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The effect of occupant behaviour on energy consumption in conventional vs. high-performance residential buildings

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Abstract: *With aggressive energy reduction targets expected in MURBs driven by codes like NECB 2015 (NRCan, 2017) aimed at more efficient building codes and HVAC, the share of lighting and appliance loads will likely increase, causing occupant behaviour to have a greater impact on overall energy consumption. To better quantify this trend, this simulation study compares the effect of three occupant scenarios, in a high-performance and conventional MURB. Using operating schedules based on assumptions for these occupant scenerios, the high-performance building was found to use between 50% and 60% less energy than the conventional building. It was also found that for the high-performance building, hot water and appliance energy consumption represented more than 50% of total energy consumption, which was on average 20 percentage points higher when compared to the conventional building. This study highlights the energy end uses that are more susceptible to occupant behaviour as building envelope performance increases.*

INTRODUCTION

Occupant behaviour represents one of the major sources of uncertainty related to energy consumption in buildings. Previous studies showed it can impact annual energy consumption by up to 150% (Clavenger, 2014). It is considered one of the main six driving factors for energy consumption in buildings as identified by the International Energy Agency (IEA), Annex 53 (Yan, 2015), yet the least understood. These factors include climate, building envelope, building equipment, operation and maintenance, occupant behaviour, and indoor environment conditions (Hong, 2017).

With many studies investigating the effect of occupants on energy consumption in commercial and residential buildings (Haldi, 2011, O'Brien, 2013, Guerra-Santin 2010), the ability for occupants to control a greater number of parameters in residential buildings made it of greater interest for our particular study. Heating setpoints for example are typically subject to more occupant control in residential buildings, unlike in commercial buildings where they are typically centrally-controlled by operators (O'Brien, 2016). Appliances, lighting and domestic hot water (DHW) are also heavily dependent on occupant behaviour, demographic profiles, and occupancy patterns (Swan, 2011), thus they can derive large variations in residential energy consumption. Previous studies showed that energy consumption in residential units of the same multi-unit residential building (MURB) can vary by more than ten-fold, mainly because of usage patterns (Yan, 2015).

As building envelopes and equipment become more efficient, the contribution of appliances and lighting loads increases, thus the effect of occupant behaviour may become more pronounced (Hoes, 2009). High-performance buildings integrate and optimize all major high-performance attributes, including energy efficiency, durability, life-cycle performance, and occupant productivity. To demonstrate their energy efficiency, these buildings typically follow certain standards or rating systems. One of these standards is the Passivhaus standard which requires aggressive energy reduction targets to be met, typically confirmed using whole building performance simulation (De Meester, 2013). In contrast, other rating systems such as Leadership in Energy and Environmental Design (LEED), gives points to a proposed building based on its percentage of energy cost savings relative to a certain baseline. In Canada, the baseline could be a building modelled similar to a building per the prescriptive path of the National Energy Code for Buildings (NECB, 2015) or American Society of Heating, Refrigerating and Air-Conditioning Engineers Standard 90.1-2013 (ASHRAE, 2013). For this study, we consider conventional MURBs as ones that follow the baseline of NECB without any energy reduction measure. The high-performance MURB is modeled by following some of the guidelines for Passivhaus standard, and on a case by case basis we expect the share of plug loads and hot water consumption to be greater than that of the conventional building. Moreover, we also expect to see larger differences in energy consumption between the different occupant cases in conventional buildings than high performance buildings. This is due to the fact that different heating and cooling temperature set points are likely to have a greater effect on

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energy consumption in a lower performance building envelope.

The goal of this study is to demonstrate the growing effect of occupant behaviour in new high-performance MURBs. Objective was to compare the effect of occupant behaviour on residential energy consumption between conventional and high-performance MURBs highlighting occupancy parameters that should be addressed to reach net-zero or other ambitious energy reduction targets. The study also addresses the impact of occupants' purchasing decisions by modeling more efficient appliances, lighting and water fixtures in the high-performance building, and comparing their consumption to standard ones. The study focuses on a proposed MURB in Ottawa, ON by modeling proto-type residential units on the south and north façades. Three types of occupancies are then defined as low, medium and high energy consumers based on typical Canadian household energy usage profiles or other North American references.

BACKGROUND

We reviewed studies that focused specifically on the effect of occupant behaviour on residential energy consumption, which can be classified into three main categories. The first category focused on existing buildings by measuring their energy consumption and recording specific occupancy parameters. For example, Andersen et al. (2009) monitored window opening behaviour in 15 Danish dwellings, and concluded that indoor air quality and solar radiation were the main drivers behind it. Al-Mumin et al. (2003) investigated summer air-conditioning use in 30 residences, and concluded that the thermostat set points could vary from below 19ºC to above 25ºC, which would have a significant impact on their energy consumption. Bae et al. (2009) investigated indoor temperatures in Korean residences, and found the average indoor ambient temperature ranged between 21 – 33ºC in the summer, and 17 – 28ºC in the winter. Huebner et al. (2013) found that the average heating temperature in UK households was 19.8ºC which is less than the default assumption of 21ºC in the UK Building Research Establishment Domestic Energy Model (BREDEM). The heating durations during weekdays and weekends were also found to be less than default assumptions. Using a detailed occupants' survey and measuring household energy consumption in Dutch residences, Guerra-Santin and Itard (2010) showed that the duration of using heating systems had a stronger effect on energy consumption than temperature set points. Findings of this study also suggested that some household characteristics, such as the presence of elderly occupants, had a significant effect on their energy consumption.

The second category of studies focused on modeling the effect of occupant behaviour on appliances and lighting consumption more specifically given their stronger relationship with occupant behaviour. Using a bottom-up approach, Armstrong et al. (2009) collected detailed data on appliances' consumption and durations for Canadian households. The data was used to develop electricity consumption profiles corresponding to three different types of occupants, which was then compared to actual measured data. Results showed that low energy occupants can consume twice as much electricity as the average occupants, which was confirmed using data from existing buildings. However, measured data were only collected from four existing homes in Quebec, which may not be representative of the wider spectrum of occupant behaviour. Swan et al. (2011) developed a hybrid model for estimating Canadian households' energy consumption, using artificial neural networks and a database of mechanical systems and thermal envelopes in Canadian households. The estimated electricity consumption for appliances and lighting was slightly higher than national models developed using a different approach. However, these findings illustrate the variability in electricity consumption due to occupant behaviour in Canadian households, although the study did not investigate MURBs.

The third category of studies relied on whole building performance simulations to highlight the effects of certain occupancy parameters on residential energy consumption. D'Oca et al. (2014) modeled three categories of occupant behaviour in residential buildings (active, medium, and passive) using a probabilistic approach that focused on window openings and thermostat adjustments. By comparing results with standard deterministic simulations, the study showed that energy consumption could increase by up to 61% when modeling different probabilities for occupant behaviour. De Meester et al. (2013) also investigated the effect of family size and management of heating systems on Belgian households' energy consumption. By simulating different family sizes, occupancy profiles, and thermostat setpoints, the study showed these factors alone would have a strong effect on energy consumption, that ranged from 5% in non-insulated houses to 45% in houses built to Passivhaus standards (De Meester, 2013). O'neil and Niu (2017) also found that variations in thermostat set points, occupancy and lighting schedules had a 4% impact on the HVAC annual and peak energy consumption. The sensitivity analysis showed that thermostat setpoints had the highest effect on energy consumption. However, these studies did not investigate the effect of other occupant behaviours such as window opening, or use of appliances (De Meester, 2013; O'Neill, 2017). Blight et al. (2013) focused on residential

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Passivhaus buildings by generating occupancy, appliance-use, and door-opening profiles based on the United Kingdom Time Use Survey. Simulation results were compared to measured heating consumption data from similar existing residences, which ranged from less than 5 KWh/m^2 to more than 40 KWh/m^2 with different occupancy profiles. By developing a multiple regression model, setpoint temperature, and appliance-use were shown to be the major estimators of total heating energy, while occupancy patterns were less significant (Blight, 2013).

Due to the fragmented nature of research on this topic, this study aimed to provide a higher-level analysis of popular occupancy parameters typically investigated in the literature. By modeling a high-performance MURB and a conventional one, the significance of this study stems from demonstrating the increased role occupants play in new high-performance buildings. These findings are relevant to new buildings' designers as they highlight the most significant occupancy parameters that need to be addressed especially in more efficient buildings.

SIMULATION

To investigate the effect of occupant behaviour on energy consumption in conventional and high-performance MURBs, two generic residential units for each building were simulated; one facing north and the other facing south, located in Ottawa, ON. The models were developed using BPS tool Energy Plus in conjunction with Open Studio. Each unit had dimensions W×L×H = 12×10×3 m^3 with a window of W×H = 6.0×2.0 m^2 and sill height of 0.8 m. The boundary conditions for the interior surfaces were considered adiabatic, since they are adjacent to spaces with similar thermal conditions. The south-facing and north-facing wall in each of the respective units were exposed to outdoor conditions based on the EPW weather file.

The units were assumed to have an occupant density of 60 m^2/person (i.e. two occupants per unit) per NECB (2015). The occupancy schedule was also created according to NECB which assumes lower occupancy (30%) between 8 AM and 5 PM on weekdays, and a slightly higher occupancy during these hours on weekends (50%). Figures 1 and 2 depict the operating schedules.

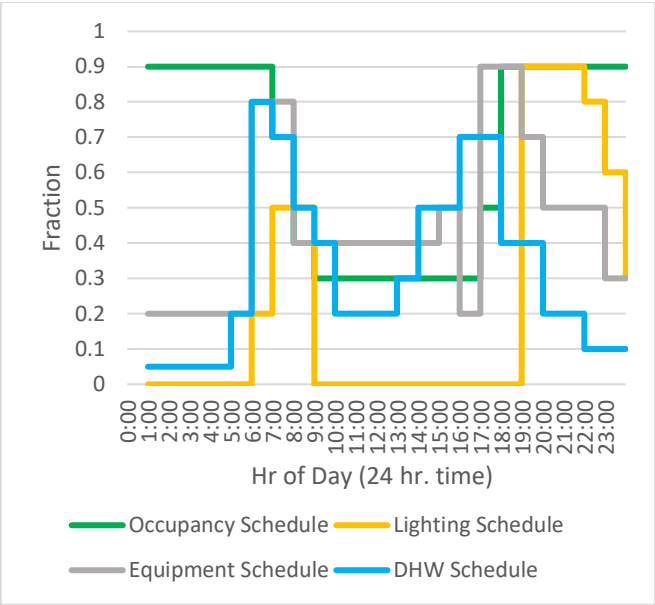

Figure 1: Weekday Operating Schedules

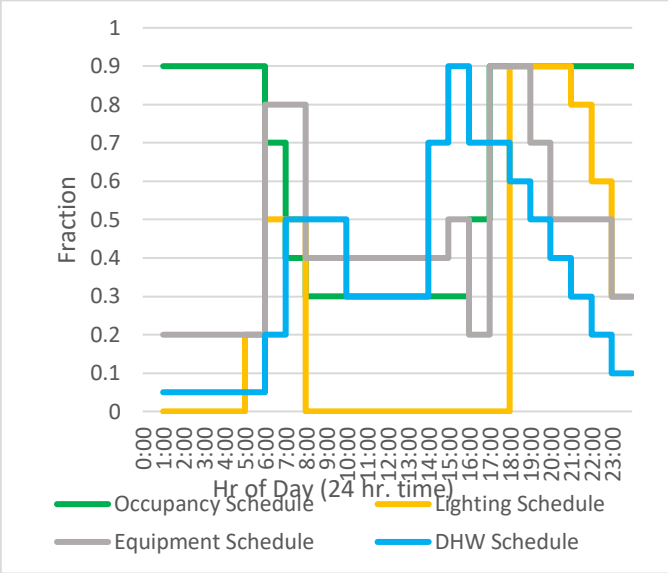

Figure 2: Weekend Operating Schedules

The assumption that occupancy rates do not drop to 0% for both weekday and weekend schedules aims to represent a wider variety of occupancy patterns, as some occupants may stay at home during these hours for various reasons.

Fresh air was supplied at a rate of 2.5 L/s.person + 0.3 L/s.m^2 based on ASHRAE Standard 62.1 (2013). The HVAC system was ideal load system for both models. However, for the high-performance model, heat recovery and an outdoor air economizer was enabled. Reported heating and cooling energy consumption is the heating and

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cooling energy supplied to the space. Auxiliary energy required for HVAC fans and pumps was not included.

Table 1: Design inputs for the conventional and high-performance MURB units

Input design parameter	Conventional MURB	High-performance MURB
Exterior Wall U-Value (W/m^2K)	0.247	0.12
Windows U-Value (W/m^2K)	2.2	0.7
Windows SHGC	0.45	0.7
Windows visible transmittance	0.8	0.8
WWR	37%	30%

Occupant Cases

Occupants' interactions with the building include adjusting thermostat settings, opening or closing windows, turning lights on/off, pulling window blinds up or down, switching plug loads on or off, and consuming domestic hot water (Hong, 2017). Therefore, the two models were subject to different occupant assumptions regarding all interactions with the building. The authors acknowledge the limitations for this assumption; the impact of design is not considered in behaviour (e.g. better windows allow occupants to have more energy conserving setpoints. To standardize our assumptions and represent a wide variety of occupant types, three cases of occupancies were investigated 1) active occupant, 2) average occupant, and 3) passive occupant. The occupancy schedules for all cases were based on NECB 2015 to focus only on occupants' interaction with the building systems, rather than the durations of their presence within the units. Using different occupancy schedules would also impact the durations of using certain appliances and lighting, which may violate some of the assumptions made for each occupancy case.

Before we provide the reasoning behind each of the different occupancy scenarios assumed in this study, it is important to understand how each of the three different occupants was defined.

Case 1: Active Occupants – These are individuals who frequently interface with their unit control systems as well as the built environment that surrounds them. Their actions are primarily motivated by improving efficiency and reducing consumption, while still maintaining a space which is comfortable through different adaptive measures that they take. They have some degree of knowledge on how their behavior in buildings can either negatively or positively impact energy and water consumption, and make an effort to consciously think about their decisions.

Case 2: Average Occupants – These are individuals who interface with their unit control systems to some extent, however their behaviors are driven by habit and their actions are taken primarily for comfort, with energy efficiency and conservation second in mind. With that said, they are not likely to take adaptive actions to conserve energy or improve efficiency, however if a certain behavior can be taken without much effort and no impact on comfort, they are likely to take this action. For example, automating a temperature setback or setup while they are away from their apartment during the day is easily done and does not impact their comfort level.

Case 3: Passive Occupants – These are individuals who rarely interface with their unit control systems or built environment, and rely on the indoor environment to be conditioned based on automated mechanical systems or set points which are rarely changed unless their comfort is disturbed. They have a lack of knowledge for how their behavior and indoor environment settings impact energy efficiency or the environment.

Besides the three occupancy cases described above, a baseline case was also simulated using the default occupancy related parameters set forth in NECB 2015 for MURBs, such as thermostat setpoints, lighting, plug loads and DHW loads. Table 2 provides an overview of the occupancy related parameters used for each case.

Table 2: Occupancy related inputs for each case

Occupancy Parameter	Baseline	Active Occupant	Average Occupant	Passive Occupant
Heating setpoint ºC	22	19	21	22
Heating set-back temp ºC	18	18, 16	18	22
Heating set-back schedule	12 AM - 6 AM	12 AM - 6 AM, and 8 AM - 5 PM	12 AM - 6 AM	No set-back
Cooling setpoint ºC	24	No cooling	23	23

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Cooling set-up temp ºC		24	No cooling	No cooling	23
Cooling set-up schedule		No set-up	No cooling	8 AM - 5 PM	No set-up
Blinds		No blinds	Blinds used extensively to reduce cooling loads, and increase privacy.	Blinds used arbitrarily, mainly just for privacy at night.	Blinds rarely used with limited change in their position throughout the year.
Window use		No windows opened	Windows used optimally during cooling and shoulder seasons	Windows used arbitrarily, and only opened at night	Windows are rarely opened (0% window opening)
Lighting W/m^2	High-performance	5.5	1.0	1.3	1.5
	Conventional	5.5	3.2	4.2	4.9
Equipment W/m^2	High-performance	5	3.2	4.5	5.6
	Conventional	5	4.3	6.6	7.9
DHW W/person	High-performance	500	231	340	483
	Conventional	500	340	500	710

Heating and Cooling Temperature Set Points

Temperature set-points for the average occupant (case 2) were based on the NRCan survey of household energy use in Canada (NRCan, 2011). Most households in Ontario set their thermostat to 21ºC in the winter and 23ºC or more in the summer (NRCan, 2011). For heating, the other cases deviated by - 2ºC for active occupants and +1ºC for passive occupants, thus they would still be within the acceptable comfort range of ASHRAE 55-2013. For cooling, active occupants were assumed to rely only on natural ventilation and not air conditioning which is not unusual for MURB residents in Ontario (NRCan, 2011).

When modeling temperature set-backs in the winter, we included both daytime and nighttime set-backs for active occupants (case 1), only night-time set-backs for average occupants (case 2), and no set-backs for passive occupants (case 3). For temperature set-ups in the summer, active occupants were not included as they were assumed to switch off mechanical cooling completely during the summer. Average occupants, were assumed to shut-off cooling during the day on weekdays before leaving their residences. Passive occupants were assumed to have no set-ups and they keep cooling set-points unchanged throughout the day. It is important to note here that a study by Meier et al. (2011) surveyed household occupants in the United States and found that almost 90% of respondents rarely or never adjusted their thermostats.

Blind Usage

With many new MURBs having increasingly large window to wall ratios, cooling energy loads will become even more sensitive to how occupants use their blinds (Bennet, 2014). Bennet et al. (2014) showed that most blind opening actions occurred in the morning before occupants left for work (7 AM – 9 AM) and most closing actions around the time that occupants get home from work (5 PM – 7 PM) (Azar, 2011). These findings were the basis for our average occupant blind use schedule (case 2), where we assumed them to use blinds on a habitual routine (i.e. closing them at night) rather than specifically for reducing cooling demand which was assumed for active occupants (case 1). Passive occupants (case 3) were assumed to rarely use their blinds or change their positions. Therefore, the average daily occlusion observed by Bennet et al. (2014) was used where, the north-facing units were found to have an average daily occlusion rate of 60%, and 80% for south-facing units.

Window Opening

40% of the window area was considered operable. Active occupants (case 1) were assumed to rely only on natural ventilation for cooling by opening windows throughout the cooling and shoulder seasons. For average occupants (case 2), windows were assumed to be opened only in the evenings, between 6 PM and 6 AM, if the indoor

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temperature was around the cooling set point (22 – 23ºC). Passive occupants (case 3), were assumed to rarely operate their windows and to simulate this scenario, the windows were considered not open at all.

Plug Loads

One of the main research questions investigated in this study was the effect of occupants' appliances purchasing decisions on their units' energy consumption. Therefore, conventional MURB units were assumed to only include standard appliances, while high-performance units were assumed to include Energy Star certified appliances, which use less electricity. Phantom loads were also considered by assuming that active occupants (case 1) always unplug appliances after they use them, while the other two occupant cases were assumed to always leave their appliances plugged in after use.

A bottom-up approach was then implemented to generate plug load profiles for each occupant case similar to the process described in Armstrong et al. (2009) Based on appliance types, and estimated durations of use, a target daily plug loads consumption was calculated for each case. Table 3 provides a list of the appliances considered in this study, their estimated power consumption and use durations which were collected from Canadian and American Government publications (Natural Resources Canada, 2004, Lawrence Berkley National Laboratory, 2017). Average use durations for the different appliances were used for the average occupants (case 2), while active occupants were considered to use the same appliances for 50% less time and unplug them afterwards, if reasonably possible. Passive occupants (case 3) were assumed to use the same appliances for 50% more time to account for frequent patterns of leaving appliances on while they are not being used.

In this study, we assumed the same appliance use schedule based on the NECB 2015 schedule for all cases. Afterwards, we calculated the equivalent peak plug load for the energy models that would correspond to the target daily plug load consumption for each case as shown in Table 2. However, the baseline case used the receptacle load specified in NECB 2015. The disadvantage in this approach is that it does not account for the time of day of using appliances which could change the impact of their heat gains on mechanical heating or cooling. More detailed analyses of plug load consumption profiles in Canadian households at lower resolutions are outside the scope of this study, and were investigated previously in Canadian households (Armstrong, 2009; Swan, 2009).

Table 3: List of appliance related parameters for each case

Appliance	**Power Consumption**				**Durations**		
	Standard		Energy Star		Active Occupant	Average Occupant	Passive Occupant
	Power (W)	Phantom load (W)	Power (W)	Phantom load (W)			
Television	150	6.4	47	0.4	2 hr/day	4 hr/day	6 hr/day
Cable box	25	17	14	0.4	2 hr/day	4 hr/day	6 hr/day
Stereo	14	8	7	0.1	0.5 hr/day	2 hr/day	3 hr/day
Coffee maker	560	1.14	N/A	N/A	0.25 hr/day	0.5 hr/day	1 hr/day
Dryer	3867 (2.9 kWh/cycle	1.4	2800 (2.1 kWh/cycle)	1.4	16 cycle/yr.	136 cycle/yr.	208 cycle/yr.
Dishwasher	650 (1.3 kWh/cycle)	1.3	550 (1.1 kWh/cycle)	1.3	52 cycle/yr.	108 cycle/yr.	182 cycle/yr.
Washer	225 (0.45 kWh/cycle)	2.7	125 (0.25 kWh/cycle)	2.7	52 cycle/yr.	136 cycle/yr.	208 cycle/yr.
Computer	45	8.9	N/A	N/A		5 hr/day	
Range with oven	3000	2.2	2500	2.2		0.8 hr/day	
Toaster	1500		900			0.1 hr/day	

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Microwave	1500	2.8	900	2.8	0.22 hr/day
Blender	1500		900		0.1 hr/day
Refrigerator	55	1.7	50	1.7	20 hr/day + 4 hr/day standby

Domestic Hot Water

Domestic hot water was calculated using a similar bottom up approach, by estimating daily hot water demand for each unit with two occupants. Daily hot water demand profiles were generated based on estimates for using showers, bathroom and kitchen faucets which represent most hot water demand in residential buildings. To further demonstrate the effects of occupants' purchasing decisions, high-performance units were assumed to be fitted with low-flow fixtures, while conventional units were fitted with standard fixtures. The United States Environmental Protection Agency (EPA) (2007) published flow rates for standard and low-flow fixtures in residential buildings, were the basis of our assumptions.

The average shower usage of Canadians is around 8 minutes/day, which was the basis for estimating the average occupants' consumption (case 2). Previous studies showed that occupants could reduce their showering energy usage by between 20 and 30%, by receiving real-time feedback on their usage (Swiss Federal Office of Energy, 2014). Therefore, shower use durations for active occupants (case 1) were assumed to be 6 minutes per occupant per day, whereas passive occupants (case 3) were assumed to be 10 minutes per occupant per day. For Kitchen and bathroom faucets, the average use duration was also 8 minutes / day, which was used for the average occupant (case 2). Active occupants were assumed to deviate from this average by 50% less and passive occupants by 50% more. Table 4 provides an overview of the assumed flow-rates and durations of using water fixtures per occupant in each case.

Once the total DHW flow rate was calculated for each case, the NECB 2015 DHW schedule was used to calculate the equivalent domestic hot water demand in Watts/occupant for each unit, to correspond to the target DHW consumption for each case. Only 10% of the energy available in the hot water was assumed to contribute to internal heat gains (Hendron, 2010).

Table 4: DHW related parameters for each case

Fixture	**Flow-rate (GPM)**		**Durations**		
	Standard	Low-flow	Active Occupant	Average Occupant	Passive Occupant
Showerhead	2.5	1.75	6 min/day	8 min/day	10 min/day
Bathroom faucet	2.2	1.5	4 min/day	8 min/day	12 min/day
Kitchen faucet					

Lighting

The United States Department of Energy (Gifford, 2012) published estimates for residential lighting consumption in different regions of the US and found the average number of lamps per household for MURBs was around 25 lamps for north-eastern states, which are closest to Ontario. The average daily hour of use per lamp in these states was 1.7 hours/day which formed the basis of our assumptions for average occupants (case 2). Active occupants (case 1) were assumed to have the same number of lamps, however, the daily duration of use per lamp was assumed to be 1.3 hours which was the lowest duration within all US states. In contrast, the daily duration of use per lamp was assumed to be 2 hours for the passive occupants (case 3) which was the highest duration within all US states. Although the number of lamps per residential unit was fixed for all cases and for the conventional and high-performance MURB, lamp types were assumed to be different between the buildings. Conventional MURB units were assumed to be fitted with incandescent lamps with lamp power of 60 W/lamp (Gifford, 2012). High-performance MURB units were assumed to be fitted with LED bulbs having lamp power of 15 W/lamp, which provides the same level of luminance as a 60 – 100 Watt incandescent light bulb (Gifford, 2012).

Based on these assumptions, the target daily lighting consumption was calculated for each case within each MURB unit. Afterwards, the NECB lighting schedules were used to calculate the equivalent lighting power inputs

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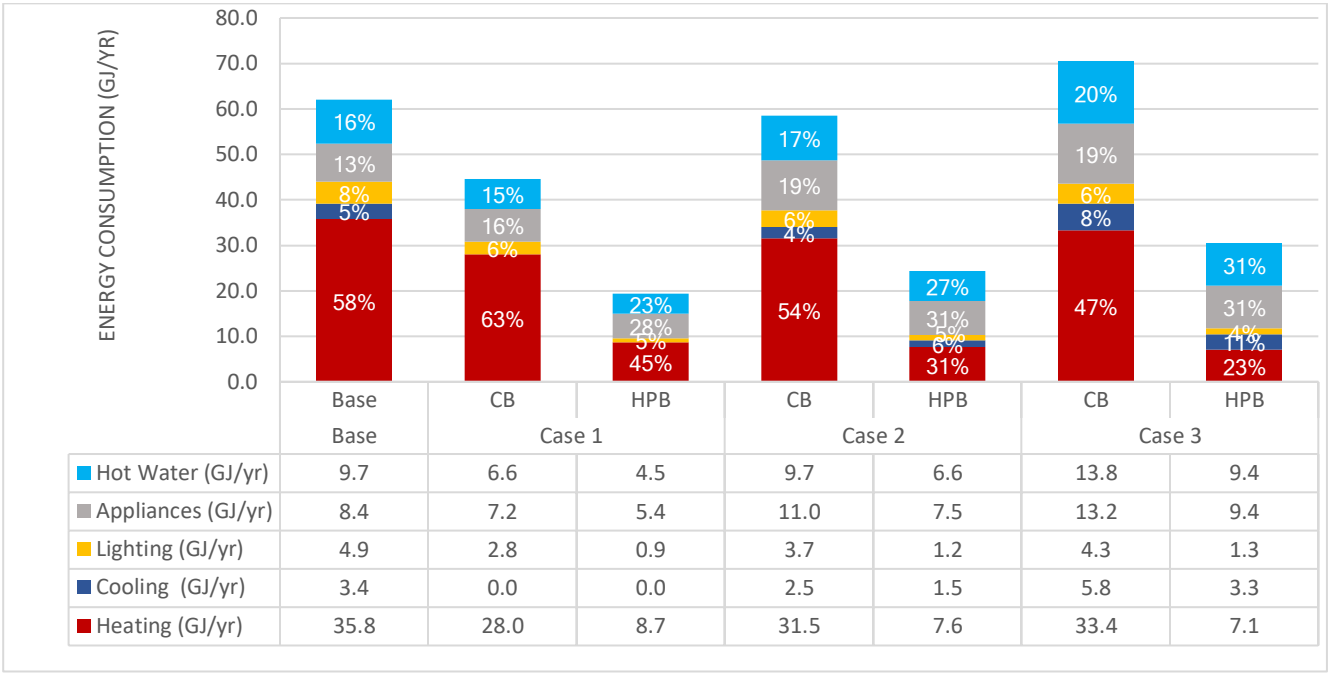
for the energy models that correspond to the target lighting consumption for each case as shown in Table 2.

RESULTS

Total energy consumption for all three occupant cases in both conventional and high-performance buildings increased between active and passive occupant behaviour. In conventional buildings, total energy consumption increased by 58%, from 44.6 GJ (active occupants) to 70.5 GJ (passive occupants). In the high-performance building, total energy consumption increased by 57%, from 19.4 GJ (active occupants) to 30.5 GJ (passive occupants).

When compared to the base case that was modelled, we can see that for the conventional building, active occupants consumed 28% less energy and passive occupants consumed 12% more energy, with average occupants almost even with the base case, consuming 6% less energy. For the high-performance building, all three occupant cases consumed less energy than the base case, with Active Occupants consuming 69% less energy, Average Occupants consuming 61% less energy, and passive occupants consuming 51% less energy. Figures 3 below provides a breakdown of the total energy consumption of each case by major end use, and the percentage that these values makeup of the total.



	Base	CB	HPB	CB	HPB	CB	HPB
	Base	Case 1		Case 2		Case 3	
Hot Water (GJ/yr)	9.7	6.6	4.5	9.7	6.6	13.8	9.4
Appliances (GJ/yr)	8.4	7.2	5.4	11.0	7.5	13.2	9.4
Lighting (GJ/yr)	4.9	2.8	0.9	3.7	1.2	4.3	1.3
Cooling (GJ/yr)	3.4	0.0	0.0	2.5	1.5	5.8	3.3
Heating (GJ/yr)	35.8	28.0	8.7	31.5	7.6	33.4	7.1

Figure 3: High Performance (HP) and Conventional (C) Building Energy Consumption for Different Occupant Cases

DISCUSSION

Results showed that the high-performance building consumes less total energy than the base building by at least 50% for all three occupant behaviour cases. Most significant was the decrease in end use energy consumption from heating, which was lower in the high-performance building. This is due to the high-performance building having a better insulated envelope as per passive house standards, which helps to keep its heating loads much lower regardless of the different occupant set points modeled here. Cooling loads for the high performance average occupant case are significantly closer to the base case than heating loads, which is likely due to the increased requirements for cooling as internal gains increase and the envelope better retains heat. Lighting was also significantly lower for all three cases compared to the base case. This is a result of not only use of efficient lighting, but also different lighting density assumptions.

For the conventional building, energy consumption results compare more closely to the base case. The Average Occupant case (case 2) consumed about the same total energy as the base case, with slight variations in how energy consumption was broken up by end use. Active Occupants (case 1) showed the significance of the impact occupant behaviour has on energy consumption, with total energy consumption almost 30% less than the base case. With both the base case and conventional building built to

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the same standard, these savings in case 1 show how active occupant behaviour can significantly reduce energy consumption. Most the savings were from a reduced heating load and no cooling load, which was the result of lower set points and efficient setbacks. However hot water and lighting use was also the source of some significant energy savings for active occupants, with consumption 63% less than the base case lighting and hot water consumption.

In both conventional and high-performance building cases, heating loads decrease significantly while cooling loads increase between the three cases. This can be explained by the fact that as hot water use, appliance use, and lighting use increase, internal heat gains increase and therefore space heating requirements decrease. However, this also creates higher demand for cooling which is what causes an increase in cooling energy consumption. All other end uses can be seen to increase in both cases for both conventional and high-performance cases.

Comparing the results of the high-performance building to that of the conventional building, provides insights into how occupants impact energy consumption as building envelopes increase in performance. As seen in the base case, the heating load makes up 58% of the dwellings overall energy consumption. On a case by case basis, the conventional building's heating load represents a significantly larger portion of the dwellings overall energy consumption relative to the high-performance building. Lighting energy consumption does not make up a significant amount of total energy consumption in either building type, and is about 2% lower for every case in the high-performance building.

The comparison of the two different building types shows hot water and appliances making up an increased share of total energy consumption in the high-performance building compared to the conventional. In all three occupant cases, appliance energy consumption and hot water consumption make up about a 10% higher share in the high-performance building type compared to the conventional building.

The reason for appliance and hot water consumption making up a significantly larger percentage of the overall energy consumption in high-performance buildings is largely due to the better insulated envelope of high performance buildings allowing for decreased heating demand. For an average occupant living in a high-performance building, this means hot water heating and appliance use account for 58% of total energy use. This can be compared to the average occupant in a conventional building where hot water and appliance use comprise 36% of energy consumption, and it can be seen that as buildings become more efficient, the energy breakdown drastically changes. More specifically, heating load share decreases while other loads such as hot water heating and appliance use increase. This means that changes in how occupants use hot water and appliances make a more significant impact in changing end use energy consumption in high performance buildings as opposed to conventional buildings.

CONCLUSION

With the push for better performing building envelopes in order to increase heating and cooling energy efficiency, the breakdown of end use energy consumption changes. Heating, though still significant, has been shown here to decrease by 22 percentage points across the three occupant behaviour scenarios. Hot water consumption and appliance usage on the other hand, have each been shown to increase by 10 percentage points each across the various occupant scenarios, both of which occupants can influence significantly.

We need to then consider how to influence occupant behaviour in a way that improves energy efficiency or design buildings to be less susceptible to occupant behaviour. Our analysis shows that both high-performance and conventional buildings are very susceptible to occupant behaviour, with close to 60% increase in energy consumption between active and passive occupant behaviour.

With results showing a decreasing share of heating in total energy by 22 percentage points and hot water and appliance usage increasing shares by around 10 percentage points each, high performance buildings are changing the way we need to look at energy conservation and what end uses we need to focus more of our attention on.

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