP</td>
<td>4.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating coil efficiency (%) (electric option)</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boiler thermal efficiency (%) (nat. gas option)</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water heater thermal efficiency (%) (electric option)</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water heater thermal efficiency (%) (nat. gas option)</td>
<td>91</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Discussions with industry experts indicate that lighting energy savings of around 20% can be readily achieved using the latest LED lighting technology. Thus, this measure assumes that all lighting fixtures in the baseline building models are replaced with high efficiency LED lights, resulting in a Lighting Power Density (LPD) reduction of 20%.

Another highly effective way to reduce operational GHG emissions is to replace existing HVAC systems that use fossil fuels as their primary heating fuel or that have low efficiencies. This measure focuses on replacing the HVAC system of the baseline models with a dedicated outdoor air system (DOAS) with fan coil air-cooled chiller and a central Air Source Heat Pump (ASHP). This is one of the recommended HVAC systems in the Advanced Energy Design Guide for Small to Medium Office Buildings from ASHRAE (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2019). Table 2 summarizes the retrofit measures that were considered in this study.

Table 2: Selected building retrofit measures for medium office buildings.

<table>
<thead>
<tr>
<th>Building retrofit measure</th>
<th>Input parameter</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add wall insulation</td>
<td>Reduce U-value to 0.165 W/m²·K</td>
<td>WALL</td>
</tr>
<tr>
<td>Add roof insulation</td>
<td>Reduce U-value to 0.11 W/m²·K</td>
<td>ROOF</td>
</tr>
<tr>
<td>Replace windows</td>
<td>Reduce U-value to 1.2 W/m²·K and SHGC to 0.25</td>
<td>WINDOW</td>
</tr>
<tr>
<td>Reduce air leakage rate</td>
<td>Reduce air leakage rate to 0.5 L/(s·m²) @ 75 Pa</td>
<td>INFILTRATION</td>
</tr>
<tr>
<td>Upgrade lighting system</td>
<td>Reduce LPD to 5.2 W/m²</td>
<td>LIGHT</td>
</tr>
<tr>
<td>Replace HVAC system with a dedicated outdoor air system (DOAS) with fan coil air-cooled chiller and a central Air Source Heat Pump (ASHP)</td>
<td>Install a chiller with a COP of 6</td>
<td>HVAC</td>
</tr>
</tbody>
</table>

GHG emissions calculation approach

The carbon accounting methodology proposed by the GHG Protocol (World Business Council for Sustainable Development (WBCSD) & World Resources Institute (WRI), 2004) and ISO 14064 (International Organization for Standardization (ISO), 2018, 2019) was used in this study to estimate operational GHG emission reductions due to the implementation of each of the building retrofit measures discussed in the previous section. First, the GHG emission sources associated with the building operation are identified and categorized as scope 1 (direct) emissions and scope 2 (indirect) emissions. Then, the operational GHG emissions of the baseline CO₂eq and of each retrofit model CO₂eq are calculated by multiplying an emission factor by the consumption of each energy source required by the building, as shown in Equation (1):
Winter 9:00 × 15:00 12:00 × 15:00 Fall

\[ CO_2_i = \sum_{t=1}^{n} CO_2_{i,t} = \sum_{t=1}^{n} (CO_2_{e,el,t} + CO_2_{NG,t}) = \sum_{t=1}^{n} (E_t \times EF_{el,t} + NG_t \times EF_{NG}) \] (1)

Where \( CO_2_{i,t} \) represents the GHG emissions at time \( t \), \( n \) is the total number of hours in a year (8760 hours in this study), \( CO_2_{e,el,t} \) is the GHG emissions from electricity at time \( t \), \( CO_2_{NG,t} \) is the GHG emissions from natural gas at time \( t \), \( E_t \) is the electricity consumption at time \( t \), \( EF_{el,t} \) is the electricity emission factor at time \( t \), \( NG_t \) is the natural gas consumption at time \( t \), and \( EF_{NG} \) is the emission factor of natural gas, which was assumed to be constant (a value of 0.18 kgCO₂e/kWh was used). For this study, this calculation was automated with an OpenStudio measure that reports the hourly GHG emissions. The measure receives the hourly consumption of each energy source, i.e., \( E_t \) and \( NG_t \), from the building energy simulations conducted with the OpenStudio SDK framework that was previously discussed.

Hourly MEFs for Ontario’s electricity system were produced by Power Advisory LLC under an engagement with Enbridge Gas Inc. These MEF estimates are based on the relationship between Ontario’s electricity demand, gas-fired electricity generation, electricity production from all other generation sources (i.e., nuclear, hydro, wind, solar and bioenergy), and imports/exports with neighbouring jurisdictions. Since the majority of Ontario’s electricity generation sources such as nuclear, hydro, wind, solar and bioenergy have little or no operational emissions, the emissions come primarily from two sources: natural gas-fired generators, and emissions associated with imported electricity. Thus, the MEFs produced by Power Advisory take into account emissions from these two sources. Although natural gas-fired generation currently supplies only a moderate share (around 12%) of Ontario’s electric energy, it plays a crucial role in balancing supply and demand, as ramping primarily comes from gas-fired and hydroelectric generation. More information about the methodology that was used to generate electricity MEFs can be found in Power Advisory’s public report (Lusney, 2020).

Finally, the GHG emissions reduction of each individual retrofit measure was obtained using Equation (2):

\[ GHG_{red} = \frac{C02_0 - C02_i}{C02_0} \times 100\% \] (2)

Where \( C02_0 \) is the GHG emissions of the baseline building model, and \( C02_i \) is the GHG emissions of the building after the implementation of a retrofit measure.

Results

The MEFs corresponding to the year 2020 are summarized in Figure 1. During the summer season, except for the early morning, the MEFs are at their highest level whereas they are at their lowest during spring. However, there is considerable fluctuation in MEFs throughout the day in all seasons, with the early evening having the highest MEFs. Figure 2 shows a heatmap summarizing the GHG emission reduction corresponding to each individual retrofit measure in Toronto. The GHG emission reduction was obtained by subtracting the emissions of the retrofit cases from emissions of the baseline building. Red indicates a decrease in GHG emissions, while blue indicates an increase in GHG emissions. HVAC is the retrofit measure that shows the highest GHG emission reductions. The HVAC measure helps to reduce GHG emissions specially during the winter and summer seasons, which have the highest MEFs. It is important to note that in the case shown in Figure 2, the baseline model uses natural gas as primary heating fuel, which is the most common scenario in Toronto’s office buildings.

Another measure that significantly helps reduce emissions is replacing windows. As indicated in Table 2, this measure includes reducing the U-value and the SHGC. As shown in Figure 2, this measure helps to reduce emissions especially during summer when cooling loads are high in office buildings. The low SHGC and U-value help to reduce these loads, resulting in a significant reduction in energy consumption and GHG emissions compared to the baseline model. Figure 2 also shows that reducing air leakage rate is another retrofit measure that significantly helps to reduce GHG emissions, especially in winter.

As seen in Figure 2, lighting retrofits partly help reduce emissions during summer, but it can also increase emissions in winter due to higher heating demand.
(internal lighting heat gains are lower). Finally, Figure 2 shows that measures aimed at increasing insulation in walls and roofs have no major effect on reducing operational GHG emissions.

Figure 2: Heat map summarizing the estimated GHG emission reductions (kgCO2e) corresponding to each individual retrofit measure in Toronto (GHG emissions are calculated using hourly MEFs).

Figure 3 shows the annual GHG emissions of the baseline and retrofitted building models in the three studied locations. For comparison purposes, indirect emissions were calculated using both AEFs and MEFs. The electricity AEF of Ontario for the year 2020 was obtained from the National Inventory Reports (NIR) published by Environment and Climate Change Canada (Environment and Climate Change Canada, 2022).

As can be seen in Figure 3, estimated GHG emissions are considerably higher when using MEFs to calculate indirect emissions, especially in cases where electricity is used as primary heating fuel. This is due to the significant difference between the annual average of hourly MEFs (173 gCO2e/kWh for 2020) and the annual AEFs published in the NIR reports (28 gCO2e/kWh for 2020).

In cases where natural gas is used as the primary heating source, direct emissions represent between 60 to 80% of the total emissions when AEFs are used to calculate indirect emissions. In contrast, when MEFs are used to calculate indirect emissions, direct emissions represent only 20 to 30% of the total GHG emissions. Figure 3 also shows that the retrofit measures that have the highest potential to reduce operational GHG emissions are replacing the HVAC system, replacing windows, and reducing air leakage rate.

Figure 4 shows the percentage of GHG emissions reductions that can be obtained by implementing each retrofit measure in all the studied locations. Similar to the previous case, the percentage of GHG emission reduction was calculated using both AEF and MEF.

Figure 3: Comparison of annual GHG emissions of baseline and retrofit models in all studied locations.
As can be seen in Figure 4, there are only differences in cases where natural gas is used as primary heating fuel. In those cases, the use of AEFs overestimates the percentage of GHG emission reduction associated with the HVAC retrofit measure by up to 23% compared to cases where MEFs are used. This is mainly due to fuel switching. When using AEFs to calculate indirect emissions, switching to electric heat pumps represents a change in the emission factor from 180 gCO₂-e/kWh (corresponding to the emission factor of natural gas) to 28 gCO₂-e/kWh (corresponding to the AEF of electricity). On the other hand, when using MEFs, the emission factors of electricity and natural gas are similar (180 gCO₂-e/kWh for natural gas and 173 gCO₂-e/kWh corresponding to the MEF of electricity), so the emission reductions are mainly due to improved efficiency.

Another important aspect that can be observed in Figure 4 is the difference in the percentage of emission reduction associated with lighting retrofits. When using AEFs to calculate emissions, lighting retrofits result in a slight increase of GHG emissions (between 0.3 and 2%). In contrast, when using MEFs, this measure results in a net GHG emission reduction of around 3 to 4%.

**Discussion**

The results of the study show that the electricity emission factors used to estimate operational GHG emissions have a significant impact on the results. For example, if AEFs are used, the results indicate that lighting retrofits tend to increase GHG emissions instead of reducing them. On the other hand, if MEFs are used, the results indicate that lighting retrofits help reduce GHG emissions, even to a greater extent than measures such as increasing insulation in walls and roofs. These results suggest that the use of the appropriate type of emission factors is essential for estimating GHG emissions. Using AEFs to estimate GHG emission reductions due to retrofit measures can produce misleading results because AEFs do not consider the time-dependent impacts of electricity generation and consumption.

The results obtained also highlight the importance of reducing the carbon intensity of the electric grid prior to or concurrently with implementing electrification measures in buildings. If this is not done, the carbon intensity of Ontario’s electric grid could be expected to increase, and electrification measures will not have a significant effect on GHG emissions reduction since the current annual average electricity MEF for Ontario is similar to the emission factor of natural gas.

According to the results of the study, the retrofit measures with the highest GHG emission reductions in all studied locations are: replacing the HVAC system, replacing windows, and reducing the air leakage rate. The results of the study also indicate that there is no significant difference in GHG emissions associated with the implementation of retrofit measures in different climate zones. Also, it was observed that lighting retrofits are less effective for reducing operational GHG emissions in colder climates, such as Timmins, since additional heating will be needed when internal heat gains from lights are reduced.

![Figure 4: Percentage of GHG emission reductions compared to baseline case for individual retrofit measures for MEF versus AEF calculation methods.](https://doi.org/10.26868/25222708.2023.1690)
Conclusion

For evaluating the impact of retrofit measures on operational GHG emissions of buildings, it is important that the emission factors that are used consider the sequence by which electricity generation facilities are dispatched to meet the demands called for by the grid. The results show that when these aspects are taken into consideration through the use of MEFs, the electricity emission estimates can be significantly higher than when using AEFs reported in NIR reports, which represents the average carbon intensity of the electricity supply mix and is commonly used to estimate operational GHG emissions from buildings. This means that indirect emissions are significantly underestimated when using AEFs compared to MEFs.

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References