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A BUILDING ENERGY AND HEALTH CONDITIONS MONITORING STRATEGY FOR CANADIAN BUILDING SECTOR

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Abstract: Energy-related decision making for a building is a demanding task, due to the challenges associated with energy system performance prediction. Performance prediction can be done either with simulation tools or by referring to the building energy performance databases. However, in Canada, interactive building energy performance databases that allow the evaluation of different energy efficiency improvement options based on actual data are not found. Therefore, most of the Canadian building construction and retrofitting projects adopt the energy simulations. However, simulation results can contain errors due to multiple reasons including data uncertainty and challenges in capturing system deterioration. Therefore, actual energy performance data is needed to support the simulation results and to inform the designers regarding the actual performance of different energy system configurations under varying environmental conditions over the years. Thus, post-occupancy energy monitoring mechanisms and building energy performance databases need to be developed for continuous data acquisition. Building energy performance is known to have a high correlation with the building indoor environmental quality, which creates high health impacts on occupants. Therefore, human health impacts associated with building energy efficiency measures have to be considered at the design stage. However, lack of information about the actual indoor environmental quality impacts associated with different retrofits and operational strategies poses challenges to building designers. Occupant health and energy use monitoring needs to be mandated for new buildings in Canada, in order to overcome these challenges. Moreover, comprehensive databases containing both energy and health performance of buildings need to be developed to inform the building designers and construction industry as a whole. This study discusses the requirements for developing a health-energy monitoring mechanism for Canada. The key parameters need to be monitored and the challenges are identified.

1 INTRODUCTION

In the recent past, energy consumption and associated environmental impacts caused by the built environment, particularly the building sector, has faced much scrutiny. Energy use in buildings is a result of meeting occupant needs, i.e. via heating, lighting, and operating other appliances. Globally, the building sector accounts for 40% of the energy consumption, which results in significant GHG emissions and other negative environmental impacts (Environment and Climate Change Canada 2016). In Canada, respectively the residential and commercial building sector is responsible for 17% and 14% of the secondary energy use and 12% of the GHG emissions (Natural Resources Canada 2019). Moreover, energy use results in economic burdens for the building owners and occupants in the form of energy bills. With the increasing concerns about the environmental and economic impacts of energy use, energy efficiency and passive building techniques have gained global attention. An energy efficient building provides the same level of service to occupants while consuming a lower amount of energy compared to an average building operating under the same conditions. Net-zero buildings take this concept a STEP further, where building energy demand is reduced by ultra-efficient measures, and the remaining demand is met through locally available renewable energy sources (Torcellini et al. 2006). Along with the reduced climate and environmental impacts energy efficient, passive, and net-zero buildings provide economic benefits to building owners through reduced energy costs, leading to reduced energy poverty socio-economic development, and value creation in a region (Natural Resources Canada 2017). The province of British Columbia has committed an incremental approach in increasing energy efficiency requirements for its buildings, ultimately aiming to make all the new buildings net-zero ready by the year 2032 (Natural Resources Canada 2018). Therefore, ensuring code-compliance of buildings is a critical necessity, especially in light of the province's ambitious emissions reduction targets (Province of British Columbia 2016).

Building energy consumption in the operational phase can be reduced by the use of efficient appliances, energy saving technologies, energy conservation practices, and implementing energy efficiency improvements (retrofits) (C.A.Roulet 2006)(Meier and Lamberts 2002). Currently, most of the Canadian new constructions rely on the simulation software such as EnerGuide and eQuest to evaluate the effectiveness of different energy system configurations. However, simulation results can vary from actual performance due to multiple reasons including occupancy patterns, system deterioration, and environmental conditions (N. Wang et al. 2018). Therefore, central interactive databases that collect post occupancy energy performance data is needed to identify the best energy system configurations and to validate the results produced by the simulations. United States Building Performance Database is a database that contains building energy performance data over 1million actual buildings. This database allows the building designers and policy makers to identify the performance of different energy retrofits under varied conditions leading to informed investment decisions on the building energy system (US Department of Energy 2018). However, the building data sources found in Canada are not interactive and do not contain any information regarding the interactions between different retrofits, climate conditions, and building types. Due to this reason, support for taking evidence-based building energy investment decisions is limited in Canada. Therefore, the investor confidence on energy performance interventions is low according to the Canada Green Building Council (CaGBC). This is a detrimental factor that hinders the financial support for energy interventions in Canada (Canada Green Building Council 2019). Therefore, post occupancy energy performance monitoring needs to be mandated through policy frameworks to confirm the true benefits of energy interventions. Moreover, the monitored data should be stored in a central database with access to building designers, policy makers, municipalities, and all other stakeholders to improve awareness among the community to ensure wide penetration of energy efficiency measures.

Buildings are inherently associated with the health and well-being of their occupants. Building parameters such as ventilation levels, indoor temperature, indoor air quality (IAQ), and lighting levels play a major role in determining the health, comfort, and wellness levels of the occupants. A healthy building is defined as *a* building that provides comfort to the occupants without adverse health impacts (Roulet 2013). In addition to physical health impacts, unhealthy and uncomfortable conditions within a building also degrade the mental wellbeing and increase the stress levels of occupants. It has also been identified that IAQ has a high correlation with the cognitive function of workers in a working environment, which deteriorates with unsatisfactory IAQ (MacNaughton et al. 2017). North Americans, including Canadians, spend around 90% of their time in indoors (Epid et al. 2008). Therefore, Canadians are at a high risk of being negatively affected by "unhealthy" building conditions.

Energy efficiency upgrades can cause poor ventilation, mould growth, excessive temperature, and emissions from building materials affecting the occupant health, comfort, and wellbeing (Harvard T. H. Chan. School of Public Health 2011). Not only indoor pollutants, but also outdoor pollutants created by energy use can contaminate indoor environments by infiltration (Epid et al. 2008). Therefore, the pollutants released by fossil fuel based energy sources, such as particulate matter, SO_x, and NO_x, indirectly impact building occupants in the long run, thus creating a cyclic effect. The operational strategy changes, occupancy pattern changes, and changing number of occupants can also create additional burdens on IAQ. On the other hand, when attempting to improve the IAQ and lighting conditions, building energy consumption can increase significantly. Therefore, identifying strategies to reduce building energy consumption and associated emissions while also maintaining occupant health and wellbeing at the desired levels is a challenge. Complicated interdependencies between governing parameters of the health-energy nexus of buildings are shown in Figure 1.

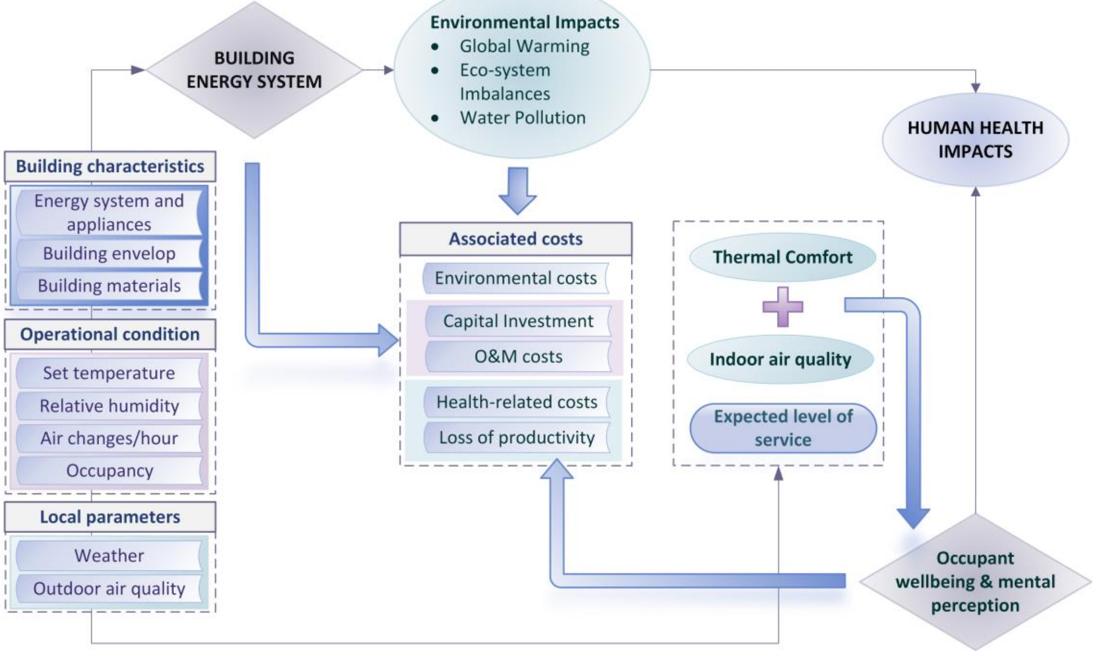

Figure 1: Health-energy nexus in buildings

There is a noticeable gap in the current body of knowledge in combining the energy efficiency and occupant wellbeing aspects in the study of buildings. Databases containing indoor environmental quality (IEQ) data associated to different energy system configurations are not found in the literature referred by the authors. Lack of available data is a main challenge in identifying the interactions between IEQ and energy retrofit options. Condition monitoring will be the initial step towards identifying the balance of health-energy nexus in buildings. Therefore, post occupancy health monitoring requirements has to be promoted alongside with the energy monitoring practices.

The goal of this research is to identify requirements to promote minimum energy and IEQ monitoring standards for Canada. Moreover, a strategy to establish building health-energy monitoring infrastructure will be proposed. Canada can take the community-oriented sustainable built environment to a new level by linking energy efficiency and human health conditions by establishing the discussed monitoring mechanisms and data collection platforms. Moreover, it will also bring Canada to the forefront of sustainable and efficient building technologies and low-impact urban development.

2 PERFORMANCE MONITORING

Identifying the parameters that need to be monitored is critical in developing a monitoring strategy. This section discusses the parameters that need to be captured in energy, IAQ, and occupancy monitoring.

2.1 Indoor Environmental Quality Monitoring

According to the reviewed literature, occupant health and building energy forms a complicated nexus. However, a lack of studies covering the holistic picture of health-energy nexus in buildings poses challenges in addressing contradictive objectives in building energy decision making. Moreover, research shows that the indoor environments are significantly polluted compared to outdoors and create significant health impacts (Huynh 2010). The operational phase is responsible for 70-90% health impacts created by buildings in its life cycle (Buyle, Braet, and Audenaert 2012). Indoor climatic condition assessments can help reduce aforementioned human health and environmental impacts while improving workplace productivity and energy performance of buildings (Ansaldi et al. 2011). However, indoor environmental quality monitoring is not a common practice in Canada.

2.1.1 Indoor Air Quality

IAQ is a key parameter affecting indoor climatic condition, which is heavily dependent on VOCs, air velocity, air changes (ventilation), set temperature, RH inside the building, and environmental tobacco smoke (ETS)

(Berlin 2015). Literature highlights the detrimental effects of ETS on human health in indoor environments and the importance of considering ETS level in HVAC design. CO, CO_2, respirable particles, condensate, nicotine, polycyclic aromatic hydrocarbons (PAHs), and nitrosamines can be used to measure the ETS level (Huynh 2010). Human health impacts and IAQ issues created by mould growth are also highlighted in previous research (Yu et al. 2015). However, automated mould growth monitoring procedures are not defined in literature. Therefore, studies suggest to mould growth prevention strategies (Yu et al. 2015).

Following the building codes and standards such as ASHRAE standards, National Energy Code of Canada for Buildings (NECB), and BC Energy Step Code is the general practice in Canada for maintaining a healthy environment inside buildings while maintaining the energy efficiency. However, IAQ can deviate from design conditions due to multiple factors including occupancy level changes, behavioral aspects, VOCs introduced by the building materials and furniture over time. In literature, temperature, humidity, air velocity, fine dust, CO_2, and VOC are identified as key parameters determining the IAQ (Berlin 2015)(J. Ahn et al. 2017).

2.1.2 Lux Level

As the time spent in indoors is increasing, the interior lighting level can affect the dim light Melatonin onset of occupants, leading to circadian system malfunctions (Roenneberg et al. 2012). Moreover, poor lighting conditions can affect non-visual health potential, perceptual visual interest, and gaze behavior (Amundadottir et al. 2017). Increased exposure of building occupants to day light has been identified as an essential factor for maintaining the circadian rhythm of the human body (Kellert, Heerwagen, and Mador 2008). Daylight exposure is identified as a beneficial factor in healing patients in health care facilities, and known to boost student performance in study environments (Boyce 2004a). Furthermore, studies show a positive correlation between daylight exposure and the productivity (Boyce 2004b). On the other hand, natural light can be used to reduce lighting and heating demand. Therefore, increasing the exposure of working spaces to daylight can be identified as a desirable factor from both human health standpoint and energy efficiency perspective. According to LEED standards, illuminance levels between 300 and 3000 should be achieved by frequently occupied indoor spaces (U.S. Green Building Council 2016). Under the ASHRAE standard 90.1-2004, the maximum lighting power density (LPD) allowed is 1W per sq.ft (Liebel, Brodrick, and Potential 2005). However, these ranges and values are simply boundaries of operation, and buildings have to be smart to vary its lighting levels depending on the occupancy patterns and purpose, to improve energy efficiency while maintaining the required lighting levels for healthy living. Lighting simulation software can model the building interior lighting conditions closely approximating the actual performance. Therefore, interior lighting condition monitoring is not a compulsory action item.

2.1.3 Noise

Similar to lighting, noise level can also affect the sleep quality (Acoustics 2012a). Chronic noise can create long term impacts on the growth of children (Shield and Dockrell 2003). The threshold sound level that is perceived as noise differs from person to person (Acoustics 2012b). Noise inside a building can be sourced from many origins such as appliances, airborne sounds such as music, human discussion, ventilation system, and outer surrounding (Ryu and Jeon 2011a). Some of these sources generate short term noises while some of them create steady noises for longer periods (Ryu and Jeon 2011b). These noises can simultaneously cause auditory impacts such as hearing disorders and non-auditory impacts such as alterations in behavioral patterns or psychological health issues (Damian and Fosalau 2011). Literature suggests the usage of noise absorbing materials in building components like ceilings and walls to control the noise levels inside the buildings (Buratti 2006). However, it is important to know the effect of different envelop materials and HVAC system configurations on building noise levels. In literature there are many noise evaluation standards including Noise Criteria (NC), Balanced Noise Criteria (NCB), Room Criteria (RC), and RC Mark II. However, NC is the most commonly used criteria due to the ease of use (L. M. Wang and Bowden 2003). Authors recommend monitoring internal noise levels in buildings to identify the effect of different energy system components and other external factor on the noise level.

2.2 Occupancy Monitoring

Occupancy level and behavioral patterns can introduce significant burden on both IAQ and energy consumption of buildings (Kim et al. 2015)(Ortega et al. 2015). Occupancy patterns can be studied employing active or passive monitoring mechanisms. For active monitoring, the internet of things (IoT) based less costly wireless sensors can be employed (Google and Dublon 2017). However, the battery life is a limiting factor for these wireless sensors, if not wired to a power supply. On the other hand, depending on the building plan and the wiring layout, drawing power lines to energize occupancy sensors might not be economical. If IoT approaches are not feasible, then passive techniques based on temperature, humidity level, motion, sound, and CO_2 level changes can be employed to identify the occupancy of a given space. Occupancy monitoring can be used for presence detection and/or identify the type of activity taking place inside the building (Ortega et al. 2015). If the monitoring strategy is proposed for a known building type (i.e. MURB), then the type of activity is already known. Therefore, in such situations, detecting the occupancy level is sufficient. Depending on the type of study, zone-wise occupancy levels or total building occupancy level can be studied. Therefore, when selecting an occupancy monitoring mechanism, it is always important to understand the expected outcomes and the available budget. Zonal occupancy level information is not required for the proposed approach as the goal is to compare buildings. Therefore, it is recommended to record total occupancy level of buildings.

2.3 Energy Monitoring

This section will focus on identifying main energy consuming systems and different energy monitoring techniques.

2.3.1 Energy System Components

There are four main categories in energy assets including mechanical system (HVAC, hot water), appliances (electrical, non-electrical), lighting, and building envelop (insulation, infiltration). Out of these components, three main energy system components including HVAC system, appliances, and lighting system actively consume energy during the operation of a building while the effect of building envelop is passively influencing the HVAC load.

HVAC System

HVAC system can be identified as the highest energy consuming component in buildings approximately accounting for 50% of building energy use (Weng and Agarwal 2012)(Pérez-Lombard, Ortiz, and Pout 2008)(Dababneh, Li, and Sun 2016). Energy consumption of HVAC systems can be altered by improving three key aspects including technological aspects, managerial practices, and behavioral patterns (Ruparathna, Hewage, and Sadiq 2016). Therefore, in addition to energy monitoring, occupancy monitoring plays a key role in determining the HVAC system performance. Indoor temperature setting, air-tightness of the building, number of air changes per hour, internal thermal loads, occupancy, activity level, climatic conditions, fenestration, building envelop and orientation are the key factors driving the HVAC load (Lin and Hong 2013). Therefore, indoor temperature setting, outdoor temperature, number of air changes per hour, internal thermal loads, occupancy level, purpose of use, percentage fenestration, glazing type and R-value, surface area exposed to building atmosphere, wall material and R-value, and building orientation are recommended to be reported to the proposed central energy database.

Plug loads / Appliances

Usually the second largest energy consumer in buildings is plug loads. IT equipment, dish washers, cloth-washers and driers, and refrigerators are some of the key energy intensive appliances in buildings (Weng and Agarwal 2012)(Cetin 2016). These appliances create a greater impact on peak load of a building while contributing to the total energy consumption. Strategies such as operation scheduling to overcome the peak times, avoid unnecessarily low temperature set points in refrigerators, shortening washing drying cycles, and reduce heated drying and washing can be adopted to overcome high peak demands and energy consumption associated with plug loads (Cetin 2016). Selection of energy efficient appliances with high energy ratings is one of the popular strategies at present for receiving energy savings. However, it is important to understand that the operational energy consumption of the discussed appliances depends not only on the energy efficiency, but also on the frequency of use. Introducing separate plug load monitoring devices to the existing buildings far from economic feasibility. The most economical method it to identify plug loads through load profile analysis techniques. This will be further disused under Energy Monitoring section.

Lighting system

Energy consumption of the building lighting system is relatively smaller compared to HVAC system and appliances (Weng and Agarwal 2012). However, with its waste heat, the lighting system introduces an additional thermal load (in cooling mode) or reduces the thermal load (in heating mode) on HVAC system, making an indirect impact on HVAC energy consumption. Even in most reputed lighting types for energy efficiency such as high power LEDs and Fluorescent lamps, more than 75% of supplied energy is wasted as heat (Ramos-Alvarado, Feng, and Peterson 2013a). Compared to Fluorescent lamps LEDs enable effective handling of waste heat emission as total waste heat from LEDs is in the form of convective heat while 37% of total energy consumed by fluorescent lamps are transformed in the form of radiant heat (Ramos-Alvarado, Feng, and Peterson 2013b). There are multiple solutions proposed in literature to reduce the impact of waste heat from LEDs on cooling load during summer and to harvest the waste heat from LEDs in the winter. Moving the LED heat sinks in and out of the building depending on the mode of operation of HVAC system (cooling/heating)(Azemati and Hosseini 2014) and integration of the LED heat sinks in the ventilation system are some innovative strategies proposed. In addition to heat recovery techniques, dimming mechanisms and day-light utilization techniques such as sky lights and auto adjusting blinds are commonly employed in lighting energy efficiency improvement strategies (B. L. Ahn et al. 2015). Hybrid systems combining solar PV and LEDs is another trending technology employed in energy efficient lighting systems. A study by Tsuei, et al. shows the possibility of using visible and non-visible wave ranges of solar rays for lighting spaces and energy generation through solar PV simultaneously (Tsuei, Sun, and Kuo 2010).

Some of the aforementioned lighting energy efficiency improvement strategies have reported over 5% energy savings while prolonging the lifetime of lights (B. L. Ahn et al. 2015). However, it is important to understand the economic feasibility of different technologies in order to identify the best energy performance improvement plan for a given situation. Similar to plug loads, the most economical method is to identify the plug loads based on load profile analysis results.

3 HEALTH ENERGY MONITORING STRATEGY FOR CANADA

In the previous sections, the critical parameters for health-energy performance assessment was identified. This section will focus on discussing the implementation aspect of the strategy.

3.1 Energy Monitoring Strategy

When selecting an energy monitoring technique, it is important to study the energy performance evaluation process first. Attention should be given to three main factors including the goal of evaluation, life cycle phase of the building being evaluated, and budgetary constraints.

The goal of this study is to identify the requirements to promote energy monitoring and to develop centralized energy use databases to assist building energy planners in energy performance evaluation and interventions planning tasks. Therefore, the selected energy monitoring and performance evaluation technique should have the capacity to identify the system level energy consumption. Part of the goal is to promote building energy monitoring in Canada. Therefore, the implementation cost has to be maintained at a minimum level. According to literature, the price point of these advanced monitoring techniques has to be maintained below USD500, in order to ensure social acceptability and market feasibility (Baechler and Hao 2016). Depending on the level of data granularity needed, different energy monitoring techniques including utility meters, non-intrusive load monitoring (NILM), semi-intrusive load monitoring (SILM), or comprehensive sub-metering systems can be employed for building energy monitoring (Martín-Garín et al. 2018)(Rahman et al. 2017)(Medina and Manera 2017). However, comprehensive sub-metering systems fail to meet the price cap discussed above. Therefore, the monitoring technology should be either utility meters, NILM, or SILM.

When proposing an energy monitoring technique, it is important to have an idea about the post data processing techniques that can be used with the selected strategy. Conventional utility meters can be coupled with baseline method or the monthly energy use data can be used in energy intensity-based energy performance evaluation procedures (N. Wang et al. 2018)(RDHBuilding Engineering Ltd 2012). The information provided by energy intensity-based techniques is mostly suitable for comparing two similar buildings. However, a basic understanding about the energy split between the HVAC load, water heating load, and appliance and lighting load of a building can be obtained by analyzing the monthly utility bills with baseline method. This is a potential initial step for developing building energy end use databases.

NILM just places a smart meter in the place of the conventional utility meter. This meter will collect high resolution energy data with time stamps, enabling the generation of electrical load profile over the time. If a robust post processing algorithm can be developed, this is one of the best energy monitoring techniques in the sense of ease of implementation, data collection, and financials as only one meter is required (Baechler and Hao 2016). SILM uses NILM technique at zonal level to reduce the complexities in post-processing. SILM can work better at situations such as MURBs where individual meters are placed at each unit or at buildings where, lighting, appliances, and HVAC loads are separately monitored.

Considering the availability of infrastructure, cost of implementation, and level of accuracy needed, authors proposes the conventional utility meter as the best initial point for collecting energy information to develop an interactive national building energy use database. When the conventional utility meters reach their end-of-life replacement with time, those meters can be replaced with high resolution smart energy meters to make the data useful for NILM algorithms with enhanced resolution. Authors believe that this transition period will also benefit the NILM technology to mature further to produce more accurate results.

3.2 Central Database Development

Energy and occupant data collection procedures need to be started in parallel to the monitoring procedures discussed above. The data collection process must be systematically designed to ensure the usefulness of the databases.

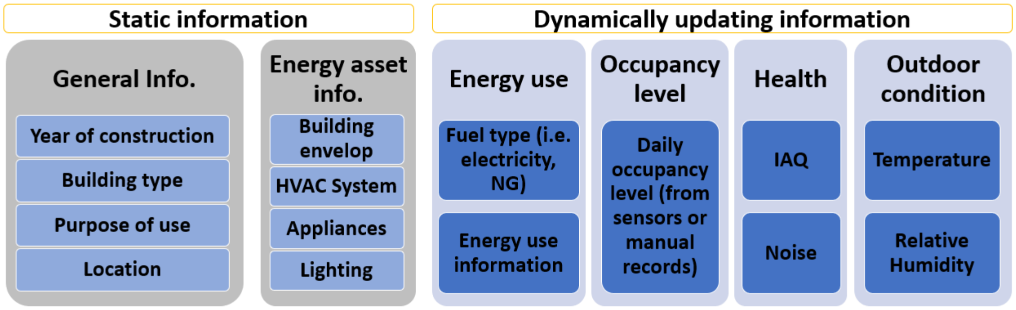

Figure 2: Building health-energy performance data types

As indicated in Figure 1Figure 2, there are two types of data that need to be incorporated into the proposed health-energy database. General information and information regarding the energy asset components are static information. Static information of a building doesn't need to be updated if no major maintenance or retrofitting activities take place. Under general information section, the year of construction, building type (i.e. Residential: MURB, Industrial: warehouse), purpose of use (i.e. residential, goods storage), and location information has to be included. Under the energy asset information section, information regarding the capacities and types of the energy system components need to be compiled.

Energy use, occupancy, health, and outdoor condition are dynamic data that changes over time. Therefore, mechanisms need to be developed to collect the discussed information dynamically. As the authors have proposed to initiate the database development process with the existing utility meters daily, weekly, or monthly time intervals can be employed. The granularity of the data collection process has to be defined based on the post processing technique. Using unnecessarily high data capturing frequencies can insert an unnecessary burden on data storages and post processing.

Authors conducted a preliminary walk through audit and interviews with building owners and occupants to identify the current state of the energy monitoring and data collection procedures. To further investigate the energy monitoring practices discussed in this paper, authors are planning to experimentally assess the effect of different data collection frequencies in identifying critical areas in buildings needing attention, by applying the discussed monitoring practices in student residences of University of British Columbia's Okanagan (UBCO) campus. Moreover, the authors are planning to investigate the feasibility of employing NILM and SILM techniques for system level energy use identification. In order to implement NILM or SILM, a database with appliance signature load profiles of all the major appliances need to be developed and energy monitoring devices that can collect energy data at a high granularity is needed. These aspects will be further investigated as a continuation of this research.

5 SURVEY RESULTS AND DISCUSSION

GHG emission mitigation initiatives, new energy codes, and policy support have escalated the penetration of energy efficiency improvement efforts throughout the Canadian building sector. However, these initiatives overlook health monitoring. At the same time the building infrastructure is not prepared for upcoming technology trend changes such as centralized energy databases, smart cities, and smart buildings. To study the actual landscape of the energy and health monitoring further, authors conducted a series of walkthrough investigations and verbal interview sessions in Kelowna.

Expert consultation sessions held by the authors with the Facilities Management Division (FMD) at UBC's Okanagan campus and the walk-through inspections in the university buildings indicated that occupant health parameters are not being monitored in non-of the buildings in the university. However, the sector wise energy consumption of the university buildings is being monitored and reported to a central server. Moreover, the FMD of UBC-O was well aware about the occupant health monitoring and energy efficiency concepts. Authors extended this survey to non-university buildings including four duplex houses, ten single family detached houses, four restaurant buildings, two MURBs. Predictably, the only energy record found in these buildings were the monthly energy bills. None of these buildings were equipped with occupant health monitoring mechanisms. Owners and the occupants of all the investigated buildings were aware about the energy efficiency techniques such as energy star rated equipment and LED lights. However, they didn't have a systematic vision for improving the energy performance in their buildings. Moreover, the occupant health condition evaluations and the possible correlation between energy use and occupant health concerns were new concepts for 80% of the interviewees out of the 30 people being interviewed.

Survey results confirmed the lack of awareness on systematic energy efficiency interventions planning in the community, despite of the emission reduction initiatives, energy step code modifications, and incentive programs for energy efficiency improvements. Moreover, lack of awareness and attention provided to the effect of building indoor conditions towards occupant health was evident. Authors identify this unawareness among the building owners and occupants as a main reason behind the lack of investor confidence for energy efficiency interventions. Developing real-time building energy monitoring strategies, interactive centralized health-energy databases, and retrofit evaluation tools is essential to overcome the identified barriers. Moreover, community awareness initiatives through online resources such as interactive databases, videos, and community engagement workshops are essential.

Dynamic benchmarking and energy end-use analysis can greatly benefit building energy planners in identifying critical areas needing energy interventions. Moreover, mandating the minimum performance monitoring requirements and compiling the monitored performance information in the form of an interactive database will significantly improve the investor confidence on investing in energy efficiency interventions by being able to take evidence-based decisions. Moreover, these databases help improve the public awareness about the occupant health concerns associated with buildings.

Even though energy performance enhancement is widely being discussed, there are no occupant health condition databases for Canadian buildings. Even the existing energy information databases developed by Natural Resources Canada are not interactive enough to inform the community and decision makers about the characteristics of different energy system configurations under varying conditions. Therefore, health-energy performance monitoring and database development need to be promoted in Canadian building sector to enhance occupant health conditions while achieving 2030 emission goals. Overcoming economic and social barriers are main requirements for the successful implementation of energy monitoring and data collection platforms in the Canadian building cluster. In order to overcome these issues, it is essential to develop low cost easy to install energy and occupant health condition monitoring mechanisms to overcome the economic barriers. Findings from this study will be employed in developing a comprehensive health-energy monitoring mechanism for Canadian buildings, in the coming phases of the study.

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5 REFERENCES

Acoustics, Wakefield. 2012a. “City of Vancouver Noise Control Manual.” Vancouver. 2012b. “City of Vancouver Noise Control Manual.” Vancouver.

Ahn, Byung Lip, Ji Woo Park, Seunghwan Yoo, Jonghun Kim, Hakgeun Jeong, Seung Bok Leigh, and Cheol Yong Jang. 2015. “Synergetic Effect between Lighting Efficiency Enhancement and Building Energy Reduction Using Alternative Thermal Operating System of Indoor LED Lighting.” *Energies* 8 (8): 8736–48. doi:10.3390/en8088736.

Ahn, Jaehyun, Dongil Shin, Kyuho Kim, and Jihoon Yang. 2017. “Indoor Air Quality Analysis Using Deep Learning with Sensor Data.” *Sensors (Switzerland)* 17 (11). doi:10.3390/s17112476.

Amundadottir, Maria L., Siobhan Rockcastle, Mandana Sarey Khanie, and Marilyne Andersen. 2017. “A Human-Centric Approach to Assess Daylight in Buildings for Non-Visual Health Potential, Visual Interest and Gaze Behavior.” *Building and Environment* 113. Elsevier Ltd: 5–21. doi:10.1016/j.buildenv.2016.09.033.

Ansaldi, Roberta, Ehsan Asadi, Jose Joaquim Costa, Marco Filippi, Jan Kaczmarczyk, Arsen Krikor Malikov, Bjarne W. Olesen, Zbigniew Popiolek, and Pawel Wargocki. 2011. *INDOOR CLIMATE QUALITY ASSESSMENT*. Edited by Stefano Paolo Corgnati and Manuel Garmeiro da Silva. Washington.

Azemati, Ali –Akbar, and Hossein Hosseini. 2014. “Effect of Educational Building’s Direction on Cooling and Heating Loads in Different Regions.” *Journal of Environmental Science and Technology* 15 (2): 147–57.

Baechler, MC, and H Hao. 2016. “Business Case for Nonintrusive Load Monitoring.” Washington.

Berlin, Wirtschaft. 2015. “Why , When and How Do HVAC-Systems Pollute the Indoor Environment and What to Do about It ? The European AIRLESS Project,” no. April. doi:10.1016/S0360-1323(02)00058-6.

Boyce, Peter. 2004a. “Reviews of Technical Reports on Daylight and Productivity.” *The Daylight Dividends Program*, 14.

Buratti, C. 2006. “Indoor Noise Reduction Index with an Open Window (Part II).” *Applied Acoustics* 67 (5): 383–401. doi:10.1016/j.apacoust.2005.07.006.

Buyle, Matthias, Johan Braet, and Amaryllis Audenaert. 2012. “LCA in the Construction Industry : A Review.” *International Journal of Energy and Environment* 6 (4): 397–405.

C.A.Roulet, ed. 2006. “Indoor Air Quality and Energy Performance of Buildings.” In *Proceedings of Healthy Buildings 2006*, 37–47. Lausanne.

Canada Green Building Council. 2019. “CaGBC Makes Strategic Recommendations to the Government of Canada in Pre-Federal Budget Consultation.” Accessed February 17. https://www.cagbc.org/News/EN/2017/20170907_News_Release.aspx.

Cetin, Kristen S. 2016. “Characterizing Large Residential Appliance Peak Load Reduction Potential Utilizing a Probabilistic Approach.” *Science and Technology for the Built Environment* 22 (6): 720–32. doi:10.1080/23744731.2016.1195660.

Dababneh, Fadwa, Lin Li, and Zeyi Sun. 2016. “Peak Power Demand Reduction for Combined Manufacturing and HVAC System Considering Heat Transfer Characteristics.” *International Journal of Production Economics* 177. Elsevier: 44–52. doi:10.1016/j.ijpe.2016.04.007.

Damian, Catalin, and Cristian Fosalau. 2011. *Sources of Indoor Noise and Options to Minimize Adverse Human Health Effects*. *Environmental Engineering and Management Journal*. Vol. 10.

Environment and Climate Change Canada. 2016. “Overview of 2014 Reported Emissions,” no. April: 14.

Epid, Robert Dales, Ling Liu Mmd, Amanda J Wheeler, and Nicolas L Gilbert. 2008. “Quality of Indoor Residential Air and Health” 179 (2): 147–52.

Google, Inc, and Gershon Dublon. 2017. “A Survey of Human-Sensing: Methods for Detecting Presence, Count, Location, Track, and Identity Distributed Sensing and Control for Cyber-Physical System(CPS) View Project EMI Sensing View Project Thiago Teixeira A Survey of Human-Sensing: Methods for Detecting Presence, Count, Location, Track, and Identity.” https://www.researchgate.net/publication/319791520.

Harvard T. H. Chan. School of Public Health. 2011. “Energy-Efficient Buildings Can Be Hazardous to Health.”

Huynh, C K. 2010. “Building Energy Saving Techniques and Indoor Air Quality - A Dilemma” 9 (1). doi:10.1080/14733315.2010.11683872.

Kellert, Stephen R., Judith Heerwagen, and Martin Mador. 2008. *Biophilic Design : The Theory, Science, and Practice of Bringing Buildings to Life*. Wiley.

Kim, Young-min, Ki-uhn Ahn, Cheol Soo Park, and South Korea. 2015. “Lessons Learned from Machine Learning Models for Existing Buildings.” In *Building Simulation Conference*, 1134–41. Department of Convergence Engineering for Future City , SungKyunKwan University , Suwon , South Korea.

Liebel, By Brian, James Brodrick, and Energy Savings Potential. 2005. “Lighting and Standard 90 . 1.” *ASHRAE Journal* 47 (10): 1–2.

Lin, Hung Wen, and Tianzhen Hong. 2013. “On Variations of Space-Heating Energy Use in Office Buildings.” *Applied Energy* 111. Elsevier Ltd: 515–28. doi:10.1016/j.apenergy.2013.05.040.

MacNaughton, Piers, Usha Satish, Jose Guillermo Cedeno Laurent, Skye Flanigan, Jose Vallarino, Brent Coull, John D.

Spengler, and Joseph G. Allen. 2017. “The Impact of Working in a Green Certified Building on Cognitive Function and Health.” *Building and Environment* 114. Elsevier Ltd: 178–86. doi:10.1016/j.buildenv.2016.11.041.

Martín-Garín, A., J. A. Millán-García, A. Baïri, J. Millán-Medel, and J. M. Sala-Lizarraga. 2018. “Environmental Monitoring System Based on an Open Source Platform and the Internet of Things for a Building Energy Retrofit.” *Automation in Construction* 87 (January). Elsevier: 201–14. doi:10.1016/j.autcon.2017.12.017.

Medina, Bruno Eduardo, and Leandro Tiago Manera. 2017. “Retrofit of Air Conditioning Systems through an Wireless Sensor and Actuator Network: An IoT-Based Application for Smart Buildings.” *2017 IEEE 14th International Conference on Networking, Sensing and Control (ICNSC)*, 49–53. doi:10.1109/ICNSC.2017.8000066.

Meier, Alan, and Roberto Lamberts. 2002. “What Is an Energy-Efficient Building ?,” 3–12.

Natural Resources Canada. 2019. “Evaluation of the Built Environment Portfolio | Natural Resources Canada.” Accessed February 22. https://www.nrcan.gc.ca/evaluation/reports/2014/16317.

———. 2017. “Build Smart Canada’s Buildings Strategy: A Key Driver of the Pan-Canadian Framework on Clean Growth and Climate Change.” New Brunswick.

———. 2018. “Waste Heat Recovery and Upgrading.”

Ortega, J. L.Gomez, L. Han, N. Whittacker, and N. Bowring. 2015. “A Machine-Learning Based Approach to Model User Occupancy and Activity Patterns for Energy Saving in Buildings.” *Proceedings of the 2015 Science and Information Conference, SAI 2015*, 474–82. doi:10.1109/SAI.2015.7237185.

Pérez-Lombard, Luis, José Ortiz, and Christine Pout. 2008. “A Review on Buildings Energy Consumption Information.” *Energy and Buildings* 40 (3): 394–98. doi:10.1016/j.enbuild.2007.03.007.

Province of British Columbia. 2016. “Climate Action Legislation.”

Rahman, Saidur, Saqif Masud, Shahida Sultana, and Mohammad Rezaul. 2017. “Web Based Electric Home Appliance Controller and Monitoring System,” 474–77.

Ramos-Alvarado, Bladimir, Bo Feng, and G. P. Peterson. 2013a. “Comparison and Optimization of Single-Phase Liquid Cooling Devices for the Heat Dissipation of High-Power LED Arrays.” *Applied Thermal Engineering* 59 (1–2). Elsevier Ltd: 648–59. doi:10.1016/j.applthermaleng.2013.06.036.

———. 2013b. “Comparison and Optimization of Single-Phase Liquid Cooling Devices for the Heat Dissipation of High-Power LED Arrays.” *Applied Thermal Engineering* 59 (1–2). Elsevier Ltd: 648–59. doi:10.1016/j.applthermaleng.2013.06.036.

RDHBuilding Engineering Ltd. 2012. “Energy Consumption and Conservation in Mid and High Rise Residential Buildings in British Columbia” 1: 264. doi:10.1017/CBO9781107415324.004.

Roenneberg, Till, Karla V. Allebrandt, Martha Merrow, and Céline Vetter. 2012. “Social Jetlag and Obesity.” *Current Biology* 22 (10): 939–43. doi:10.1016/j.cub.2012.03.038.

Roulet, Claude-alain. 2013. “Indoor Environment Quality and Energy in Buildings. Application to Mediterranean Climate.” In *ENERGY in BUILDINGS 2013*, 1–13.

Ruparathna, Rajeev, Kasun Hewage, and Rehan Sadiq. 2016. “Improving the Energy Efficiency of the Existing Building Stock: A Critical Review of Commercial and Institutional Buildings.” *Renewable and Sustainable Energy Reviews*. doi:10.1016/j.rser.2015.09.084.

Ryu, Jong Kwan, and Jin Yong Jeon. 2011a. “Influence of Noise Sensitivity on Annoyance of Indoor and Outdoor Noises in Residential Buildings.” *Applied Acoustics* 72 (6). Elsevier Ltd: 336–40. doi:10.1016/j.apacoust.2010.12.005.

———. 2011b. “Influence of Noise Sensitivity on Annoyance of Indoor and Outdoor Noises in Residential Buildings.” *Applied Acoustics* 72 (6). Elsevier Ltd: 336–40. doi:10.1016/j.apacoust.2010.12.005.

Shield, Bridget, and Julie E Dockrell. 2003. “The Effects of Noise on Children at School: A Review.” *Building Acoustics* 10 (2): 97–116. doi:10.1260/135101003768965960.

Torcellini, P., S. Pless, M. Deru, and D. Crawley. 2006. “Zero Energy Buildings: A Critical Look at the Definition.” In *2006 ACEEE Summer Study on Energy Efficiency in Buildings*. Pacific Grove, CA.

Tsuei, Chih-Hsuan., Wen-shing. Sun, and Chien-Cheng. Kuo. 2010. “Hybrid Sunlight/LED Illumination and Renewable Solar Energy Saving Concepts for Indoor Lighting.” *Optics Express* 18 Suppl 4 (November): A640–53. doi:10.1364/OE.18.00A640.

U.S. Green Building Council. 2016. “LEED Reference Guide for Building Operations and Maintenance.”

US Department of Energy. 2018. “Building Performance Database.” Accessed July 24. https://bpd.lbl.gov/#compare.

Wang, Lily M, and Erica E Bowden. 2003. “PERFORMANCE REVIEW OF INDOOR NOISE CRITERIA.” In *Architectural Engineering 2003*, 1–4.

Wang, Na, Supriya Goel, Atefe Makhmalbaf, and Nicholas Long. 2018. “Development of Building Energy Asset Rating Using Stock Modelling in the USA” 1493. doi:10.1080/19401493.2015.1134668.

Weng, Thomas, and Yuvraj Agarwal. 2012. “From Buildings to Smart Buildings-Sensing and Actuation to Improve Energy Efficiency.” *IEEE Design & Test of Computers* 29 (4): 36–44. doi:10.1109/MDT.2012.2211855.

Yu, Shui, Shu Zheng, Keran Li, and Guohui Feng. 2015. “Assessment of Human Health in Northeast China Apartments with Mould Growth.” *Procedia Engineering* 121: 122–28. doi:10.1016/j.proeng.2015.08.1033.