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Sustainability of telework: Systematic quantification of the impact of teleworking on the energy use and emissions of offices and homes

Farzam Sepanta [*], Melina Sirati, William O'Brien

Department of Civil and Environmental Engineering, Carleton University, Colonel By Dr, Ottawa, ON, K1S 5B7, Canada

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ABSTRACT

Previous research has explored the impact of telework on homes and offices separately, but it is necessary to examine these domains together, as energy savings in one may be offset by increased consumption in the other. Therefore, the present study aims to fill this gap by quantifying the impact of telework on the energy use of homes and offices simultaneously. Using a medium office building reference model and four home models, the present study simulates telework scenarios from 0 % teleworking to 100 % teleworking in 20 % increments in six different Canadian climate zones in EnergyPlus. The results show homes and offices with technologies that adapt to occupancy levels (adaptable) consume less energy and produce less emissions compared to inadaptable ones. However, energy use associated with homes increases slightly due to longer hours of occupancy. Emissions associated with telework depend on the impact of telework on internal heat gains, climate zones, and sources of energy (emission factors). The results demonstrate that the increase in energy consumption associated with various teleworking scenarios ranges from approximately 0.6 %–6.1 %. Similarly, the increase in emissions varies, ranging from nearly 0.5 % to 7.6 %. The present study is the first comprehensive study that considers the home type and size and other statistical data for different Canadian climate zones. The results have major implications for employers and policymakers aiming to adopt telework as a sustainable practice. The results of this study create the foundation for future comprehensive studies on teleworker behavior, transportation, and the internet use associated with telework.

1. Introduction

1.1. Teleworking and occupancy

Partial occupancy in offices has become a more common global phenomenon after the COVID-19 pandemic, as many employers started offering flexible schedules with telework options [1–4]. Teleworking has different definitions but it can be generally defined as an umbrella term referring to working outside of a traditional office by using the internet [5]. Telework is often considered a sustainable alternative to traditional work arrangements as it can potentially reduce commute or the need for office space [4]. However, recent studies have shown that the potential sustainable benefits of teleworking significantly rely on teleworkers' behaviors and decisions for four domains of homes, offices, transportation, and the internet [4,6,7]. Among all the four domains, the relationship between homes and offices has been less studied – especially quantitatively. Thus, the literature is inconclusive about the impact of

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[*] Corresponding author.
E-mail address: Farzamsepanta@cmail.carleton.ca (F. Sepanta).

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telework on homes and offices concurrently.

Offices and homes are not typically designed to adapt to partial occupancy, meaning building systems such as HVAC systems are designed for full capacity. For instance, actual occupancy pre-COVID was usually between 50 % and 70 % in office buildings while office buildings are assumed to be operating under near-full occupancy [8,9]. Consequently, studies have shown building systems normally operate at their full capacity without considering occupancy [10,11]. The disproportionate decreases in the energy use of office buildings compared to occupancy during the COVID-19 pandemic are evidence of this phenomenon [12–17]. Meanwhile, home energy use may increase significantly as a result of the use of more comfortable temperature setpoints or even the purchase of new HVAC equipment, like air conditioning. In part-time teleworking scenarios, such equipment may be operated every day, regardless of occupancy [6,18,19]. Therefore, it is important to have buildings that can adapt to partial occupancy [20]. As a result, there is an urgent need to quantify the impact of telework and partial occupancy on two main building types, homes and offices, under different teleworking scenarios.

1.2. A brief literature review

Most occupancy profiles for buildings were developed during the 1980s when teleworking was not widespread due to technological limitations [21] and employer acceptance. With recent developments in technologies, the literature on building adaptability to partial occupancy is still limited. Table 1 summarizes the literature with the main findings.

1.3. Importance and novelty

While most studies in Table 1 focused on lighting and DCV, studies on other technologies and strategies such as occupancy-based plug loads or thermostat setpoints are limited. A recent study on offices systematically studied the impact of 0 %, 50 %, and 100 % occupancy on offices with different technologies [22]. However, the aforementioned study did not quantify the impact of lower and higher than 50 % occupancy levels. In addition, it did not study the impact of telework on homes and offices simultaneously. A recent study suggested quantifying the impacts of telework simultaneously on different domains, including homes and offices, since energy savings from one can be offset by energy use increase in the other [6]. With major changes to traditional working arrangements and a widespread shift to telework [29–32], it is essential to quantify the impact of telework on homes and offices as two main building types occupied by teleworkers and non-teleworkers.

1.4. Aim and research questions

To quantify the impact of telework on offices and homes simultaneously, this study aims to quantify the impact of 0 %–100 % teleworking scenarios with 20 % increments on homes and offices in climate zones 4 to 8 that span all of Canada (Zone 4 includes areas like Vancouver while Zone 8 includes areas like Nunavut province). Each building type (home and office) includes an adaptable and inadaptable version in which adaptable refers to a building type equipped with occupancy-based systems. The adaptable office is equipped with occupancy-based lighting, occupancy-based receptacles (smart plugs), demand-controlled ventilation (DCV), and an occupancy-based thermostat (relaxed setpoints for unoccupied hours). The adaptable homes are equipped with reduced thermostat setpoints when occupants are away and during the night. To compare the results, the study reports on the energy use intensity (EUI) and associated GHG emissions in a medium Canada's National Energy Code for Buildings (NECB)-compliant office building. Home models are derived from an earlier study on homes and telework [19]. This study tries to address the following research questions (RQ):

- RQ1. What is the impact of telework on the office-and-home combination in terms of energy use in different climates?
- RQ2. What are the differences between adaptable and inadaptable offices and homes in terms of energy use in different climates?
- RQ3. How do adaptable and inadaptable offices and homes impact the associated GHG emissions with telework and different occupancy scenarios?

1.5. Contributions

With scarce literature on telework and energy use in offices and homes and a vital need to quantify the impact of telework on offices and homes, this study is the first comprehensive quantification of the impact of telework in terms of energy use and GHG emissions on

Table 1
A literature review on partial occupancy and telework.

Study	Main findings	Domain
[22]	Using occupancy-based systems in offices can result in savings of up to almost 42 % on overall building energy consumption	Offices
[23]	Demand-controlled ventilation (DCV) can save between 8 % and 16 % based on occupancy on the overall annual HVAC system energy use	Offices
[24]	20.3 % savings on the HVAC system are possible by using DCV and changing thermostat setpoints based on occupancy	Offices
[25]	Different strategies, such as using blinds or DCV, can result in up to 12 % savings on the overall energy use of the building	Offices
[10]	Occupancy-based lighting energy use decreased by controlling lighting zones (more than 50 % savings in partial occupancy)	Offices
[26]	Occupancy-based systems (such as lighting and DCV) can help reduce energy use in buildings	Offices and homes
[19]	Dual-zone HVAC systems can reduce energy use by up to 31 % on the overall energy use of homes	Homes
[27]	Household energy use can increase to more than 100 % in some scenarios	Homes
[28]	Using setbacks in thermostat setpoints resulted in up to 20 % savings on heating	Homes

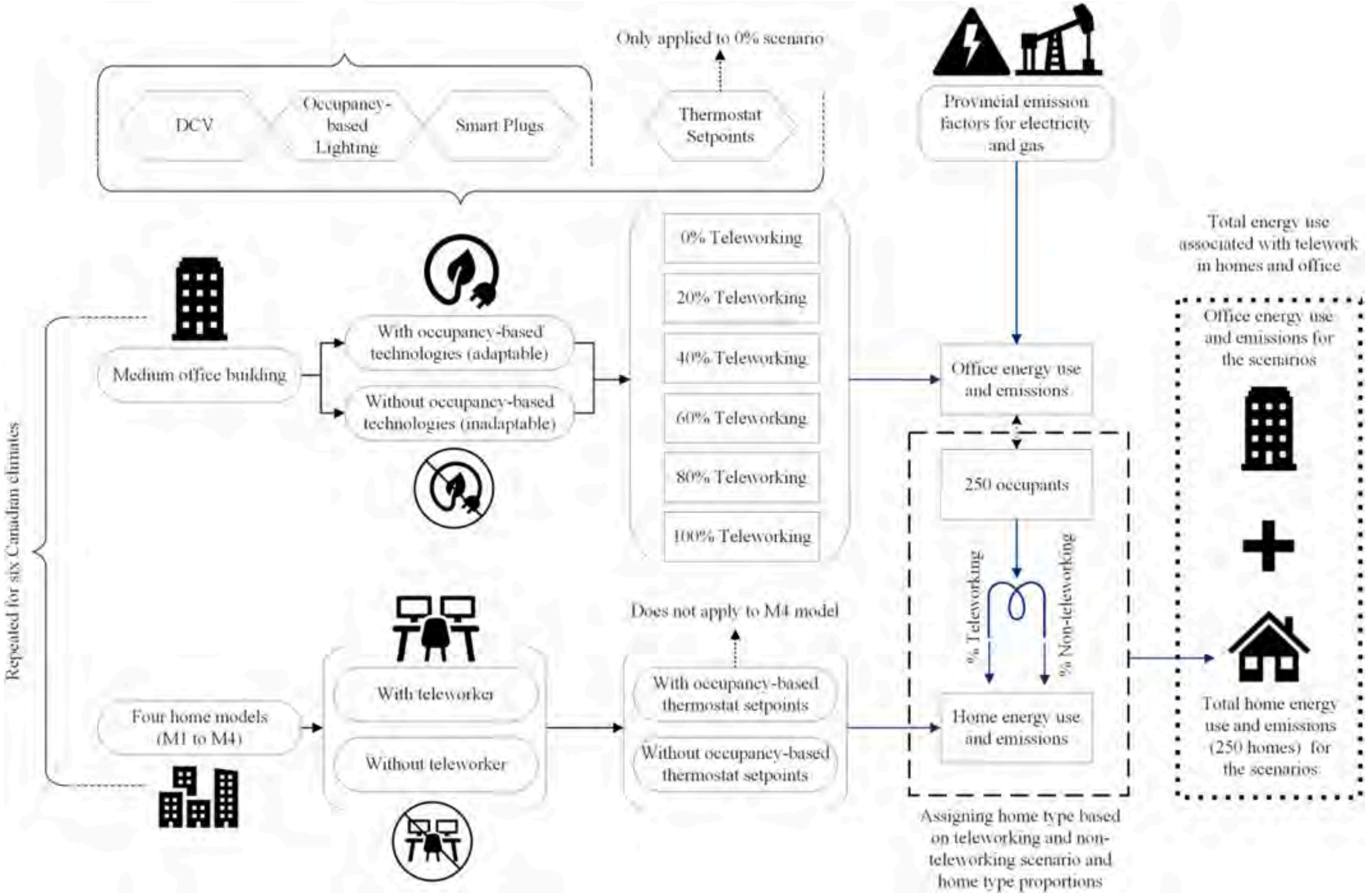

Fig. 1. An overview of the research method.

offices and homes simultaneously. Furthermore, the present study demonstrates the impact and differences of adaptable and inadaptable offices and homes in terms of energy use and GHG emissions.

The upcoming sections of this paper describe the simulation models (Section 2.1.1) and occupancy scenarios in detail (Section 2.1.2). Then, different methods of implementation of technologies are explained in Section 2.1.3. Energy use and values for GHG emissions are described in section 2.2. After that, the results and major findings are presented for offices and homes (Sections 3.1 to 3.3).

2. Research methodology

Fig. 1 shows the overall research method of this paper. After developing a base case, four technologies and operating strategies including demand-controlled ventilation (DCV), occupancy-based lighting, smart plugs (occupancy-based plug loads), and scheduled thermostat setpoints in permanently unoccupied zones are investigated and compared to the baseline. In the end, the compound effect of all controls is investigated as well. This section of the article presents the models (Section 2.1.1 and Section 2.2), scenarios (Section 2.1.2), methods of implementation of technologies (section 2.1.3), and reporting metrics (Section 2.3).

2.1. Office building

2.1.1. Simulation model

The simulation model consists of five thermal zones (four perimeter zones and one core zone) that follow the National Energy Code of Canada for Buildings (NECB) in EnergyPlus version 22.2.0 [33]. The floor area of the core zone and perimeter zones are equal. Fig. 2 shows the simulation model and Table 2 describes the simulation model's parameters.

Table 3 summarizes the R-values for different surfaces of the simulation model based on the NECB in different climates. The corresponding heating degree days (HDD) and Köppen–Geiger classification are also summarized [34–36]. The model is also compared to ASHRAE's international benchmark to make sure the model functions as expected [37]. The representative cities of each climate are selected based on their HDDs. The selection criteria of the cities were having the average HDD for the corresponding climate zone.

2.1.2. Scenario analysis for offices and homes

Six main scenarios are carried out from 0 % teleworking (100 % occupancy in office – scenario 1) to 100 % teleworking (0 % occupancy in office – scenario 6) with 20 % increments for each adaptable and inadaptable home and office (Fig. 3) in six different Canadian climates. The 0 % teleworking (100 % occupancy in office – scenario 1) schedules follow the schedules of NECB which is very similar to ASHRAE 90.1 [38,39]. The 100 % teleworking scenario (Scenario 6) indicates the office building's ability to adapt to 0 % occupancy when all employees are teleworking from home (home occupancy = 100 %). In reality, office buildings rarely reach full occupancy [20]. Office buildings might only reach their full capacity if the total number of users exceeds the number of workstations, which is most likely to happen if employers apply activity-based unassigned work environments.

In this study, home type proportion is assigned by statistical surveys of 2019 and 2021 [40,41]. The home types were used and assigned to different teleworking and non-teleworking occupants similarly (Table 4). The scenario analysis for this study for the net integrated energy use of homes and offices (E) is calculated using (non)teleworking ratio, office occupants, assigned home type ratio, corresponding energy use or emissions plus office energy use or emissions for the corresponding teleworking ratio (Eq. (1) where $E_{scenario}$ is total energy use or emissions, E_{home} is the total energy use or emissions based on home type and proportions as per Table 4 for the total number of homes (this paper assumes 250 homes for 250 occupants in the office building), and E_{office} represents the office energy use or emissions for the particular scenario). To calculate emissions, natural gas and electricity consumed by homes and offices are multiplied by the corresponding emission factors of the climate zones using Eq. (2) where $Em_{Scenario}$ represents the total emissions from both homes and offices under the analyzed scenario. $E_{gas,\ home}$ and $E_{elec,\ home}$ denote the energy consumed from natural gas and

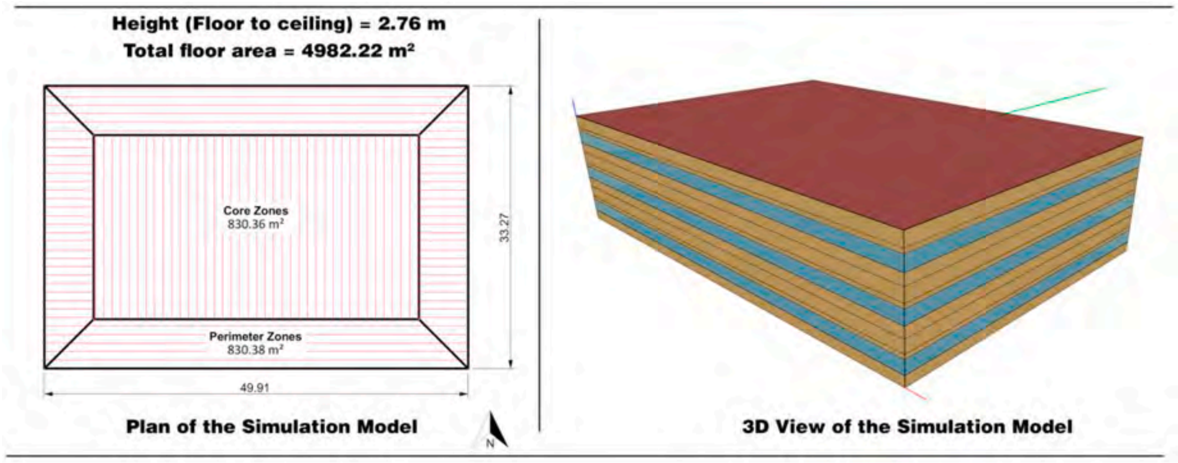

Fig. 2. The simulation model in EnergyPlus; the model is the reference building model for medium office buildings [22].

Table 2
Simulation parameters [22].

Parameter	Value
Maximum number of occupants	250 people
Zone net floor area per person	19.92 m^2/person
Occupant heating gain	130 W/person
Lighting |Lighting power density (LPD)	175.37 W/person | 8.79 W/m^2
Plug load	10.27 W/m^2
Infiltration rate	0.00025 m^3/s-m^2
Outdoor airflow per person	0.00863 m^3/s-person
Economizer[a] control type	Fixed Drybulb
Economizer maximum limit dry bulb temperature	18 °C
Economizer minimum limit dry bulb temperature	5 °C
Economizer lockout type	Lockout with Compressor
HVAC type	Baseboards connective water heaters and VAV with Reheat
Heating coil fuel type	Natural gas
Boiler efficiency	0.95
Chiller type	Scroll - Electric
Chiller reference COP	4.5
Supply air temperature[b] setpoint	13 °C
Supply air temperature setpoint (thermostat)	Varies

[a] The economizer controls are used to increase outdoor airflow beyond that needed for ventilation when the outdoor temperature is between the specified values, in order to reduce reliance on mechanical cooling.

[b] Air temperature that is distributed by the HVAC system.

Table 3
R-values and U-values for different surfaces of the office building model in six different climates of Canada [22].

Climate Zone	Climate info		Walls		Foundation		Roof		Windows	
	HDD (°C-day)	Köppen–Geiger classification	U-value W/m^{2}K	R-value m^{2}K/W	U-value W/m^{2}K	R-value m^{2}K/W	U-value W/m^{2}K	R-value m^{2}K/W	U-value W/m^{2}K	SHGC
4	<3000	Cfb (oceanic climate)	0.315	3.175	0.757	1.321	0.193	5.181	2.1	0.31
5	3000–3999	Dfa (hot-summer humid continental climate)	0.278	3.597	0.757	1.321	0.156	6.410	1.9	0.31
6	4000–4999	Dfb (warm-summer humid continental climate)	0.247	4.049	0.757	1.321	0.156	6.410	1.9	0.31
7A	5000–5999	Dfb (warm-summer humid continental climate)	0.210	4.762	0.757	1.321	0.138	7.246	1.9	0.31
7B	6000–6999	Dsc (subarctic climate)	0.210	4.762	0.757	1.321	0.138	7.246	1.9	0.31
8	>7000	ET (tundra climate)	0.183	5.464	0.379	2.638	0.121	8.264	1.4	0.31

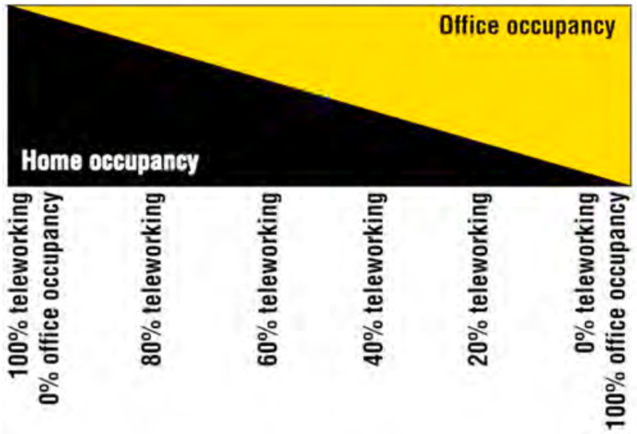

Fig. 3. The sum of teleworkers and non-teleworkers is always 100 %.

electricity in homes, respectively, while $E_{gas,\ office}$ and $E_{elec,\ office}$ refer to the energy consumed from these sources in office settings. The emission factors for natural gas and electricity are represented by $EF_{gas,\ zone}$ and $EF_{elec,\ zone}$, respectively, which quantify the emissions per unit of energy consumed and are specific to the climate zones. The emission factors for natural gas and electricity are described in

Table 4
Home type distribution.

Zone	Home type[a]			
	Type 1	Type 2	Type 3	Type 4
Zone 4	0.14	0.14	0.12	0.6
Zone 5	0.14	0.25	0.17	0.44
Zone 6	0.16	0.29	0.24	0.31
Zone 7A	0.24	0.35	0.19	0.22
Zone 7B	0.15	0.35	0.17	0.33
Zone 8	0.29	0.42	0.29	0

[a] Home types are described in Section 2.2 (They are labeled as M1 to M4).

section 2.3.

$$E_{Scenario} = E_{home} + E_{office} \tag{1}$$

$$Em_{Scenario} = \left(E_{gas,home} \times EF_{gas,zone} + E_{elec,home} \times EF_{elec,zone}\right) + \left(E_{gas,office} \times EF_{gas,zone} + E_{elec,office} \times EF_{elec,zone}\right) \tag{2}$$

2.1.3. *Methods of implementing occupancy-based systems*

2.1.3.1. Equipment sizing. The HVAC equipment defined in the simulation model is hard-sized (meaning they are assigned a total capacity) based on 100 % occupancy.

2.1.3.2. Plug loads and smart plugs. Plug loads are one of the uncertain components of office buildings as plug loads depend on the actual number of occupants in buildings. A recent paper introduced an equation for plug loads based on occupancy (W/m^2) which makes the plug loads a function of the actual number of occupants [42]. To address the uncertainty associated with plug loads in offices, the present paper utilizes Eq. (3) to simulate plug loads as a function of the number of occupants. The equation works for occupied and unoccupied hours.

$$y = \frac{x - d}{c} \tag{3}$$

Where c is 0.00703 (constant) and d is -0.0222 (constant), and x is 0.05 (person/m^2) (x represents the instantaneous occupant density). The total and minimum plug load (y) are 10.27 W/m^2 for 250 occupants (total number of occupants) and 3.16 W/m^2 for the empty building, respectively. The plug load for full occupancy based on the schedule is 9.56 W/m^2 because of the 0.9 fraction in the full occupancy schedule. These values and hourly changes based on occupancy are modeled in EnergyPlus using schedules (see Fig. 4).

To model the smart plugs, the present study conducted a comprehensive literature review on the potential electricity savings of smart plugs. Table 5 summarizes the major findings. Consequently, results show an average of 25 % savings in electricity consumed by plug loads is reasonable according to larger datasets. To simulate savings from smart plugs, a 25 % savings is applied to plug loads (see Fig. 4, Fig. 5 and Fig. 6). Smart plugs generally achieve these savings through load-sensing, schedule timer, or both features.

2.1.3.3. Occupancy-based lighting. Lighting is assumed to be controlled based on occupancy for adaptable offices, meaning lighting

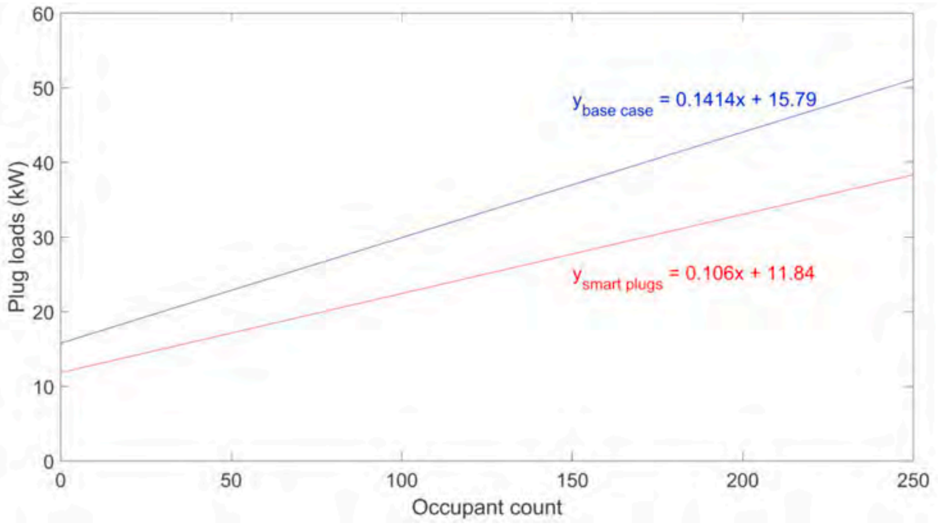

Fig. 4. Relationship between plug loads and occupant count (office); note that occupant count never reaches 250 due to the maximum fraction of 0.9 in occupancy schedules. The figure shows using smart plugs reduces the y-intercept and slope of the line by 25 %. Y-intercept never reaches zero in this case because of the reserved plug loads for occupancy-independent activities within the buildings [22].

Table 5
Potential savings from smart plugs in different studies.

Study	Findings	Quality of dataset
[43–47]	9 %–60 % potential savings relative to electricity consumed by plug loads	Average
[48,49]	An average of 25 % savings relative to electricity consumed by plug loads	High

follows occupancy schedules plus an extra 5 % for safety and security purposes (see Fig. 8). The base normalized light power in this study is 175.4 W/person (refer to Figs. 7 and 8 for examples of occupancy-based lighting in the simulation model).

2.1.3.4. Occupancy-based thermostat setpoint schedule. Occupancy-based thermostat setpoint change refers to reducing the standard NECB-based thermostat setpoints to 17 °C degrees for all hours in the office model only in the 100 % teleworking scenario. The regular setpoint schedule is shown in Fig. 9 (Regular heating setpoints are 18 °C, 20 °C, and 22 °C). Cooling setpoints are not changed since the air system is turned off at night. However, the heating setpoint is reduced from its daytime level because a hydronic system maintains it, even when the air handling units are turned off.

2.1.3.5. Demand-controlled ventilation (DCV). According to NECB, DCV is not mandatory for office buildings. Therefore, DCV is not used in the inadaptable (base) model. In the adaptable model, DCV is activated using the "Proportional Control Based on Design Occupancy" method in EnergyPlus. This technique establishes the lowest external airflow rate that the mixed air box of the AHU must supply. The flow rate is calculated using the design occupancy (occupant density multiplied by occupancy schedules) along with a minimum outdoor flow rate of 0.00863 m^3/s for each person. Fig. 10 shows a typical week with DCV. This approach is preferred over the CO_2 concentration approach for this study because the study's goal is to quantify the impact of telework on office buildings, not to sense occupants.

2.2. Home models

Table 6 presents the presumptions linked to the home archetypes as outlined in a prior research paper [19]. The thermal characteristics of the home designs are provided in Table 7, while Table 8 sets out the months designated for cooling and heating in each climate zone. Fig. 11 shows the simulation models.

2.2.1. Occupancy and thermostat setpoints

In all scenarios explored in M1 to M3, three residents have full-time jobs or attend school and leave home at 8 a.m., returning at 6 p.m. on weekdays (with a presumed 1-h daily commute [55]). One resident works full-time for five days, while in the baseline scenario, this resident leaves during office hours. During teleworking days, this individual is alone at home from 8 a.m. until 6 p.m., leading to partial occupancy for 10 h a day. The house is fully occupied on weekends in all scenarios. It's important to note that there are no warmup hours considered in modeling the HVAC system. This means that when the household uses setback temperatures in winter or set-up temperatures in summer, these settings are used exactly during their absence between 8 a.m. and 6 p.m.

The assumptions for thermostat setpoints were derived from Section 9.36 of NBC 2020 requirements [53]. Thermostat setbacks and set-ups were established based on a survey of household energy use in 2019 as there are no specific recommendations regarding these in the NBC [56]. In all cases, the winter setpoint (excluding the basement) is maintained at 20 °C and summer at 25 °C, with a setback to 18 °C in winter and set-up to 27 °C in summer (Table 9) [53]. The setbacks/set-ups may be used based on the scenario to see the effects of different occupants' behavior in addition to teleworking on energy consumption and GHG emissions. The impacts of different occupant behaviors, including teleworking, on energy consumption and GHG emissions can be observed by applying these setbacks/set-ups based on two scenarios: households not adjusting their thermostat during away hours or overnight and those utilizing both during away hours and night. The basement is heated to a minimum of 19 °C during the day in winter when the house is occupied

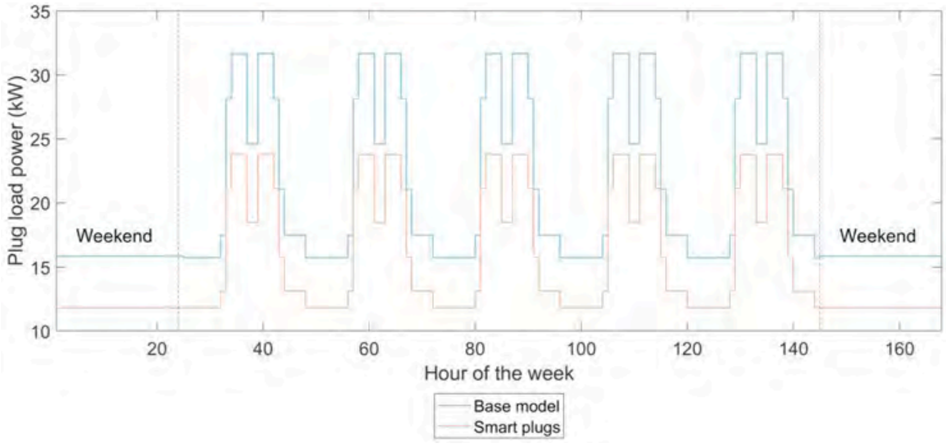

Fig. 5. A typical week for building-level plug loads (Office) comparing smart plugs and the base model during the full occupancy scenario [22].

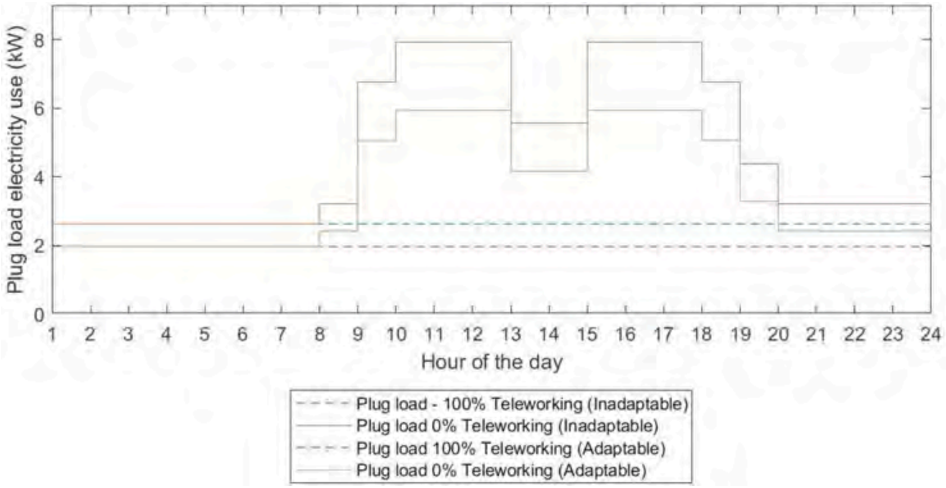

Fig. 6. A typical hourly plug load for the office building [22]. The schedules are based on Eq. (3) for both adaptable and inadaptable models meaning the plug loads follow the occupancy regardless. Smart plugs are modeled by applying a 25 % savings on the traditional plug loads calculated using Eq. (3).

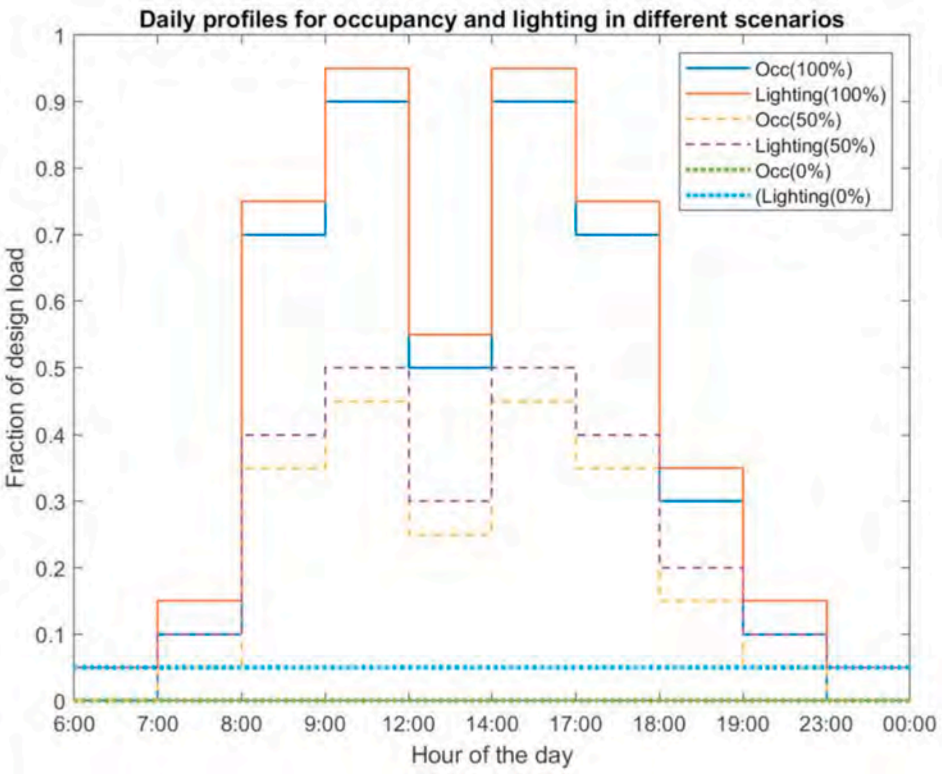

Fig. 7. Occupancy and lighting profiles for occupancy-based lighting in offices. Weekends follow the schedule for unoccupied hours (23:00 to 7:00) [22].

and a minimum of 17 °C during unoccupied hours, but it does not follow the cooling setpoint requirements outlined in NBC 2020 section 9.36 (Detailed design values are outlined in Table 9). [53]. In the mid-rise (M4) model, we assumed that all households adjust their thermostat settings at night and during away hours to conserve energy, employing setback temperature in winter and set-up temperature in summer. We analyzed a baseline scenario and a scenario that assumes 100 % of households have a teleworker who remains at home for full-time work (32 suites).

2.3. Reporting metrics for comparisons

Energy Use: is the total energy use reported in kWh, MWh, or GWh. It also reports on electricity for different components,

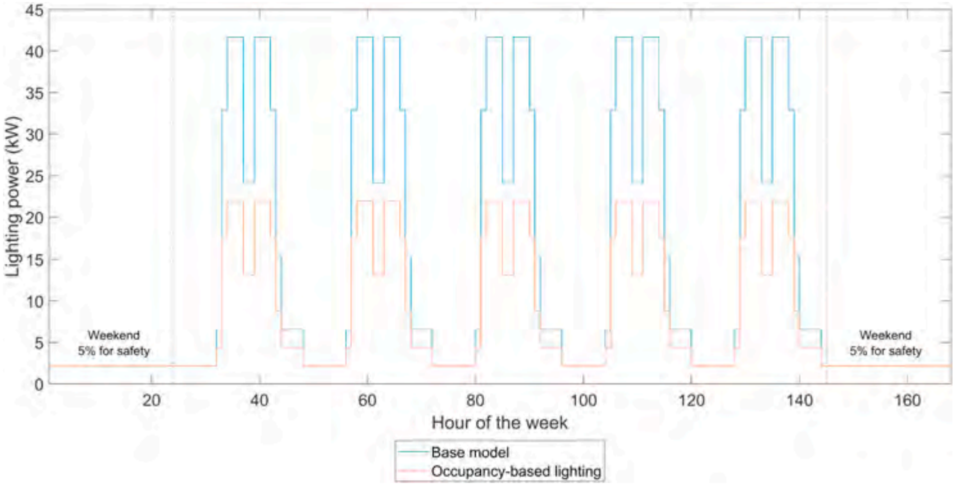

Fig. 8. A typical week for occupancy-based lighting for offices [22].

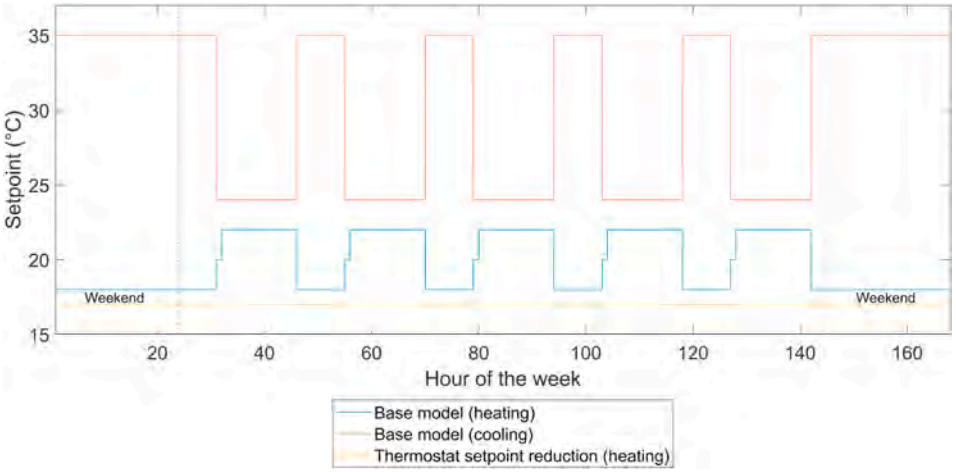

Fig. 9. Thermostat setpoints in the base model and thermostat setpoint strategy in offices [22].

including space cooling, fans, lighting, receptacle equipment, and gas for the boiler.

GHG Emissions: are calculated using the CO_2 equivalent (CO_2e) based on the data from Natural Resources Canada for natural gas and electricity in the provinces of Canada [60]. The emission factors (Table 10) are then multiplied by the total energy used by end-uses (i.e., electricity and natural gas). Note that significant differences in values are due to a wide variety of electricity sources ranging from mainly hydroelectric (in zone 4 – British Columbia) and nuclear to those heavily reliant on fossil fuels (in zones 7A and 8 – the territories).

3. Results

In this section, energy use and emissions associated with offices, homes, and their integrated net are described in Sections 3.1, 3.2, and 3.3. The results presented in the Offices and Homes sections are applicable to their respective domains.

3.1. *Offices*

3.1.1. *Internal gains and inadaptable and adaptable offices*

Fig. 12 shows the internal heat gain in W for adaptable and inadaptable offices in six different climate zones. While previous studies pointed to the impact of internal gains [22], the present study quantifies the impact. Fig. 12 shows reduced heat gains from people, equipment, lights, hot water equipment, gas equipment, and other equipment. The reduction in heat gains causes more demand for heating in buildings.

3.1.2. *Teleworking scenarios and offices*

Fig. 13 shows the results of different teleworking scenarios in adaptable and inadaptable offices in different climates. Zone 8 as the

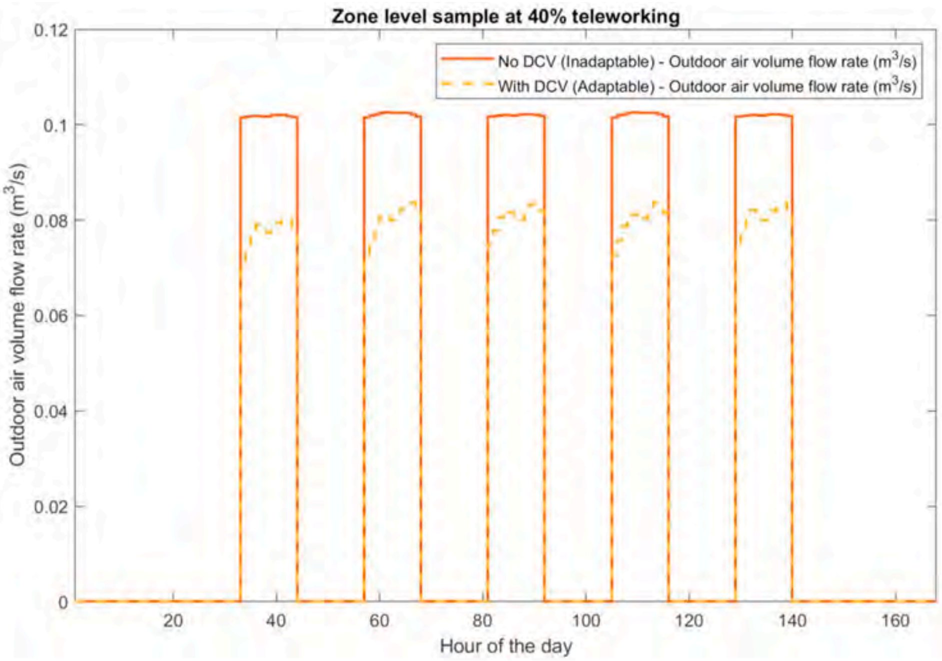

Fig. 10. A typical week with and without DCV in offices [22]. Values are plotted for a single zone.

Table 6
Home archetypes for simulation [19].

Model	Source of Archetypes	Residential building type	Foundation type	No. of floor levels excluding the basement	Window to wall ratio (WWR %)	Heated floor area (m^2)	No. of bedrooms	No. of occupants[c]
M1	NRCan [50]	Single detached	Basement	2	7.8	137	3	4
M2	NRCan [50]	Single detached	Basement	2	14.5	230	3	4
M3	NRCan [50]	Row house, middle unit	Basement	2	21.8	200	3[b]	4
M4	DOE [51]	Mid-rise apartment	Slab-on-grade	4	20	3128[a]	2 per suite	3 per suite

[a] Every suite has a floor area of 88 m^2.

[b] The M3 model, sourced from NRCan [50], originally specified one bedroom. However, due to an inconsistency in its floor area for a one-bedroom configuration, we decided to adjust the number of bedrooms.

[c] No explicit requirements about the number of occupants or occupant schedule are specified in NBC 2020. As such, the number of occupants assumptions were obtained from ASHRAE Standard 62.2 [52], which states that full occupancy equals the number of bedrooms plus one.

Table 7
Thermal Properties of building surfaces (exterior) for six different climate zones of Canada based on NBC 2020 for house models M1 to M4 [19,53,54].

M1 to M3					
Climate zone	HDD* (°C•day)	Above-grade exterior wall R-value (m^2•K/W)	Floor R-value (m^2•K/W)	Roof R-value (m^2•K/W)	Window U-value (W/(m^2•K))
4	<3000	2.78	4.67	6.91	1.80
5	3000–3999	3.08	4.67	8.67	1.80
6	4000–4999	3.08	4.67	8.67	1.60
7A	5000–5999	3.08	5.02	10.43	1.60
7B	6000–6999	3.85	5.02	10.43	1.40
8	>7000	3.85	5.02	10.43	1.40
M4					
4	<3000	3.45	5.18	6.10	1.90
5	3000–3999	3.77	5.71	6.41	1.90
6	4000–4999	4.17	6.41	7.25	1.73
7A	5000–5999	4.65	7.25	8.27	1.73
7B	6000–6999	5.26	8.27	8.55	1.44
8	>7000	6.06	8.55	9.09	1.44

Table 8
Heating and cooling months in every city for all four building models [19].

City	Cooling months	Heating months
Climate Zone 4	Mid-April until mid-September	Mid-September until mid-April
Climate Zone 5	Mid-May until mid-September	Mid-September until mid-May
Climate Zone 6	Mid-May until mid-September	Mid-September until mid-May
Climate Zone 7A	Mid-May until mid-August	Mid-August until mid-May
Climate Zone 7B	Mid-June until mid-August	Mid-August until mid-June
Climate Zone 8	Mid-July until mid-August	Mid-August until mid-July

coldest climate consumes the highest energy for heating (Natural gas). The heating energy consumption for Zone 8 increases by almost 30 % in the 100 % teleworking scenario compared to the 0 % teleworking scenario in inadaptable offices. In adaptable offices, the 100 % teleworking scenario consumes only 8 % more natural gas compared to the 0 % teleworking scenario due to setpoint reduction from regular setpoint schedules to a flat 17 °C in 100 % teleworking. A major trend is a significant reduction in energy use in 100 % teleworking scenarios where the energy use of empty adaptable offices drops significantly. Higher rates of teleworking mostly result in overall decreased energy consumption in offices. In 100 % teleworking scenarios, a substantial part of this decrease is mainly due to switching from a flat 17 °C to regular thermostat setpoints. This phenomenon shows the energy intensity of offices in lower occupancies. The results confirm buildings' sensitivity to occupancy, especially in adaptable buildings. In other words, buildings equipped with measures to adapt to partial occupancy (occupancy-responsive) consume less energy. Otherwise, office buildings remain unresponsive to occupancy and their energy consumption does not vary based on occupancy or teleworking percent for inadaptable buildings.

3.1.3. *Total energy use and GHG emissions in offices*

Fig. 14 compares the overall energy use in adaptable and inadaptable offices. The code-compliant offices in this study consume from about 400 MWh in climate zone 4 to almost 1000 MWh in climate zone 8, whereas the average energy use in Canadian offices is 288 kWh/m^2 [61]; approximately equivalent to 1400 MWh for the office spaces used in this study. The difference is due to the average value across all Canadian provinces for efficient and inefficient offices coupled with the assumption that the office archetype follows the NECB 2020, which is the most efficient energy code [54]. The results show adaptable offices save energy overall although the potential savings decrease in colder climates. Furthermore, the magnitude of savings is higher in 100 % teleworking scenarios because of relaxed thermostat setpoints. The minimum savings are in 0 % teleworking scenarios. Fig. 15, Fig. 16, and Fig. 17 illustrate the emissions (CO_2e) for natural gas, electricity, and a combination of both in different climates. An exception to this trend is Zone 4 because of its clean electricity sources. In Zone 4, internal gains are reduced, resulting in increased demand for heating and natural gas. The results of simulations suggest all climates significantly benefit from GHG emission reductions in adaptable offices. The potential reductions are almost 40 % in the 100 % teleworking scenario gradually decreasing to approximately 10 % in the 0 % teleworking scenario. The findings suggest either 100 % teleworking or 0 % teleworking can be optimum solutions when it comes to energy savings because savings are significantly high in the former scenario and buildings are fully occupied in the latter scenario. As discussed in the literature review, activity-based unassigned work environments that keep the buildings fully occupied are the optimum solution when it comes to working arrangements. The results suggest that creating flexible working environments with different strategies such as activity-based unassigned work environments for keeping the buildings fully occupied to the maximum of their capacities can be environmentally sustainable. Similarly, 100 % teleworking or divesting office buildings can significantly contribute to a reduction in GHG emissions and energy consumption whenever such strategies and plans are possible.

3.2. *Homes*

Figs. 18 and 19 demonstrate the impact of telework on home energy use and emissions in different climate zones. Teleworking, whether in adaptable or inadaptable home types, increases energy use and emissions due to extended hours of occupancy. The results are in accordance with previous studies on homes and telework [62–64]. The adaptable homes consume less energy compared to inadaptable ones; similarly, they produce less emissions. While adaptable homes consume less energy, they are more responsive to changes in occupancy meaning the overall percentage of change between teleworking and non-teleworking scenarios is greater compared to inadaptable homes.

3.3. *Combined emissions of homes and offices*

Fig. 20 shows that the overall energy use of teleworking scenarios rises with the number of teleworkers. Although the increase is generally not significant (less than 5 % for entire remote scenarios), inadaptable scenarios consume more energy than adaptable ones. Fig. 21 demonstrates the overall emissions associated with teleworking increase slightly (mostly less than 5 %) based on different climate zones and home type distribution. However, the increase in adaptable scenarios is less than in inadaptable scenarios. Results also show homes consume more energy in colder climates and consequently, cause more emissions due to heating. Another contributing factor is the differences between home types and sizes in different climate zones. Results are consistent with previous studies on home energy use and teleworking [66,67]. In essence, teleworking increases the occupancy hours in teleworkers' homes resulting in more heating and electricity use [68]. The impact of teleworking on homes can be mitigated by using dual zones (thermostats) for HVAC systems at home [19].

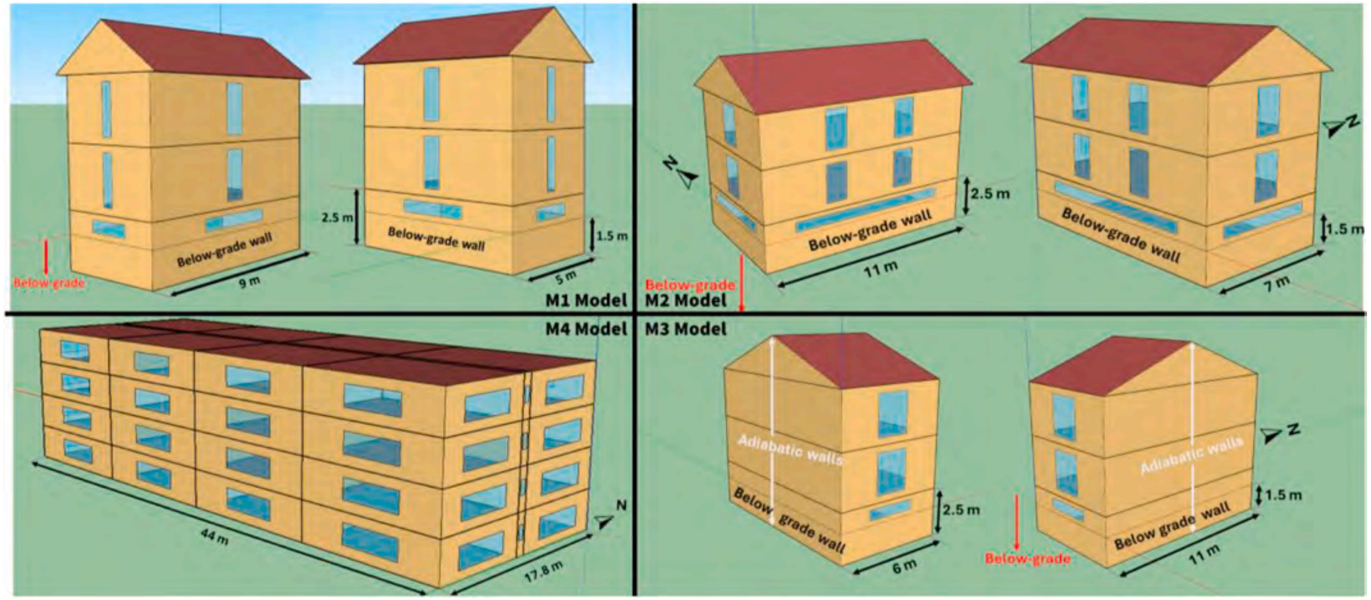

Fig. 11. Home models M1 to M4.

Table 9
Summary of inputs for the home models in EnergyPlus [19].

Variable	Amount	Reference
Setpoint temperatures	M1- M3: 20 °C heating temperature setpoint and 25 °C cooling temperature setpoint for the first and second floor. 19 °C heating temperature setpoint for the basement. M4: 20 °C heating temperature setpoint and 25 °C cooling temperature setpoint.	NBC 2020 [53]
Setback/set-up temperatures for the households who change their setpoint during the night, away hours, or both	M1-M3: 18 °C heating temperature setback and 27 °C cooling temperature set-up for the first and second floors. M4: 18 °C heating temperature setback and 27 °C cooling temperature set-up. M1- M3: 17 °C heating temperature setback for the basement.	SHEU 2019 [56] The assumption in this study
Mechanical ventilation	M1: 35 L/s M2 and M3: 49 L/s M4: $R_p \times P_z + R_a \times A_z$, where R_p is people's outdoor air rate and is 2.5 L/s/people, P_z is the number of people in the zone, R_a is the area outdoor air rate and is 0.3 L/s/m^2, and A_z is the zone area.	ASHRAE Standard 62.2, 2022 [52] ASHRAE Standard 62.1, 2022 [57]
Infiltration	M1-M3: 3.2 ACH (at 50 Pa with 0.67 pressure exponent) M4: flow per exterior surface area of every suite from the ground floor to the third floor: 0.001 m^3/s.m^2, flow per exterior surface area of every suite located on the top (fourth) floor: 0.0002 m^3/s.m^2	NBC 2020 [53] Adopted from DOE prototype building model [51] ASHRAE901_ApartmentMidRise_STD2019
Lighting	M1-M3: 7.3 W/m^2 M4: 4.8 W/m^2	NECB 2020 [54]
Equipment	M1-M4: 17 kWh/day	HOT2000 [58]
HVAC systems' efficiencies	M1 to M3: annual fuel utilization efficiency of the gas-fired warm air furnace: 95 % M4-heat pump: coefficient of performance (air to air) in heating mode at −8.3 °C: 2.05 and at 8.3 °C: 3.2, and coefficient of performance in cooling mode: 2.9 M4-fan coil unit: nominal thermal efficiency of the gas-fired boiler (water): 90 %, and coefficient of performance of the Chiller: 2.866	NECB 2020 [54], table 5.2.12.1.
Ground heat transfer modeling	Kiva model was used to simulate a 3D heat transfer between the floor and below-grade walls and ground.	[59]

Table 10
CO_2e emission factors of electricity and natural gas for the representative city in each climate zone.

Province/Territory		British Columbia	Ontario	Ontario	Yukon	Alberta	Nunavut
CO_2e	Electricity gCO_2e/kWh	15	30	30	80	540	840
	Natural gas gCO_2e/m^3	1966	1921	1921	1966	1962	1966
	Natural gas gCO_2e/kWh	186	182	182	186	186	186

4. Conclusion: sustainable teleworking; key factors and strategies

This paper presented the first comprehensive study on the impacts of telework on homes and offices in different Canadian climates. This study analyzed the impact of occupancy-based systems on energy use and emissions of homes and offices. Then, the results were used to quantify the total net energy use associated with teleworking in homes and offices. The results of this study demonstrate that the net total energy use and emissions associated with teleworking increases slightly as the number of teleworkers increases although the impact is less than 5 % in adaptable scenarios (RQ1 and RQ3). However, the overall impact of telework must be determined by also considering energy use and emissions associated with commuting and ICT; which are significant contributors to overall energy use and emissions. While the adaptable scenarios have the lowest energy use and emissions, they experience greater fluctuations compared to inadaptable offices. This is due to their adaptability to occupancy (RQ2 and RQ3). In adaptable scenarios, the greatest change in energy use and emissions occurs in the 80 % teleworking scenario. This is because the 100 % teleworking scenario allows relaxed setpoints for offices contributing to overall reduced energy use. In general colder climates consume more energy and cause higher emissions compared to warmer climates (RQ2). The higher teleworking percentage is also linked to an increase in total energy use and emissions (RQ3). Various home types also play a major role in determining the overall energy use associated with teleworking. However, this study had different distribution values for each home type in different provinces. Therefore, it's impossible to draw any conclusions as part of the scope of this study. This section describes key components and factors for achieving sustainable teleworking and explains a future roadmap for studies on telework. The results have major implications for employers and corporations aiming to adopt telework as a sustainable practice for reducing their carbon footprint. The results show how different occupancy-based technologies in buildings

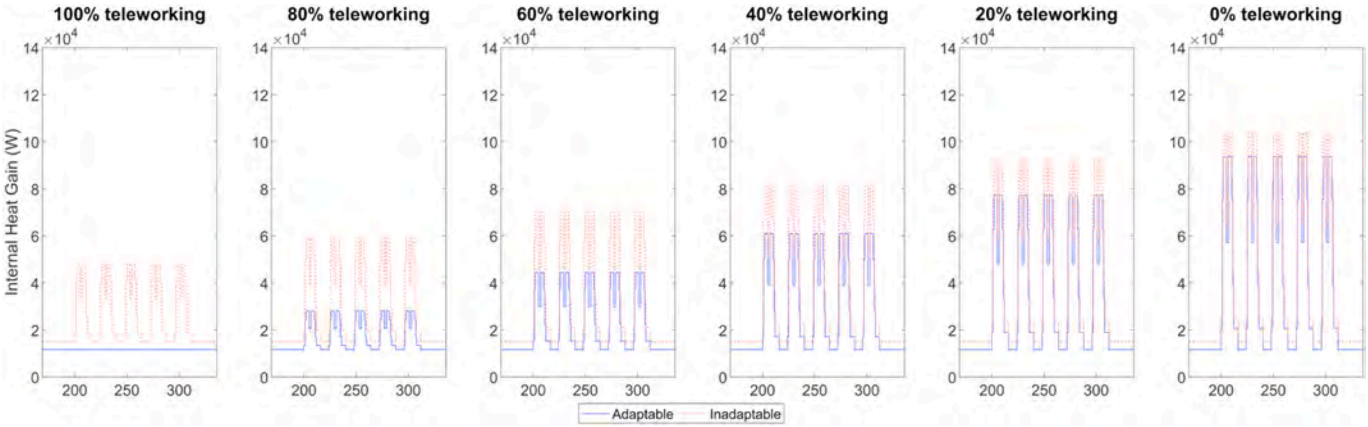

Fig. 12. Internal heat gains in different scenarios for offices; internal gains are significantly reduced in adaptable offices in the 100 % teleworking scenario.

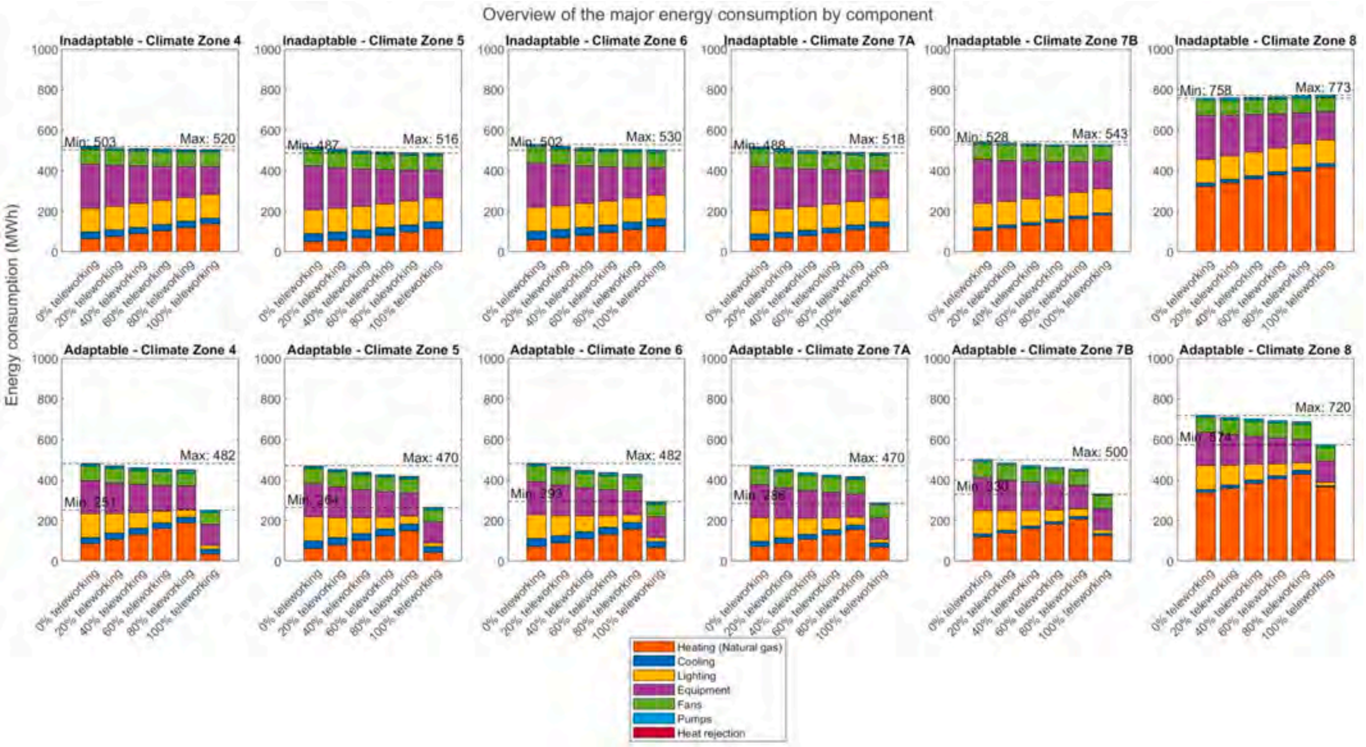

Fig. 13. Impacts of teleworking scenarios in different climates on energy end uses of offices; results show the 100 % occupancy of the inadaptable office aligns with ASHRAE's international benchmark [37]. Heat rejection values are nominal and not visible in the figure.

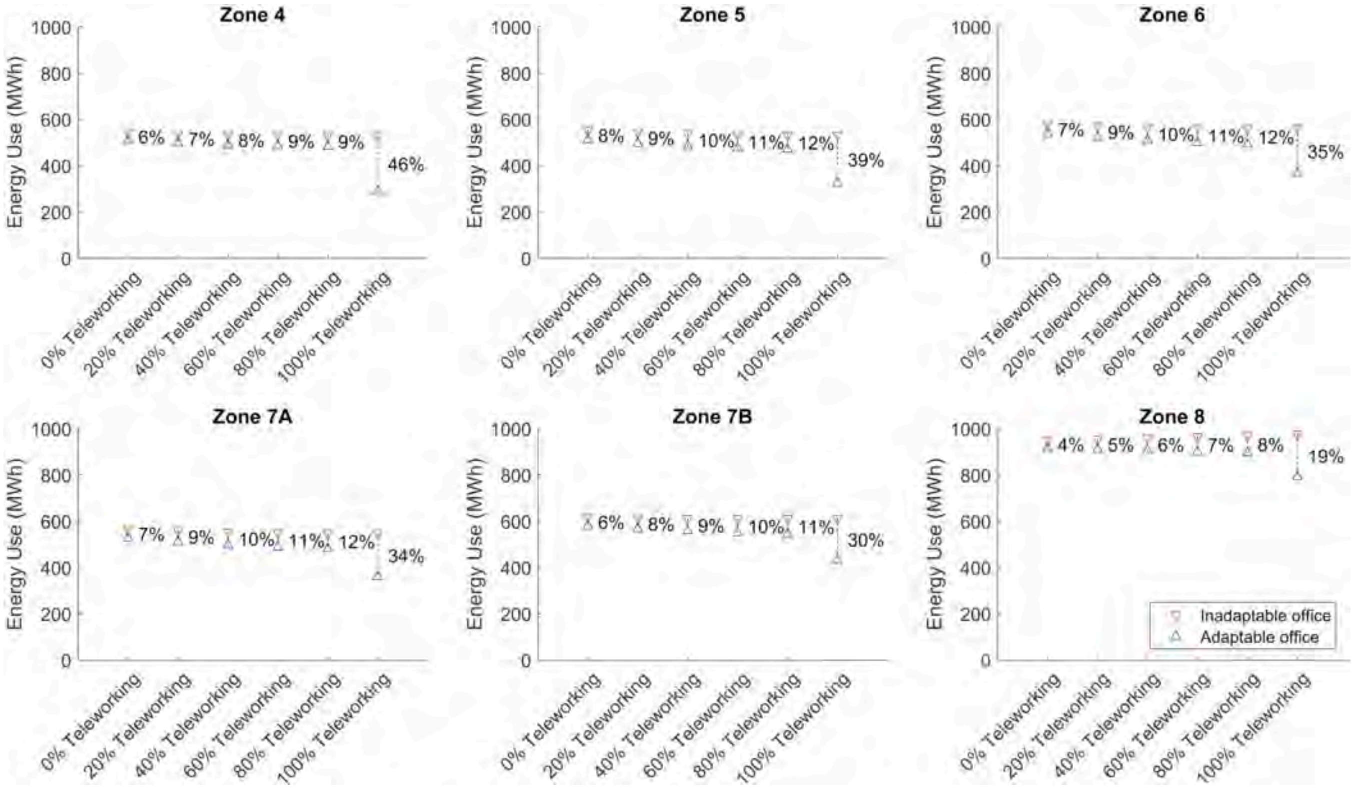

Fig. 14. Total energy use in offices; percentage values represent the difference in energy use (reduction) for adaptable buildings relative to the baseline of an inadaptable building.

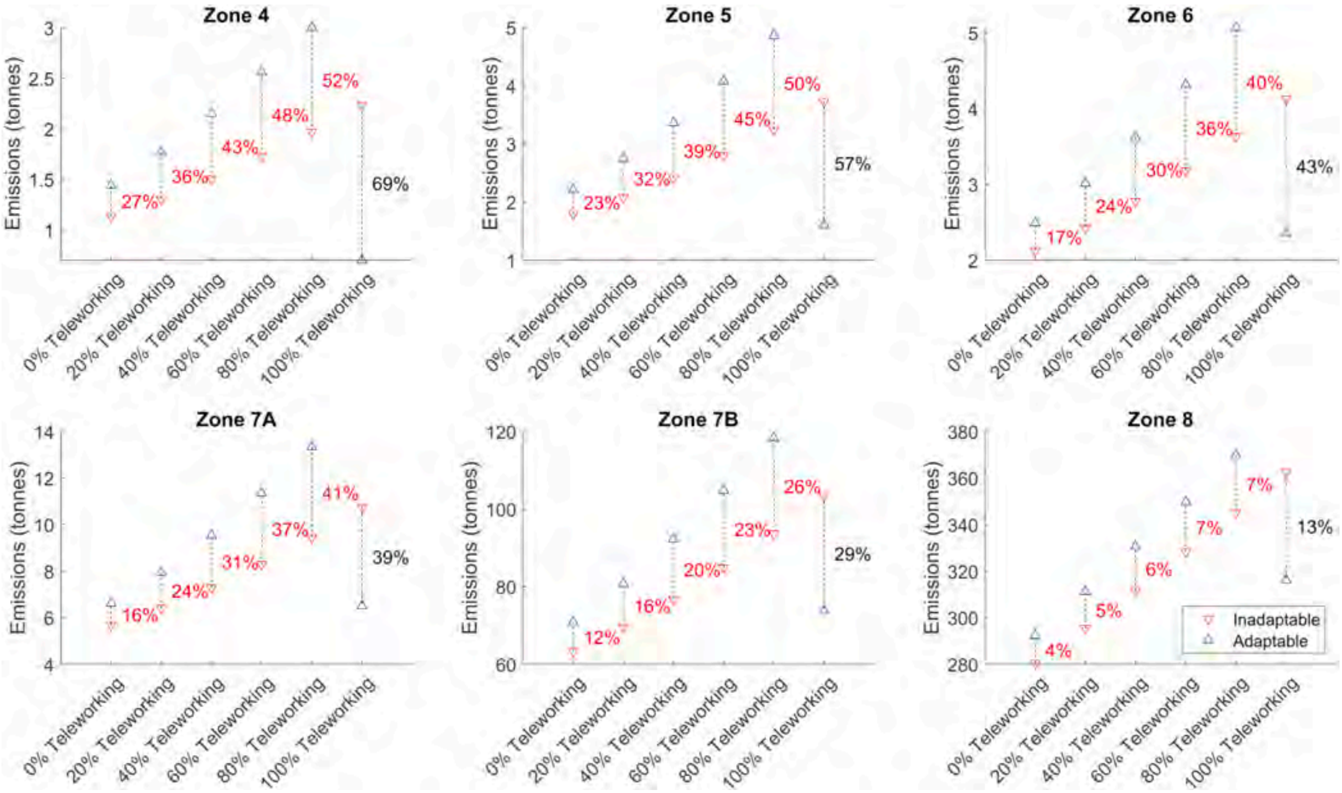

Fig. 15. Overall emissions associated with natural gas (CO_2e) for offices; red values show an increase in emissions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

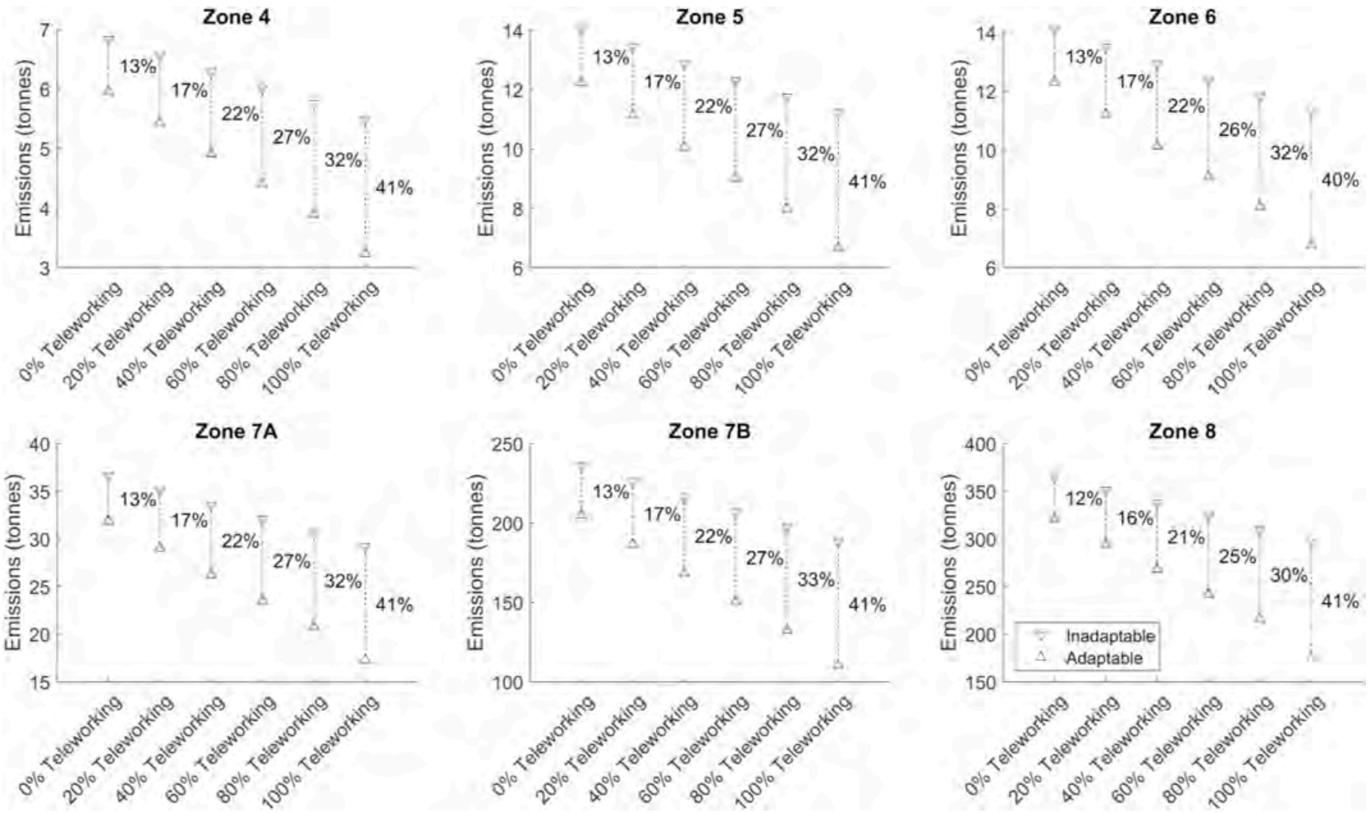

Fig. 16. Overall emissions associated with electricity (CO_2e) for offices. The values represent a decrease from inadaptable to adaptable.

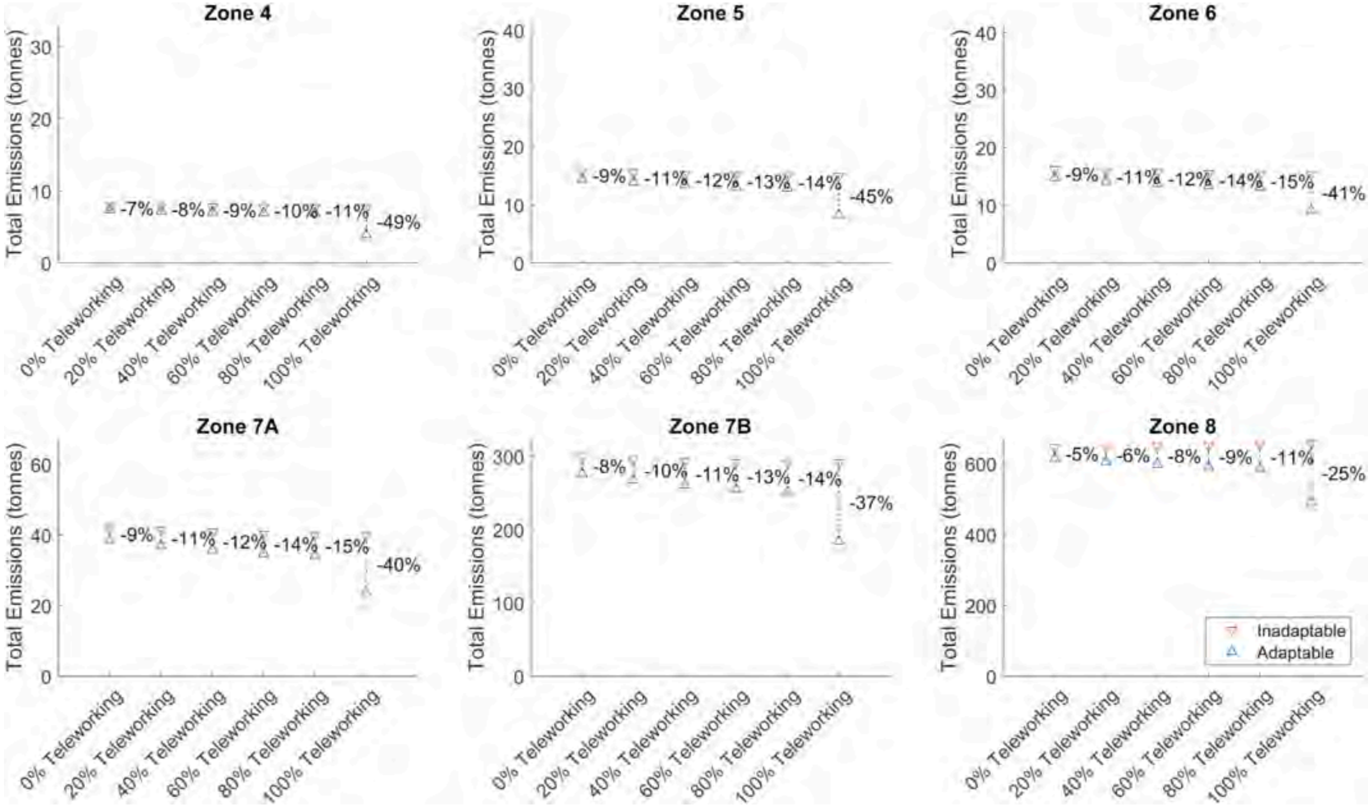

Fig. 17. Total emissions associated with natural gas and electricity (CO_2e) for offices; negative values show a decrease in emissions.

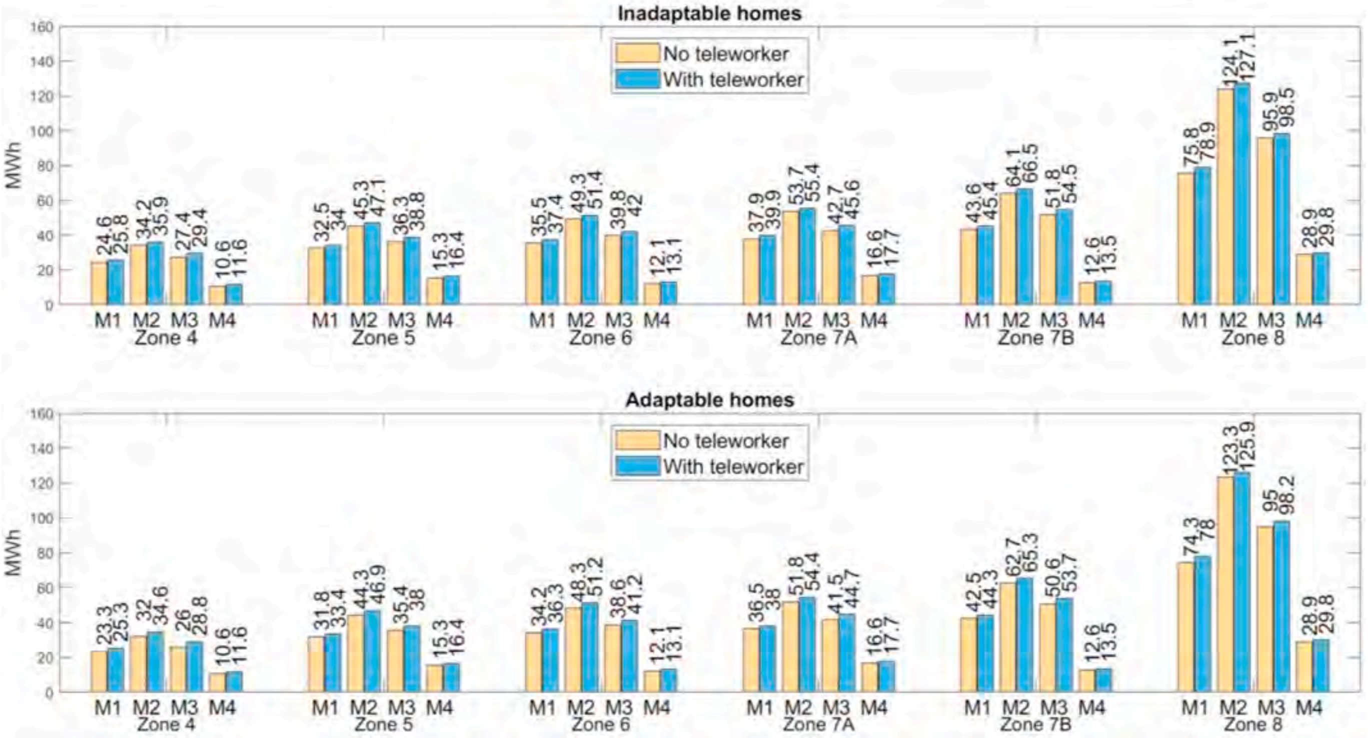

Fig. 18. Home energy use in different climates and building types; the average Canadian household energy use is about 24.5 MWh for different home types, climates, and fuel types across Canada [65]. The M4 model's consistent values in adaptable and inadaptable graphs stem from a lack of control over individual apartments and are included only for visual consistency (refer to section 2.2). M4 is also normalized by the total number of apartments.

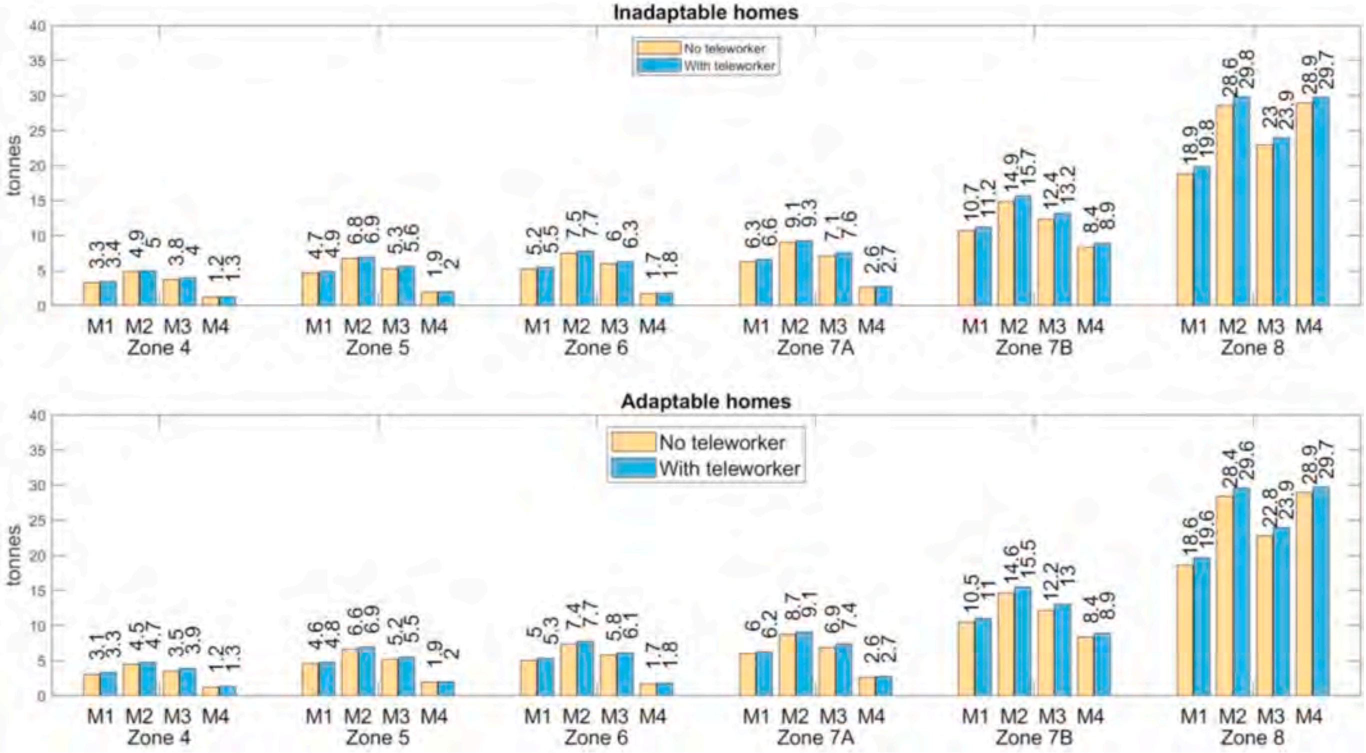

Fig. 19. Home total emissions in different climates and building types. The M4 model's consistent values in adaptable and inadaptable graphs stem from a lack of control over individual apartments and are included only for visual consistency (refer to section 2.2). M4 is also normalized by the total number of apartments).

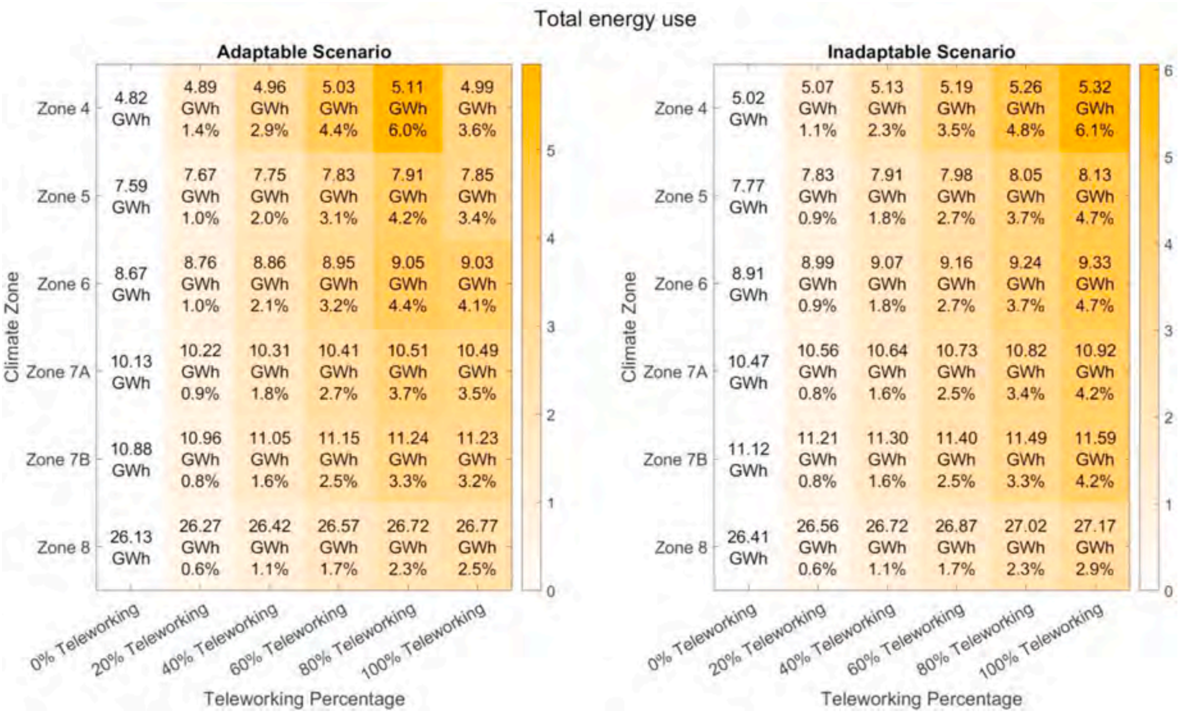

Fig. 20. Total energy use associated with teleworking (the percent changes compare the results to the 0 % teleworking scenario, where positive values indicate an increase).

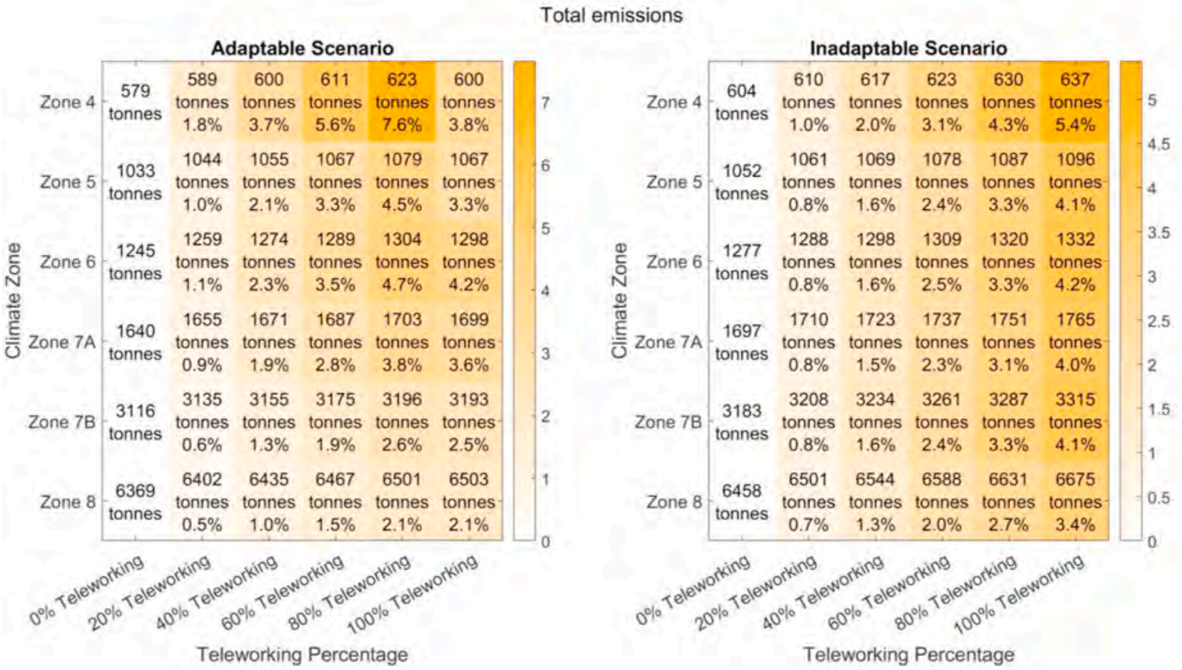

Fig. 21. Total emissions associated with teleworking (the percent changes compare the results to the 0 % teleworking scenario).

can potentially reduce energy use and emissions. This study also creates the foundation for future research on telework and its sustainability.

4.1. Occupancy-based technologies for homes and offices

The results of the present study demonstrated that occupancy-based technologies for homes and offices have the potential to decrease energy use. However, decreased energy use can impact emissions as occupancy-based technologies can impact internal heat gains since internal heat gains can impact the balance between natural gas and electricity use which have different emission factors in different regions. As a result, a sustainable approach to telework requires mapping the sources of energy and emission factors before implementing teleworking for particular regions when the aim is to reduce GHG emissions and achieve the 2050 vision.

4.2. Teleworker behavior

A major contributor to sustainable telework is teleworker behavior which can impact the overall energy use, efficiency, and emissions. The scope of this study covered the home size and home type in Canada for different regions. The results show bigger homes require more conditioning and contribute to the overall energy use and emissions associated with telework. Therefore, it is essential to involve teleworkers in the process of reducing emissions by raising awareness among them.

4.3. Home size and type

Home size is a major contributor to energy use associated with telework. As demonstrated in this study M2 homes use more energy than M1 homes. Therefore, it is important to consider the impact of telework on home size. This issue becomes of significant importance when teleworkers decide to acquire bigger homes to have more rooms, especially dedicated offices [6,18]. This means that a comprehensive evaluation of teleworkers' behaviors and preferences is necessary prior to implementing teleworking as a sustainable practice. Similar to home size, home types play an important role in achieving a sustainable teleworking practice.

4.4. Office space and strategies to reduce emissions

Office space is a major component of energy use and emissions associated with telework. Adaptable offices consume less energy than inadaptable offices. 100 % teleworking scenarios allow offices to utilize different strategies to minimize energy use and emissions such as relaxed setpoints. However, with increasing occupancy, the building requires maintaining a bare minimum indoor condition resulting in an increase in energy use and emissions. A solution to these can be utilizing strategies such as activity-based unassigned work environments to maintain high levels of occupancy for multiple teleworkers to decrease the overall footprint of energy use and emissions associated with each teleworker. A greater resolution in HVAC zoning could allow parts of the building to maintain relaxed setpoints, while others (in occupied zones) to have comfortable setpoints. Consolidation of occupants such that buildings can be repurposed or divested is an important consideration because our results show that even an unoccupied building consumes significant energy.

4.5. Concluding remarks

Telework can save energy and contribute to reducing emissions as long as effective strategies for reducing the emissions and energy use associated with homes and offices are taken into account. The scope of this study demonstrated using effective thermostat setpoint changes based on occupancy at homes along with occupancy-based technologies in offices can reduce the overall energy use and emissions associated with telework. However, more innovative solutions, such as heat pumps and heat recovery systems, should be studied to quantify the effectiveness of newer technologies in reducing energy use and emissions.

Another major component of the emissions associated with teleworking is emission factors associated with each region. Therefore, it is essential to have a comprehensive approach to calculating and quantifying the emissions associated with teleworking since a decrease in energy use does not necessarily translate to a decrease in emissions.

While the present study conducted comprehensive quantifications of energy use and emissions associated with telework. It did not assess and quantify the impact of telework on other domains, including transportation and the internet as suggested by researchers [4,6] where major savings can happen when teleworkers adopt sustainable behaviors. Furthermore, the present study assumed that someone is either at home or in their office. In addition, the analysis in this paper assumed only a single office building type and only four home types. Another limitation of the study was its scope in implementing more innovative technologies for reducing energy use at homes as well as offices. In this study, we compared the energy use and emissions of a single office building with 250 occupants to that of 250 homes, assigning one home per occupant for the calculations. Therefore, this study neglected multi-teleworker households. Another consideration for the current study is its calculation method for emissions associated with household members as it did not normalize the energy use and emissions of homes per teleworker as this study was a scenario analysis. This study also did not quantify the impact of telework on transportation and the internet.

CRediT authorship contribution statement

Farzam Sepanta: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Melina Sirati:** Data curation, Visualization, Software, Methodology, Formal analysis. **William O'Brien:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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