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04

COVID-19 Response: Impact of Adaptive Working Behavior on Operating Carbon

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Abstract

The COVID-19 public health crisis has affected many aspects of daily living and working behavior, impacting carbon footprint. This research aims to explore adaptive working behavior and its direct and quantifiable environmental impacts. It studies various working and commuting behavior scenarios on energy consumption and the carbon footprint of commuting and building operations. The paper develops a methodology for calculating the impacts of variable working patterns for a North American business. We then conduct two case studies in our own Atlanta and Vancouver studios to model the specific changes in behavior and resulting carbon implications. Considering both buildings and commute patterns, the analysis shows the impact of behavior change on reducing the carbon emission profile of a city, which varies by location. Atlanta can experience more reduction in CO2 emission related to both building operation and transportation due to the higher utility of the electric grid system in the city and heavy reliance on driving cars, compared to Vancouver. The contribution of this work is the methodology for calculating and comparing carbon impacts of different results from home scenarios and the data from two case studies. The work has short-term implications for understanding the impacts of the COVID-19 quarantine and longer-term consequences due to increasing telework demand.

Keywords: *building energy performance, occupancy, adaptive working behavior, greenhouse gas emission*

Nomenclatures: *Domestic Hot Water (DHW), Department of Energy (DOE), Equipment Power Density (EPD), Energy Use Intensity (EUI), Greenhouse Gas (GHG), Lighting Power Density (LPD), Multi-Unit Residential Building (MURB)*

1.0 Introduction

Our working and living behavior changed due to the COVID-19 pandemic. Worldwide, people stayed at home and practiced social distancing to contain the spread of the virus. A disease claiming people's lives certainly should not be seen as a way of changing energy and emissions patterns. However, the COVID-19 public health crisis has affected many aspects of our typical daily routine, which changed the way we used energy. The behavioral changes could carry over beyond the current COVID-19 pandemic. Not only the imperative social distancing temporarily transitioned many office workers to work from home, but telework has also been an ongoing demand in recent years.[1] The surge in teleworking raises questions about its impact on different aspects of our life. Environmental impacts associated with buildings' energy performance and commute patterns could lead to some longer-lasting changes in emission profiles of cities.

Buildings consume around one-third of total primary energy resources in the U.S., accounting for 30 percent of CO_2 emissions.[2] On the other hand, transportation is responsible for nearly one-fourth of the world's CO_2 emissions. The road sector holds the most significant share.[3]

This research hypothesizes that adaptive working behavior will have direct and quantifiable energy and carbon impacts on both buildings and the commuting pattern. We aim to explore the impact of working from home, either considered as a short-term scenario due to COVID-19 lockdown or long-term scenario due to potential telework demand, on energy consumption and carbon footprint related to buildings and work-related travel.

1.1 Environmental Impacts of Pandemic in Literature

According to the International Energy Agency (IEA), the current Covid-19 pandemic has had major implications for global economies, energy use, and CO_2 emissions.[4] The first quarter of 2020 showed that countries in complete lockdown were experiencing an average 25 percent decline in energy demand per week and countries in partial lockdown an average 18 percent decline. Daily data collected for 30 countries showed that demand depression depended on the duration and stringency of lockdowns. Global CO_2 emissions were over 5 percent lower in Q1 2020 than in Q1 2019. This is mainly due to an 8 percent decline in emissions from coal, 4.5 percent from oil, and 2.3 percent from natural gas. CO_2 emissions decreased more than energy demand, as the most carbon-intensive fuels experienced the most significant declines in demand during Q1 2020.[4]

In addition to the IEA report, recent literature has addressed the environmental changes impacted by the pandemic at various scales, from aggregated levels in a country or region to a building level. The studies are predominantly conducted based on the observed data. Geraldi et al., for instance, have monitored the electric energy use of municipal buildings in Florianopolis, Brazil, during the five months lockdown, from March to August 2020.[5] The observed data provided by City Hall revealed a significant reduction in electricity use, depending on building types. Health centers, administrative buildings, elementary schools, and nursery schools showed a mean decrease of 11.1 , 38.6, 50.3, and 50.4 percent. Aruga et al.also showed that lockdown measures directly impacted energy consumption in India.[6] They reported the positive influence of COVID-19 cases on Indian energy consumption and how it recovered again as the lockdown was relaxed.

Another set of building energy use metering has been reported by Garcia et al., using the data from advanced metering infrastructure in Manzanilla, Spain.[7] The study analyzed the consumption behavior and the impact that the crisis has had and showed a 15 percent increase in residential energy consumption during a full lockdown and 7.5 percent during the reopening period. Non-residential customers had a 38 percent decrease in consumption during the full lockdown and 14.5 percent during the reopening period. The customer metadata in each building type was highly correlated to the restrictions imposed to control the spread of the virus.

While the studies provide insight into energy use patterns based on metered data, they fell short on detail that resolves building-level and occupant-level energy consumed. As an alternative, building performance simulation can be used to conduct a detailed predictive study for energy demands during the pandemic. An example of a study using computer simulation is shown by Zhang et al. in Sweden, where three levels of confinement for occupants have been simulated to evaluate the impact of Covid-19 on buildings' energy demand at a district level.[8] Compared with the base case, the average delivered electricity demand of the entire district increased 14.3 to 18.7 percent under the three confinement scenarios. However, the mean system energy demands (sum of heating, cooling, and domestic hot water) decreased in a range of 7.1 to 12.0 percent. The two variations nearly canceled each other out, leaving the total energy demand almost unaffected for the location under study.

As different studies suggest, there is a high correlation between the pandemic's level of confinement, humans' behavior, and buildings energy consumption. A more detailed analysis of the working behavior and its impact on the operation of the built environment is required.

1.2 Buildings Occupancy and Working Behavior

The energy performance of buildings is governed by various parameters, such as their physical characteristics, external environment, internal services systems, and the behavior of their occupants.[9] Human presence and behavior are essential components in the energy performance of a building. According to Robinson, the most complex processes within facilities result from human presence patterns and flows.[10] Many studies, such as Emery and Kippenhan[11] and Masoso and Grobler,[12] acknowledged that the diversity of user behavior has an illustrious effect on energy consumption while keeping other building parameters alike. Clevenger et al. suggested that variant occupant behavior can impact annual energy usage on the order of 75 percent in residential buildings and 150 percent in commercial buildings, with modest variations across climates.[13,14] Yun et al. also investigated the influence of human behavior on an office building.[15] They showed the 50 percent lighting energy increment due to the change of occupancy presence schedule in observed spaces.

The relationship between the behavior of occupants and the operation of buildings is highly complex. Occupants participate in the heat balance of the building through their body heat. Furthermore, occupants' intervention in the control of heating, ventilation, and air conditioning systems and their operation of lighting and appliances (such as cooking) directly affect internal heat loads and ultimately building energy consumption.[16] Understanding, quantifying, and modeling the influence of occupant's behavior in buildings energy simulation tools are essential if we are to evaluate the performance of a building.

1.3 Modelling Human Behavior in Simulation Tools

The building energy simulation tool is a theoretical representation of the status and operation of a building, designed to replicate the dynamics that govern energy use. Occupant behavior is modeled in simulation tools as Operation Schedules and Loads:

- Operation Schedules: By identifying the occupant behaviors in a building as schedules, including occupancy, lighting, equipment, and HVAC schedules, to reflect the usage patterns. Schedules are accounted as hourly data for weekdays, weekends, holidays, and separately for summer and winter design days.
- Operation Loads: Quantifying the behavioral information, such as occupancy density, the lighting loads, and equipment loads based on tasks.

Both schedules and loads are often modeled in existing simulation practices as simplified predefined fixed profiles.[17] These inputs are mostly based on historical data[18] or as a discrete "stimulus-behavior relationship".[19] In an office, the existing empirical models of equipment loads tend to be based on statistical algorithms that predict the probability of equipment used from observations of actual case studies. The operational pattern and related occupancy of buildings are different depending on the function of the building and spaces. Consequently, the operational schedules in residential buildings show remarkable differences

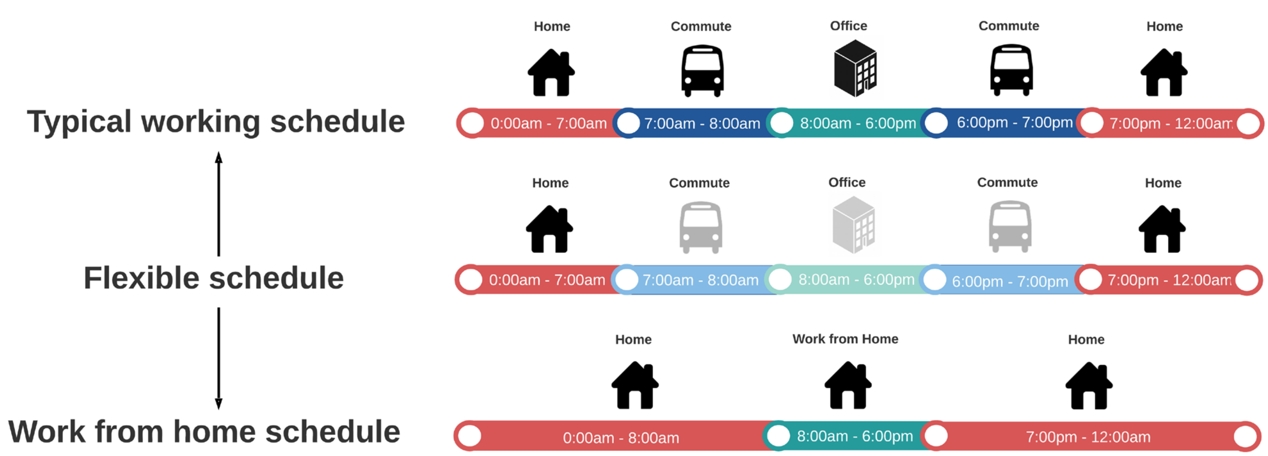


Figure 1: *Schedule examples of working behavior changes.*

compared to commercial buildings.[20] Therefore, knowledge and modeling of such user numbers, actions, and events/schedules are crucial to better predicting and understanding building performance in the time of change.

When working behavior changes, the activity location, patterns, and schedule during a day changes, as depicted in Figure 1. Additionally, occupants' needs for thermal comfort, lighting, appliance, and other internal services change in both workplaces and residential spaces. Clearly, these changes are not affecting commercial and residential buildings proportionally, nor are they similar in various locations. In addition to the changes in buildings' energy performance, working from home can significantly impact the emissions associated with daily travel made by individuals. This research, therefore, quantifies the changes in working behavior for various scenarios and evaluates the impact on buildings and work-related travels in different urban contexts and climate conditions using computer simulation. The following section presents the methodology for quantifying and modeling adjustable working behavior. Section 3 presents the results and discusses the data for two selected climate locations, followed by a conclusion and future work in section 4.

2.0 Methodology

While most studies rely on the observed data at an aggregated level to evaluate the changes in buildings' energy consumption during the pandemic, this study aims to highlight the role of “working behavior” and its quantifiable impact on the built environment in a controlled experiment. Due to the limitations of isolating a factor in an observational study and the difficulties of gathering the actual energy use data from an individual’s residential building, this study is conducted based on simulations. The computer simulation method has its limitation due to various modeling uncertainties. Still, it is a good candidate in such an exploratory experiment to quantify the changes in loads and schedules and help us predict the consequences of such changes on all categories of energy used in commercial and residential buildings.

This study quantifies and models adjustable schedules and load changes derived from adaptive human behavior for various scenarios of working patterns during a week and ultimately over a year. It focuses on two Perkins&Will studios and their employees in Atlanta and Vancouver. The office buildings, as well as residential buildings and commuting networks of all employees, are modeled. The predicted energy use, peak loads, and carbon emission of defined scenarios are compared to assess how the new telework behavior affecting building performances in different climate and urban contexts. Figure 2 presents an overview of the

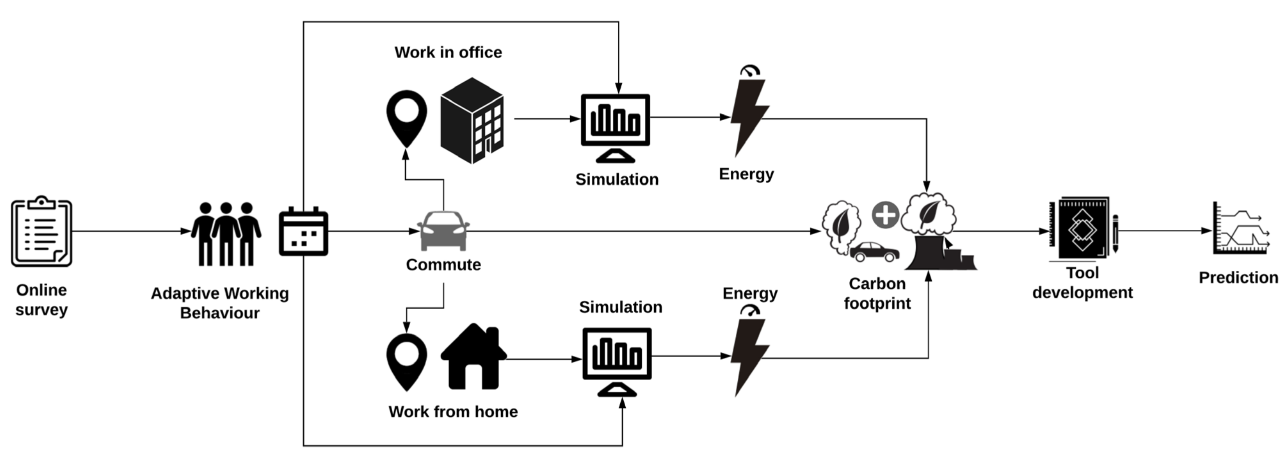


Figure 2: *Overview of research methodology.*

methodology, consisting of five steps, explained in detail in the following sub-sections:

- Defining scenarios of adaptive working behavior
- Identifying prototype buildings
- Running Energy simulations
- Online survey for residential typology and commute information
- Energy and carbon data integration.

2.1 Defining Scenarios of Adaptive Working Behavior

The flexible schedule reflects the changing and adjustable operational schedules for occupancy, lighting, equipment, and HVAC and calculates the corresponding load changes. The modifications in schedules and loads followed different logics in commercial and residential buildings. The updated data is reflected differently in these two types of buildings.

This study defines working scenarios as the percentage of employees working within the office, assuming the rest are working from home. The first scenario is the pre-pandemic situation with a 100 percent occupancy working in the office, considered the study's baseline. The rest of the scenarios generated a 10 percent decrement in occupancy until the scenario of an empty office (0 percent occupancy). The occupancy scenarios indicate the offices keep operational with fewer employees present compared to the baseline. Altogether, we study eleven working scenarios and monitor both office and residential buildings' energy performance (Figure 3). For each working scenario, the associated changes in loads and schedules of lighting, equipment, and occupancy for commercial and residential buildings are modified separately.

- **Occupancy:** when fewer employees work in an office, they still follow the same occupancy behavior schedule (e.g., 8am to 5pm) with a decreased number of occupants. While in a residential building, the occupancy number remains the same as the pre-pandemic situation, but occupancy hours are extended to reflect working from home behavior.
- **Equipment:** the updated scenario of working in an office does not change the pattern of equipment loads but the amount of their use. As a result, the same equipment schedule in the office is maintained. In contrast, the equipment load decreases proportionally to reflect occupancy reduction. In residential buildings, based on the current assumption of the equipment loads and schedules that are averaged evenly during a week and over a year, the work-from-home triggers an increase in the home-office equipment load, as part of variable miscellaneous electric loads.[21]
- **Lighting:** the majority of the lighting load in an office is related to the ambient light, which does not echo the reduced number of employees. On the other hand, the task light decreases proportionally to reflect occupancy changes. Although the more recent office buildings might be equipped with advanced lighting control, we decide to take the ordinary and conservative scenarios in which the ambient lighting is independent of the number of occupants. For residential, an increase in task light is sufficient to reflect the scenario when occupants work from home.

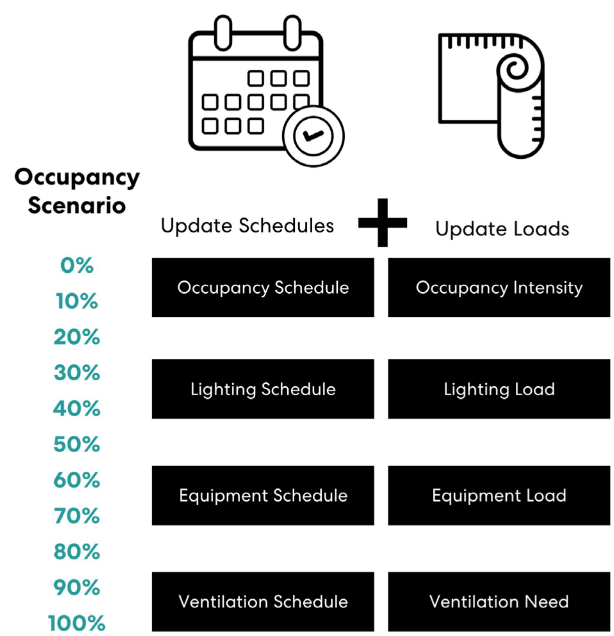


Figure 3: *Modified schedules and loads.*

2.2 Identifying Prototype Buildings

The study uses the U.S. Department of Energy (DOE) prototype building models developed for commercial and residential buildings to reduce the discrepancies among the individual buildings and facilitate cross-comparisons.[22] According to the DOE documentations, the prototypes cover 75 percent of the commercial buildings. Medium to high-rise residential floors are in the United States, which can serve as a valid representation of most structures for study. For the commercial building, the medium-size office model has been chosen to represent the Perkins&Will offices in two locations under study, with a floor area of 53,628 sf and 3 stories. The occupancy is assumed to be 0.0537 people/m^2 in a medium-size office, meaning that 268 people occupy the building.

In parallel to modeling an office building with different scenarios, we manage to model different residential types accommodating the 268 employees. They include single-family detached houses, a multi-unit residential building (MURB), low-rise apartments, and multi-family high-rise apartments, as shown in Figure 4. It is essential to recognize the differences associates with various residential types. The proportion of different residential types in locations under investigation would affect the total energy use patterns. Therefore, it is within the research scope, and we investigate it through the online survey discussed in the next section.

2.3 Online Survey: Residential Typology Distributions and Commute Information

We designed and distributed an online survey for the employees of the two offices of Vancouver and Atlanta. We asked them to identify their residential types from a list, including low-rise apartments, high-rise apartments, or single-family houses/townhouses/duplex. We asked them to describe their commuting patterns, including distance traveled and mode used for commuting) and to map and report estimated carbon emissions through the https://mapmyemissions.com website.

2.4 Energy Simulation Platform

We created 88 energy models to explore the 11 occupancy scenarios in two offices and six residential buildings for Atlanta and Vancouver. The models are in idf format, EnergyPlus input files. Energy use, peak loads, and carbon emission were eventually calculated through the EnergyPlus platform. To streamline and semi-automate the simulation process, we have developed scripts in Eppy.[23] Eppy is a scripting language for EnergyPlus idf files and EnergyPlus output files written in Python. All the loads and schedule changes for models s are modified by the scripts.

2.5 Results Integration

Next, we summarized energy and carbon footprint at both building and commute levels. Buildings' operational carbon is calculated at the building's level based on the energy performance results. The commute's carbon emissions, on the other hand, are calculated concerning the number of office occupants and their typical commute types and distances, as collected from the online survey (see Figure 5). Finally, we assess the total energy and carbon footprint of both buildings and the commute system.

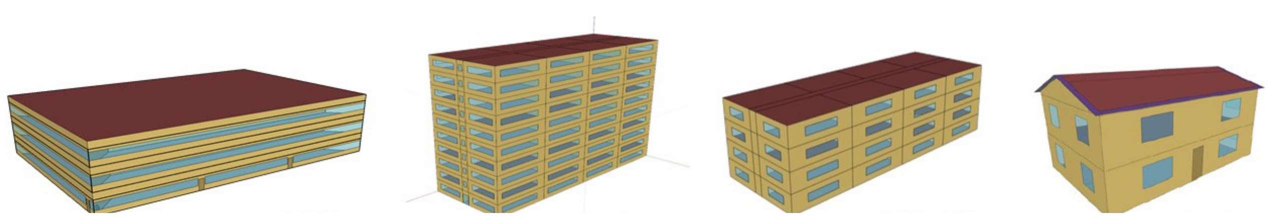


Figure 4: *DOE Prototype buildings used in the study.*

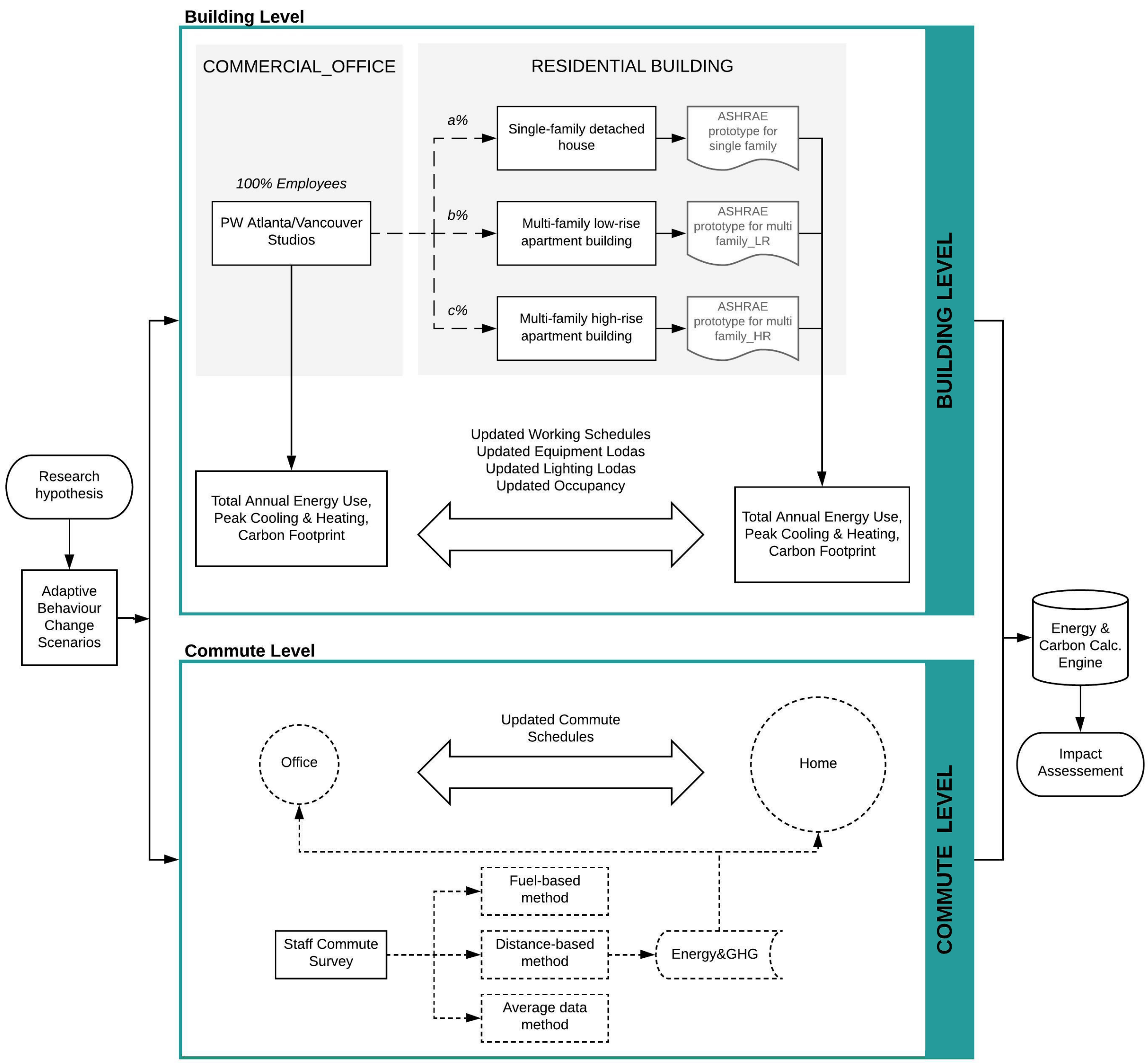


Figure 5: *Energy and carbon data integration.*

3.0 Results

3.1 Survey Results

More than 170 employees in Atlanta and Vancouver offices participated in the online survey, which is about 65 percent of total employees. Based on the data sorted in Table 1, the Atlanta office's employees mostly live in a single-family house, followed by low-rise and high-rise apartments. In Vancouver, employees are primarily residing in high-rise apartments, followed by single houses and low-rise apartments. It is noteworthy that single-family house prototypes are modified and classified to accommodate four different heating systems and four foundation types. The data and literature suggest that Vancouver's single houses' most representative heating system is a gas furnace with a crawl space foundation,[24] while in Atlanta is the heat pump system with an unheated basement.[25, 26]

According to the commuting data in Table 2, most employees in Atlanta drive to work, and only about 13 percent of employees commute by walking or biking. Public transportation commuters constituted about 20 percent of workers in the Atlanta office, based on the survey. On the other hand, Vancouver employees most often rely on walking or biking to work, followed by public transportation. Only about 8 percent of employees drive to work regularly. Figure 6 summarizes the differences between the two offices.

Table 1: *Residential typology distribution.*

RESIDENTIAL TYPES & DISTRIBUTION	ATLANTA	VANCOUVER
Low-rise Apartment	18.2%	11.8%
High-rise Apartment	15.9%	52.9%
Single-family House	65.9%	35.3%
Single Family House's Heating System	Heat pump	Gas furnace
Single Family House's Foundation Type	Unheated basement	Crawl space

Table 2: *Commute patterns.*

COMMUTE SYSTEM	ATLANTA	VANCOUVER
Walking/ Biking	13.6%	58.8%
Driving Car	65.9%	8.8%
Public Transportation	20.5%	32.4%
Avg. One-Way Commute Distance (miles)	9.63	4.76
Avg. One-Way Commute Emissions (lb of CO2-e)	5.88	1.25

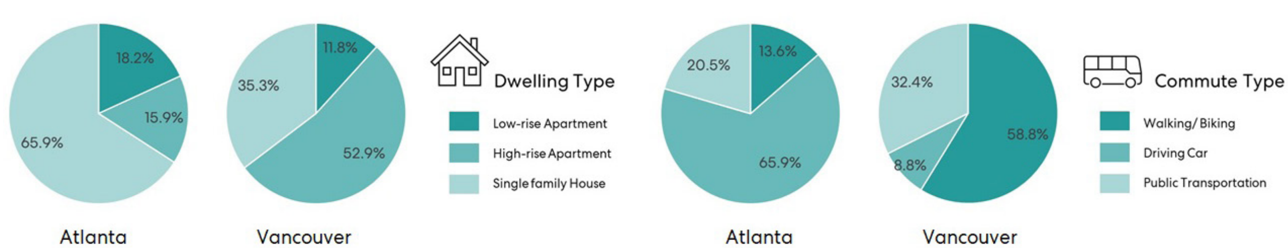
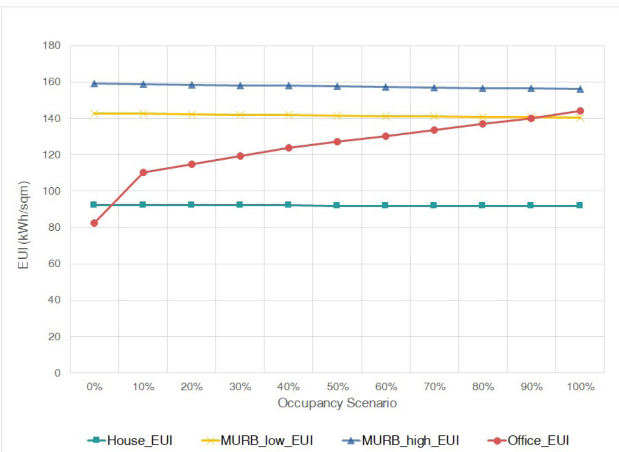


Figure 6: *Dwelling and commute types in Atlanta vs. Vancouver.*

3.2 EUI and Climate Differences

The Energy Use Intensity (EUI) data for eleven predefined working scenarios, from 0 to 100 percent office occupancy, have been plotted in Figure 7, cross-comparing commercial and three types of residential buildings. Figure 8 shows the total energy use of the office buildings and the residential units of 268 employees. As depicted, the energy use patterns in the two Perkins&Will office locations behave differently due to the climate difference. Vancouver is in a heating driven climate, Climate Zone 4C, which is defined as Mixed Marine with 2000 < HDD18oC ≤ 3000 (3600 < HDD65oF ≤ 5400). Atlanta, on the other hand, is in a cooling driven climate, Climate Zone 3A, which is defined as Warm Humid with 2500 < CDD10oC < 3500 (4500 < CDD50oF ≤ 6300). To better understand energy consumption behavior in each building type and location, the total energy consumption in each building type,including electricity and gas, is listed in Tables 3.1 to 3.4 for Vancouver in section 3.3 and Tables 4.1 to 4.4 for Atlanta in section 3.4, respectively.



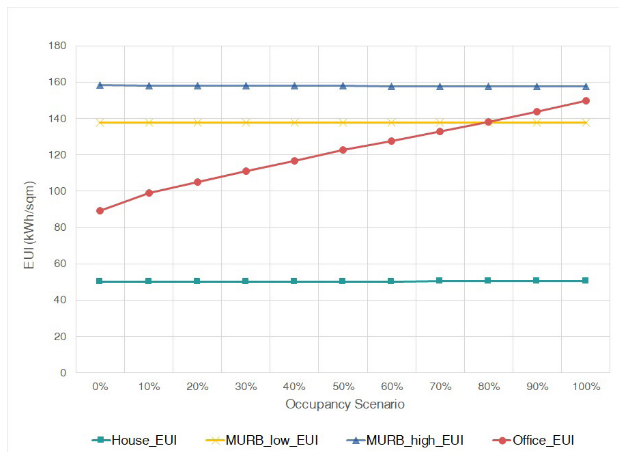
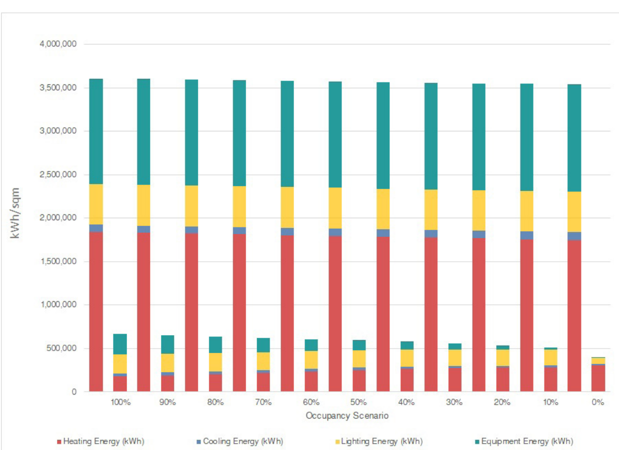


Figure 7: *EUI pattern in Atlanta (left) and Vancouver (right).*



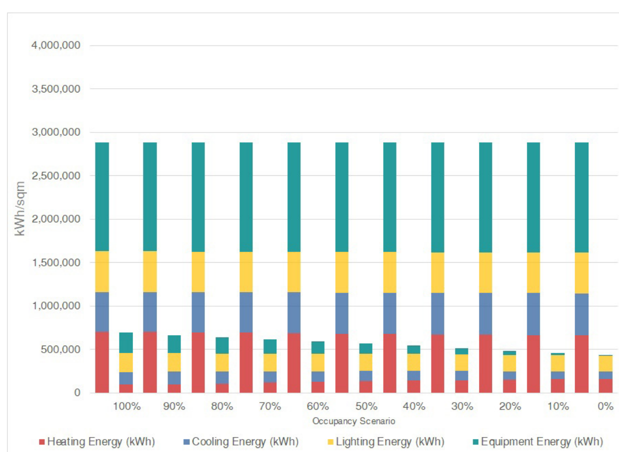


Figure 8: *Energy use breakdown in residential (first bars) & office (second bars) in Atlanta (left) and Vancouver (right).*

3.3 Changes in Buildings' Energy Performance in Vancouver

In Vancouver, office buildings with lower occupancy rates will trigger lower cooling, lighting, equipment, fan, pump, and DHW energy use. The only energy increase due to less internal heat gain is heating energy. Overall, energy use in an office building would be reduced significantly. Residential building in Vancouver is still heating energy dominated. With a higher occupancy rate in the dwelling space, internal heat gain increases, and heating energy (gas) reduces slightly in MURB-high and low. In Vancouver single-family houses, with higher occupancy rate in the dwelling space, internal heat gain increases and heating energy (gas) reduces. Although more cooling/equipment/fan energy (electricity) is required, the overall energy would be reduced.

Table 3.1: *Vancouver Office energy use for various occupancy scenarios.*

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Heating Energy (kWh)	309,319	286,369	281,508	274,866	267,237	254,663	239,095	224,113	206,851	189,846	177,075
Cooling Energy (kWh)	13,253	17,455	18,959	20,711	22,626	24,910	27,518	30,286	33,076	35,907	38,799
Lighting Energy (kWh)	73,881	184,232	187,763	191,295	194,827	198,358	201,890	205,421	208,953	212,484	216,016
Equipment Energy (kWh)	2,822	25,552	48,408	71,377	94,465	117,681	141,036	164,542	188,213	212,064	236,112
Fan Energy (kWh)	12,127	16,673	17,474	18,303	19,132	19,997	20,931	21,973	22,929	23,990	25,212
Pump Energy (kWh)	0	4	8	12	16	20	24	29	33	37	41
DHW Energy (kWh)	0	18,479	18,479	18,479	18,479	18,479	18,900	20,186	21,617	23,073	24,598
Total Electricity (kWh)	*355,697*	*454,546*	*473,208*	*492,443*	*512,152*	*532,773*	*554,173*	*576,546*	*596,612*	*617,080*	*641,960*
Total Gas (kWh)	*55,705*	*94,217*	*99,391*	*102,599*	*104,629*	*101,335*	*95,220*	*90,004*	*85,059*	*80,320*	*75,894*

Table 3.2: *Vancouver MURB-high energy use for various occupancy scenarios.*

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Heating Energy (kWh)	371,484	368,524	365,577	362,666	359,741	356,832	353,986	351,141	348,257	345,448	342,627
Cooling Energy (kWh)	8,070	8,272	8,480	8,694	8,911	9,136	9,364	9,600	9,840	10,087	10,339
Lighting Energy (kWh)	152,061	152,061	152,061	152,061	152,061	152,061	152,061	152,061	152,061	152,061	152,061
Equipment Energy (kWh)	325,972	326,252	326,531	326,810	327,090	327,369	327,648	327,928	328,207	328,487	328,767
Fan Energy (kWh)	51,862	51,733	51,606	51,480	51,351	51,224	51,096	50,958	50,830	50,715	50,606
Pump Energy (kWh)	12,587	12,651	12,718	12,796	12,871	12,938	13,021	13,103	13,196	13,273	12,587
Heat Rejection (kWh)	387	396	406	416	426	436	446	457	468	479	491
DHW Energy (kWh)	325,113	325,113	325,111	325,112	325,111	325,112	325,114	325,111	325,112	325,112	325,112
Total Electricity (kWh)	*631,057*	*630,870*	*630,694*	*630,543*	*630,394*	*630,251*	*630,144*	*630,027*	*629,938*	*629,872*	*629,812*
Total Gas (kWh)	*616,479*	*614,132*	*611,797*	*609,490*	*607,168*	*604,857*	*602,593*	*600,332*	*598,033*	*595,789*	*593,538*

Table 3.3: *Vancouver MURB-low energy use for various occupancy scenarios.*

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Heating Energy (kWh)	101,137	100,066	99,001	97,936	96,882	95,835	94,793	93,760	92,737	91,719	90,714
Cooling Energy (kWh)	10,638	10,797	10,956	11,117	11,280	11,443	11,608	11,774	11,942	12,111	12,280
Lighting Energy (kWh)	58,964	58,964	58,964	58,964	58,964	58,964	58,964	58,964	58,964	58,964	58,964
Equipment Energy (kWh)	143,788	143,893	143,998	144,103	144,208	144,313	144,418	144,523	144,627	144,732	144,837
Fan Energy (kWh)	20,105	20,129	20,153	20,175	20,198	20,218	20,241	20,263	20,285	20,308	20,331
DHW Energy (kWh)	112,984	112,981	112,978	112,975	112,972	112,969	112,966	112,962	112,959	112,956	112,953
Total Electricity (kWh)	*346,479*	*346,764*	*347,049*	*347,334*	*347,622*	*347,907*	*348,196*	*348,486*	*348,777*	*349,072*	*349,365*
Total Gas (kWh)	*101,137*	*100,066*	*99,001*	*97,936*	*96,882*	*95,835*	*94,793*	*93,760*	*92,737*	*91,719*	*90,714*

Table 3.4: *Vancouver House energy use for various occupancy scenarios.*

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Heating Energy (kWh)	21,028	20,970	20,913	20,856	20,800	20,744	20,688	20,632	20,576	20,521	20,466
Cooling Energy (kWh)	607	613	618	624	630	636	642	648	654	660	666
Lighting Energy (kWh)	2,003	2,003	2,003	2,003	2,003	2,003	2,003	2,003	2,003	2,003	2,003
Equipment Energy (kWh)	7,048	7,066	7,084	7,102	7,121	7,139	7,157	7,175	7,194	7,212	7,230
Fan Energy (kWh)	791	794	796	798	800	803	805	807	809	811	813
DHW Energy (kWh)	6,084	6,084	6,084	6,084	6,084	6,084	6,084	6,084	6,084	6,083	6,083
Total Electricity (kWh)	*10,448*	*10,475*	*10,501*	*10,527*	*10,554*	*10,580*	*10,606*	*10,632*	*10,659*	*10,685*	*10,711*
Total Gas (kWh)	*30,338*	*30,281*	*30,225*	*30,169*	*30,114*	*30,058*	*30,004*	*29,949*	*29,894*	*29,840*	*29,786*

3.4 Changes in Buildings' Energy Performance in Atlanta

In Atlanta, with an increased work-from-home ratio, only the Office EUI is descending. MURB-low and MURB-high EUI curves are almost flat, and the House EUI curve trends upward. The Atlanta office building with a lower occupancy rate triggers less cooling, lighting, equipment, fan, pump, and DHW energy use. The only significant energy increase due to less internal heat gain is heating. Overall, energy use in an office building would be reduced, and the building could be heating rather than cooling-dominated. In Atlanta, the MURB building consumes more heating energy than cooling. More cooling/equipment/fan energy (electricity) is required with a higher occupancy rate in the dwelling space.

On the other hand, with internal heat gain increases, heating energy (gas) reduces. The trade-offs lead to insignificant energy change with a flat curve. In Atlanta,

Table 4.1: *Atlanta office energy use for various occupancy scenarios.*

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Heating Energy (kWh)	159,854	156,215	152,392	147,776	143,311	138,306	127,847	118,881	108,495	100,785	93,711
Cooling Energy (kWh)	84,763	91,166	97,530	103,870	110,092	116,171	122,239	128,510	135,081	141,960	148,765
Lighting Energy (kWh)	180,864	184,392	187,924	191,455	194,987	198,518	202,050	205,581	209,113	212,645	216,176
Equipment Energy (kWh)	2,825	25,552	48,408	71,377	94,465	117,681	141,036	164,542	188,213	212,064	236,112
Fan Energy (kWh)	15,908	17,085	18,300	19,565	20,850	22,156	23,431	24,844	26,243	27,795	29,363
Pump Energy (kWh)	0	4	8	12	16	20	24	29	33	37	41
DHW Energy (kWh)	0	18,479	18,479	18,479	18,479	18,479	18,613	19,226	20,268	21,467	22,770
Total Electricity (kWh)	*391,720*	*419,056*	*446,837*	*475,282*	*503,980*	*532,972*	*560,070*	*590,064*	*619,363*	*651,278*	*683,718*
Total Gas (kWh)	*52,494*	*73,836*	*76,203*	*77,251*	*78,218*	*78,359*	*75,170*	*71,547*	*68,083*	*65,473*	*63,219*

Table 4.2: *Atlanta MURB-high energy use for various occupancy scenarios.*

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Heating Energy (kWh)	248,610	246,653	244,737	242,807	240,882	238,975	237,090	235,223	233,355	231,459	229,610
Cooling Energy (kWh)	135,913	136,716	137,523	138,331	139,145	139,963	140,787	141,620	142,454	143,306	144,150
Lighting Energy (kWh)	152,213	152,213	152,213	152,213	152,213	152,213	152,213	152,213	152,213	152,213	152,213
Equipment Energy (kWh)	325,972	326,252	326,531	326,810	327,090	327,369	327,648	327,928	328,207	328,487	328,767
Fan Energy (kWh)	68,253	68,328	68,412	68,496	68,579	68,661	68,741	68,823	68,905	68,975	69,059
Pump Energy (kWh)	17,313	17,374	17,439	17,501	17,568	17,631	17,705	17,779	17,842	17,920	17,313
Heat Rejection (kWh)	6,400	6,435	6,470	6,506	6,542	6,578	6,615	6,653	6,691	6,731	6,771
DHW Energy (kWh)	286,269	286,266	286,264	286,264	286,266	286,266	286,266	286,266	286,266	286,266	286,266
Total Electricity (kWh)	*760,405*	*761,264*	*762,144*	*763,022*	*763,913*	*764,806*	*765,723*	*766,654*	*767,573*	*768,512*	*769,474*
Total Gas (kWh)	*480,538*	*478,974*	*477,446*	*475,905*	*474,371*	*472,850*	*471,343*	*469,851*	*468,361*	*466,844*	*465,363*

Table 4.3: *Atlanta MURB-low energy use for various occupancy scenarios.*

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Heating Energy (kWh)	53,638	53,124	52,616	52,097	51,600	51,102	50,613	50,123	49,643	49,162	48,685
Cooling Energy (kWh)	48,653	48,960	49,266	49,572	49,900	50,214	50,525	50,837	51,148	51,458	51,770
Lighting Energy (kWh)	59,016	59,016	59,016	59,016	59,016	59,016	59,016	59,016	59,016	59,016	59,016
Equipment Energy (kWh)	143,788	143,893	143,998	144,103	144,208	144,313	144,418	144,523	144,627	144,732	144,837
Fan Energy (kWh)	26,036	26,099	26,161	26,224	26,268	26,329	26,392	26,455	26,519	26,579	26,644
DHW Energy (kWh)	100,912	100,910	100,908	100,906	100,904	100,901	100,899	100,896	100,894	100,893	100,891
Total Electricity (kWh)	*378,406*	*378,878*	*379,349*	*379,821*	*380,295*	*380,772*	*381,249*	*381,727*	*382,205*	*382,679*	*383,159*
Total Gas (kWh)	*53,638*	*53,124*	*52,616*	*52,097*	*51,600*	*51,102*	*50,613*	*50,123*	*49,643*	*49,162*	*48,685*

Table 4.4: *Atlanta House energy use for various occupancy scenarios.*

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Heating Energy (kWh)	5,161	5,150	5,139	5,128	5,118	5,107	5,096	5,084	5,074	5,063	5,053
Cooling Energy (kWh)	2,837	2,850	2,863	2,876	2,889	2,902	2,915	2,929	2,943	2,956	2,969
Lighting Energy (kWh)	2,003	2,003	2,003	2,003	2,003	2,003	2,003	2,003	2,003	2,003	2,003
Equipment Energy (kWh)	7,792	7,809	7,825	7,841	7,858	7,874	7,890	7,907	7,923	7,940	7,956
Fan Energy (kWh)	1,133	1,135	1,137	1,139	1,140	1,142	1,144	1,144	1,146	1,148	1,149
DHW Energy (kWh)	3,147	3,147	3,147	3,147	3,147	3,147	3,147	3,147	3,147	3,147	3,147
Total Electricity (kWh)	*22,073*	*22,093*	*22,114*	*22,134*	*22,154*	*22,175*	*22,196*	*22,215*	*22,236*	*22,256*	*22,278*
Total Gas (kWh)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*

residential building is still heating energy dominated. With a higher occupancy rate in the dwelling space, internal heat gain increases, and heating energy (gas) reduces. Although more cooling/equipment/fan energy (electricity) is required, the overall energy would be reduced.

3.5 Changes in Buildings & Commute CO_2 Performance

This study uses the default fuel analysis approach, which requires only the type and quantity of the fuel to calculate the GHG emissions associated with buildings. Depending on the location, the emissions we consider in the calculation differ and incorporate carbon dioxide, methane, and nitrous oxide emissions to provide a single carbon dioxide equivalent number. This number varies by fuel type and accounts for differences in content and supply across the country. The equivalent factors are regional according to the eGRID sub-regions in the U.S. and provincial levels in Canada for the emission from electricity.[27] For the emission from gas, these factors are computed at the national level in the U.S. and vary by province in Canada.

The top two charts in Figure 9 depict the carbon emission changes by varying occupancy scenarios in buildings. As seen, the percentage of GHG emissions associated with buildings in Atlanta and Vancouver are similar (around 5 percent in 0 percent office occupancy); however, the absolute reduction in Atlanta is much higher because of the higher utility of the electric grid system in the region. The electricity in Atlanta comes mainly from coal and natural gas. Only 6 percent comes from renewable sources, while close to 95 percent of electricity in Vancouver and British Columbia is generated from renewable sources such as hydro and biomass.[28]

Similar to each buildings' operational carbon, GHG emissions associated with commute also show a much higher reduction in Atlanta than in Vancouver due to heavy reliance on driving cars to work. The total emission of buildings operational and commute systems can contribute to a 14 and 18 percent reduction in Atlanta and Vancouver, respectively, if employees continue working from home.

Figure 9: *Carbon reduction amount (kg/year) and percentage related to buildings (a1&a2: on top), commute (b1&b2: in the middle), and the total (c1&c2: bottom) for Atlanta and Vancouver offices.*

3.6 Simulation Results Summary

In Vancouver offices, telework can decrease total energy use, up to 42.7 percent, primarily due to reduced equipment and lighting loads. Working from home can also decrease residential energy use, up to 1.2 percent, mostly due to increased equipment and heating loads. Telework reduces carbon emission in a city, both from buildings operation and commute system. Since the environmental attribute of electric power in Vancouver is already small due to the plants and electric grid systems available in the region, CO_2 reduction is not huge. In cities such as Vancouver, with reliance on walking, the decrease in CO_2 emission related to transportation is also small. In total, telework for a medium-size office can reduce CO_2 emissions by up to 3.3 percent in Vancouver.

In Atlanta, telework can decrease total energy use in offices, up to 40.5 percent, mostly due to reduced equipment and cooling loads. Working from home can increase residential energy use, up to 0.6 percent, mostly due to increased equipment and heating loads. Telework decreases carbon emission in a city, both from buildings operation and commute system. The environmental attribute of electric power in Atlanta is high due to the plants and electric grid systems available in the region. Therefore reduction of CO_2 can have a significant impact on the environment. In cities with heavy reliance on driving personal cars, telework decrease CO_2 emissions related to transportation significantly. In total, telework for a medium-size office can reduce CO_2 emissions of up to 4.8 percent in Atlanta.

3.7 Simulation Results vs. Actual Energy Use

Due to the limitations of controlling the experiment in an observational study and the difficulties of gathering the actual energy use data from an individual's residential building, this study was conducted based on computer modeling and simulation. The authors collected a portion of actual data before and during the pandemic from the office of Vancouver. It consisted of energy consumption and occupancy schedules; an extra analysis has been performed to compare the simulation findings with observed data.

Energy use data provided by BCHydro (British Columbia Hydro and Power Authority) were obtained for the Vancouver office from 1st January 2019 until May 2021. We believe that the data covers both pre-pandemic (2019) and pandemic lockdown periods (2020 & 2021). As we expected, energy use reduction is observed during the pandemic when the office is not fully occupied. Figure 10 provides evidence of a clear trend of energy use reduction between pre-pandemic (2019) and pandemic lockdown (both 2020 & 2021). On average, the annual energy use savings is 18 percent (see Table 5), comparing the years 2019 and 2020. We do not have complete consumption data for the year 2021 yet. Still, the energy-saving trend has been maintained similarly in the first five months. It is also interesting to observe that in January 2020, as the starting of pandemic lockdown, the energy reduction is not apparent compared to January 2021. This is probably due to the reality that the office occupants just started shifting from work in the office to work from home.

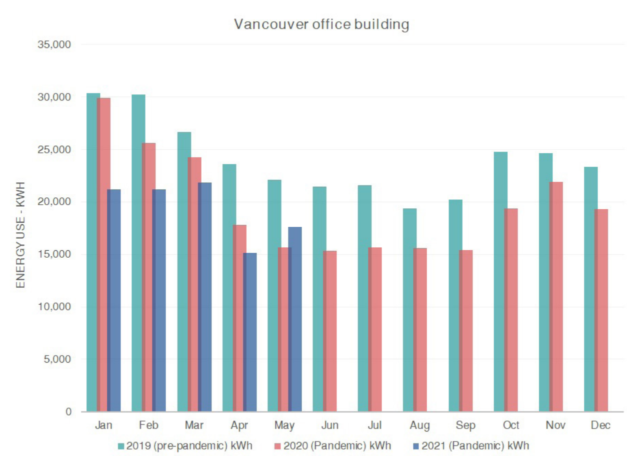


Figure 10: *Energy use of Vancouver office in 2019 to 2021.*

Table 5: *Comparison between 2019 and 2020 energy consumption of Vancouver office.*

2019 (PRE-PANDEMIC) KWH	2020 (PANDEMIC) KWH	SAVINGS
30,349	29,921	1%
30,240	25,611	15%
26,687	24,266	9%
23,586	17,820	24%
22,088	15,691	29%
21,431	15,338	28%
21,589	15,683	27%
19,395	15,620	19%
20,250	15,435	24%
24,795	19,384	22%
24,638	21,884	11%
23,364	19,314	17%
288,411	*235,967*	*18%*

Based on the previous simulation findings, we believe the energy reduction is closely related to the occupancy behavior change. Occupancy behavior during the pandemic lockdown has to be tracked to correlate energy use and occupancy. Fortunately, Vancouver studio employees use two systems, Return To Studio (RTS.) and Robin, to self-report their office-desk booking during the pandemic. RTS provides tracking information before Dec 2020. The office decided to use Robin to replace RTS due to the more stringent office self-reporting requirements requested by the local health authority. Occupancy data obtained from RTS and Robin are shown in Figure 11. It indicates that the office's occupancy rate fluctuates between 5 to 30 percent, and the average monthly occupancy rate is around 20 percent. When this 20 percent occupancy rate is applied back to the outputs of the energy simulations (see Figure 7), an energy-saving of 20 percent is expected. It happened when Vancouver office EUI reduced from 144.1kWh/sqm (100 percent office occupancy) down to 114.9kWh/sqm (20 percent office occupancy).

The energy savings derived from the simulations (20 percent) and actual utility data (18 percent) are similar. It should be noted that the first month of 2020 may have a higher occupancy rate than during the pandemic and consume slightly more energy. It also indicates the energy simulations can generate reasonable energy-saving estimations in the context of a low-rise office building in Vancouver.

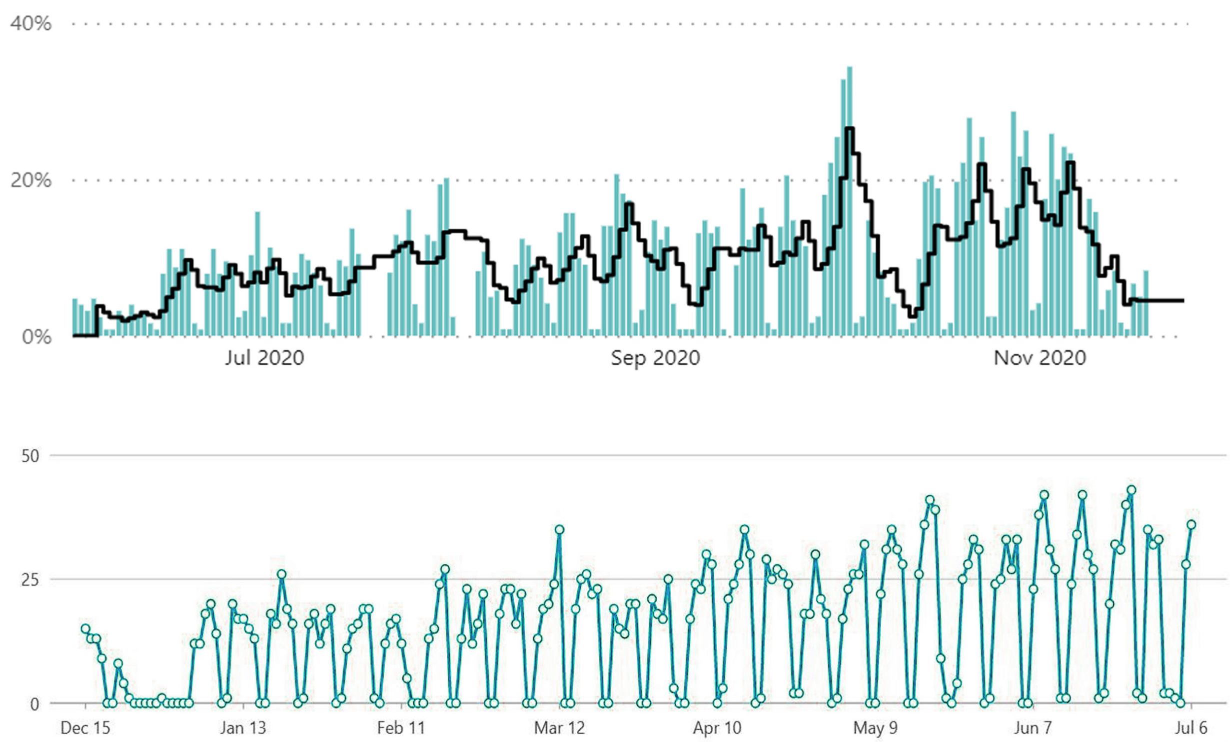


Figure 11: *Occupancy tracking information of Vancouver office from RTS (top, before Dec 2020) and Robin (bottom, Dec 2020 till now).*

4.0 Conclusion

This study explored the influence of working from home, either as a short-term scheme due to COVID-19 lockdown or long-term strategy due to telework demand, on energy consumption and carbon footprint of buildings and commute systems. It defined adaptive working behavior, reflected in buildings' operational schedules and loads, and developed a methodology for calculating and comparing carbon impacts of various scenarios for two locations of Atlanta and Vancouver. The study has shown a considerable influence of adaptive working behavior on the energy demand in office buildings; however, the changes are not equally affecting residential buildings. Telework can decrease total energy use of office spaces up to 40.5 percent in Atlanta and 42.7 percent in Vancouver. The energy performance of offices and all residential buildings of employees collectively can be reduced by 3.2 and 4.5 percent in Atlanta and Vancouver, respectively, if adopting the work-from-home pattern. The changes in CO_2 emission associated with buildings in Atlanta are more remarkable because of the higher utility of the electric grid system in the city compared to the renewable sources of electricity in Vancouver.

In general, the CO_2 emission reduction related to commuting is higher than buildings operations in both cities. However, Atlanta experiences a much higher decrease than Vancouver due to heavy reliance on driving cars to work. In both buildings and commutes, the behavior change can transform the emission profile of a city at a larger scale, depending on the location and the aviable infrastructures. The research outcome can inform the designers, office managers, and policymakers of the potential energy-saving and low carbon emission measures due to telework. It is entirely possible to develop a framework to propose a future hybrid working policy.

Figure 12: *Atlanta office (left) and Vancouver office (right).*

A sweet point to achieve reductions of both carbon emissions and office energy is achievable in theory. Still, the research indicates the complexity of interactions among offices, employees' residences, carpooling, and public commute system. Other exchanges occur with first and last-mile travel and beyond the scope of this research in accounting for the differences in emissions. The study is only the first step to understanding the impact of adaptive working behavior on energy and carbon. Limitations are:

- Only two climate zones are included in the study. For a more comprehensive understanding of climatic impact, the study should be extended to other climate zones.
- Only two office buildings are included in the study. Instead of modeling the buildings (see Figure 12), two prototype buildings are used. The Perkins&Will offices have been considered in determining the schedule and load assumptions for simulation. The specific building form, orientation, and envelope details will deviate the energy and carbon performance compared to the prototype office models.
- The study is based on energy simulations with assumptions. More accurate results are expected if measurement and verification data are available.

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