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RESEARCH

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Pilot study to measure the energy and carbon impacts of teleworking

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ABSTRACT

Teleworking offers various socio-economic benefits to the workforce, especially during major disasters. However, the holistic net energy and greenhouse gas (GHG) emissions impacts of telework remain poorly understood. This paper develops and tests a longitudinal mixed-methods approach to estimate energy and emissions in three domains: home office, transportation, and information and communications technology (ICT). A pilot study of 11 participants from Ottawa, Canada, is used to evaluate the method, while generating a rich dataset and new insights. The results show transportation, home heating and cooling account for > 94% of telework-related energy, while home office equipment, lighting and ICT account for the remaining 6% (and < 2% of GHG emissions). Not including employer offices, teleworking will likely yield a net reduction in energy and GHG emissions compared with conventional working arrangements, but this result is dependent on personal choices, routines, purchasing decisions and household structure. The paper concludes with a discussion and future recommendations for the developed method based on the lessons learned.

PRACTICE RELEVANCE

A new mixed-methods approach was developed and piloted to study the holistic energy impacts of teleworking. This demonstrates measurement tools, data analysis measures and scenario modelling. It provides lessons learned and acknowledges limitations. It is a major step forward in setting the stage for larger scale studies. The specific results showed that compared with conventional working arrangements, nine of the 11 participants are likely to consume less energy and produce fewer GHG emissions when teleworking based on a scenario-based analytical approach. However, if workers use sustainable transportation, teleworking may not yield any energy savings as increases in the home domain are expected. Future studies should include the employer offices.

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1. INTRODUCTION

Although initially proposed in the 1970s, the adoption of teleworking remained slow, even when technology and infrastructure were advanced and cost-effective in the 2000s (Ansong & Boateng 2018). However, crises such as 9/11, Hurricane Katrina and COVID-19 have reignited the need for teleworking to maintain business continuity (Belzunegui-Eraso & Erro-Garcés 2020; Greenberg & Nilssen 2008). Similar to worldwide trends (OECD 2021), the percentage of teleworkers increased from < 15% to 40% in Canada after the declaration of the COVID-19 pandemic in March 2020 (Deng *et al.* 2020). As the pandemic wanes, teleworking is likely to exceed pre-pandemic levels (Bérastégui 2021), due to the economic and social benefits (Pérez *et al.* 2002) afforded by flexible working arrangements (Baert *et al.* 2020).

The net impact of teleworking on energy use and greenhouse gas (GHG) emissions is not fully understood, and uncertainty from past studies is significant (Hook *et al.* 2020). Most studies suggest a net reduction in energy consumption due to reductions in commute and energy consumption in offices (Koenig *et al.* 1996). Conversely, others suggest an increase in energy consumption due to rebound effects such as longer commutes on non-teleworking days, an increase in non-work travel and home energy usage (Zhu & Mason 2014). Hook *et al.* (2020) reported that 26 of 39 reviewed studies suggest a decrease in energy, while eight suggest an increase or neutral impact. Yet, the majority of past studies relied solely on self-reporting or modeling with simplistic assumptions, thus putting such results into question. Few mixed-methods or field measurement-based studies have been performed (O'Brien & Aliabadi 2020).

The present research develops and pilots a longitudinal field study methodology to quantify the net energy and emissions impact of teleworking (*i.e.* partially working outside of a central workplace at home during normal business hours). This pilot study provides a comprehensive and repeatable approach with current best practices that can be applied in various settings to explore the underlying habits and energy behaviors of teleworkers. The depth and transparency of this approach enables the direct comparison of study results and teleworking scenarios, addressing a significant limitation of previous studies. Given the study's measurement occurred during COVID-19 lockdowns, the focus is only on the home, transportation and information and communication technology (ICT) domains, not employer offices.

2. TELEWORKING RESEARCH METHODS AND LIMITATIONS

Teleworking studies have reported heterogeneous results due to their methods employed, assumptions and study scope (Hook *et al.* 2020; O'Brien & Aliabadi 2020). To date, researchers have used surveys, secondary data analysis (*e.g.* census), and scenario-modeling to investigate specific domains. Transportation is the most researched domain due to its significant impact (Hook *et al.* 2020). Only a handful of teleworking studies have attempted to include buildings (see O'Brien & Aliabadi, 2020, for a comprehensive review of the scope of previous studies). Notably, O'Brien & Aliabadi (2020) reported that broader and newer studies tend to reduce estimated energy savings from telework.

Researchers have used surveys to collect data from a large sample (Hook *et al.* 2020). However, respondents often reply inconclusively, approximate values or provide socially acceptable answers when providing physical or spatial estimates (Atkyns *et al.* 2002; Helminen & Ristimäki 2007). Participants often lack the technical knowledge to accurately report critical details, such as home, office and equipment performance specifications. Additionally, studies that use survey data tend to aggregate data into large groups (*e.g.* teleworkers versus non-teleworkers) (Asgari & Jin 2018). For each group, variables linked to energy usage (*e.g.* the number of teleworking days and size of household) are left unexplored.

Diaries have also been used to estimate the travel behavior of individuals. However, their application in a teleworking context is problematic. Most teleworkers work from home two to three days per week (Atkyns *et al.* 2002). Since travel diaries are typically completed over a short period (up to three days), the results may represent a mix of (non)teleworking and sick days

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(Zhu & Mason 2014), making it difficult to determine whether the identified trends are genuine or a sampling artifact (Mokhtarian *et al.* 2004). Additionally, the limited number of survey days cannot adequately capture rebound effects (Hook *et al.* 2020).

Scenario-modeling is used for forecasting and long-term planning at a city or regional scale (O'Brien & Aliabadi 2020). The inputs for these simulations are often derived from surveys and travel diaries with some general assumptions and widely accepted relationships (Alonso 1964). There are major gaps in knowledge about how people behave in their homes during teleworking, and past studies have used highly simplistic assumptions. For example, it is not known how teleworkers use heating, cooling, and office equipment and lighting when they are home versus away, and this uncertainty is compounded by the presence of family members. Additionally, scenario-modeling oversimplifies complex problems, reducing the applicability of the study results.

Although these methods yield results, they do not minimize bias, relying heavily on the participants' memory and truthfulness. Also, these approaches cannot adequately describe the dynamic nature of teleworking and its impact on the individual and household. To address these limitations and achieve a more comprehensive scope, a mixed-method field study that includes surveys and longitudinal field measurements is developed and piloted in this paper.

3. METHODS

3.1 RESEARCH DESIGN

Based on the literature that investigated numerous social, economic and environmental impacts of teleworking, the authors focused this study on measuring the domains of transportation, home and ICT on the basis of their significant energy impacts. Employer offices were excluded due to restrictions from COVID-19 lockdowns. Embodied energy (*e.g.* new buildings, equipment, vehicles) was excluded on the basis that the study duration was only one year. Exclusions of other possible domains include food and clothing, only the latter of which is mentioned in the telework literature.

This research involved the development of a mixed-methods field study, involving a combination of entry and exit questionnaires and a year-long monitoring campaign, as summarized in Figure 1. The entry and exit surveys/interviews (participants were given a choice) played the critical roles of both informing the measurement campaign and characterizing the households (*e.g.* home and vehicle characteristics). The surveys informed the researchers of the appropriate number, type and placement of sensors (*e.g.* number of lamps or pieces of office equipment to measure power for). In some cases, the measured data were used to verify survey responses (*e.g.* work hours and habit of turning off office equipment). Deployable sensors were installed to monitor energy-related behaviors and proxies for behavior with high temporal variability (*e.g.* computer and lighting power use, and indoor air temperature).

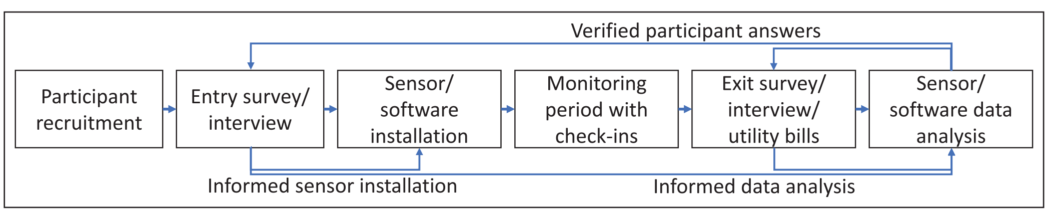

Figure 1: Summary of the research process.

3.2 STUDY AREA

The method was piloted in the Greater Ottawa region that comprises Ottawa (the capital of Canada) and surrounding municipalities (Figure 2). The region has a humid continental climate with cold winters and warm summers where the average heating and cooling degree-days are > 4000 and < 1000 (°C·days), respectively. For all domains beside transportation, associated GHG emissions were estimated based on Ontario's electricity emissions factor of 31 gCO_{2e}/kWh (The Atmospheric Fund 2019) and natural gas emissions factor of 1.8 $kgCO_{2e}/m^3$ (Government of Canada 2018).

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3.3 SELECTION OF PARTICIPANTS

Given the piloting goal of this study, constraints for the participants (*e.g.* teleworking during the study), accessibility to the researchers (*e.g.* within an hour's drive) and the disruption to participants, a convenience sampling approach was used. Individuals who met all the following criteria were recruited:

- live/work in the study area and perform their work duties in office settings
- work from home at least two days per week from a designated room
- provide access to their home information and data, travel schedules and utility bills for one year.

The principal investigator of the project identified a list of people in his extended network who he thought met the criteria, while the lead researcher (who did not know the participants) invited them to participate. Approximately one-third of the invited participants declined due to the time commitment, permission to install sensors or expected long-term travel. Eleven full-time, knowledge-based workers were recruited, as summarized in Table 1 and Figure 2. The sample is typical of working professionals who can telework: they live in a variety of home types (detached, attached and high-rise) and settings (urban and suburban). Due to recurring lockdowns, an energy assessment of the work office domain was prevented. Since the beginning of the pandemic, half of the participants never returned to their offices, while the remainder worked from their employer office one to three times per week or month when lockdowns were lifted.

During the study, many participants changed their work laptops, primary vehicle, internet service provider and job. One participant did not give access to his location history. Others purchased a new home, renovated their home offices and installed a new air-conditioning (AC) system. Participant 7 ended their participation after six months and was replaced by participant 11.

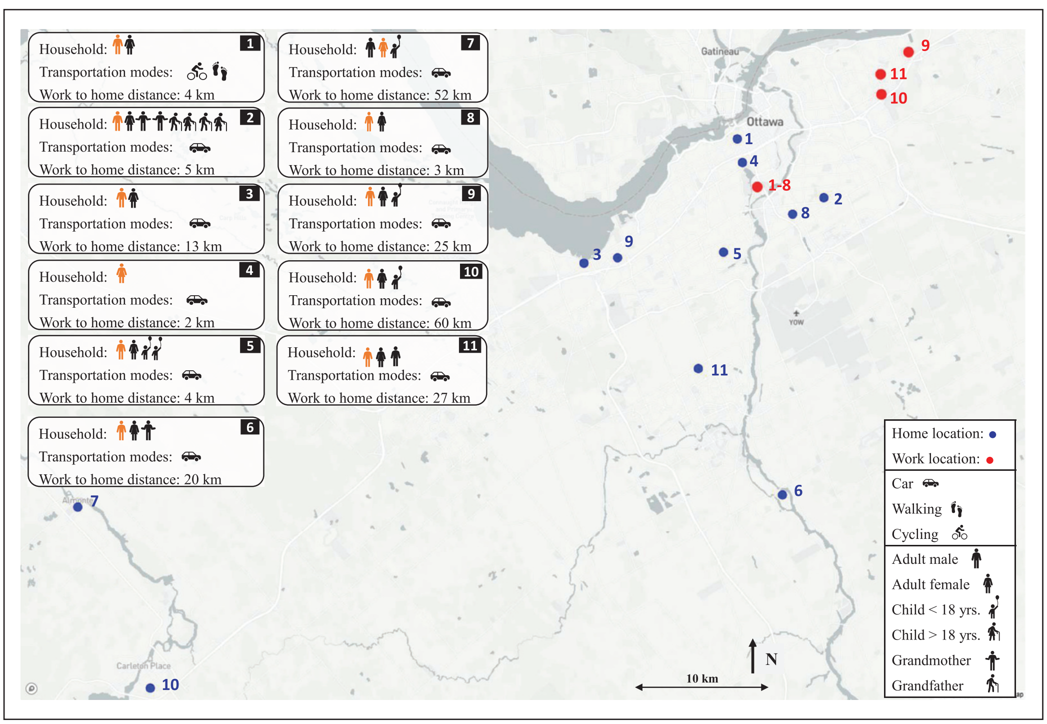

Figure 2: Participants' home and work locations, including their primary mode of transportation and household size.

Note: Participants are highlighted in orange.

PARTICIPANT	HOME TYPE AND AGE	WALK SCORE	HOME SIZE (m²)	HOME OFFICE SIZE (m²)	OFFICE LIGHTING, TYPE (NUMBER) OF LAMPS, WATTAGE	COMPUTER AND PHONE TYPE	DATA COLLECTION PERIOD
1	Semi-detached ~100 years	90	64	6	Ceiling CFL (2) 13 W	Windows Android	4 October 2020–3 October 2021
2	Detached ~50 years	37	483	15	Ceiling LED (3) 5 W	Mac OS Apple	
3	Town house ~35 years	16	138	16	Ceiling LED (3) 6 W	Windows Apple	
4	Condo ~2 years	89	88	22	Ceiling LED (8) 8 W	Windows Android	
5	Detached ~60 years	32	223	8	Ceiling LED (1) 13 W	Mac OS Apple	
6	Detached ~36 years	42	242	13	Ceiling LED (8) 5.5 W	Windows	
7	Detached ~100 years	88	166	8	Ceiling CFL (3) 40 W	Mac OS Apple	4 October 2020–3 April 2021
8	Detached ~50 years	70	111	6	Ceiling LED (8) 10 W	Windows Apple	4 October 2020–3 October 2021
9	Detached ~30 years	62	260	11	Ceiling LED (3) 6 W	Windows Android	
10	Semi-detached ~1 year	41	163	8	Ceiling LED (2) 30 W	Windows Android	13 January 2021–12 January 2022
11	Town house ~60 years	54	166	8	Standing LED (1) 8 W	Windows Android	16 May 2021–16 November 2021

Table 1: Selected demographics captured during entrance interviews for the 11 participants.

Note: Walk score is a measure of the walkability of a neighborhood given the distance to nearby amenities. A low walk score (*e.g.* < 50) indicates that most errands require the use of a car; a high walk score (*e.g.* > 70) indicates most or all errands can be accomplished on foot.

CFL = compact fluorescent bulb; LED = light-emitting diode.

3.4 DATA COLLECTION

At the start of the data-collection phase, interviews were conducted via Zoom, or written responses by email were also accepted. Survey questions captured demographic information, home, office and vehicle details, and energy-related habits and preferences. Participants were then provided a box of calibrated sensors (Table 2) with an installation manual. Some participants installed the sensors using the manual; others allowed the researcher to install the sensors. Meters and applications were installed on participants' work computers and global positioning satellite (GPS) settings were enabled on their phones; furnace and AC model/serial numbers, vehicle type, and light bulb wattage were also recorded. Based on the memory capacity and battery life of the sensors, data were downloaded after 90, 180 and 365 days, or soon after battery failure, typically by the researcher. At the end of this phase, utility bills (electricity and gas bills) and additional smart thermostat data (if available) were also collected. An exit interview was conducted to capture any major changes that would affect energy usage (*e.g.* change in or renovation of home/home office, change in vehicle and extended vacation).

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DOMAIN	SENSORS, METERS AND APPLICATIONS	LOGGING FREQUENCY (min)	KEY OUTPUTS
Transportation	Google Timeline	Event-based	GPS location: home, office or daytrips Seasonal mode variations Average daily travel distance for errands
	FollowMee app		
ICT	BitMeter OS	Event-based	Average data used during (non) working hours/days
	Peak Hour 4		
Home	HOBO UX80 Occupancy/Light	Event-based	Occupancy in home office; arrival and departure times Light state and average hourly and daily usage in home office Average hourly and daily energy used by office equipment Average temperature in office, living room and outdoors Length of time HVAC fan is on
	HOBO UX120-018 Plug Load Logger	5	
	HOBO MX CO_2 Logger (home office)	10	
	HOBO UX100 Temp/RH Logger (living room)	10	
	HOBO UX100 Temp/RH Logger (ductwork)	10	
	HOBO MX2302A Ext Temp/RH	10	

Table 2: Sensors and meters installed.

Note: ICT = information and communication technology; GPS = Global Positioning System; HVAC = heating, ventilation, and air-conditioning; RH = relative humidity.

3.5 DATA ANALYSIS

The data collected was analyzed using Python to determine the energy used (hourly, daily and annually) in each domain (Table 2). A scenario-based approach was employed to assess the impact of teleworking on energy use and GHG emissions. This approach was selected because not all scenarios could be directly measured due to the closure of the participants' work office. Three scenarios were investigated:

- *Scenario 1: Baseline*

  The participant works from their employer office five days per week for one year. The total commute distance comprises the two-way trip distance to their office with an additional distance for errands. Even when participants use trip-chaining, errands are expected to have some impact on their total weekly commute distance, especially for individuals with a short home-to-work commute. Also, the participant uses temperature setbacks when working from their employer office. For the home office equipment, energy usage is estimated from phantom loads. Lighting energy is negligible as no electric lighting is used when the participant works away from home.

- *Scenario 2: Teleworking*

  The participant works three days per week from their employer office and two days from home for one year. The total commute distance comprises the two-way trip distance to their employer office for three days with an additional errand distance; no trips are completed on work-from-home days. Like scenario 1, the participant has primary control over their heating with setbacks employed for the three days they work away from home. For the home office equipment, energy usage is estimated from phantom loads when their home office is unoccupied for three days and the energy used during the two days the participant works from home. Lighting energy is only estimated for the two days the office is occupied.

- *Scenario 3: Remote*

  The participant works from home five days per week during the study period. The energy usage from office equipment, lighting, heating, cooling, transportation and ICT is calculated based on their measured usage during the study period.

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For all scenarios, the total heating energy includes both working and non-working hours. For scenarios 1 and 2, cooling energy usage is considered negligible due to the sporadic usage patterns and ICT usage is the same as scenario 3. The following sections detail how energy usage is quantified for each scenario.

3.5.1 Transportation

Using Google Timeline and the FollowMee app, travel data were passively collected including GPS locations, distances and travel times. Unlike Google Timeline, FollowMee does not provide the transportation mode. Based on the survey responses, the primary mode of transport was determined using their travel speed and path. The daily travel distance was summed based on the transportation mode and location (*i.e.* working from home or their employer office, and day trips where the participant do not return to their primary residence by the end of the day). Trip-chaining was calculated based on the average number of daily trips.

For individuals who used a personal vehicle as their primary mode of transportation (Figure 2), their vehicle specifications (Table 3) were entered into the Natural Resources Canada's (2016a) fuel consumption search tool to estimate the standard performance data of the vehicles (*i.e.* fuel consumption and CO_2 tailpipe emissions). Using these values, the energy equivalent (kWh) and CO_2 emissions (kg) were calculated for the total distance travelled during the study period (scenario 3).

PARTICIPANT	CLASS	FUEL CONSUMPTION (L/100 km)			CO_2 TAILPIPE EMISSIONS (g/km)
		HIGHWAY	CITY	COMBINED	
1	None	–	–	–	–
2	SUV	8.3	11.6	10.1	236
3	Sedan	5.1	4.5	4.7	111
4	SUV	7.5	9.9	8.8	207
5	Sedan	7.0	9.6	8.4	196
6	Sedan	6.3	8.4	7.5	173
7	Sedan	6.7	9.1	8.0	184
8	SUV	9.7	11.9	10.9	251
9	SUV	7.3	8.9	8.2	189
10	Sedan SUV	6.3 7.1	8.4 9.1	7.5 8.2	173 194
11	SUV	6.9	8.6	7.8	179

Table 3: Participants' vehicle specifications.

Note: Participant 10 changed vehicles midway through the study period.

SUV = sports utility vehicle.

To assess the energy used for scenarios 1 and 2, the number of days worked from their employer office and commute distance were used with an additional secondary errand distance derived from scenario 3 (*i.e.* average daily distance traveled by the participant when they worked from home).

3.5.2 ICT

The data measured in scenario 3 represent the hourly (BitMeter OS) or daily (Peak Hour 4) internet usage by participants during their work activities. Using a conservative electricity intensity factor of 0.06 kWh/GB (Aslan *et al.* 2018), the total data (GB) were converted to energy (kWh).

For scenarios 1 and 2, no change in internet usage was assumed due to the low impact of internet usage on the total energy used to do work. Also, no data were available to compare data usage when participants work from home versus from their employer office. The amount of energy used locally by network devices (*e.g.* modem and Wi-Fi extender) to provide a steady internet connection was not included in this assessment.

3.5.3 Home office: office equipment and lighting

The energy used by office equipment and lighting energy data were segmented based on working and after-work hours. Additional statistics, such as the average hourly and daily energy usage, were calculated to confirm survey responses about energy-saving practices (*e.g.* switching off equipment). For scenarios where participants go to their employer office, the equipment energy use is assumed to equal the phantom/base loads (determined based on measurements when participants were absent). For lighting, the number of hours electric lighting was used during work hours and the lamp power rating were used to calculate the energy usage. Based on the study results, when the participant works from their employer office for scenarios 1 and 2, negligible lighting energy usage is assumed since the home office remained unoccupied for five or three days.

3.5.4 Home heating energy

Centralized residential heating, ventilation and air-conditioning (HVAC) systems are commonplace in North America, including the participants of this study. Thus, a simple linear changepoint model was developed for each home such that the impact of setpoint schedules could be estimated.

For scenario 3, the total heating energy comprises the natural gas used for heating and estimated HVAC fan energy. The amount of gas used for heating was obtained from the utility company and corrected based on an estimate of hot water consumption (calculated from the average monthly gas used during summer). HVAC fan energy was calculated based on the total HVAC runtime for the equivalent heating period and the fan power. The HVAC runtime was estimated using the time the temperature in the ductwork remained above a threshold (typically 5°C above the maximum living room temperature) or data logs from their smart thermostat.

For scenarios 1 and 2, the total heating energy calculation assumes that the teleworker uses a temperature setback of 5°C for 10 h when they work from their employer office. This conservative setback was selected based on survey responses as participants often use deep setbacks (> 5°C). Using the estimated HVAC runtime, the relative heating degree-hours were calculated using the indoor living room temperature as the base temperature. This base temperature varies from the standard heating degree-days calculation, which uses a base temperature of 18°C. Linear relationships were then derived between the monthly gas used for heating, relative heating degree-hours per month and monthly HVAC runtime (equations 1 and 2). The relationship between the monthly gas used and relative heating degree-hours per month was used to determine monthly gas savings when the participant worked away from home for five (scenario 1) or three days (scenario 2) per week per month (equation 3). The equivalent runtime savings were determined based on the monthly gas savings and the relationship between the monthly gas used and HVAC runtime (equation 4). The equivalent HVAC fan energy savings were based on the monthly runtime savings and the HVAC fan power (equation 5). Using the monthly gas and fan energy savings, the impact of the temperature setbacks was compared with the total energy used in scenario 3 when the participant works fully from their home office.

$$G = m \times HDH_{\text{total}} + c \quad (1)$$

$$G = n \times T + c \quad (2)$$

$$G_s = m \times S \times d \quad (3)$$

$$T_s = G_s / n \quad (4)$$

$$E_s = (T_s / 60) \times p \quad (5)$$

where m, n and c are equation parameters; G is the monthly gas consumed for heating (m^3); HDH_{total} is the monthly relative heating degree-hours (°C.h); T is the monthly HVAC runtime (min); G_s is the monthly gas savings (m^3); d is the total number of days (*i.e.* five days for scenario 1 and three days for scenario 2 per week) they worked away from home during each month; S is the daily temperature setback of 5°C for 10 h when the participant works from their employer office; T_s is the monthly runtime savings (min); E_s is the monthly fan energy savings (kWh); and p is the HVAC fan power: 400 W for residential houses (Saldanha & Beausoleil-Morrison 2012) and 100 W for apartment buildings.

3.5.5 Home cooling energy

Similar to home heating, the central cooling system conditioned the air in the entire home. Some participants used a portable fan to circulate the air in their home offices during the summer; the energy used by these fans was measured as part of home office equipment.

For scenario 3, the total cooling energy comprised the energy used by the AC unit and HVAC fan. From equation (6), the HVAC runtime and AC specifications (derived from the model/serial number or read directly from the data plate) were used to calculate the energy used by the AC unit. Similar to home heating, the HVAC runtime was calculated based on temperature changes in the ductwork or data logs from their smart thermostat. Equation (5) was used to calculate the HVAC fan energy consumption:

$$E_{\mathrm{AC}} = (T/60) \times \left[\left(\frac{\mathrm{BTU}}{\mathrm{AC\ SEER}} \right) /1000 \right] \tag{6}$$

where E_{AC} is the AC energy usage (kWh); T is the monthly HVAC runtime (min); BTU is the AC tonnage; and SEER is the AC seasonal energy efficiency ratio.

For scenarios 1 and 2, no further analysis was conducted as AC was generally not consistently used by the participants. Unlike heating, participants used various coping mechanisms before switching on their AC unit.

4. RESULTS

4.1 SURVEY RESULTS: DEMOGRAPHICS AND OFFICE SPACE

Nine of the 11 participants identified as male and two as female, working in the education, engineering and information technology sectors (Table 1). During the study, participants lived alone or with their immediate or extended family members (Figure 2) in (semi)-detached homes, a townhouse and an apartment. Only two participants had a designated home office, whereas six participants used an empty bedroom or worked from their living room (one) or basement (two).

Participants used similar office equipment as their employer offices, comprising a laptop, computer monitors and ceiling/desk lighting. The primary heating and cooling sources were provided from centralized forced-air systems; some participants also used a heating pad, space heater or fan for further room-level temperature control.

4.2 ENERGY USAGE BY DOMAIN

4.2.1 Transportation

During the work-from-home period, the main modes of transportation for all participants except participant 1 were driving their vehicles (Table 3) with increased cycling during the summer, mostly for leisure. Convenience, shorter commute times and lack of direct public transportation routes were the primary reasons for their choice in transportation, even for participants living in neighborhoods with a high walk score (Table 1). Participant 1 walked during the winter and cycled in the other seasons.

During the study period, participants traveled a mean daily distance of 11–60 km (Figure 3) for everyday errands (notably trips taken during house-hunting, socialization to combat feelings of isolation, school drop-offs/pick-ups, lunch and coffee breaks, and exercising), usually after 12:00 hours. These results were inconsistent with the survey responses where five participants stated that they conducted errands at the end of the workday, on their vacation days or during the weekends. Their measured travel data showed that errands were mostly performed during their workday, similar to the other participants.

The daily travel distance excludes vacation trips and errands performed by a spouse on behalf of the participant. The mean daily travel distance when working from home for participants 3 and 9–11 is 35–86% shorter than their typical one-way commute to their employer office (Figures 3

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and 4). (Note: Participants 9–11 have the longest commute to their employer office, ranging from 25 to 60 km.) For the other participants, their daily travel distance is 140–800% longer than their typical commute to their employer office. For example, when participant 5 worked from home, he was responsible for school drop-offs/pick-ups and took several trips for coffee and lunch. However, these trips would be avoided when working from his company office, especially since he can walk to the cafeteria during his breaks. Additionally, although participant 8 lived only 3 km from his work, he would regularly drive an additional 60 km or more for leisure and exercise (*e.g.* outdoor winter activities, cycling or golfing).

Figure 4 shows example trips for a sample of the participants, with clear differences as a result of their proximity to amenities and their primary mode of transportation. For example, participants 7 and 10 travelled into Ottawa (> 50 km) for specialty shopping and medical visits (participant 10), even when working remotely. When asked to describe their travel behavior, suburban dwellers (*e.g.* participants 7 and 10) noted that the long travel distance deterred them from visiting the city regularly, especially during the winter. Instead, the participants would only visit the city when they had multiple appointments. In contrast, urban-dwellers give less forethought about their trips because of the ease of access. A yearlong analysis of travel destinations suggests that participants behave in a predictable manner with easily identifiable travel patterns. If select days were sampled, these patterns would be less recognizable.

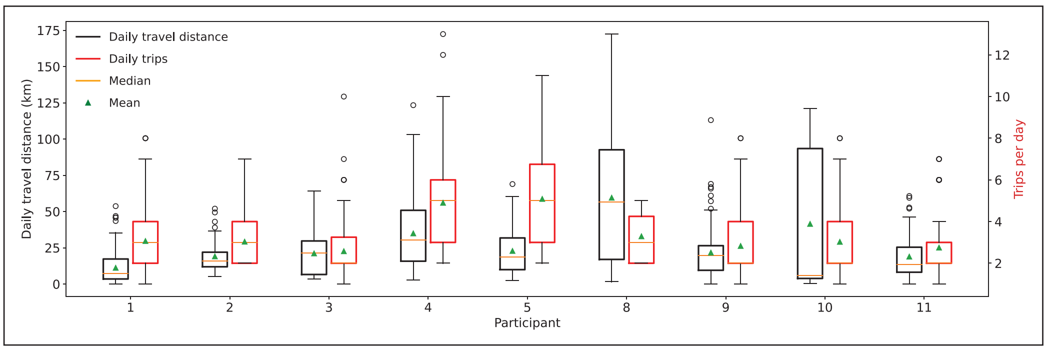

Figure 3: Daily travel distance during the study period and mean number of daily trips when the participants worked from home.

Note: Black circles indicate outliers. Participants 6 and 7 are not included due to the lack of measured data.

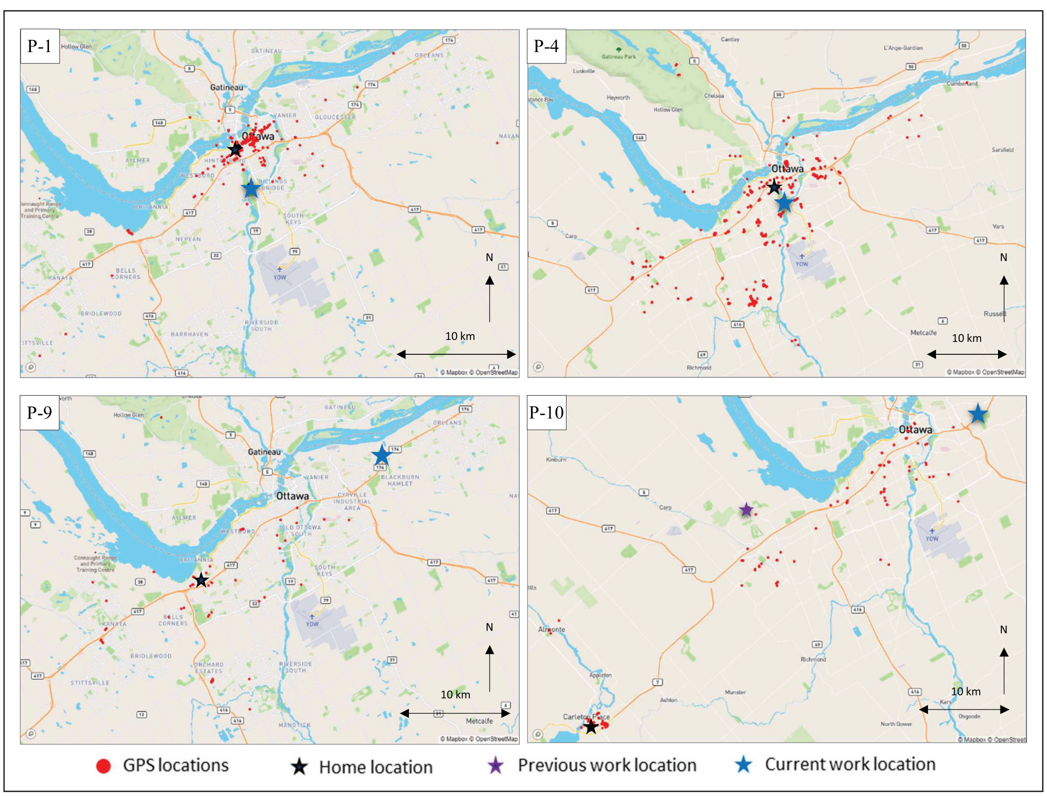

Figure 4: Participant (P) travel destinations during the work-from-home period: P-1, P-4, P-9 and P-10.

Note: P-10 changed jobs during the study. P-1 walks and cycles, whereas P-4, P-9 and P-10 travel via personal vehicles.

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4.2.2 ICT

High-quality, reliable internet access was crucial for all participants, with four participants upgrading their data packages or changing their service provider during the study. Based on survey responses, internet usage included typical work-related tasks (*e.g.* email exchanges, teaching or teleconferencing online, data backup, and transfer) and entertainment purposes (*e.g.* streaming music and television shows, and online shopping).

Internet usage varied between participants, with mean daily usage ranging between 1.5 and 8.4 GB on weekdays and between 0.2 and 8.2 GB on weekends (Figure 5). All participants, except participants 1 and 9, used less data during the weekends due to their work schedule. Day-to-day usage patterns vary based on the length of the workday, tasks undertaken, use of the internet for entertainment purposes and whether the participant shuts down their laptop after working.

The survey results revealed that some participants probably used more data at home as they would watch a video, stream music or shop online. Others noted the opposite, since they had private offices and worked in an unsupervised environment.

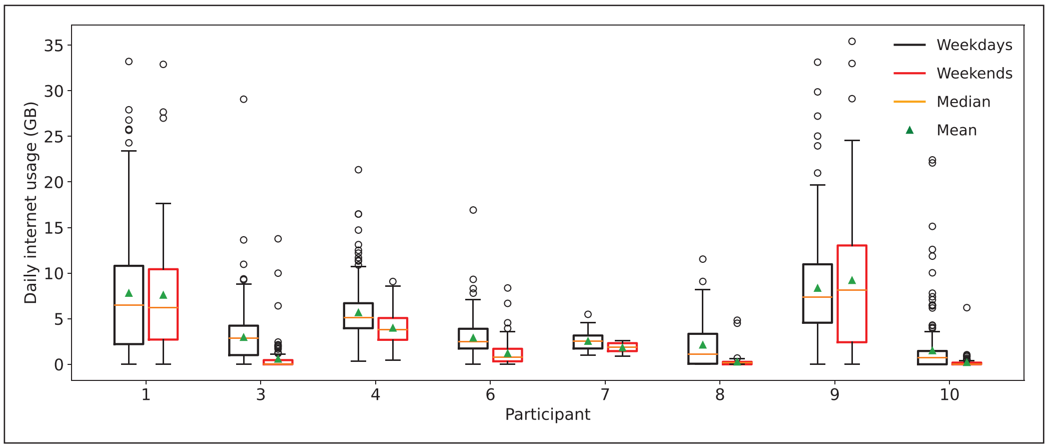

Figure 5: Mean daily internet usage during the weekdays and weekends.

Note: Black circles indicate outliers.

4.2.3 Home office: equipment and lighting

Office equipment and lighting energy usage were segmented based on their home office occupancy. In most cases, the first arrival and last departure were later than the working hours recorded in their interviews. Participant 8 had the most significant deviation in office hours, where the individual spent less than one-quarter of their time working from their designated office space. This validates the participant's survey response that he would often work from another unmonitored location in his home.

The late departure times can also be attributed to the multipurpose use of the home office by the participants and other family members. Additionally, the integration of plug load to identify when participants shut down (or put it in standby mode) their equipment at the end of the workday only improved the last departures by 30 min, suggesting that participants continue to use their work office equipment for personal reasons. In general, occupants worked shorter periods punctuated by frequent breaks with later start and end times.

During working hours, the average hourly energy used by office equipment ranged from 0.004 to 0.08 kWh (average daily energy usage ranged from 0.08 to 1.8 kWh) (Figure 6). Participants' 3–5 and 8 hourly energy usage was consistently low (< 0.03 kWh) due to the number and type of energy-consuming devices (*e.g.* computer monitors (less than two) and laptop) and their length of operation. During non-work hours, the average hourly energy usage decreased by 66–80% to 0.001–0.01 kWh, since participants closed down devices or put them in standby mode, which is consistent with the survey responses.

Artificial lighting usage ranged from 0.1 to 6.8 h/day (Figure 7), varying seasonally with a greater reliance on artificial lighting during the winter and natural lighting during the summer. The average daily lighting energy usage ranged from 0.004 to 0.5 kWh depending on the length of usage, lamp power rating and number of lamps on the fixtures.

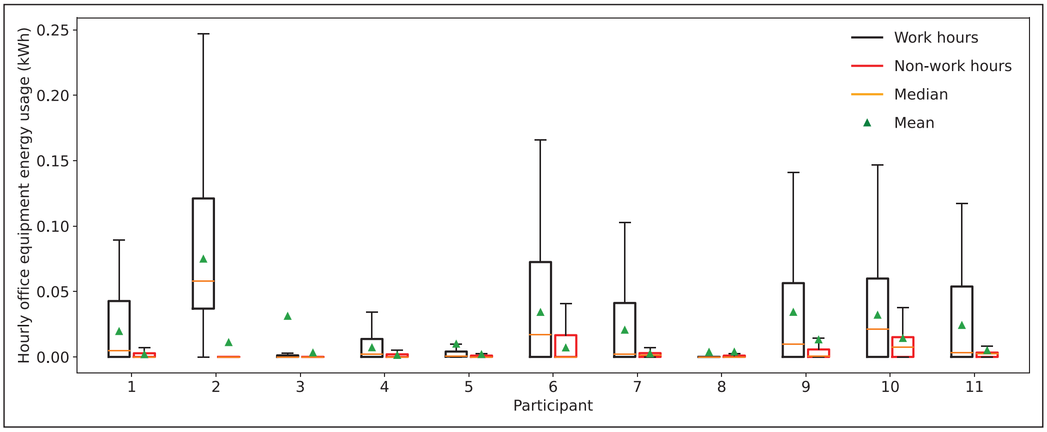

Figure 6: Home office equipment energy usage.

Note: Outliers are not shown.

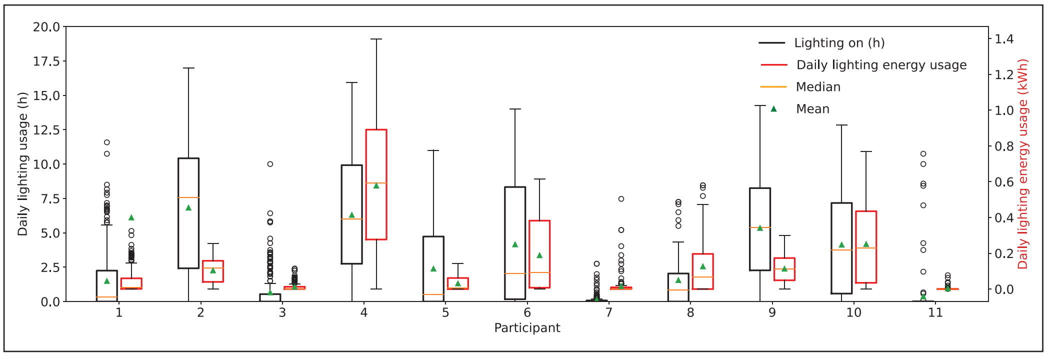

Figure 7: Length of time artificial lighting is used daily and the corresponding energy.

Note: Participant 4's energy usage is high due to the use of two lighting fixtures (six lamps at 10 W and three lamps at 8 W each).

4.2.4 Home heating and cooling energy

The mean temperatures in the participants' living room, close to their thermostats, ranged from 18 to 23°C, with minor seasonal variation for most participants (Figure 8). Indoor temperatures varied by 5°C for participant 1 between the winter and summer; conversely, only a 2–3°C variation occurred for the other participants. When the households contain young children (*e.g.* participants 7, 9 and 10) and older family members (*e.g.* participant 2) or the heating bill (*e.g.* participant 4) is included in their rent, the mean indoor temperatures ranged between 21 and 23°C during the winter. Lower indoor temperatures (18–21°C) were present in households only with adults (*i.e.* participants 1, 3 and 8), except for participant 5. Home offices on the same floor or one storey above the living rooms had similar or slightly warmer temperatures; for basement home offices, average temperatures were 1–2°C colder.

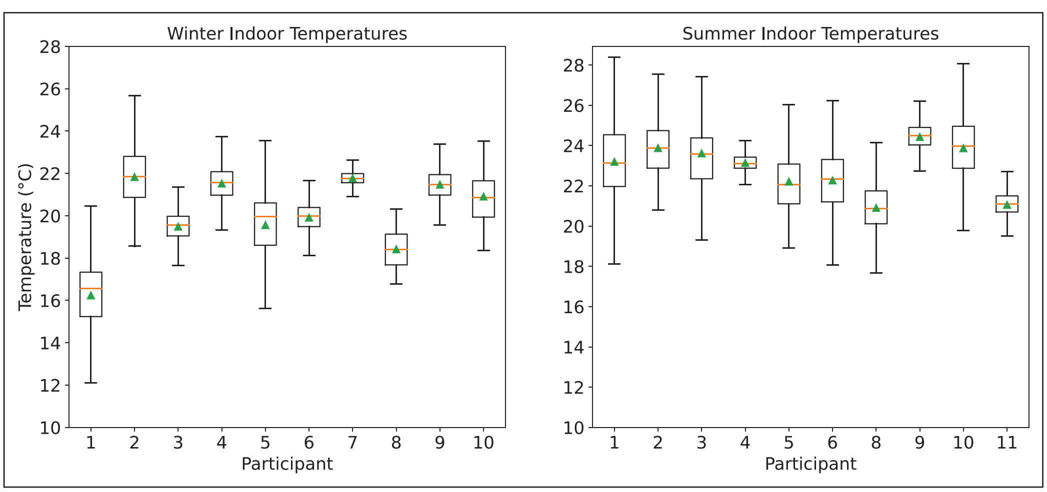

Figure 8: Living room temperatures during the winter and summer.

Note: Data were only collected for the winter for participant 7 and for the summer for participant 11. Outliers are not shown.

Figure 9 shows a sample changepoint model result (note that heating time was converted to energy based on each home's HVAC characteristics). While the trends are similar, the slopes vary by a factor of 4 and the *x*-intercepts vary by > 10°C. The significant diversity among homes—due from

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both behavior and home characteristics—indicates the importance of high-resolution monitoring (versus surveys or less frequent measurements) which may have resulted in homogeneous assumptions about the households.

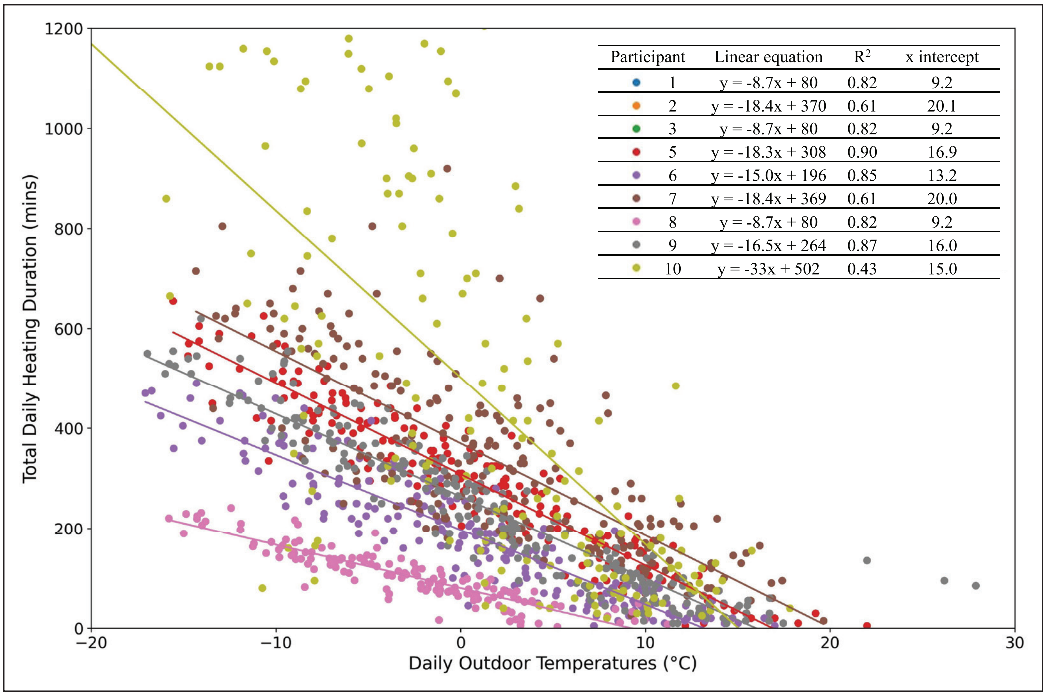

Figure 9: Total daily heating duration versus average daily outdoor temperatures.

Note: The intercept indicates the average outdoor temperature at which the participant switched on their furnace during the heating season. The slope shows the relationship between furnace runtime and outdoor temperatures. Participants 1, 3 and 8, and 2 and 7 have similar linear relationships, resulting in overlapping lines. Participants 4 and 11 are not represented here.

The same changepoint model approach was applied to AC. To a much greater extent than heating, models showed that AC is highly dependent on personal preferences rather than outdoor temperatures. For example, participant 11 switched on their AC unit in the spring (outdoor air temperature about 14°C) and used it consistently throughout the summer and fall. Conversely, participant 9 used AC only when outdoor temperatures were > 25°C. Other participants (*e.g.* 6 and 10) appear to use AC intermittently. Survey responses revealed that some participants may use a fan, open windows or even relocate to cooler parts of the home before switching on their AC unit. Some participants even pre-cool their homes overnight when outdoor temperatures are mild, reducing their need for AC the next day. Notably, participant 1 purchased an AC system during the pandemic due to the high indoor temperatures during working hours.

4.3 AGGREGATED RESULTS

Figures 10 and 11 show that for all participants and scenarios, transportation, heating, cooling and the HVAC fan accounted for > 94% of the energy needed for work; home office equipment, lighting and ICT comprised the remaining 6%.

Mixed results are predicted if participants work part-time from their employer offices (scenario 2) in comparison with working fully from home (scenario 3) (Figure 10). For participants 1–5 and 8, a 0.4–19% reduction in total energy is estimated, due to the combined energy savings in all domains. For the other participants, a 12–187% increase is predicted as the energy savings for heating, plug load and lighting are outweighed by the increase in transportation energy.

If participants work full-time from their employer offices (scenario 1) when compared with scenario 2 (part-time from home), the results are less variable (Figure 10). For scenario 1, where participants travel to their employer's office five days per week with additional errands and home heating is controlled by the participant only, a 1.4–59% increase in energy is predicted for all participants, except for participants 1 and 4.

The main sources of GHG emissions in all scenarios were home heating and transportation (> 98%) (Figure 11). Since Ontario's electricity grid is low-carbon, office equipment, lighting, AC, HVAC fan operation and ICT have a much lower impact on GHG emissions (< 2%).

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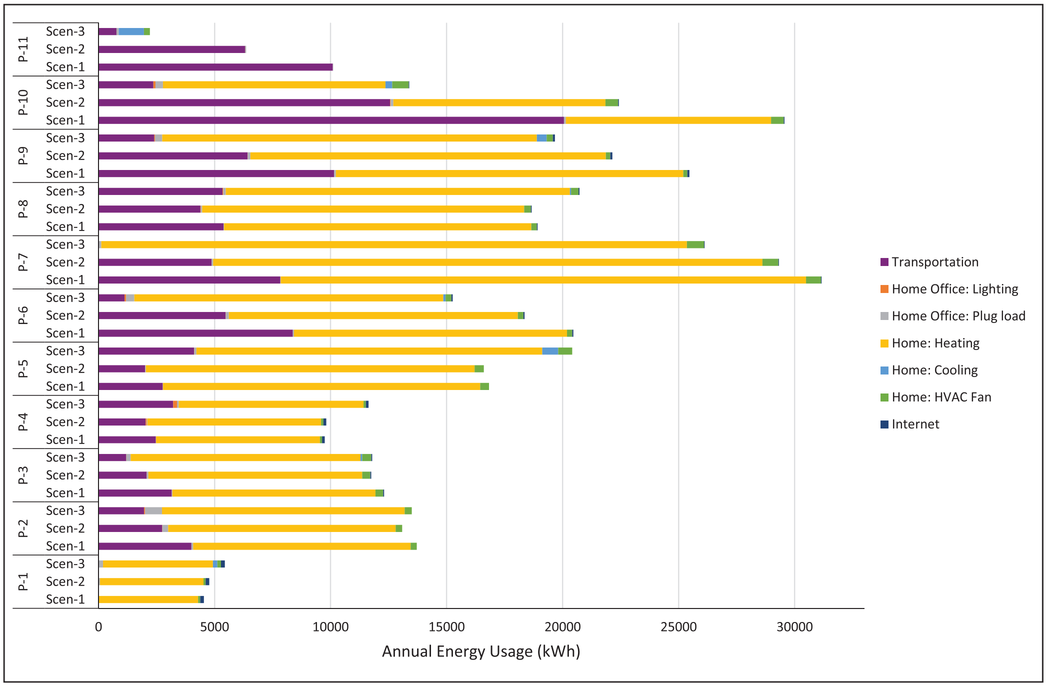

Figure 10: Participants' (P) energy usage for three scenarios: fulltime telework (Scen-1), three days in the office and two days home per week (Scen-2), and fulltime work from home (Scen-3).

Note: For P-7 and P-11, data were only measured for six months compared with one year for the other participants.

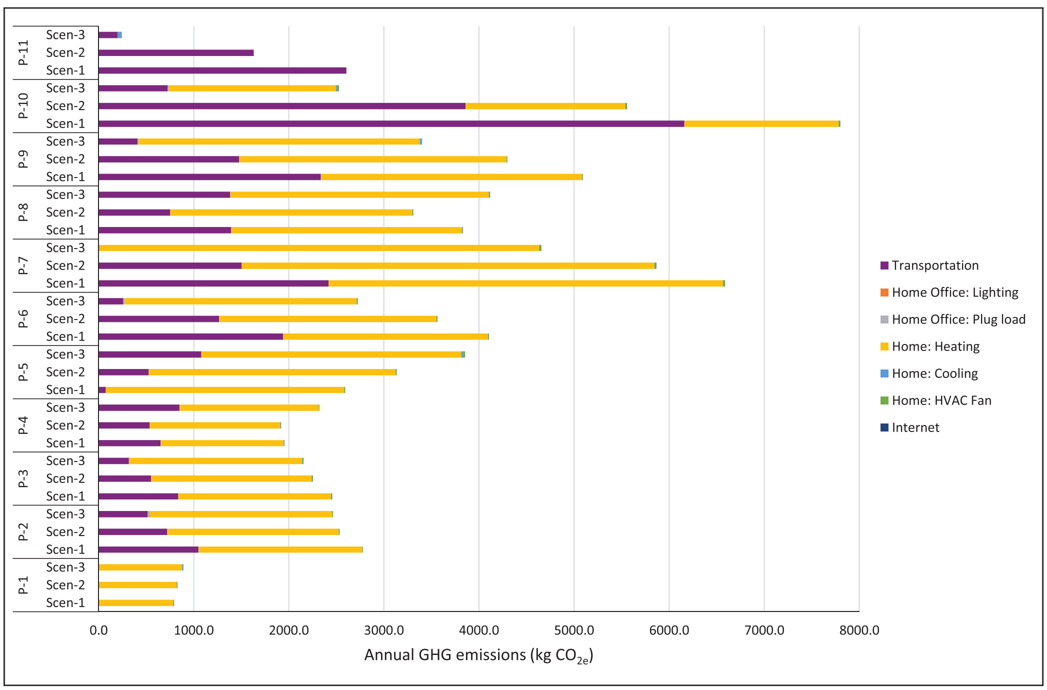

Figure 11: Participants' (P) greenhouse gas (GHG) emissions for three scenarios: fulltime telework (Scen-1), three days in the office and two days home per week (Scen-2), and fulltime work from home (Scen-3).

Note: For P-7 and P-11, data were only measured for six months compared with one year for the other participants.

5. DISCUSSION

5.1 IMPLICATIONS

Energy use from the three domains is influenced by the teleworker's habits and choices, their family schedule and structure, and proximity to amenities. Although the home-to-work distance is a significant variable for personal vehicle users, urban and suburban dwellers behave differently, influenced by convenience and cost. Conversely, this value can be an insignificant compared with the distance traveled for other activities (*e.g.* recreation). Energy usage can be easily measured for home office lighting and equipment, but is difficult to conclusively attribute solely to the teleworker. Heating and cooling energy usage from centralized air-based systems are complex and very difficult to attribute to individual rooms. Here, researchers need to consider whether or not the home is typically occupied, by adults only, or by young children and elder family members, whether the home office is located within a space that requires constant heating/cooling (*e.g.*

in a basement or attic), the teleworker's typical response to cold/hot temperatures, and the magnitude, if any, of temperature setbacks. The impact of these factors is difficult to quantify and untangle from the teleworker's effect.

The results of this study provide empirical evidence to support the hypothesis that teleworking may result in a net reduction in energy usage and GHG emissions (*i.e.* nine out of 11 participants for scenarios 1 and 2). Energy savings are not uniform but are most significant when participants live further away from their employer office (*e.g.* > 20 km) and use vehicles for transportation. Some rebound effects cautioned by the literature (*e.g.* the purchase of a less efficient vehicle and AC, and changing jobs or homes to be further from work/amenities) was observed for several of the participants (Hook *et al.* 2020; O'Brien & Aliabadi 2020). These key decisions were attributed to routine lifestyle changes or arose due to additional needs associated with working from home.

From a policy perspective, governments and employers seeking to use teleworking as a strategy to reduce GHG emissions must consider details (*e.g.* home HVAC controls and transportation modes) without assuming universal savings. In this study, an order-of-magnitude difference between participants' energy use were observed. While such findings are available from the literature outside of the narrow scope of telework (*e.g.* Goldstein *et al.*, 2020; Guerra Santin *et al.*, 2009), they are often concealed by highly aggregated databases (*e.g.* Natural Resource's Canada's, 2016b). Thus, researchers often lose sight of the major (perhaps inequitable) distributions of household energy use among a population. More relevant to this paper, the net impact of teleworking on energy use was generally limited to 20% for individuals, except for the participant with the longest commute (participant 10). This suggests that governments should continue implementing policies to reduce the energy usage in buildings and transportation as the impact of teleworking is largely bound by these preconditions. Conversely, it is a mistake to accommodate urban sprawl with large, low-density housing (as is common in North America) under the premise that teleworking and remote working are prevalent.

5.2 RESEARCH METHOD LIMITATIONS

Unlike previous studies that relied solely on surveys, diaries and modelling, the current method focuses on direct longitudinal measurements. A mixed-methods approach combined interviews/surveys to obtain household information, while the sensor and meter-based measurement collected longitudinal data that participants were unlikely to report accurately. The longitudinal measurements were critical for developing models to extrapolate results to other scenarios. The study revealed some erratic and unexpected behavior that simplistic assumptions (*e.g.* workers commute directly from home to work) or one measurement method alone would fail to capture. For example, participants 4 and 8, who live near their work, travelled farther than most of the other participants. These results were validated and explained during the closing interview—participant 4 was house-hunting for a couple of months and participant 8 engaged in leisure activities far away from his home.

Although the developed approach is well suited for assessing longitudinal effects, it is costly (approximately US$2000 and 100 h of incremental researcher labor per participant). While the participants were compensated, the eligibility criteria and high level of participant involvement poses a constraint. In post-COVID times, the researchers could reduce participants' efforts by installing the sensors. Scaling the study by one or two orders of magnitude—the level at which generalized conclusions could be formed—would be a major undertaking, requiring a team of research assistants.

The scenario approach taken in this study comes with its own limitations; namely that assumptions had to be made about how participants' short- and long-term decisions would be affected by different teleworking circumstances. For example, how non-teleworkers or part-time teleworkers set their thermostats on days that they are absent was not directly observed. Ideally, larger scale studies would instead compare different groups (*e.g.* full-time teleworkers versus full-time office workers) so that all energy-related decisions could be directly observed.

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5.2.1 Transportation

Research on the use of Google Timeline to determine the location of a mobile device is currently limited and hindered by Google's lack of transparency. Although Google Timeline can be used to determine whether a phone was present in an area, trip location 'errors are of the same order of magnitude as their accuracies' (Macarulla Rodriguez *et al.* 2018: 253). The magnitude of these errors is affected by the phone configuration (*e.g.* 2G, 3G and Wi-Fi), environment (*e.g.* rural or urban), and means of transportation (*e.g.* still, walking, biking and vehicle). While this study involved participants with good network coverage, errors could increase for rural areas.

Fuel efficiencies are measured under controlled laboratory testing environments by vehicle manufacturers (Natural Resources Canada 2016a). These values cannot fully represent the actual fuel consumption as it also depends on traffic, roadway quality and driver-behavior factors (Chen *et al.* 2014). More advanced models could be used, but they require additional data that are difficult to quantify (Li *et al.* 2017).

Another limitation is that the participants' travel pattern is assessed rather than the households' (O'Brien & Aliabadi 2020). When the office worker starts teleworking and work trips are eliminated, there is a corresponding increase in car usage by other household members (Kim *et al.* 2015). Our method could not measure vehicle occupancy beyond the participant. de Abreu e Silva & Melo (2018) suggested that the increase in the household size (*e.g.* one- or two-worker households) results in a more efficient division of tasks between members, even though the number of trips may increase when one party begins teleworking. Regardless, the salient point is this: the study results may be optimistic as any savings from reduced travel by the teleworker may be offset by increases in trips by other household members.

5.2.2 Home heating and cooling

This study is based on central HVAC, whereby a home office or workspace cannot be independently conditioned. This explains the high sensitivity of heating energy to the teleworking scenarios. However, other family members who are present (*e.g.* another teleworker) would benefit from a comfortably controlled home. Ideally, future studies would involve at least surveying all household members, consider the allocation of HVAC energy for each occupant and the impact of various temperature setbacks. The impact of teleworking would be much greater for homes in mild climates with room-by-room HVAC control. A 5°C setback is only a fraction (15–20%) of the difference between typical winter temperatures in Ottawa and indoor temperatures, meaning that the potential energy impact of teleworking is limited. In contrast, a recent study in the UK (with a milder climate) found much greater heating energy sensitivity from teleworking because of the possibility of turning the heat off or only heating select rooms (Shi *et al.* 2023).

5.2.3 Employer office

The employer office domain was not quantified during this study due to the enforcement of work-from-home policies. However, studies conducted during the pandemic have shown that commercial office spaces consumed significant energy due to the implementation of infectious disease control strategies (*e.g.* increasing the amount of outdoor air and running the HVAC system for longer), the low levels of centralized controls, the lack of responsiveness of building systems to changing occupancy levels, the continued hosting of data servers, and work computers left on for remote desktop connection (Chihib *et al.* 2021; Gaspar *et al.* 2022; Schoen 2020). Moreover, unless space utilization is improved (*e.g.* via hotdesking) and employees do not have dedicated workstations, teleworking does not necessarily yield space savings (and associated HVAC and lighting savings). Thus, the omission of offices from this study is not expected to profoundly affect the total energy/emissions results in the short term until optimized office space management is widespread (*i.e.* telework actually results in reduced office space and demand-based lighting and HVAC are implemented) (O'Brien & Aliabadi 2020).

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6. CONCLUSIONS

The study revealed the importance of collecting both self-reported data from participants (*e.g.* home and vehicle characteristics, rational for decision-making) and long-term sensor/meter-based measurements to capture teleworker habits and the corresponding energy use. These two major data sources are complementary in forming a more complete picture of teleworker energy use, while serving as verification. While high-resolution measurement used in this study were labor intensive, they were critical for certain aspects of the study, including separating work and non-work travel and office electricity use, and characterizing the homes' thermal properties, heating, ventilation and air-conditioning (HVAC) equipment, and corresponding behavior. This allowed multiple scenarios to be modelled. Monthly or annual vehicle distances travelled and utility bills would be insufficient for these investigations. In climates necessitating heating or cooling for a large portion of the year, measurement of office equipment, lighting, and information and communication technology (ICT) is less critical since these are at least an order of magnitude smaller than transportation and HVAC energy/emissions. Future studies should, however, include office buildings for completeness. Inter-household dynamics can play a major role in household energy use (*e.g.* carpooling, trip-chaining, HVAC setpoint selection) and thus future studies should attempt to survey and/or measure all household members.

While the sample was small, the results consistently indicate that home heating and transportation are dominant among the explored domains of home, transportation and ICT. Similar to previous studies, the results ranged significantly among individuals due to their transportation mode, home and household characteristics, and distance to their workplace. The low- and high-energy/emissions participants ranged by an order of magnitude—much more than the impact of teleworking. Nine of the 11 participants used less energy and produced less greenhouse gas (GHG) when teleworking than working from their employer office; transportation, home space heating and cooling have the greatest impact on the total energy (> 94%) and GHG emissions (> 98%). In general, the highest energy savings are likely to occur when individuals live further away from their employer office and use personal vehicles as their primary mode. Heating energy use is profoundly affected by home thermal characteristics, but in the current cold climate, setbacks enabled by working away from home have only modest (about 10%) potential savings.

As employers and employees weigh future teleworking options, and as climate policies increase in urgency, evidence will be critical for informing policy. The results from this pilot study suggest that teleworking cannot be considered to be universally more sustainable. The results are far more complex and circumstantial, encompassing a wide variety of circumstances—well beyond the individual teleworker.

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COMPETING INTERESTS

The authors have no competing interests to declare.

DATA AVAILABILITY

The data are not available for open access, but data summaries related to this paper can be requested from the authors.

ETHICAL APPROVAL

Ethics clearance (ID: 113350) was obtained from Carleton University. This required that the participants remain anonymous. The nature of data collection, study purpose and participant rights were communicated with the participants via a consent form.

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