P. Rajagopalan and M.M Andamon (eds.), *Engaging Architectural Science: Meeting the Challenges of Higher Density: 52nd International Conference of the Architectural Science Association 2018*, pp.205–212. ©2018, The Architectural Science Association and RMIT University, Australia.

Review of Holistic Research on NetZero Energy Homes: Energy Simulation, Energy Monitoring, and Performance Improvement

Hong Xian Li
Deakin University, Geelong, Australia
hong.li@deakin.edu.au

M. Reza Hosseini
Deakin University, Geelong, Australia
reza.hosseini@deakin.edu.au

Peng Zhang
Western Sydney University, Sydney, Australia
p.zhang@westernsydney.edu.au

Mark Luther
Deakin University, Geelong, Australia
mark.luther@deakin.edu.au

Anthony Mills
Deakin University, Geelong, Australia
anthony.mills@deakin.edu.au

Abstract: A NetZero Energy Home (NZEH) is designed, modelled, and constructed to produce as much energy as it consumes on an annual basis, with the required energy generated from renewable energy resources. This paper reviews holistic research on NZEHs from the perspectives of energy simulation, energy monitoring, actual energy performance, and operation/design improvement. HOT2000, developed by Natural Resources Canada, is utilised as the tool to simulate the energy performance of NZEHs. Using multiple NZEHs as the case projects, sensor-based monitoring systems are developed to evaluate the actual energy performance of NZEHs, and the results are used to analyse the discrepancy among different NZEHs and to compare with the simulated results. Based on comprehensive analysis and comparison, operation and design strategies are proposed to improve the performance of NZEHs.

Keywords: NetZero Energy Home (NZEH); energy simulation; energy monitoring; performance improvement.

1. INTRODUCTION

The building design philosophy necessary to realize net-zero energy or carbon neutral housing has become a driving force toward achieving green building design strategies (Chang et al., 2011). The Canadian Home Builders' Association (CHBA) defined an NZEH as a home "that is designed, modelled and constructed to produce as much energy as it consumes on an annual basis" (CHBA, 2015). Systematic and holistic research has been conducted by Li et al. (2016, 2017, and 2018), utilizing NZEH projects in Calgary and Edmonton, Alberta, Canada, developed by Landmark Group of Companies, as the case examples. In these NZEH projects, grid-connected solar PV systems are used as the only energy generation means to meet the energy requirement of NZEHs. During the design stage of NZEHs, energy simulation is utilized as an approach to quantitatively evaluate the energy performance of design options. Hong et al. (2000) described building simulation as a technique "available to architects, engineers and building managers concerned with energy conservation", and conducted a comprehensive overview of building simulation. There are several energy simulation engines available, including EnergyPlus, ESP-r, TRNSYS, and HOT2000. HOT2000, developed by Natural Resources Canada (2016) and used as an official energy simulation tool in Canada, is utilized to conduct building performance simulation in the present research. Specifically, the Batch Version of HOT2000 is chosen as the simulation engine to achieve energy simulation automation. Additionally, RETScreen, also developed by Natural Resources Canada (2014), is used to simulate the energy performance of solar PV systems.

The examination of actual energy performance is another domain of research on NZEHs, as the actual energy performance of an NZEH may vary from the design objective. Deng et al. (2014) conducted a comprehensive review on evaluating the energy performance of a zero-energy building and summarized the evaluation process as follows: simulate the energy performance during the design stage; after construction, monitor the energy performance using sensor instrumentation;

and validate the simulation results with the monitored data. Deng et al. (2014) also summarized the representative evaluation indicators, including energy consumption, system efficiency, and life cycle assessment, among others. In the present research, in order to assess the actual energy performance, sensor-based monitoring systems are developed and utilised to monitor the detailed energy performance of NZEHs, and the monitored results are used for comprehensive analysis and comparison with simulation. Furthermore, the actual energy performance of a given NZEH may differ from others; therefore, collective perspectives are necessary for NZEH studies. Also, the actual energy performance of multiple NZEHs is monitored and compared, and the energy performance discrepancy is identified among multiple NZEHs. Comprehensive information is extracted through the analysis and comparison of the simulated and monitored results, based on which operation and design suggestions are proposed to improve the performance of NZEHs. This research contributes to the body of knowledge of NZEHs.

2. ENERGY SIMULATION

In the present study, among multiple NZEHs, a single-family house located in Edmonton (latitude 53°34′ N, longitude 113°31′ W), Canada, is first monitored using sensors. The average maximum, mean, and minimum temperatures in Edmonton over a 25-year period (1990–2014) are 34.1°C, 4.3°C, and –32.1°C, respectively, and thus space heating encompasses one of the primary challenges for NZEH design due to the cold weather. The building is east-oriented with a 12.94 kW grid-connected solar PV system installed on a south-facing roof. The summative characteristics of the NZEH design are as follows: (1) high-performance insulation is applied to the building envelope, including main (exterior) wall, roof, exposed floor, basement wall, and basement floor; (2) triple-glazed windows with different R-values are used for different orientations (i.e., lower values for south-facing windows and higher values for other orientations), and sun-stop film is applied on the west-facing windows to mitigate the solar radiation in summer; (3) heat pump technology is utilized for space heating and hot water heating; (4) heat recovery technology is used for ventilation and drain water; and (5) electricity is the only energy source in this NZEH, and the solar PV system is employed as the energy generation means.

In order to examine the energy performance of different design scenarios, energy simulation is conducted for this NZEH following two steps. (1) By incorporating current building codes and industry partner practice, representative design scenarios are considered for main wall, roof, basement wall, exposed floor, basement slab, hot water tank, space heating furnace, and ventilator, resulting in a total combination of 16,200 design scenarios for this NZEH. (2) In order to achieve effective energy simulation, an automated simulation program is developed using the Batch Version of HOT2000, the flowchart of which is demonstrated in Figure 1. The automated simulation program results in 16,200 scenarios with regard to the energy performance of the NZEH design, and a representative result plotted according to the furnace type is illustrated in Figure 2.

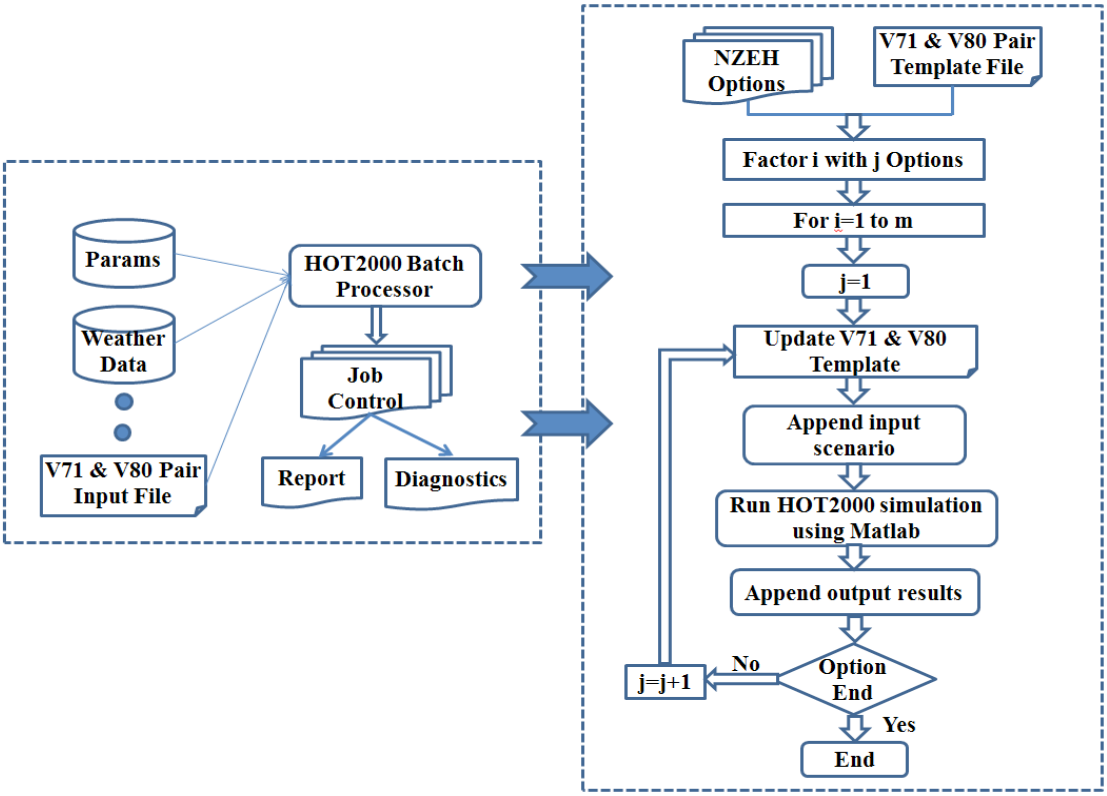

Figure 1: Batch energy simulation using automated program. (source: Li et al., 2017)

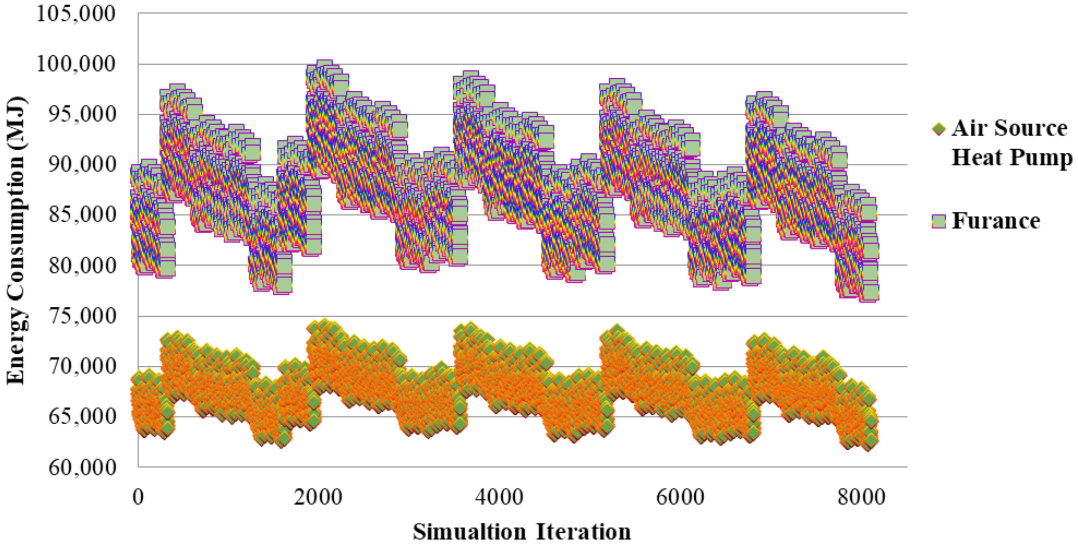

Figure 2: Results of batch energy simulation. (source: Li et al., 2017)

On the other hand, energy generation is simulated using RetScreen for this NZEH. There are 42 units of 308 W monocrystalline silicon (mono-Si) PV panels mounted on the south-facing roof, with a slope of 33° and azimuth of 0°, and connected with the grid. The energy generation system contributes the total power of 12.936 W that is used to offset the energy consumption of the NZEH. The energy generation of the PV system primarily depends on the weather conditions, with solar radiation as the determining factor. RetScreen predicts an annual energy generation of 17.466 kWh for this system, with the monthly distribution displayed in Figure 3, from which seasonal fluctuations can be observed (i.e., more energy generated in summer than winter).

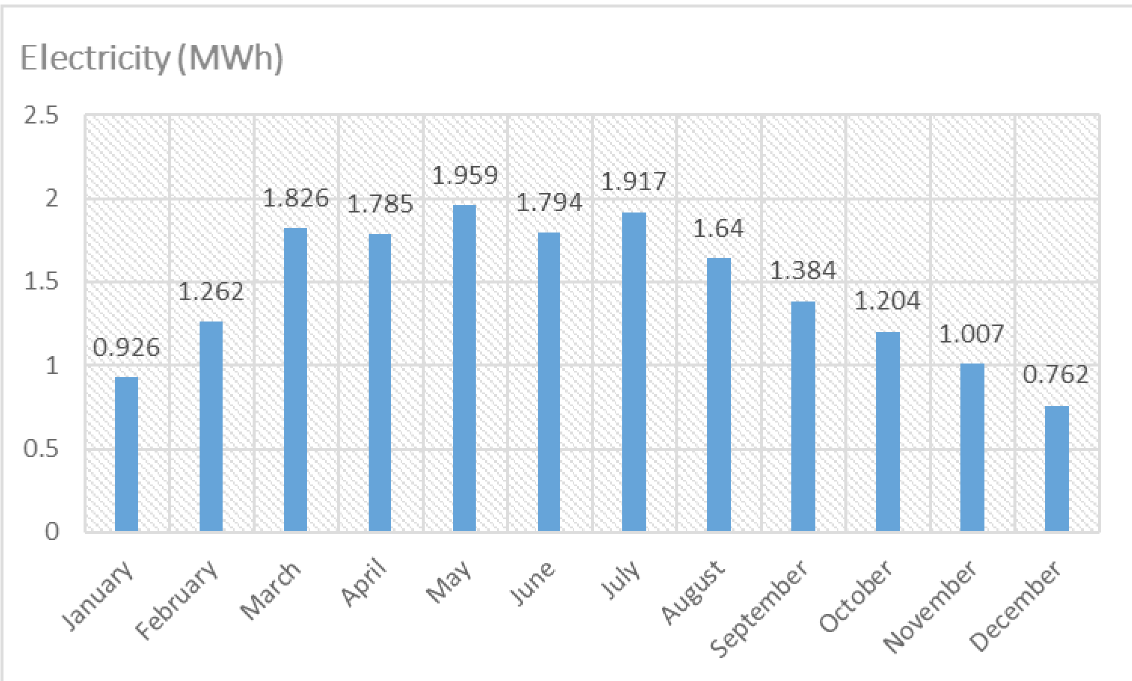

Figure 3: Sensor instrumentation of energy monitoring.

3. ENERGY MONITORING

In order to examine the actual energy performance of the NZEH design, a sensor-based monitoring system is developed and utilised to collect the detailed energy consumption data, while solar PV generation data is obtained from a third-party device, Solar-Log. Electricity is the only energy source deployed in this NZEH, and current transformer (CT) sensors are installed in the electrical panel to measure the electricity consumption of each channel. The collected data is stored locally on a single-board computer, and then transmitted to a database server via a secure Internet connection. The schematic diagrams of sensor instrumentation and data transmission are illustrated in Figure 4. Valid data has been successfully collected from the monitoring system since September, 2014. The annual energy performance and the monthly consumption and generation are displayed in Table 1 for this NZEH.

From Table 1, it can be observed that: (1) during the analysed period, the monitored NZEH consumed 16,381.24 kWh of electricity, while the solar PV system generated 15,711.86 kWh of electricity, which results in an energy deficit of 669.38 kWh (4.1% of the total consumption); and (2) energy deficits in the winter season (Oct., 2014 – Feb., 2015) and energy surplus in the other seasons can be observed from the monthly energy balance presented in Table 3.

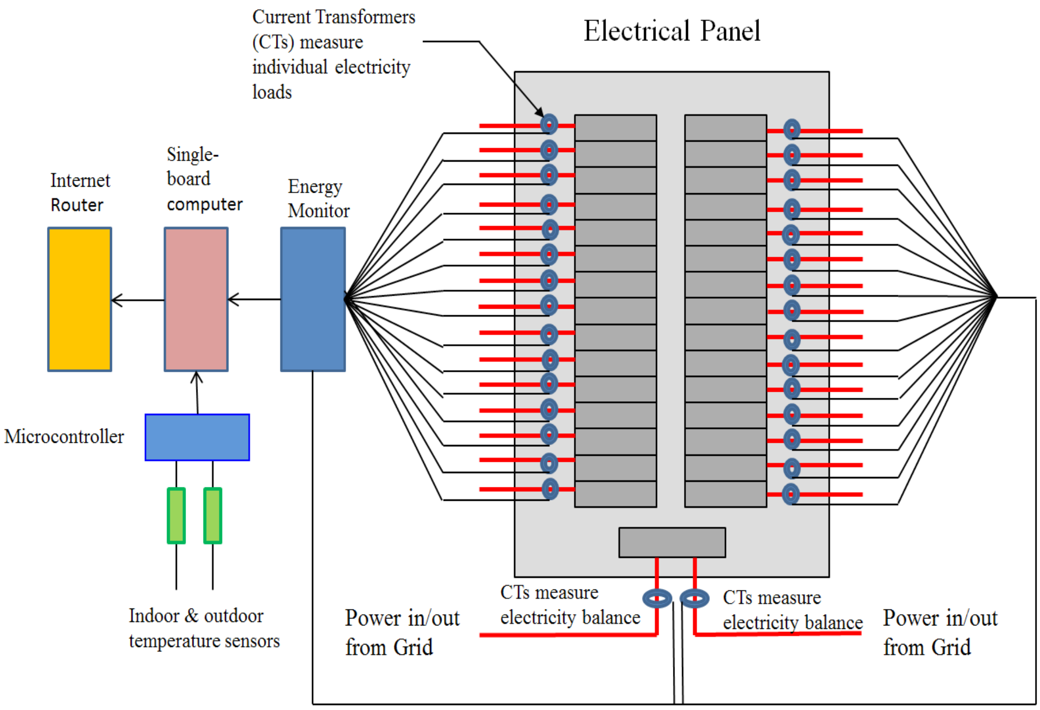

Figure 4: Sensor instrumentation of energy monitoring. (source: Li et al., 2016)

Table 1: Annual monitored energy performance. (source: Li et al., 2016)

Month	Energy Consumption (kWh)	Energy Generation (kWh)	Energy Balance (kWh)
Sep-2014	968.05	1,386.47	418.42
Oct-2014	1,247.05	1,160.41	–86.64
Nov-2014	2,177.68	273.22	–1,904.46
Dec-2014	1,995.74	294.11	–1,701.63
Jan-2015	2,095.12	413.16	–1,681.96
Feb-2015	1,914.73	520.33	–1,394.40
Mar-2015	1,421.37	1,649.37	228.00
Apr-2015	1,128.65	1,795.31	666.66
May-2015	926.22	2,291.94	1,365.72
Jun-2015	747.93	1,981.05	1,233.12
Jul-2015	964.88	2,150.60	1,185.72
Aug-2015	793.84	1,795.90	1,002.06
Total	16,381.24	15,711.86	–669.38

4. COMPARISON BETWEEN ENERGY SIMULATION AND MONITORING

The actual energy performance of an NZEH may vary from the design objective, and thus it is necessary to verify the simulation results using the monitored data. In this research, the monitored annual energy performance is compared with that of simulated by category of space heating/cooling, domestic hot water heating (DHW), heat recovery ventilator (HRV), base load, and energy generation. The comparison is demonstrated in Table 2, from which it can be observed that: (1)

this NZEH consumes 14.4% less than estimated; (2) the solar PV system generates 10.0% less than estimated; (3) space heating/cooling and HRV use more energy than estimated (27%); and (4) base loads and DHW consume less energy than predicted (–50.7% and –14.0% respectively).

Table 2: Annual monitored energy performance.

Comparison		Energy Consumption				Energy Generation
		HRV	DHW	Space Heating/ Cooling	Base Loads	
Individual	Measured (kWh)	644	2,120	9,300	4,317	15,712
	Estimated (kWh)	599	2,465	7,322	8,760	17,466
	(Measured-Estimated)/Estimated	7.5%	–14.0%	27.0%	–50.7%	–10.0%
Overall	(Measured-Estimated) (kWh)			–2765.0		–6,314.9
	(Measured-Estimated)/Estimated			–14.4%		–10.0%

5. ENERGY PERFORMANCE DISCREPANCY OF MULTIPLE NZEHS

5.1 Overall energy performance discrepancy

The actual energy performance of a given NZEH may differ from others, and thus it is essential to study the discrepancy among multiple NZEHs. A total of six NZEHs in Edmonton and Calgary, Alberta, Canada, are monitored using sensors, including three single-family homes as well as one middle unit and two end units of a town-home. Only four of the six monitored NZEHs yield complete annual data; two result in incomplete data due to issues with third-party generation monitoring systems. Distinctive designs are applied to these single-family homes and town-homes, primarily for space heating: (1) electrical baseboard heaters are used for space heating in the town-homes; (2) air source heat pump furnaces are selected as the main equipment for space heating and cooling in the single-family homes; (3) air source heat pump hot water tanks are installed in both single-family homes and town-homes; (4) two different types (brands) of HRVs are used in these NZEHs in Edmonton and Calgary respectively; (5) roof-top solar PV systems with different energy generation capacity are installed in the monitored NZEHs; (6) high-performance insulation with different R-values is applied to the building envelope, including main (exterior) wall, roof, exposed floor, basement wall, and basement floor; and (7) triple-glazed windows with different R-values are used for all the monitored NZEHs.

The actual energy performance of the four NZEHs is listed in Table 3, from which it can be observed that: (1) two of the four NZEHs confront energy deficit, and the others have energy surplus; (2) the middle unit (Edmonton 3) of the town-homes generates slightly less electricity than each of the two end units; (3) the average energy balance, excluding the middle unit (which underwent a period of non-occupancy while listed for sale) reaches –1.4%, which is near the net-zero target; and (4) a single-family house (Edmonton 4, which is analysed in Section 3 above) consumes the most energy of all the town-home units, the cause of which may include the difference in house type, floor area, and occupant behaviour.

Table 3: Annual monitored energy performance. (source: Li et al, 2018)

NZEH Case	Energy Consumption`(kWh)	Energy Generation (kWh)	Energy Balance (Generation – Consumption) (kWh)	Energy Balance/ Consumption (%)
Edmonton 1	12,017	12,653	636	5.3%
Edmonton 2	13,288	12,564	–724	–5.4%
Edmonton 3*	8,325	11,388	3,063	36.8%
Edmonton 4	16,381	15,712	–669	–4.1%
Average	12,498	13,044	547	7.8%

*Including a period of non-occupancy (listed for sale)

The overall energy consumption is also broken down into space heating/cooling, ventilation, DHW heating, base loads, and others for the four monitored NZEHs, as displayed in Figure 5a to Figure 5d, from which it can be observed that: (1) space heating/cooling consumes approximately 50% of the total energy usage of the NZEHs; (2) DHW uses approximately 10% of the total energy consumption, near to that of major appliances, including dryer, washer, range, dishwasher, and fridge; and (3) HRV consumes a small portion (4% to 5%) of the total consumption in the monitored NZEHs.

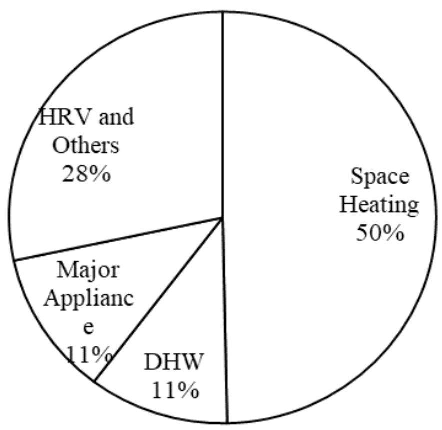

Figure 5a: Edmonton 1_Town-home (HRV not monitored separately). (source: Li et al., 2018)

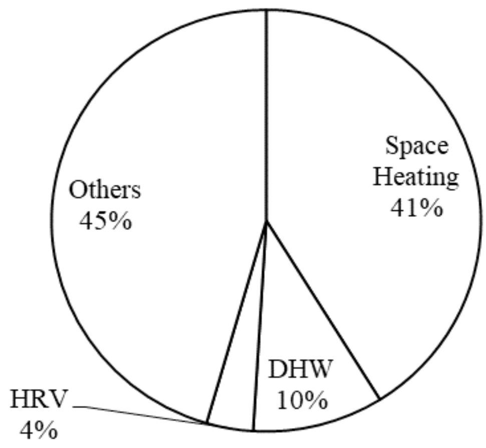

Figure 5b: Edmonton 2_Town-home. (source: Li et al., 2018)

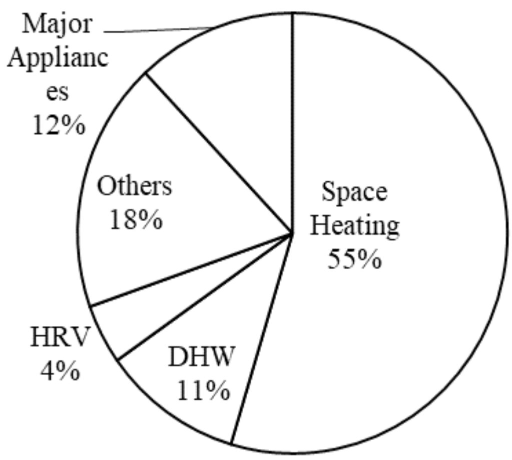

Figure 5c: Edmonton 3_Town-home. (source: Li et al., 2018)

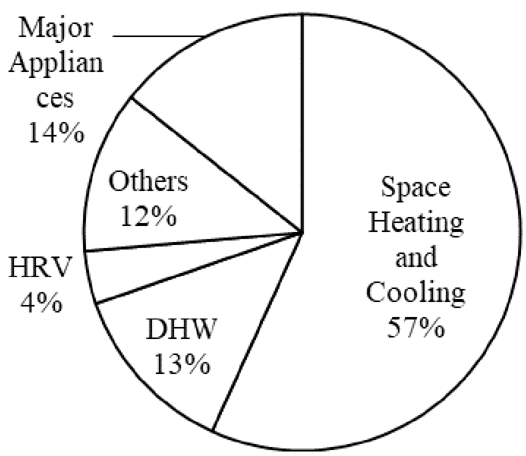

Figure 5d: Edmonton 4_Single-family House. (source: Li et al., 2018)

5.2 Base load discrepancy

Base load, including the electricity usage for major appliances, lighting, electrical outlets, exterior usage, and garage, is an essential portion of the energy consumption for NZEHs. Among the six monitored NZEHs, three provide valid categorical data of base loads, and the other three cannot provide categorical information for base loads due to issues with the third-party generation systems or with the sensor instrument design. The average and monthly base loads of the three NZEHs are displayed in Figure 6, from which it can be observed that: (1) the base load discrepancy can be observed for three NZEHs; (2) no seasonal fluctuation is observed for the base load; (3) the average base load of each house is less than 19.5 kWh, which is predicted in the new version of HOT2000 (Natural Resources Canada, 2016); and (4) the overall average base load of the three monitored NZEHs is 12.33 kWh/day, accounting for approximately 63% of the 19.5 kWh predicted in HOT2000.

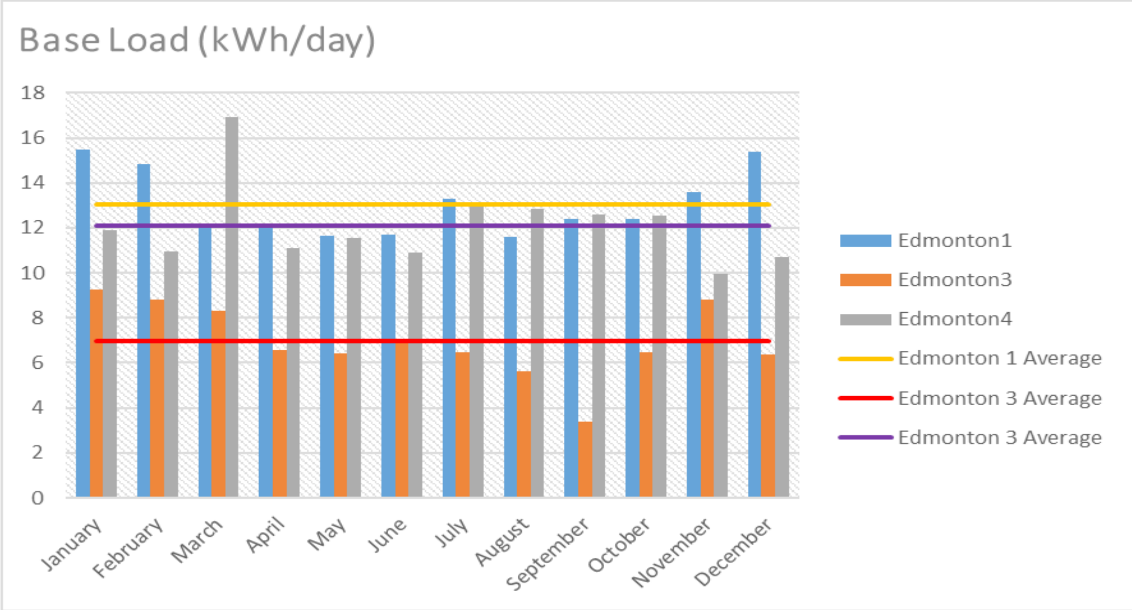

Figure 6: Average base loads.

5.3 Major appliance discrepancy

As part of the energy usage of base loads, major appliances consume a considerable amount of electricity. In this research, all five major appliances, including fridge, range, dishwasher, washer, and dryer, are instrumented with sensors in the following NZEHs: Edmonton 1, Edmonton 3, Edmonton 4, and Calgary 1. The average daily energy consumption of each appliance is displayed for the four NZEHs in Figure 7, from which it can be observed that: (1) as a continuous operating appliance, fridge uses the most electricity among the major appliances; (2) among the non-continuously operating appliances, dryer uses the greatest amount of electricity, equivalent to range; (3) washer consumes the least electricity; and (4) the energy consumption variation of each appliance can be observed for the analysed NZEHs.

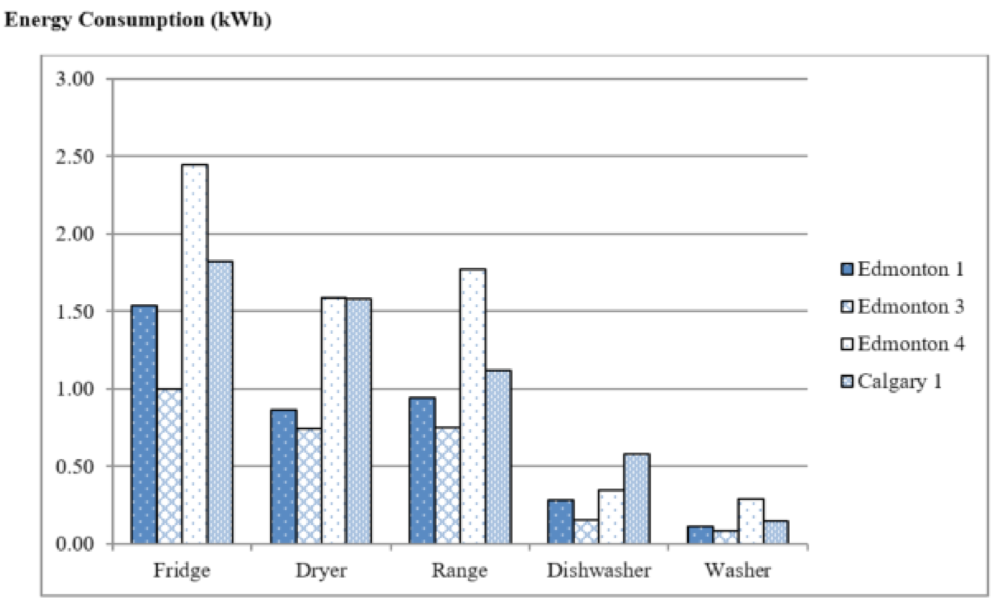

Figure 7: Major appliances. (source: Li et al., 2018)

6. DISCUSSION AND CONCLUSION

This paper reviews holistic research on NZEHs, from the perspectives of energy simulation, energy monitoring, performance discrepancy among multiple NZEHs, and the difference between the simulated and monitored results. The monitored results reveal that space heating is a dominant energy consumer in cold regions such as Edmonton, accounting for approximately 50% of the total energy usage, although advanced heat pump technology is used for most of the NZEHs. In order to further reduce the energy consumption of space heating, this research suggests: (1) scheduling the thermostat based on the occupant routine (e.g., set a lower indoor temperature in winter during non-occupancy periods), by which to reduce the indoor and outdoor temperature difference and the energy usage for space heating; and (2) adjusting the HRV operating mode according to the occupant routine and the number of occupants, by which to reduce the heat loss due to ventilation. For common HRVs, there are usually three operating modes, including 20 minutes of operation per hour, 40 minutes of operation per hour, and continuous operation, and a lower operating mode is recommended to be set for the daily non-occupancy periods.

Base loads are monitored and compared with that of simulated in HOT2000, and it is found that all the measured base loads are less than the energy sizing conducted in HOT2000, which has been changed from 24 kWh/day to 19.5 kWh/day in the new version (version 11) (Natural Resources Canada, 2016). The overall average base load of the three monitored NZEHs is 12.33 kWh/day, and this research suggests that further studies are required to minimise the difference between the monitored and predicted base loads in HOT2000. As one of the major appliances, dryer is found to consume the most electricity among the non-continuously operating appliances; the occupants may be advised to consider drying clothes naturally on a drying rack in such dry regions as Edmonton. Considering that the solar PV systems generate electricity during daytime, pre-scheduling such appliances as washer, dryer, and range to operate during this time is recommended to avoid the electricity transmission loss and the price difference between using electricity from the grid and supplying extra electricity to the grid. Based on the comparison among the monitored NZEHs, energy performance discrepancy is identified for base loads and major appliances, which is related to occupants' behaviour. Further studies are recommended to identify the relationship between the energy performance discrepancy and occupants' behaviour in future research.

Passive design is also found to be insufficient for the studied NZEHs. For example, the first monitored NZEH has a 12 m-long south-facing wall; however, only a 1.2 m × 1.0 m window is installed on this wall. On the other hand, there are four large west-facing windows installed on a small wall of the same NZEH, which increases the cooling load in summer. In order to improve passive solar gain and passive lighting, more and larger south-facing windows are recommended, and fewer and smaller west-facing windows are recommended for this house model. This research also found that although triple-glazed windows are used for NZEHs, the R-value of windows is still low, between R4 and R5. On the other hand, high R-value (approximately R40) walls are usually used for NZEHs. To reduce the R-value difference between windows and walls, two-layer triple/double glazed window systems are recommended for NZEHs, and more technical issues in this regard will be addressed in future research.

References

Canadian Home Builders' Association (2015) Introduction to the CHBA Net Zero Energy (NZE) Labelling Program PILOT.

Chang, N.B., Rivera, B.J., Wanielista, M.P. (2011) Optimal design for water conservation and energy savings using green roofs in a green building under mixed uncertainties. Journal of Cleaner Production, 19(11), 1180-1188.

Deng, S., Wang, RZ., and Dai, YJ. (2014) How to evaluate performance of net zero energy building-A literature research, Energy, 71, 1-16.

Hong T., Chou S.K., Bong T.Y. (2000) Building simulation: An overview of developments and information sources. Building and Environment, 35: 347-361.

Li, H. X., Gül, M., Yu, H., Awad, H., and Al-Hussein, M. (2016) An energy performance monitoring, analysis and modelling framework for NetZero Energy Homes (NZEHs). Energy and Buildings, 126, 353-364.

Li, H. X., Chen, Y., Gül, M., Yu, H., and Al-Hussein, M. (2018) Energy performance and the discrepancy of multiple NetZero Energy Homes (NZEHs) in cold regions. Journal of Cleaner Production, 172, 106-118.

Li, H. X., Gül, M., Yu, H., and Al-Hussein, M. (2017) Automated energy simulation and analysis for NetZero Energy Home (NZEH) design. Building Simulation, 10 (3), 285–296.

Natural Resources Canada, 2016. HOT2000. http://www.nrcan.gc.ca/energy/efficiency/housing/home-improvements/17725. (Accessed 6 December 2016).

Natural Resources Canada (2014) RETScreen International: Empowering cleaner energy decisions. Available from: Open Source Repository < http://www.retscreen.net/ang/home.php > (accessed 23 April 2016).