Examination of occupant-related aspects of the National Building Code of Canada

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Abstract

With the ongoing significance of energy efficiency in the building sector, the National Building Code of Canada (NBC) and the National Energy Code of Canada for Buildings (NECB) are essential for improving energy efficiency and minimizing energy consumption in housing and small buildings, and large buildings, respectively. Given that human behaviour is increasingly recognized to play an important role in building energy use, the validity of occupant-related assumptions in the building code and in the energy performance modeling tools used for demonstrating compliance to the code is a central concern. This paper is an investigation of current occupant-related assumptions in the NBC and modeling tools such as HOT2000 compared to new and emerging data sources, along with their potential energy and design impacts. The objective of this study is to identify the suitability of existing occupant-related assumptions, and accordingly, propose a set of initial recommendations for the NBC. Initial results indicate that several code assumptions are substantially different from findings in recent measurement-based studies, while others are quite representative.

Background

Beginning in the early 1940s, the federal government of Canada, like many other countries, promulgated national construction codes, including the National Building Code (NBC 2015). The primary initial goal was to ensure structure integrity and safety, but recently energy efficiency has been added as an objective. Currently, residential buildings in Canada consume about 17% (1458.2 PJ) of national energy consumption, with a total growth rate of 2.4% between 1990 and 2015 (NRCan 2018). Almost 61%, 19.5%, 13.6%, 3.7%, and 2.6 % of the total annual energy consumption are attributed to heating demand, water heating, appliances, lighting, and space cooling, respectively. Considering new priorities on energy efficiency and the resulting carbon emission reductions, the NBC Section 9.36 provisions address the energy performance of buildings by setting requirements on building design, construction and compliance. Accordingly, the NBC sets mandatory requirements for the building envelope, heating, ventilation, and air conditioning (HVAC) equipment, and service water heating equipment. The NECB addresses these building parameters as well as lighting, and electrical power. However, it is noteworthy that actual heating and cooling consumption is highly dependent on occupant behaviour and thermostat use (D'Oca and Hong 2015). In addition, appliance energy use is also highly dependent on occupants (Zhao and Magoulès 2012). Such influence is stronger in residential buildings, owing to a higher level of freedom and control over the indoor environment (Juodis et al. 2009). A research study by Gram-Hanssen (2010) has demonstrated that occupant behaviour impacts the energy use for heating in identical houses by a factor of up to three. In another study of 290 identical townhouses in Denmark, Andersen (2012) found the largest variation between heating energy consumption was 20 to 1, emphasizing the significance of occupant behaviour in buildings' energy use. Also, a similar study by Bahaj and James (2007) in nine identical low energy houses, found that the behaviour of occupants led to a significant discrepancy in energy consumption of up to 80%.

Objective and scope

The aim of this study is to examine the suitability of existing occupant-related assumptions, and accordingly, propose a set of initial recommendations for possible updates to the NBC and/or to the modeling tools used to demonstrate compliance to the NBC. While it is generally understood that energy models cannot be expected to perfectly predict energy use of real buildings, a greater concern is that inappropriate occupant-related assumptions in the NBC could lead to suboptimal requirements as the impact analysis of proposed changes is assessed by modeling according to the provisions in the performance compliance path, including the occupant schedules or assumptions stated therein. Six parameters related to occupant assumptions were selected: setpoint temperatures, hot water use, lighting and plug loads, internal heat gains, mechanical ventilation, and the number of occupants. This study was designed to exploit new and emerging data sources to benchmark current occupant-related NBC requirements. For each parameter, the following aspects were studied:

1. The NBC occupant schedules or other areas that are affected by the requirements;

2. The potential impacts of the schedules, including: a) impacts on energy and b) impacts on design; and
3. A review of existing data sources that provide comparative or contrasting evidence to the NBC schedules.

Temperature setpoints

When using the performance path as a compliance option to section 9.36 of the NBC, constant and straightforward modelling assumptions are given for heating and cooling setpoint temperatures to simulate the use of thermostats in households. These assumptions state that the energy model calculations shall account for space heating temperature setpoints of 21 °C in all living spaces above the basement. The space cooling temperature setpoint is 25 °C. In Canada, space heating demand accounts for 61% of all energy end-use in the housing sector (NRCan 2018). These further emphases the need to understand occupants' thermostat setpoint preferences, which have substantial energy and design implications for households. In general, widening the thermostat setpoint range reduces HVAC energy consumption (Andersen 2012). It has been found that that a 1 °C change in setpoint affects heating or cooling energy by on the order of 10% (Hoyt et al. 2005). On design impacts, more extreme setpoints (higher in winter; lower in summer) lead to higher heating and cooling demands and energy consumption, which justify more efficient HVAC equipment and building envelopes, as the operating costs increase relative to the capital costs. Thus, if available setpoint data indicate that prevalent setpoint values are more extreme than the current NBC requirements, it could justify increasing equipment/envelope efficiency. Conversely, if setpoint temperatures are less extreme, there could be an economic justification to reduce efficiency requirements. Finally, homes with poorer envelopes may have higher thermostat heating setpoints to compensate (Hong et al. 2017). To provide comparative evidence for the assumptions in the NBC in terms of temperature setpoints, three data sources were analyzed. First, the 2015 Survey for Household Energy Use (SHEU) (NRCan 2015) surveyed several thousand households in Canada on their heating and cooling setpoints during awake, asleep, and absent periods. The sample size was substantial and geographically representative for Canada. It relies on self-reporting, which may introduce bias. Also, the aggregated published SHEU results did not distinguish cooling setpoints for homes with and without air-conditioning, which introduces further error. The second data source used is obtained from ecobee thermostats owners who opt into the 'Donate Your Data' (DYD) program administrated by ecobee (Huchuk et al. 2018). The DYD program provides five-minute resolution data for tens of thousands of homes in North America. While this data avoids self-reporting errors on the quantitative data (e.g., setpoints and schedules), it has bias because ecobee users may be wealthier and thus may prioritize comfort over energy costs or may be more diligent about saving energy. Moreover, the behaviour data is less straightforward than basic mechanical thermostats because energy efficiency options in the thermostat software may override user-selected setpoints or may otherwise affect setpoints relative to what a user chooses. For the SHEU, the median space-heating temperature setpoint is 21°C (27.47% selected this value) during awake hours and 19 °C (13.65% selected this value) during sleep hours (see Figure 1). The median cooling setpoint is 22 °C (17.79%) during awake hours and 21 °C (13.40%) during sleep hours (see Figure 1). On the other hand, analysis of about 2500 DYD data of homes in Canada shows that the average heating setpoint temperature is nearly constant throughout the day and within 0.8 °C of 18.5 °C. The cooling setpoint temperature is nearly constant and within 0.5 °C of 23.3 °C (see Figure 2). Finally, Pardasani et al. (2020) describe a study of >500 electrically-heated, single-family homes in New Brunswick, in which smart thermostats were used to facilitate demand response. Further analysis of the data collected is valuable to this paper. Participants were asked how they normally set their thermostats prior to the study. For those with primary electric baseboard heating (N=475) the median setpoint when present and awake was 20 °C, and 17 °C when asleep or when absent during the day. For participants with primary mini-split heat pump heating (N=78) the median setpoint when present and awake was again 20 °C, and 18 °C when asleep or when absent during the day.

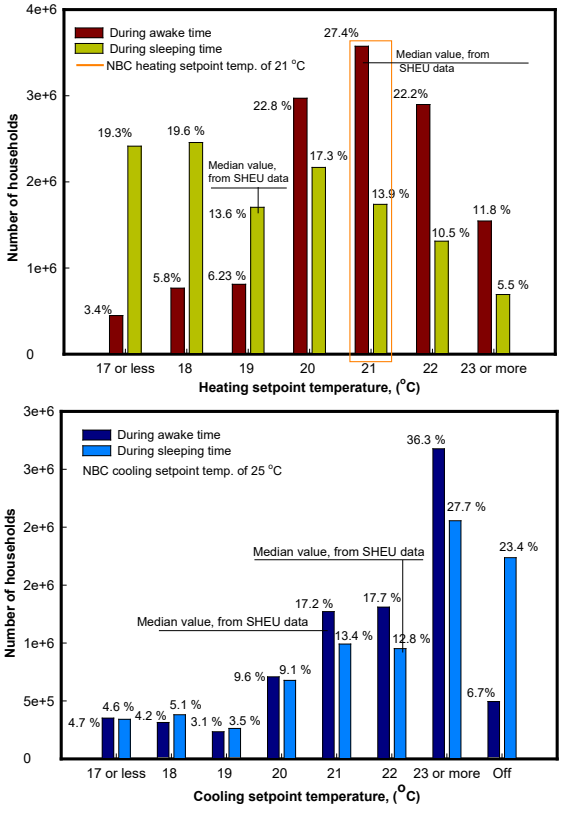


Figure 1 Dwelling setpoint temperature (heating: upper; cooling: lower) during the awake and sleep hours from SHEU data

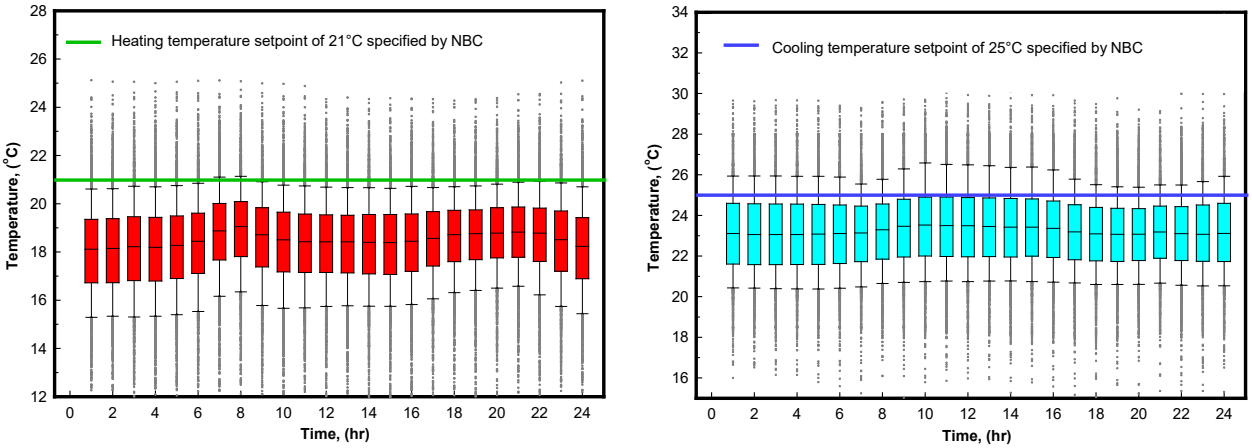


Figure 2 Hourly setpoint temperature: heating (left) and cooling (right) from Ecobee data. The box indicates the 25th and 75th percentiles; the median is indicated by a centerline in the boxes; and the whiskers show the position of the 5th and 95th percentiles.

Domestic hot water (DHW)

Section 9.36 of the NBC states that energy model calculations shall use a daily hot water use of 225 L. In Canada, DHW demands account for 18% of all energy end-use in the housing sector and 3% of the total secondary energy consumption (NRCan 2018).

Approximately, 288.8 PJ are used to heat water for residential use on an annual basis, and this leads to about 13 megatons of CO_2 equivalent GHG emissions (NRCan 2018), which is a robust motivation for understanding DHW consumption levels. In this context, both magnitude and temporal distribution of DHW draws can have a large impact on the optimal design of DHW equipment and controls, as well as fixtures, in several ways. Like for space temperature setpoints, overestimation of hot water use may lead to excessively stringent requirements for efficient equipment and distribution (e.g., insulated pipes, tank sizing and boiler efficiency) and may justify hot-water heat recovery. Conversely, underestimates may mean that current DHW requirements are insufficient and suboptimal. Also, there are implications for design in terms of DHW temporal consumption; solar thermal systems are more efficient if the majority of hot water consumption immediately follows peak solar availability (i.e., afternoon and early evening). Also, more extreme DHW consumption justify more efficient equipment in solar DHW system, solar combi systems, and other such technologies (Edwards et al. 2015). To provide comparative evidence for the DHW specifications of the NBC, DHW consumption data collected by the Natural Gas Technologies Center (NGTC) for 41 homes across Canada were investigated (see Figure 3). Data were collected for one year or more to create annual profiles. The average daily DHW draw for 41 households was 195 L/day (13% less than the NBC assumption).

Moreover, a comparative analysis of different DHW studies in the Canadian context was conducted against the DHW assumption of the NBC in terms of average daily consumption (see Figure 4) and hourly pattern (see Figure 5). In Ontario, Perlman and Mills (1985) collected DHW flow measurements at 15-min time-steps in 59 homes and examined household DHW consumption. Further, Becker and Stogsdill (1990) compiled several hundred DHW consumption measurements for both apartment buildings and homes from nine different studies across North America. Although these studies provided several contributions with a wealth of experimental data, they date back several decades, and as such, may no longer reflect current usage patterns, owing to the marked demographic change in Canada during past decades (Martel 2015), along with efficiency development of water fixtures such as faucets and showers. In 2008 a field study (Thomas et al. 2011) supported by NRCan measured hot water use in 74 houses in Ontario. In 2015, Edwards et al. (2015) developed new DHW profiles based on measurements that were conducted in 73 houses in Quebec; their findings show that the mean daily averaged DHW consumption was 189 L/day and that the median was 173 L/day, values within 2% of the results of the Thomas et al. (2011) study.

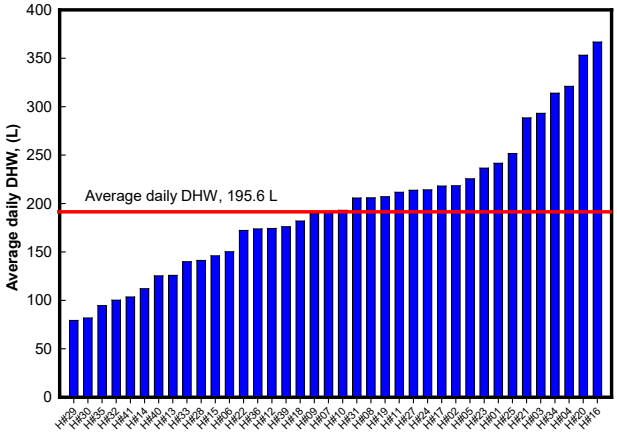


Figure 3 Average daily DHW use from NGTC data

In Halifax Nova Scotia, Evarts and Swan (2013) estimated DHW usage for a large sample of houses. The recent field study of George et al. (2015) measured hot water flow rate and in 119 homes in Halifax. Rouleau et al. (2019), using probabilistic models developed by other researchers, together with experimental measurements, identified domestic hot water use in 40 residential units of a social housing building in Quebec City. From Figure 4, it is clear that the NBC default schedule in the performance path overestimates the daily DHW consumption, except for the older studies by Becker and Stogsdill (1990) and Perlman and Mills (1985), that may no longer reflect current usage patterns. Despite the difference in total daily consumption, the daily pattern of the older studies closely follows the pattern of more recent studies, and differs from the NBC, as shown in Figure 5. It is also interesting to note that morning hot water consumption peaks in all studies occur earlier in the day, with a morning peak between 6 AM and 7 AM as opposed to between 9 AM and 10 AM in NBC. Also, the evening peak happens between 6 PM and 7 PM as opposed to between 4 PM and 5 PM in NBC assumptions.

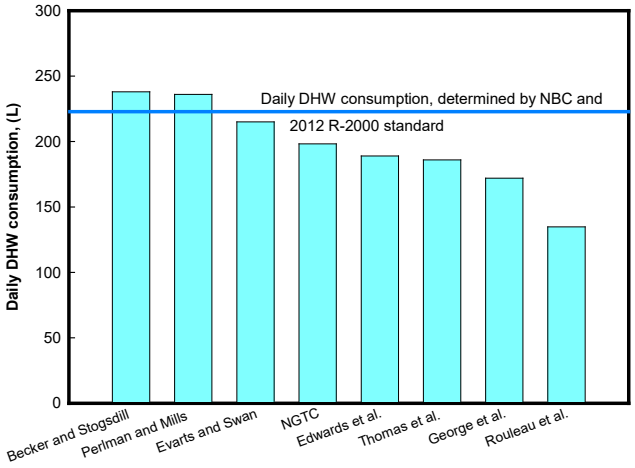


Figure 4 Comparison of average DHW daily consumption

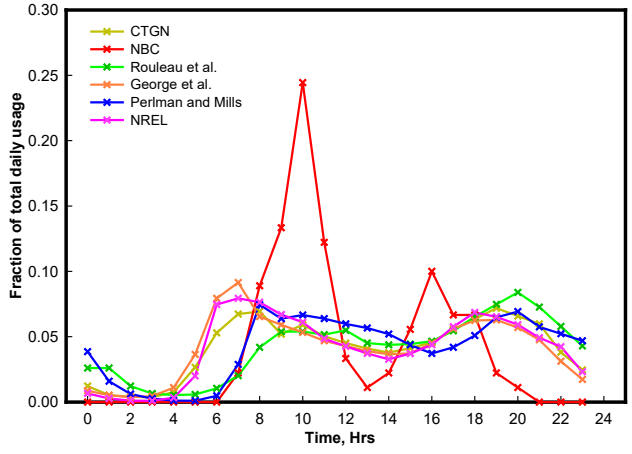


Figure 5 Comparison of DHW hourly profile

Appliances, lighting, and plug (ALP) loads

In the Canadian residential sector, the end-uses of appliances, and lighting loads account for 17% of total end-use energy consumption, however, there is no available information about the plug loads in terms of end-use energy consumption. Approximately, 251.9 PJ is used by appliances and lighting loads in residential use on an annual basis, and this leads to about 9.6 megatons of CO_2 equivalent GHG emissions (NRCan 2018).

In light of design implications, inaccurate assumptions for energy use of ALP loads have a direct impact on the optimal level of efficiency for these end-uses. For example, under-estimates for lighting energy use underestimates the importance of efficiency measures (e.g., occupancy-controlled lighting, efficient lamps). Similarly, underesti-mates of plug loads underestimate the value of efficient appliances, their use, and controls (e.g., smart plugs). Inaccurate predictions on these loads in building energy models can cause significant cost implications on renewable energy supply or distributed generation such as photovoltaic array sizing for net-zero energy homes. For instance, the overestimation of building plug loads may push designers to exploit sub-optimal building surfaces for mounting, or sub-cost-optimal PV products due to space constraints. Finally, overestimation of ALP loads diminishes the importance of efficient heating and an efficient envelope; conversely, underestimating these loads may increase the need for efficient heating equipment and an efficient envelope. In the section that follows, an Ottawa dataset (Johnson and Beausoleil-Morrison 2017; Saldanha and Beausoleil-Morrison 2012) was investigated. In this study, 23 houses in Ottawa were monitored for energy use at 1-min resolution for both non-HVAC and HVAC appliances. Like the DHW analysis, some post-processing analysis was employed to generate the average daily ALP loads (see Figure 6).

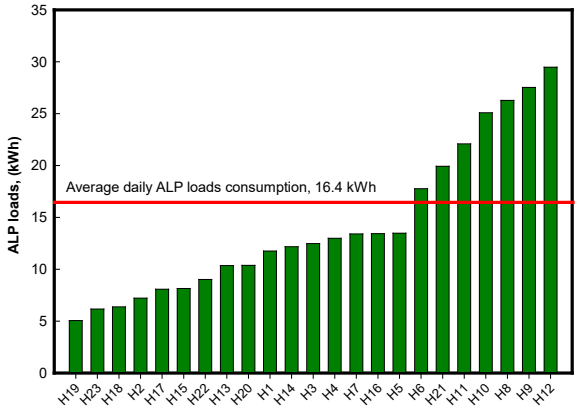


Figure 6 Average daily ALP loads from Ottawa dataset

Further, data on plug loads in Canadian residential buildings were collected from two published papers and compared to the daily and hourly consumption of Johnson and Beausoleil-Morrison (2017). First, non-HVAC electricity demand from 57 single detached homes at 15-minute

intervals was collected by Hydro-Quebec from 1994 to 1996 (Knight et al. 2007). Second are measurements of ALP loads for 160 homes, conducted by Nova Scotia Power Incorporated (George and Swan 2017). In HOT2000 software, the default plug load assumption is 19.5 kWh/day, which is 19.6% higher than the mean daily Nova Scotia ALP loads value, and 16.7% higher than the mean daily Ottawa ALP loads value (see Figure 7). Despite the temporal and geographical differences of these data sets, their daily patterns are very similar, as depicted in Figure 8. These results strengthen the validity of the suggestion that this daily profile could be adopted by the NBC in the future.

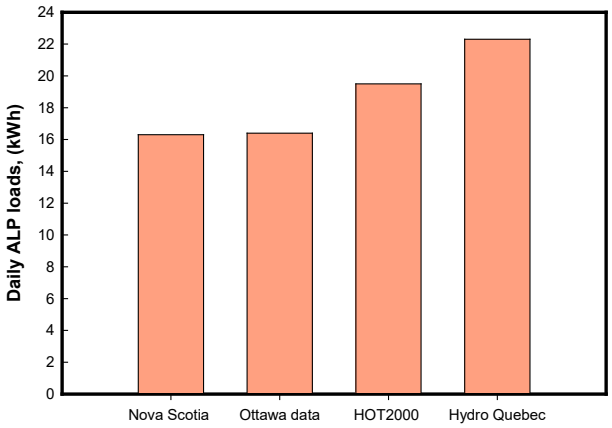


Figure 7 Comparison of average daily ALP loads from various datasets

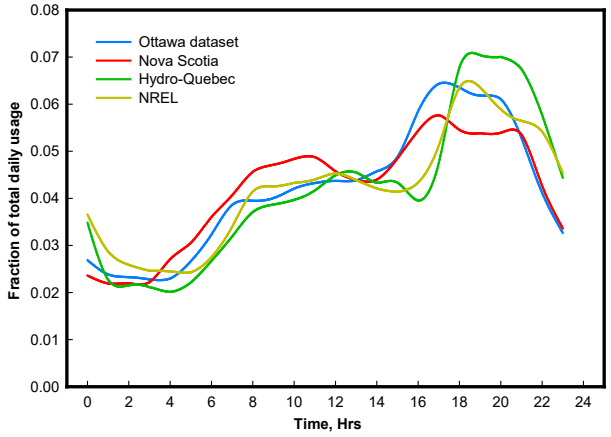


Figure 8 Hourly ALP loads profile comparison

Internal heat gains

The NBC states, in Section 9.36, that energy model calculations shall account for the loads due to heat gains from occupants, lighting, and miscellaneous equipment of 22.4 kWh/day. The direct energy impact of internal heat gains depends on the source (e.g., occupants vs. appliances). As described in the previous section, internal heat gains may have a significant impact on design because of their effect on the overall heat balance of homes. It is challenging to measure internal heat gains; accordingly, there is a dearth of research work in related occupant behaviour. Thus, we developed a new daily profile for internal heat gains using the following datasets: NRCan data for Energy Consumption of Major Household Appliances (NRCan 2018), and Standard conditions for evaluating R-2000 energy performance (NRCan, 2012) (see Figure 9), and the fraction of heat released from the appliance operation (see Table 1). Table 1 contains the list of daily consumption of each appliance considered along with fraction of heat released indoors (vs. outdoors via exhaust and drainage).
As shown in Figure 10, a noticeable difference is observable during the daytime between the NBC profile and our developed profiles.

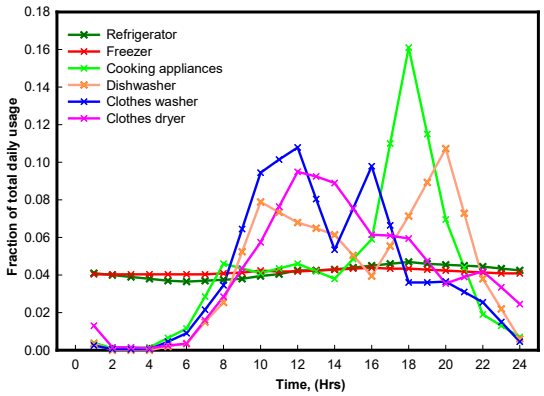


Figure 9 Daily profile for household appliances (Wilson et al. 2014)

Table 1 Major appliances in Canadian household (NRCan 2018)

Appliance type	Daily energy use	Fraction of heat
Refrigerator	1.50 kWh	1.00
Freezer	0.51 kWh	1.00
Dishwasher	0.13 kWh	0.75
Clothes Washer	0.11 kWh	0.80
Clothes Dryer	1.98 kWh	0.20
Range	1.69 kWh	0.70
Other appliances	4.63 kWh	0.95

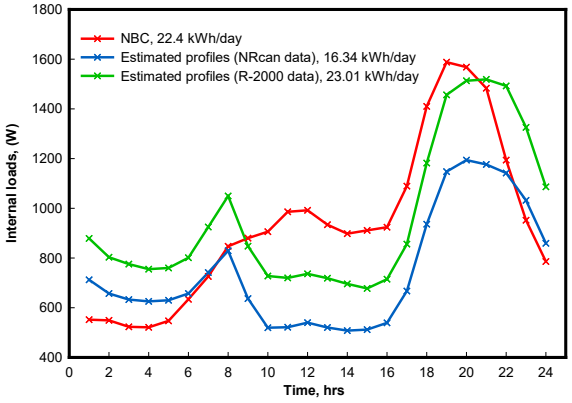
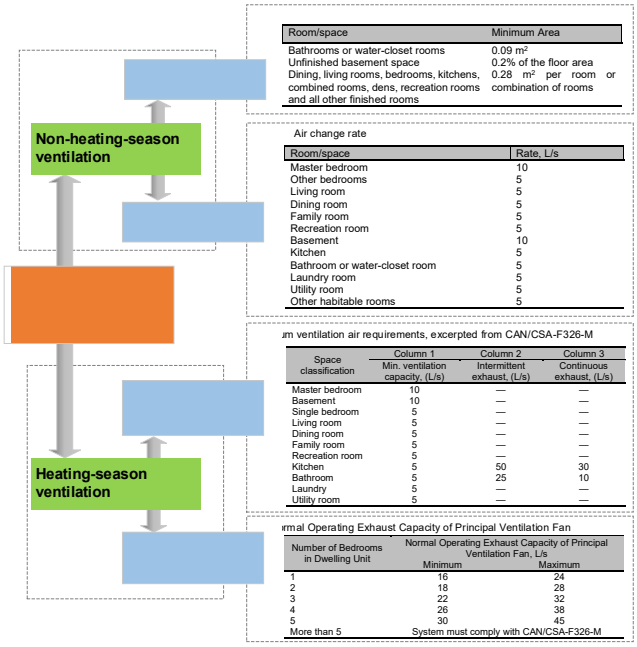


Figure 10 Daily profile for internal heat gain

Mechanical ventilation

Although the energy efficiency requirements in Section 9.36 of the NBC do not mandate mechanical ventilation, certain requirements are stated if mechanical ventilation is supplied e.g. sensible heat recovery when the design includes heat/energy-recovery ventilators. Section 9.32 of the NBC states that every residential occupancy shall incorporate provisions for non-heating-season ventilation and provisions for heating-season ventilation. These requirements pertain to the health objective of the NBC. Figure 11 describes the ventilation requirements under different conditions along with different standards.



Room/space	Minimum Area
Bathrooms or water-closet rooms	0.09 m²
Unfinished basement space	0.2% of the floor area
Dining, living rooms, bedrooms, kitchens, combined rooms, dens, recreation rooms and all other finished rooms	0.28 m² per room or combination of rooms

Air change rate

Room/space	Rate, L/s
Master bedroom	10
Other bedrooms	5
Living room	5
Dining room	5
Family room	5
Recreation room	5
Basement	10
Kitchen	5
Bathroom or water-closet room	5
Laundry room	5
Utility room	5
Other habitable rooms	5

m ventilation air requirements, excerpted from CAN/CSA-F326-M

Space classification	Column 1 Min. ventilation capacity, (L/s)	Column 2 Intermittent exhaust, (L/s)	Column 3 Continuous exhaust, (L/s)
Master bedroom	10	—	—
Basement	10	—	—
Single bedroom	5	—	—
Living room	5	—	—
Dining room	5	—	—
Family room	5	—	—
Recreation room	5	—	—
Kitchen	5	50	30
Bathroom	5	25	10
Laundry	5	—	—
Utility room	5	—	—

rmal Operating Exhaust Capacity of Principal Ventilation Fan

Number of Bedrooms in Dwelling Unit	Normal Operating Exhaust Capacity of Principal Ventilation Fan, L/s Minimum	Maximum
1	16	24
2	18	28
3	22	32
4	26	38
5	30	45
More than 5	System must comply with CAN/CSA-F326-M	

Figure 11 Ventilation requirements under different conditions, stipulated by the NBC (2015)

Higher mechanical ventilation rates of buildings have a significant impact on building energy consumption; as the average annual ventilation energy use for a typical USA dwelling is thought to account for 1/3 to 1/2 of the space conditioning energy (Sherman and Matson 1997). Moreover, a considerable amount of literature has been published on the effect of insufficient building ventilation on occupants' health (Sundell et al. 2011). In light of design implications, a higher mandated ventilation rate justifies greater expenditure on efficient ventilation (e.g. a heat/energy-recovery ventilator, efficient fans, etc.). In exhaust-only systems in detached homes, make-up air would come from uncontrolled air leakage from outside and greater ventilation rates would increase energy use to condition this outdoor air, especially in winter and summer. In a balanced system (supply and exhaust) such as the heat/energy-recovery ventilator, there would still be impact of greater ventilation rates but lessened as there would be some energy recovery from the exhausted air. While it is not currently commonplace, greater ventilation rates could also justify ventilation that can be controlled for each room, and demand-controlled ventilation. In contrast, lower ventilation rates reduce the importance of efficient and effective ventilation systems. Given the lack of granularity over control, the design ventilation rate is likely to remain fixed for a long duration – at the long-term cost of extra energy use or underventilation (and associated comfort and health impacts). To provide comparative evidence for the mechanical ventilation requirements of the NBC, the required mechanical ventilation for 11 different Housing Technology Assessment Platform (HTAP) archetypes developed by NRCan, were calculated (see Figure 12). It is clear that there is a difference between the standards in terms of required ventilation, owing to the number of rooms, house area, and house volume. As such, new estimates for the number of occupants as a function of bedrooms need to be developed for calculating the corresponding prescribed ventilation rate.

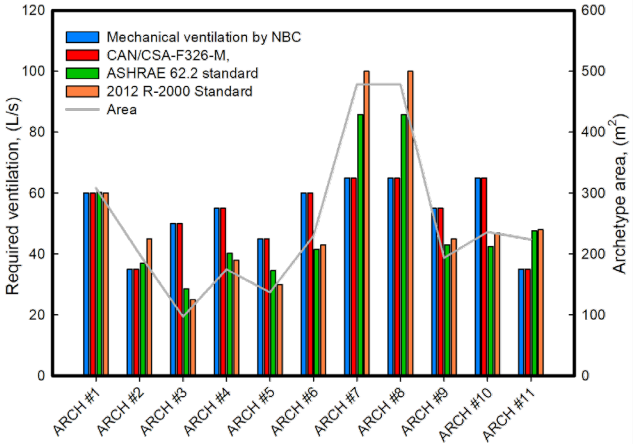


Figure 12 Required mechanical ventilation calculated using different standards.

Number of occupants

There is no occupant schedule specified in NBC, although it is an implicit or explicit input in internal heat gains and ventilation rates. While occupants do not substantially directly affect energy use, the number of occupants, their occupancy schedules and behaviours profoundly affect ventilation requirements, DHW use (George et al. 2015), ALP loads (Johnson and Beausoleil-Morrison 2017) which significantly affect cooling and heating loads.

Several data sources were examined to obtain data on the number of occupants in households. The National Renewable Energy Laboratory (NREL) (Wilson et al., 2014) estimated the number of occupants in single-family dwellings during non-vacation periods as a function of number of bedrooms:

$$N_{occ} = 0.59N_{br} + 0.87$$

R-2000 provided the following guidelines for number of occupants in the home (NRCan, 2012):

- 2 adult occupants, at home 50% of time
- 2 child occupants, at home 50% of time

ASHRAE Standard 62.2 (2019), implies that the number of occupants equals the number of bedrooms plus one.

NRC analyzed data from two recent independent samples of single-family homes in southern Ontario. The first sample (ON-1) was derived from municipal property tax records (N=857); the second sample (ON-2) was self-reported by home energy management system subscribers (N=254). Collectively, these sources suggest that the ASHRAE assumption is higher than the current average occupancy.

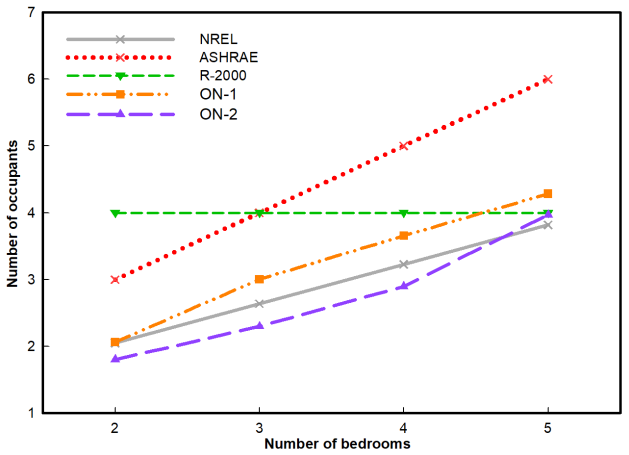


Figure 13 Number of occupants as a function of number of bedrooms, from several sources.

Conclusion

The suitability of existing occupant-related assumptions in the NBC were investigated and compared against new and emerging data sources in our study. Six parameters related to occupant assumptions were selected: setpoint temperatures, hot water use, lighting and plug loads, internal heat gains, mechanical ventilation, and the number of occupants. This preliminary study indicates a need for more research and deeper investigation – particularly regarding the following areas and possible recommendations for which the current study indicated significant differences between the NBC and the best available datasets.

- For the temperature setpoints, our analysis of ecobee data showed that the mean heating setpoints are approximately 1.5°C cooler than the current NBC specification (21°C) while; the mean cooling setpoints are around 1.5°C cooler than specified by NBC (25°C).
- For DHW, our analysis showed that the hourly schedule for DHW use specified by NBC is significantly different than all data sources found (primarily in the timing and magnitude of morning and evening peaks in usage). All data sources had relatively similar schedules (see Figure 9), suggesting that any combination of them (e.g., the mean) would be a suitable replacement schedule.
- For the energy end-uses of appliances, lighting, and plug (ALP) loads, our recommendations for the NBC committee are to adopt the ALP loads profile in in the future editions. All data sources had the relatively similar temporal pattern (see Figure 8), suggesting that any combination of them (e.g., the mean) would be an improvement to the NBC.
- For Internal heat gains, we recommend that the schedule of internal heat gains be modified (primarily to address the morning peaks in the usage and mid-day gains).
- For the number of occupants, we recommend that the ratio of occupants to bedrooms for determining ventilation requirements be reconsidered to use NREL's recommendation ($N_{occ} = 0.59N_{br} + 0.87$).

Planned future work will perform a batch simulation study on Canadian home models to understand the role of all occupant-related assumptions on predicted energy use and optimal design.

Acknowledgement

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