On the behavioral effects of residential electricity submetering in a heating season

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Abstract

In general, occupants' only visible connection to their energy consumption is the bimonthly or monthly statements that summarize the cost of their energy use. However, a quarter of Canadian households do not directly pay for their energy bills. Instead, the landlord, property manager, or the condominium corporation are responsible for energy bills. As such, there is no monetary incentive for tenants to make energy-saving retrofits or modify their behaviors to save energy. In this study, a questionnaire survey was carried out with 20 participants who were responsible for their energy bills and 20 participants who were not responsible for their energy bills. Temperature loggers were placed in the living rooms and bedrooms of these participants' apartments during two consecutive heating seasons in Ottawa, Ontario. Results showed that occupants who were responsible for their energy bills were more diligent and active in controlling indoor air temperature. These occupants chose to heat different areas of their units at different times. On the contrary, the occupants, who were not responsible for their energy bills, rarely adjusted their thermostat settings or setback their thermostats. Furthermore, the occupants who were not responsible for their energy bills maintained their apartments about 2°C higher than their counterparts who were responsible for their energy bills.

Keywords: Metering; residential energy use; comfort perception; visibility of energy use; billing type; energy use feedback

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1. Introduction

A major challenge in promoting residential energy conservation, as stated by Brandon and Lewis [1], is to increase the visibility of energy consumption in homes and occupants' awareness to the connection between their behavior and financial/environmental consequences. Typically, occupants' only apparent connection to their energy consumption is their bimonthly or monthly statements that summarize the cost of their energy consumption. However, the Survey of Household Energy Use (SHEU) in 2007 revealed that 26% of the Canadian households (3.1 million households) were not responsible for their energy bills [2]; instead the landlords, property managers, or the condominium corporations were responsible for any energy bills. Similarly, the rental agent survey within the residential energy consumption survey (RECS) in the United States reported that 829 out of the 12083 respondents were not responsible for their utilities [3]. In this paper, we define this group as the households living in bulkmetered buildings. All others are defined as the households living in submetered buildings.

Levinson and Niemann [4] reported that rents and monthly condominium payments are notably higher in bulkmetered apartments compared to submetered apartments, however the premiums that bulkmetered apartment renters are willing to pay typically exceeded the cost of their energy consumption. This suggests that tenants place significant value on having the freedom to use energy freely without concern for monetary consequences. However, occupants failed to see this implicit cost of energy —perhaps due to a lack of feedback on household energy consumption [5-7]. In fact, this lack of energy use feedback may result in significant impacts on residential energy consumption [8]. Anecdotal evidence [4, 8-12] suggests that submetering of household utilities, as opposed to including energy costs with rent or condominium payments, can result in 30% energy savings. For example, the monthly electricity use metered in a large electrically heated/cooled residential building (280 units) near Toronto, Ontario is shown in Figure 1. In these apartments, the heating and cooling were provided through terminal units controlled by the residents of each apartment. The building was bulkmetered until June 2011 and, then, it was retrofitted with submeters in each unit. No other retrofits in the envelope or HVAC systems or change in the level of occupancy were reported for the building. The monthly electricity use with respect to the mean monthly outdoor temperature data reported by EnvironmentCanada [13] is shown in Figure 1.b. Once the data (see Figure 1.b.) were fitted with two second-order polynomial models, both of them resulted in a coefficient of determination of 0.95. By observing these polynomial curve fits, it can be seen that the baseline electricity use during the shoulder seasons and the electricity use during the heating season decreased notably after submetering. In line with these observations, Maruejols and Young [14] analyzed SHEU data in 2003 [15] and reported that bulkmetered households consumed significantly higher energy, maintained their units at higher temperatures during the heating season, and were less likely to undertake adaptive measures, such as clothing level adjustments and night-time or holiday thermostat setbacks. However, it should be noted that the SHEU in Canada is not designed for such high resolution information. For example, to reveal temperature preferences during the heating season in 2003 SHEU [15], participants were asked to answer the following question:

"At what temperature did you usually maintain the largest heated area in your dwelling in the daytime (roughly 6 a.m. to 4 p.m.), in the evening (roughly 4 p.m. to 11 p.m.), at night (roughly 11 p.m. to 6 a.m.)? "

It is difficult to draw quantitative conclusions based on this question for numerous reasons: (1) the indoor temperature is a spatiotemporal distribution rather than a single number. (2) In 2007, about 10% of the households did not own a thermostat [2]. (3) It is likely that the setpoint readings of the HVAC unit (possibly further corrupted due to miscalibration) were perceived as the temperature of the living space [5, 16]. These findings and observations formed the basis for the following research questions: (1) Do occupants apply adaptive measures (e.g., turning off lights and idling appliances, clothing level choices, window and blind adjustments) more consciously and responsibly, if they are responsible for paying their own energy bills? (2) Does living in a bulkmetered, instead of a submetered, building affect occupants' indoor temperature settings?

The current paper presents an observational investigation of forty occupants living in submetered and bulkmetered buildings in Ottawa, Ontario to reveal behavioral, attitudinal, habitual, and perceptional differences about heating energy use, as posed in the first research question. Furthermore, the indoor air temperature was measured during the heating season in the living rooms and the bedrooms of participants. These data were analyzed to answer the second research question.

2. Methodology

2.1. Participants

Participants in this study were largely university students or young professionals living in small downtown dwellings (one or two bedroom apartments) in Ottawa, Ontario. After receiving approval from the Research Ethics Board to conduct the study, participants were recruited using postings left on the bulletin boards of six high-rise residential buildings. These buildings were all constructed during 1970s with similar construction characteristics. The study's sample is comprised of a diverse group of participants, (e.g., nationality, age, sex) living in different types of apartments (e.g., storey, facade orientation). However, before the recruitment process the key characteristics that can bias the study's results were identified. These were reported as the age and gender of the participants [17], the duration that participants lived in Canada and in their apartments [18], the apartments' facade orientations, and the storey number [19]. Thus, particular attention was paid to preserve the distribution of these characteristics in both groups (see Table 1).

Forty participants, each living in separate apartments, were recruited. Of these, twenty were living in bulkmetered apartments and twenty were living in submetered apartments. Heating systems in all the apartments were packaged terminal units with electric heaters and baseboard heaters. All participants had control over these heating systems to maintain their preferred indoor environment. Baseboard heaters were provided with a separate control in each room and controlled by the occupants with an adjustable knob. These packaged terminal units were controlled with an adjustable knob or button labels with up and down arrows to adjust the temperature setpoint.

2.2. Procedure

The air temperatures in the apartments were measured using LogTag Trix-8 temperature loggers, which are thermistor-based devices with internal memory storage that can be configured to record temperatures at regular intervals. The manufacturer specifies an accuracy of ±0.5°C for these devices. To verify this, the loggers used in this study were placed in a constant temperature incubator along with a reference resistance temperature detector (RTD). The reference RTD (Fluke 1524 with Fluke 5615 probe) had a reported accuracy of ±0.02°C. Once steady conditions were reached, the measurements from the temperature loggers were contrasted to the reading from the reference RTD. The greatest deviation between a temperature logger and the reference

RTD was found to be 0.3°C, which is better than the manufacturer's claimed accuracy. These measurements were further analyzed to verify that there was no bias between the temperature loggers that were to be installed in the submetered and bulkmetered apartments. The mean values of the temperature readings from the two groups of loggers were found to differ by less than 0.1°C. Likewise, the standard deviations of the two groups of measurements were also found to differ by less than 0.1°C.

Following this, the temperature loggers were installed in the submetered and bulkmetered apartments. Two loggers were located in each apartment: one in the living room and one in a bedroom. The loggers were configured to record temperatures once an hour, from the beginning of January to the end of March in two consecutive heating seasons.

All participants were administered a questionnaire assessing behaviors, attitudes, habits, health and financial perceptions toward energy consumption, shown in Tables 2 to 6, respectively. Two previous studies [20, 21] formed the basis for the questionnaire used in this study. The main objective was to reveal differences in attitudes and behaviors related to energy consumption between occupants living in bulkmetered and submetered apartments. The questionnaire contained 36 items in total. Of these, six were introductory questions to determine demographic variations of the participants (e.g., age, sex, and ethnicity) and to prompt participants to think about their indoor environment (e.g., IAQ, thermal comfort, heating system satisfaction). This was followed by four questions that asked them to think about the way they adapt to seasonal and daily thermal changes (e.g., clothing level changes, thermostat setpoint adjustments). Finally, participants answered 26 true/false questions meant to assess self-reported differences in aspects related to household energy consumption between participants living in bulkmetered and submetered apartments. Of these 26 items, five addressed participants' willingness to undertake adaptive behaviors to conserve energy, seven were formulated to assess perceived levels of comfort associated with indoor temperature, six aimed to identify differences in heating habits, four addressed the relevance of health concerns associated with indoor temperature, and four assessed the importance of financial incentive in relation to energy consumption.

3. Results and Discussion

3.1. Effect of submetering on behaviors, attitudes, habits, and beliefs about heating energy consumption

Five constructs were suggested to describe the effect of submetering on heating energy consumption. The first construct represents behaviors used to adapt to varying indoor temperatures. Five questionnaire items, shown in Table 2, were used to investigate adaptive behaviors related to indoor temperature. Of these five items, the first three are personal adaptive behaviors, reflecting ways in which occupants can adapt themselves to their environment (e.g., clothing level adjustments) [22]. The remaining two items are environmental adaptive behaviors, reflecting ways in which occupants can adapt their environment to varying indoor temperatures (e.g., opening blinds to admit more solar gains) [22].

Responses to items in Table 2 are shown in Figure 2. Contrary to expectations, fourteen out of the twenty participants living in the bulkmetered apartments reported that they were willing to wear heavier clothes to set back their thermostats, while eight out of the twenty participants living in the submetered apartments reported that they would wear heavier clothes to set back their thermostats. This finding suggests that the participants living in the submetered apartments appeared to be more reluctant to undertake personal adaptive behaviors, such as adjusting their clothing level, in order to adapt themselves to varying indoor temperatures. Responses to two of the introductory questions were used to explain this difference in personal adaptive behaviors between the two groups. These introductory questions asked the participants to identify what best describes their indoor clothing during the day and at night. Eight out of the twenty participants living in the submetered apartments reported typically wearing long pyjamas while sleeping, while eight out of the twenty participants living in bulkmetered apartments reported wearing *as little as possible* while sleeping. The question addressing typical daytime clothing also confirmed that participants in submetered apartments were more likely to wear heavier clothes. The reluctance of participants living in the submetered apartments to increase their clothing level in order to adapt to varying indoor temperature could be explained by their initial tendency to wear heavier clothing. In other words, participants living in bulkmetered apartments may have demonstrated more interest in personal adaptive behaviors to varying indoor temperature because of their tendency to wear lighter clothing, which may be due to higher baseline temperatures in their apartments. The results also indicated that participants from submetered apartments reported more interest in undertaking environmental adaptive behaviors, in particular sealing or caulking windows, compared to participants living in bulkmetered apartments. It is worth noting, however, that apartment tenants often encounter restrictions with regards to making changes to the envelope of their apartments in order to conserve energy. For example, one participant living in a submetered apartment indicated that the manager of his/her building prohibited residents to make changes in the building perimeter.

The second construct represents participants' attitudes regarding thermal comfort. Seven items, shown in Table 3, were used to investigate attitudes related to thermal comfort. The first four items assessed tolerance related to lower indoor temperatures, the fifth and sixth items assessed attitudes related to thermostat setback at night, and the seventh item assessed attitudes regarding manual thermal zoning (i.e., preference with having the room in which they sleep be cooler than the rest of their apartment with different heating schedules).

Responses to items in Table 3 are shown in Figure 3. Responses to the questions 2 and 4 to 7 in this construct indicated no significant difference between participants living in submetered and bulkmetered apartments. However, responses to the first and third question revealed a notable difference between the two groups. Fourteen of the twenty participants living in submetered apartments agreed that a 2°C setback would have made them "very uncomfortable", whereas only one out of twenty participants living in a bulkmetered apartment agreed with this statement. In line with question 3, fourteen out of the twenty participants living in the submetered apartments agreed with question 1 as they perceived temperatures below 20°C in the winter months as uncomfortable, whereas only eight out of the twenty participants living in the bulkmetered units agreed with this statement. This suggests that the occupants living in submetered apartments were more sensitive to lowering their indoor temperature compared to the occupants living in bulkmetered apartments.

The third construct represents habits related to energy consumption and thermal adaptation, in particular thermostat use and clothing choice. Six items, shown in Table 4, were used to investigate habits related to thermal adaptation. The first item assessed habits related to clothing level adjustments, and the remaining five items assessed habits related to thermostat use.

Responses to items in Table 4 are shown in Figure 4. Based on the responses to the first item, nearly half of the participants living in the bulkmetered apartments showed reluctance to changing their clothing habits, while this ratio was only about one-fourth for the submetered apartments. Responses to the second item indicated that thirteen out of the twenty participants living in bulkmetered apartments reported that they were unlikely to change their energy consumption habits, whereas fourteen out of the twenty participants living in submetered apartments disagreed with this statement. This suggests that the occupants living in the submetered units were more open to changing their clothing and heating habits compared to the participants living in the bulkmetered apartments.

The fourth construct represents the role of health as an incentive to choose indoor temperatures. This construct was investigated using four items shown in Table 5. These items aimed to better understand the perceived relationship between one's health and indoor temperatures.

Responses to items in Table 5 are shown in Figure 5. Both groups differed in how they perceived their health to be related to indoor temperature. Responses to all items indicated that a significant ratio of participants living in submetered apartments associated their well-being directly with the indoor temperature of their apartment. On the contrary, only a few participants living in the bulkmetered apartments reported such a connection between their health and heating. This suggests that participants living in submetered apartments attribute their health and well-being to the indoor temperature of their apartment more so than participants living in bulkmetered apartments.

The fifth construct represents the financial aspect of energy consumption. This construct was investigated using four items shown in Table 6. These items were used to assess the extent to which financial incentives impact energy consumption.

Responses to items in Table 6 are shown in Figure 6. Thirteen out of the twenty participants living in the bulkmetered apartments reported that they would wilfully reduce their thermostat settings if they were convinced it would achieve significant savings, whereas eight out of the twenty participants living in submetered apartments agreed with this statement. This is in line with the responses to the items shown in Table 2, suggesting that occupants living in submetered apartments are less inclined to undertake adaptive measures related to energy consumption. This may be related to participants' greater concern with the impact of indoor temperature on their health.

3.2. Effect of submetering on temperature preferences

Figures 7.a and 7.b present histogram plots comparing the distribution of the indoor air temperature measurements in the bulkmetered and in the submetered units. About 50000 individual temperature measurements were used to build each of these histograms.

Figure 7.a illustrates a comparison between the distributions of the living room temperature measurements in both groups. Results indicate a pronounced difference between the submetered and bulkmetered units. During the heating season, the temperature in the living rooms of bulkmetered units was on average 1.8°C higher than it was in the submetered units. Figure 7.b presents a comparison between the bedroom temperature distributions in the submetered and the bulkmetered apartments. Similar to the observations in the living room temperature measurements, the bedroom temperature in the bulkmetered apartments was on average 2.6°C higher than it was in the submetered units. These differences may explain why participants living in submetered apartments appeared to be more sensitive about their thermal discomfort (see responses to item 3 in Table 3 shown in Figure 3) and showed more reluctance to change personal behaviors to adapt to varying indoor temperature.

Figure 8.a presents two scatter plots for the temperature measurements of a bedroom and a living room in one of the submetered and one of the bulkmetered units. If temperature measurements in

both rooms were perfectly related to each other at any given time, the data scatter would have formed a straight line and the correlation coefficient (ρ) would have equaled one. In reality, the simultaneous measurements in both rooms were not proportional. It is evident that the deviation in this proportionality could be caused by a number of uncertainties. These uncertainties include, but not limited to: (1) the non-Gaussian measurement error and (2) the disproportional disturbances due to the position of the data loggers. It was assumed that the influence of these outliers should dissipate within all participants. With this assumption, it became reasonable to propose that the correlation coefficients between the bedroom and the living room temperature data records can be attributed to occupants' efforts to condition different portions of their units at different times. In other words, if the occupants divide their apartments into zones and condition these zones independently depending on their schedules and activities, the correlation coefficient diverges from one. This type of behavior was typical in submetered units. Figure 8.b presents a representative two day period for one submetered and one bulkmetered apartment. It is evident that the temperature difference between the living room and bedroom sensors remained somewhat constant in the bulkmetered unit, whereas in the submetered unit the living room temperature declined at night and the bedroom temperature declined during the day. This figure illustrates the relationship between the correlation coefficient and an occupant's active efforts to control the temperature in different portions of the dwelling at different schedules. Figure 9 illustrates two box-whisker plots for correlation coefficients of the bulkmetered and submetered units. As shown in Figure 9, the median correlation coefficient between the living room and the bedroom data records in submetered units were significantly lower than it was in bulkmetered units. In line with this, many of the participants living in the submetered units reported that they turn off their bedroom baseboard heaters during the day and their living room baseboard heaters during the night. This manual zoning behavior was not reported by any of the participants living in the bulkmetered units.

Figure 10 presents two box-whisker plots to contrast the diurnal setback behavior of occupants in both groups. The magnitude of diurnal indoor temperature fluctuations (averaged between two temperature loggers) were computed for each of the occupants. Although the magnitude of daily temperature fluctuations can be influenced by many contextual factors (e.g., apartment's geometry and the interior design), it was assumed that the influence of these factors in individual units can be lessened amongst all participants. Thus, a qualitative comparison could be made between the bulkmetered and submetered units. The median diurnal temperature fluctuations observed in the bulkmetered apartments were notably less than those observed in the submetered apartments. This can be interpreted as the occupants in the submetered units adjust their temperature settings depending on their personal schedules (e.g., setbacks before leaving for work), whereas occupants in the bulkmetered units adjust their temperature settings less frequently. This contradicts with the fact that there was not a noticeable difference between two groups for the questionnaire item 3 in Table 4 (see Figure 4). In this item, most participants in both groups reported that it was hard to remember to set back their thermostat settings upon departure. This also underlines the risks associated with interpreting self-reported questionnaire data in absence of physical measurements.

Interventions or manual overrides on the thermostat settings are crucial to reveal the activeness of occupants to control indoor temperature. It is important to recall that none of these units were equipped with a functioning programmable thermostat during the data acquisition. Thus, the pronounced diurnal periodicity may be attributed to the conscious thermostat adjustments; e.g. night setbacks. In this study, pronounced diurnal periodicity is defined as local minima and maxima repeated in 24 hours. Autocorrelation functions for stationary records by projecting the time-related properties such as data periodicity can reveal differences between bulkmetered and submetered apartment thermostat use frequencies. The autocorrelation function can be estimated by delaying the data set relative to itself by some fixed time delay, then multiplying the original data set with the delayed data set, and finally averaging the resulting product values over the available record length or over some desired portion of this record length [23]. Figure 11 illustrates a representative autocorrelation curve which exhibits a pronounced periodicity and a representative autocorrelation curve which does not exhibit periodicity. Such periodicity was noted in only two out of the twenty participants living in the bulkmetered apartments, whereas it was captured in seventeen out of the twenty participants living in the submetered apartments. This difference can be interpreted as the occupants living in the submetered units tend to have more systematic and repeatable temperature habits than the occupants living in the bulkmetered units. Karjalainen [24] acknowledged this variation between the occupants who were responsible for their energy bills and who were not. The active use of the thermostats in a periodic manner, in the submetered apartments, was most likely undertaken consciously and responsibly. A similar interpretation was drawn by Gram-Hanssen [25] that three of the five interviewed families living in submetered dwellings had a periodic variation in the indoor temperature. These periodic variations were deemed as systematic. For example, the occupants in the submetered units may set back their heaters before leaving for work; while the occupants in the bulkmetered units may only respond to the thermal discomfort to adjust their thermostats.

3.3. Unresolved issues and future work

The differences in indoor temperature distributions shown in Figure 7 can be explained in two different ways: (1) Occupants living in the submetered units consciously set back their thermostat settings for unoccupied spaces and before leaving their apartments. (2) Occupants living in the submetered units kept their apartments at lower levels of their thermal comfort during the occupied periods. Figures 8 to 11 support the first explanation and the questionnaire responses for the health construct (see Figure 5) support the second explanation. However, current study could not reach a quantitative conclusion about the relative significance of these explanations as the occupancy was not monitored. Future work should include the monitoring of occupancy.

Anecdotal observations during the interviews with participants suggested that occupants in the bulkmetered apartments are more likely to leave their windows open (for airing purposes) than occupants in the submetered apartments, when their heating systems can compensate for the incremental heating load. However, the occupants' window use was not monitored in this study. Future work should therefore contrast the occupant use of operable windows in submetered and bulkmetered apartments. During the interviews, six of the twenty participants living in the bulkmetered apartments acknowledged that they tend to forget switching off their lights and/or computers upon departure. However, the lights and the plug loads were not monitored in this study. Future work should also contrast the lighting energy use and the plug loads between the submetered and the bulkmetered apartments.

Findings of this work are intended to form a basis for more comprehensive future work with a larger sample size. This way, a factor analysis can be carried out to understand the underlying relationship between the constructs proposed in this study and indoor environment. The final outcomes of these studies can provide evidence for policy makers to create initiatives that encourage submetering in the housing sector.

4. Conclusions

Temperature loggers placed in submetered and bulkmetered apartments during two consecutive heating seasons and questionnaires conducted with the participants living in these apartments provided valuable insight into the role of submetering on heating energy use, thermal comfort, and behaviour. Results suggest that, on average, participants living in the bulkmetered apartments keep their units about 2°C warmer than participants living in the submetered apartments.

Participants living in submetered apartments reported being more sensitive to engaging in personal adaptive behaviors (e.g., wearing heavier clothes) and were more sensitive about their thermal comfort (e.g., reducing their thermostat settings). Moreover, participants living in submetered apartments were found to be more influenced by health concerns related to indoor temperature compared to participants living in bulkmetered apartments.

Participants living in submetered apartments frequently adjusted their thermostats in a periodic manner, whereas participants living in bulkmetered apartments appeared to have interacted with their thermostats less frequently and less regularly. In submetered apartments, these frequent and periodic interactions with the thermostat settings were most likely undertaken consciously and responsibly to save energy. For example, participants living in the submetered apartments are more likely to set back their thermostats at night or before leaving for work. Moreover, it was also noted that many of the participants living in the submetered apartments chose to heat only part of their apartments. This suggest that participants who were informed about their energy use and responsible for its financial consequences chose to heat only a portion of their apartments at different personal schedules.

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