Influence of Early Stage Design Variables and Thermal Mass on Energy Flexibility in Net-Zero Energy Buildings

Samson Yip[1], Andreas Athienitis[1], Bruno Lee[1]
[1]Concordia University, Montreal, Canada

Abstract

Demand side energy flexibility measures based on demand response can assist in grid stability by minimizing energy demand and generation mismatches in net zero energy buildings (NZEBs) due to onsite renewables' generation. Thermal mass has been found to be beneficial in such energy flexibility measures, but its relationship to architectural design variables typically considered at the early design stage has not been examined. Therefore in this paper, an NZEB with a building-integrated photovoltaic/thermal (BIPV/T) roof system was considered. Different plan shapes and orientations were analysed with variable building thermal mass and a heat pump through an automated simulation workflow for their impact on flexibility over the critical Canadian winter period. A flexibility strategy of temperature setpoint ramps was used for peak load and energy consumption reduction targeting the morning and afternoon peak periods. The generated designs were compared by their flexibility potential.

When using the flexibility scenario, results show that thermal mass on the floor is the most influential variable for peak load among the ones examined, with the thermal mass on the wall second. The different plan shape and orientation configurations using the flexibility strategy and thermal mass were able to reduce morning and evening peak power by up to 16.98% and 21.67%, respectively, and reduce total electricity imported during the same peak periods by up to 3.10% and 20.68%, respectively.

The results demonstrate that through a design approach integrating passive and active components, thermal mass and energy flexibility measures, there are different building form pathways to net-zero energy while providing energy flexibility potential.

Introduction

As more solar net-zero energy buildings (NZEBs) are realized, their relationship to the electrical grid demands closer research attention. These buildings are not simply consumers of electricity; they also produce their own (prosumers) (Jensen et al., 2017). But, on-site electricity generation from photovoltaic (PV) systems may not match building load profiles causing load matching issues. This creates a knock-on effect for electricity import and export (grid interaction) (Salom et al., 2014), which needs to be managed to ensure grid stability (Jensen et al., 2017; Salpakari and Lund, 2016).

One way to address such mismatches is through energy flexibility strategies. Energy flexibility is generally described as the "ability to adapt the energy profile without jeopardizing technical and comfort constraints," (Reynders et al., 2018). These can be implemented on the supply (or grid) side or the demand (or building) side (Aduda et al., 2016; Lund et al., 2015). On the building side, the demand side management strategy of demand response is the typical mechanism used to deliver this flexibility. It can be used to reduce energy cost, shift peak power, reduce the amount of electricity fed into the grid, or increase grid stability through control strategies (Masy et al., 2015; Salpakari and Lund, 2016).

Among the principal building components, thermal mass has potential to assist in energy flexibility scenarios. Previous research has shown that thermal mass coupled with set point controls can assist in reducing and shifting peak loads (Braun, 2003). Other building components and characteristics have also been studied in conjunction with thermal mass in various combinations for energy flexibility potential: other thermal storage (PCM, electrical, furniture), thermal insulation, envelope airtightness, type of heating system, control systems, demand response strategies, and shiftable appliances (Johra et al., 2019; Le Dréau and Heiselberg, 2016; Reynders et al., 2013; Salpakari and Lund, 2016). However, the previous studies focused on single family dwellings and did not always include renewables. There is less information specifically for larger buildings and the application to different building forms in NZEBs.

A common renewable energy technology used in solar NZEBs is PV. Building-integrated photovoltaic (BIPV) systems integrate the PV modules as a component in the building envelope to help reduce materials and permit greater architectural and systems integration. Heat generated by the PV modules during electricity generation is exhausted to the outside to cool the modules and increase PV efficiency and to prevent damage to adjacent building components. In a building-integrated PV and thermal (BIPV/T) system, this exhaust heat is captured for low-grade thermal uses within the building, thus increasing the combined PV and thermal efficiency of the system (Athienitis et al., 2015).

In terms of whole building design of NZEBs, there have been studies of form factors for BIPV-clad buildings (Hachem et al., 2011; Youssef et al., 2016). For BIPV/T-clad buildings, small-scale non-residential and high rise

(Athienitis et al., 2018; Buonomano et al., 2016) have been studied, as well as different building forms involving single-family homes (Delisle and Kummert, 2016). As NZEBs involve a complex integration of many different systems, researchers have observed the need to study both the passive and active systems together (Athienitis et al., 2018). However, in this context, building form – especially for BIPV/T roof-clad NZEBs – is an important component typically addressed at the early design phase that is missing from the literature.

In this paper, a BIPV/T roof-clad medium-sized institutional building is used to analyse the relationship between building form, renewable energy generation, thermal mass, and the potential to assist in demand side energy flexibility measures. Different plan shapes, building orientations, thicknesses of concrete floor slabs, and two different kinds of wall finishes are tested with temperature set point ramping controls. The objective is to determine how design combinations of these variables may reduce a building's peak load during the critical winter hours in a Montreal climate to help maintain grid stability.

Methods

Building archetypes

A series of archetype plan shapes derived from the work of Martin and March (1972) was used to represent general plan morphologies for building energy performance applicable at early stage design. Similar shapes have been used by other researchers (Hachem et al., 2011; Tuhus-Dubrow and Krarti, 2010).

The building type is medium-sized (930 to 4 645 m^2) institutional. This corresponds to the category with the largest percentage of floor space (33%) based on a national survey of commercial and institutional buildings in Canada (Natural Resources Canada, 2012).

For this building size, of two to three storeys in general, the largest surface area for PV deployment is the roof. The plans are limited to 15 m in depth to enhance solar utilization for BIPV/T energy generation through increased exterior surface areas while limiting overall building height, and for daylighting with open planning. Previous research has shown that there is a maximum building depth for daylighting for an entire floor plate (Guglielmetti et al., 2010; Yip et al., 2015).

The plan shape families representing the courtyard, rectangle, L-shape, and U-shape are shown in Figure 1. The wings in the L- and U-shapes are rotated in 15° increments. All shapes are oriented within 45° of either side of due south to enhance solar radiation capture.

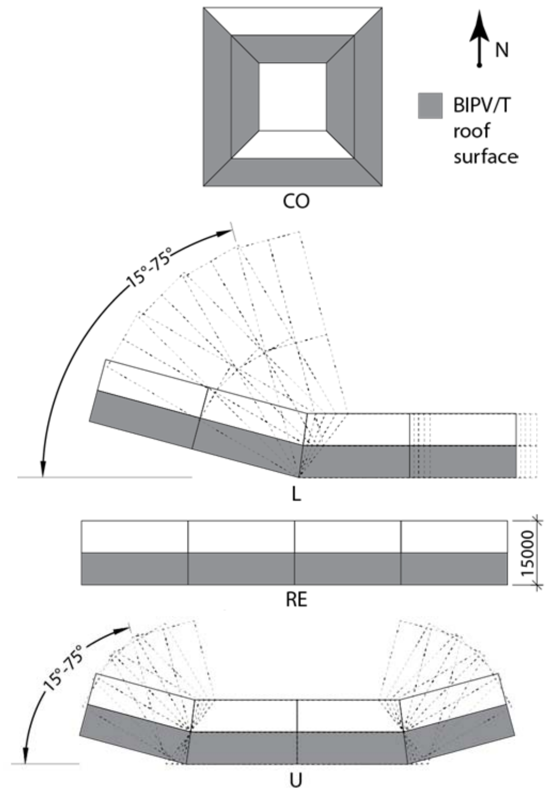

Figure 1: Archetype plan shapes.

The building depth limitation also constrains the maximum BIPV/T roof tilt angle. Figure 2 shows how a roof tilt angle increase from 35° to 45° increases the overall building height by over 2 m. This extra 2 m of height and the increased building volume will increase material quantities and require additional space planning to make use of the interior volume. The roof surfaces on which the BIPV/T systems are placed are illustrated in Figure 1 and Figure 2. A detail is shown in Figure 3.

Simple electric lighting controls were used to turn on electric lighting when daylight illuminance is below 300 lx and turn off when over 500 lx. Each window was fitted with an internal shading device programmed to open when total impinging exterior solar radiation is below 120 W/m^2 and close when over 140 W/m^2.

A summary of the input variables, non-varying parameters, and window properties are shown in Table 1, Table 2, and Table 3, respectively. All building enclosure thermal design values used exceed those required by the National Energy Code of Canada for Buildings (NECB) (Canadian Commission on Building and Fire Codes and Construction, 2015). The window to wall ratios, insulation levels, and window properties are similar to those from an existing NZEB in the Montreal area (Dermardiros et al., 2019). The climate used is for Montreal, Quebec (45.500°N, −73.580°W).

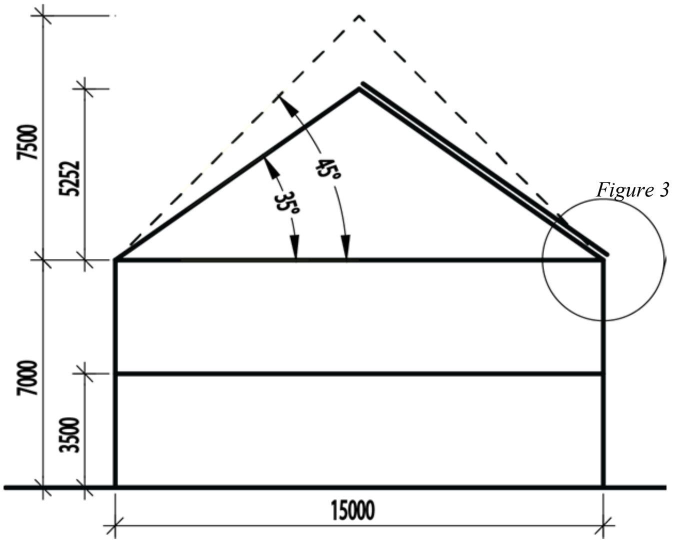

Figure 2: General building section; measurements in mm.

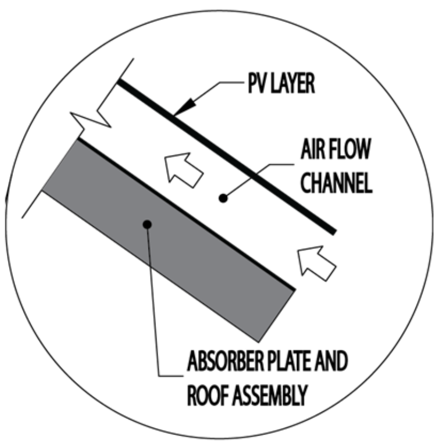

Figure 3: Detail of BIPV/T assembly.

Table 1: Input variables and domain

Input Variable	Values
Plan shape	RE, CO, L15, L30, L45, L60, L75, U15, U30, U45, U60, U75
Azimuth	−45° to 45°; 7 levels
Floor slab thickness	0.060, 0.120, 0.180 m
Wall thermal mass	0.032 m gypsum board, 0.045 m thin brick

Thermal mass

There were three options for thermal mass on the floors and two for the walls of the archetype buildings. The floor consists of a concrete slab of 0.060 m, 0.120 m, or 0.180 m on metal decking typical of steel frame construction with slab on grade. For the walls, the options were 0.032 m of gypsum board or 0.045 m of thin brick veneer, both backed by steel stud framing. The floor slab is a passive system. An ideal air system assuming a heat pump was used for heating and cooling for early stage design analysis.

Table 2: Non-varying parameters

Parameter	Value (s)
Floor plate/storeys	1 500 m^2 / 2
Total floor area	3 000 m^2
Window/Wall Ratio (N,E,S,W)	0.1/0.2/0.3/0.3
Wall insulation	6.79 R_{si}
Roof insulation	7.92 R_{si}
BIPV/T channel height	0.025 m^2
BIPV/T roof tilt angle	35°
PV nominal elect. efficiency	0.17
Heating COP	2.5
Cooling COP	3.5
Heating set point/ set back	21 / 18°C
Cooling set point	24°C
Building open hours	07:00 – 20:00
Occupant density	10 m^2/person
Occupant gains	7.5 W/m^2
Plug loads	9 W/m^2
Electric lighting	7 W/m^2
Infiltration	1 ACH @ 50 Pa
Ventilation	5.6 L/(s·person)

Table 3: Window properties

Parameter	Value
Description	Double-glazed, kryption, low-e
ID from Window Database	3210
U-value	0.97 W/m^2K
SHGC	0.53
Tsol	0.445
Tvis-daylight	0.70

Simulation model and automated workflow

TRNSYS 18 (Klein et al., 2017) was the energy simulation software used. The main building models are contained in the TYPE 56 module and the air-based BIPV/T component is modelled in the TYPE 568 module. The BIPV/T outlet air was used to preheat the supply air in winter conditions to reduce the energy needed to raise its temperature to required room conditions. In warm weather, the BIPV/T outlet air was exhausted to the outdoors.

Using the previously described domain of input values in Table 1, a full factorial design was performed using an automated workflow managed within the modeFRONTIER (ESTECO SpA, 2017) software environment. Python (Python Software Foundation, 2019) scripting was used to generate the input files for each design configuration that were subsequently run in TRNSYS. The results were collected in the modeFRONTIER database where data post-processing such as a global ANOVA sensitivity analysis (Rigoni and Ricco, 2011) was performed.

For this early design stage analysis, an ideal air system assuming a heat pump using the energy rate balance method was employed. Load spikes at temperature set point changes occur using this method (Klein et al., 2017). To minimize their effects, one-minute time steps were used and the load values were averaged over 15-minute periods.

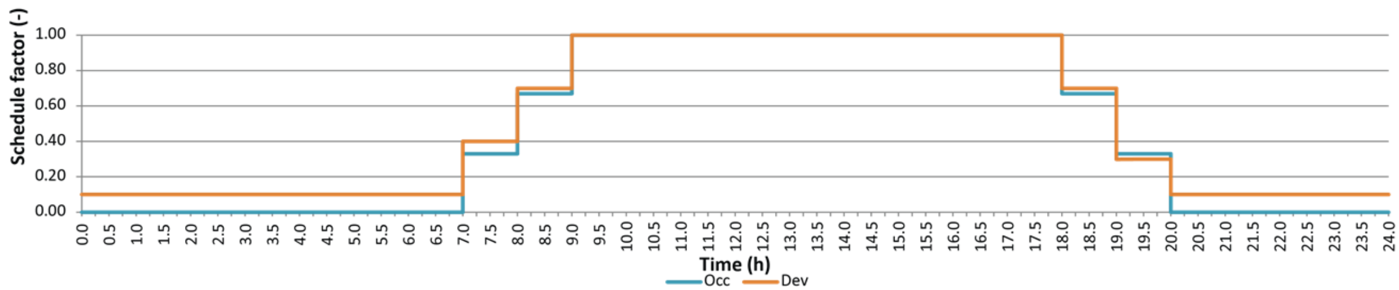

Figure 4: Occupancy (Occ) and plug load (Dev) schedule.

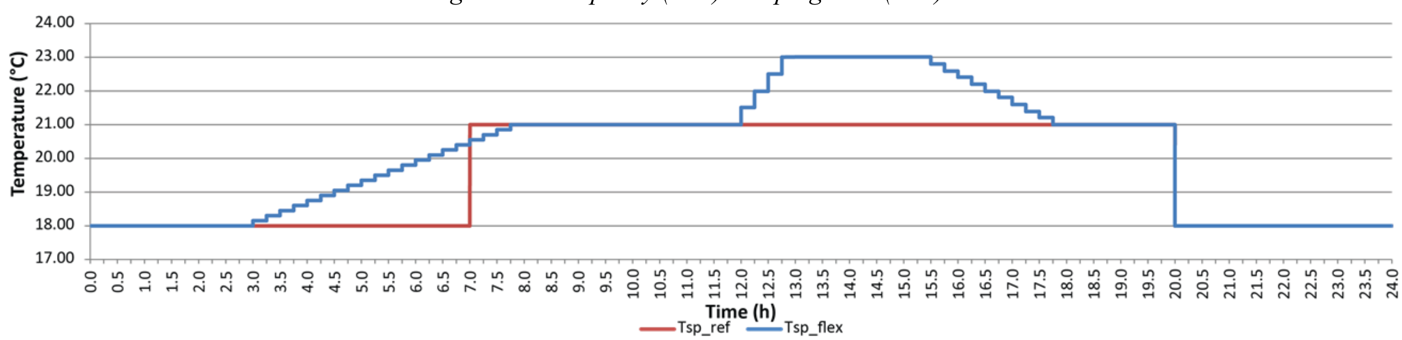

Figure 5: Temperature set point schedules for reference (Tsp_ref) and flexibility (Tsp_flex) scenarios.

Energy flexibility scenario

The building is open for business between 07:00 and 20:00 everyday. For simplicity, Saturday and Sunday hours follow the same schedule. The occupancy and plug load schedules are shown in Figure 4.

Set point schedules, shown in Figure 5, were used to modify the electrical demand in consideration of grid peak demand times. The set point temperatures were ramped up and down to increase self-consumption of on-site generated electricity and charge the building thermal mass and shift demand away from the utility's peak demand hours while respecting thermal comfort requirements. For the case of Quebec, the utility peak power periods are in the winter months (December to March) on weekdays from 06:00 to 09:00 and from 16:00 to 20:00 (Hydro-Québec, 2019).

Performance indicators

Net-zero site energy – which accounts for all energy import and export at the level of the building site – is the net-zero energy definition used to calculate all energy balances. This is the strictest definition for an NZEB (Torcellini et al., 2006).

In this paper, energy flexibility is the amount by which a building may reduce its peak demand (kW) and energy consumption (kWh) over a given period of time relative to a reference case.

Two demand response indicators that can assist in energy flexibility are used. The peak power reduction, Equation (1),

$$Peak\ power\ reduction = \frac{(P_{ref} - P_{flex})}{P_{ref}} \cdot 100\%, \qquad (1)$$

is the amount the electricity load under an energy flexibility scenario, P_{flex}, is reduced as compared to a reference scenario, P_{ref}, for the same period. The energy reduction, Equation (2),

$$Energy\ reduction = \frac{(E_{ref} - E_{flex})}{E_{ref}} \cdot 100\%, \qquad (2)$$

is the difference between the amount of imported electricity under an energy flexibility scenario, E_{flex}, as compared to a reference scenario, E_{ref}, for the same period.

For this analysis, the hourly periods evaluated correspond to the Quebec utility peak power periods described in the previous sub-section.

Results

Results are shown for the month of January. A first order global sensitivity analysis was carried out with the targets of peak load during morning peak hours (6:00 – 09:00) and evening peak hours (16:00 – 20:00) for the reference and flexibility scenarios and with input variables thermal mass on floor and wall, plan shape, and nominal building orientation.

The results in Figure 6 to Figure 9 show that the thermal mass on the floor is the most influential variable for both flexibility cases – by a significant margin over the thermal mass on the walls. For the reference cases, the thermal mass on the floor was also most influential for the evening peak hours but the building orientation (azimuth) was the most influential for the morning peak hours.

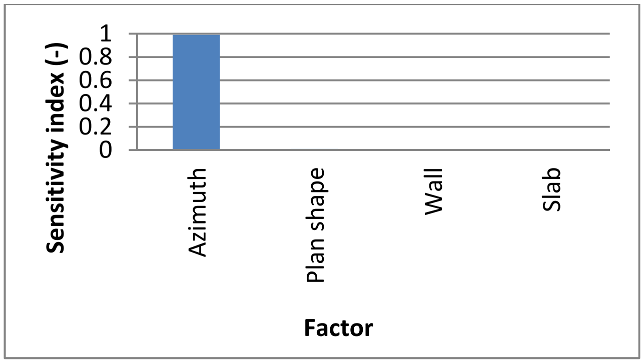

Figure 6: Sensitivity analysis: target of peak load during morning peak load hours; reference scenario

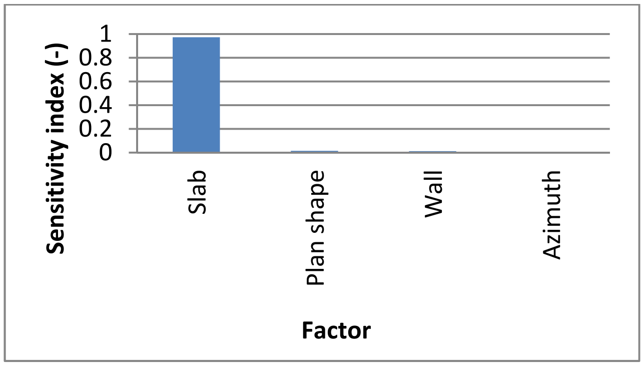

Figure 7: Sensitivity analysis: target of peak load during morning peak load hours; flexibility scenario

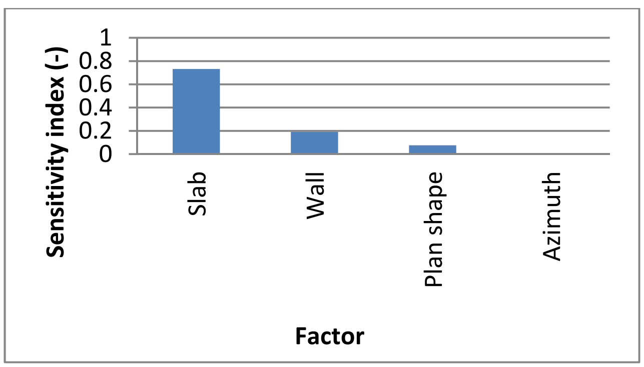

Figure 8: Sensitivity analysis: target of peak load during evening peak load hours; reference scenario

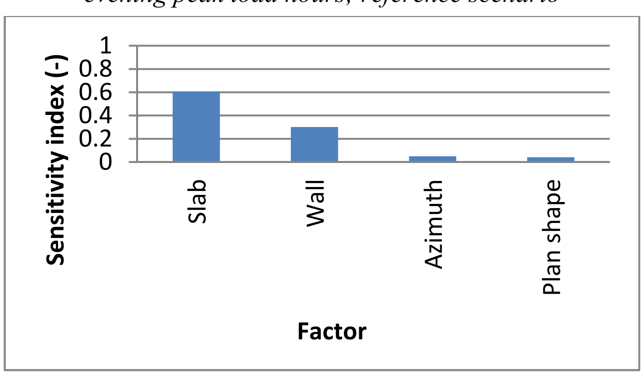

Figure 9: Sensitivity analysis: target of peak load during evening peak load hours; flexibility scenario

Table 4 shows the best results by plan shape based on lowest peak power demand during the utility's peak power periods – which occurs during the morning peak hours. The concrete slab thickness was 0.180 m and the wall composition was thin brick veneer. Note that these results occur at different orientations for the different plan shapes. The results were filtered this way to see the greatest flexibility potential offered by the plan shapes. Under the flexibility scenario, peak power reduction was between 14.58 – 16.98% and 19.67 – 21.67% for the morning and evening peak hours, respectively. The total energy imported during the morning peak hours was reduced by between 2.11 – 3.10%, and between 20.22 – 20.68% for the evening peak hours.

A cold sunny day in January in Montreal, Figure 10, was used to highlight some representative results. Figure 11 shows the power demand for the courtyard, CO, shape at an orientation of 15° east of south showing the differences between the reference and energy flexibility setpoint scenarios for a combination of floor and wall thermal masses. For the case with 0.180 m floor slab and thin brick veneer walls, the peak demand occurs in the morning and the flexibility scenario is able to reduce the peak load from 92.91 kW to 77.56 kW for a peak power reduction of 16.52%. For the evening peak demand period, the peak load decreased from 82.95 kW to 65.54 kW for a reduction of 20.99%.

During the morning peak demand period, the peak load from the different flexibility scenarios varies in a narrow band from 77.56 kW to 79.11 kW, while during the evening peak period it varies from 63.54 kW to 65.54 kW. Of note, for the reference case with 0.120 m floor slab and gypsum board walls the morning peak load was 92.91 kW and 82.37 kW for the evening peak load. Results for the other plan shapes with their respective optimal orientations are similar.

Discussion

Thermal mass

The SA showed that the thermal mass on the floor was the most influential variable for the flexibility scenario. The largest thermal mass on the floor slabs (0.180 m), and the walls (0.045 m thin brick veneer), offered the best performance for energy flexibility. Typically, the slab thickness for structural loading of this building type is in the range of 0.120 m – 0.125 m. As well, interior brick finishes – whether thin brick or whole brick – are not common in an institutional setting. Building services, structural design, construction sequencing, and future space planning flexibility would have to account for this design feature. An overall design analysis considering cost factors would need to be made to evaluate the pros and cons of increasing the thermal mass.

In the reference setpoint scenario, increasing the quantity of thermal mass from 0.120 m slab and gypsum board

Table 4: Power peak and total imported electricity; reference and flexibility scenarios; slab thickness 0.180 m, wall of thin brick veneer; ψ is the orientation/azimuth in degrees

Plan Shape	06:00 – 09:00 Power Peak			16:00 – 20:00 Power Peak			06:00 – 09:00 Total Imported Electricity			16:00 – 20:00 Total Imported Electricity		
	Ref.	Flex	Reduction	Ref.	Flex	Reduction	Ref.	Flex	Reduction	Ref.	Flex	Reduction
	kW	kW	%	kW	kW	%	kWh	kWh	%	kWh	kWh	%
RE ψ=15	93.10	78.13	16.08	83.04	65.05	21.67	166.78	161.91	2.92	281.73	223.46	20.68
CO ψ=-15	92.91	77.56	16.52	82.95	65.54	21.00	162.68	159.18	2.15	280.43	222.85	20.53
L15 ψ=0	92.40	78.22	15.35	83.12	65.20	21.56	164.30	159.21	3.10	282.01	223.75	20.66
L30 ψ=0	93.18	78.36	15.90	83.35	65.37	21.58	167.56	163.09	2.67	282.85	224.51	20.63
L45 ψ=0	93.94	78.54	16.39	83.63	65.62	21.54	170.91	167.14	2.21	283.88	225.48	20.57
L60 ψ=-15	93.37	78.74	15.67	83.87	65.97	21.35	169.22	165.44	2.23	284.76	226.35	20.51
L75 ψ=-30	92.97	79.03	15.00	84.27	66.50	21.09	168.41	164.85	2.11	286.19	227.78	20.41
U15 ψ=15	93.14	78.31	15.92	83.26	65.26	21.62	167.26	162.71	2.73	282.52	224.20	20.64
U30 ψ=30	94.30	78.29	16.98	83.41	65.39	21.62	172.85	168.85	2.31	283.01	224.70	20.60
U45 ψ=15	93.04	78.49	15.64	83.56	65.72	21.35	168.46	164.16	2.55	283.56	225.32	20.54
U60 ψ=0	92.24	78.69	14.69	83.85	66.25	21.00	166.15	161.93	2.54	284.60	226.61	20.38
U75 ψ=0	92.35	78.89	14.58	83.99	67.48	19.67	166.78	162.96	2.29	285.15	227.49	20.22

walls to 0.180 m slab and thin brick veneer walls did not influence the peak load in the morning or evening for all practical purposes. This reinforces previous research that connects thermal mass with appropriate setpoint controls.

Energy flexibility

From the perspective of the building, the most important utility peak demand period is the morning since it was within this period that the building configurations had their peak load. However, from the utility and grid stability perspective, the evening peak demand period is as important if not greater since the building configurations with flexibility controls were able to achieve a more significant peak power reduction.

Plan shapes

The configurations based on the courtyard shape showed the lowest peak demand loads during the determinant morning peak power period. The courtyard shape has the most compact shape of the options in this paper. But, it also had the least efficient deployment of BIPV/T due to many residual triangular roof intersections where standard rectangular-shaped PV modules were not fitted. Typical rectangular-shaped PV modules can be deployed on practically 100% of the equatorial-facing roof surfaces of the RE shape whereas for the courtyard shape with 35° roof tilt angle, only 85%. It was also the only plan shape configuration that had self-shading of the PV.

However, looking at the environmental conditions of Montreal in winter, the critical winter morning peak occurs at 6:00 to 09:00 when there is little solar radiation and hence little PV generation. During these hours, the passive design elements become more significant. The relative compactness of the courtyard shape limits losses through heat transfer through the building envelope.

Orientation

The orientation was an influential variable for the reference scenario with morning peak power as the target. This is due to the plan configurations having unequal window to wall ratios for the different façade orientations.

Conclusion

Using thermal mass on the floor, thermal mass on the walls, building form, and orientation as design variables, it was found from sensitivity analysis that the thermal mass on the floor was the most influential of the variables when using energy flexibility. The second most influential variable was the thermal mass on the walls.

The combination of thermal mass with temperature setpoint ramps was useful in reducing peak demand during the critical winter peak demand hours in Quebec by up to 16.98% in the morning peak and up to 21.67% in the evening peak, and reducing total electricity imported by 3.10% and 20.68%, respectively, for the same periods, across all plan shape and orientation combinations. Of the options analysed, the largest peak power reduction came from the configurations with the largest thermal mass on the floor slab and on the walls.

Based on these findings, integrating thermal mass with building form configurations and setpoint ramps in NZEBs can be beneficial to peak power reduction and offer

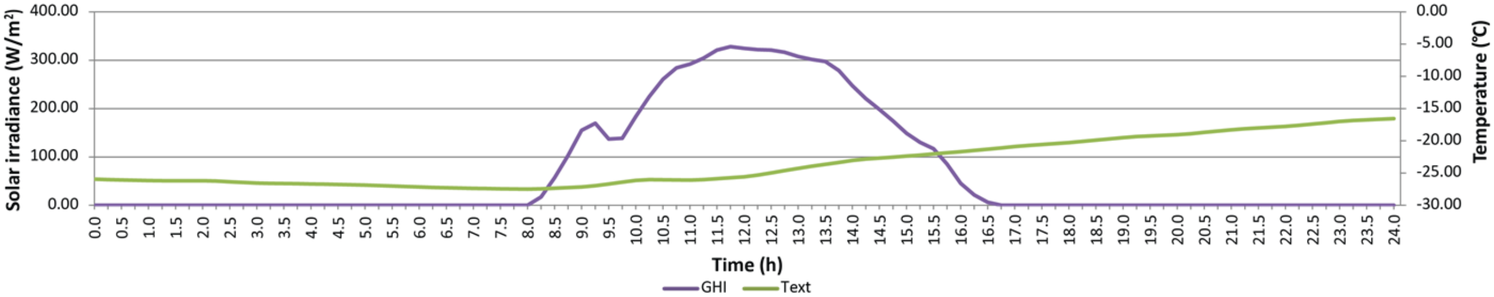

Figure 10: Very cold sunny day conditions in January. Global horizontal irradiance (GHI) and exterior temperature (Text).

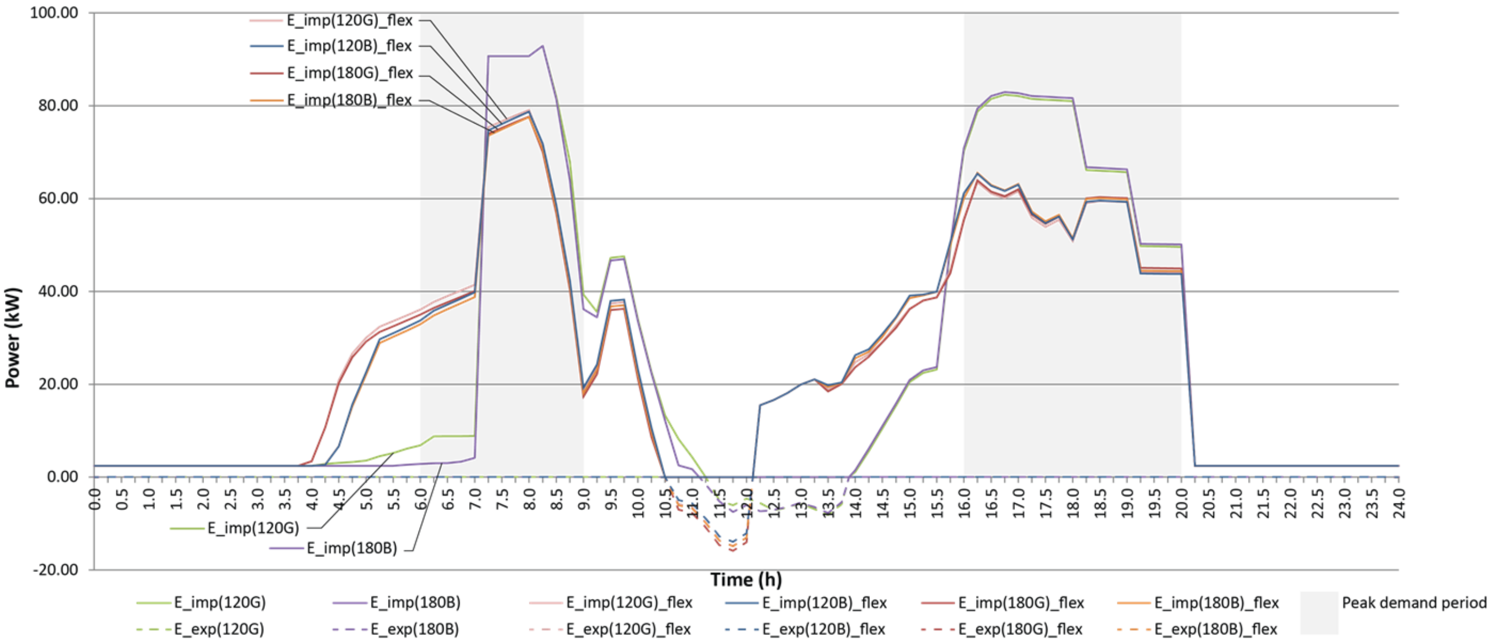

Figure 11: Very cold day in January. Electricity imported/exported (E_imp/E_exp) for reference ( ) and flex (_flex) cases. Slab thickness in mm (120 or 180); thermal mass on walls is either gypsum board (G) or thin brick (B).

building designers different design pathways to net zero energy while offering potential energy flexibility to the grid.

Acknowledgements

This work was supported by the Natural Sciences and Engineering Research Council of Canada/Hydro-Québec Industrial Research Chair in Optimized Operation and Energy Efficiency: Towards High Performance Buildings; and the Fonds de recherche du Québec – Nature et technologies.

References

Aduda, K.O., Labeodan, T., Zeiler, W., Boxem, G., Zhao, Y., 2016. Demand side flexibility: Potentials and building performance implications. Sustainable Cities and Society 22, 146-163.

Athienitis, A.K., Barone, G., Buonomano, A., Palombo, A., 2018. Assessing active and passive effects of façade building integrated photovoltaics/thermal systems: Dynamic modelling and simulation. Applied Energy 209, 355-382.

Athienitis, A.K., Cellura, M., Chen, Y., Delisle, V., Bourdoukan, P., Kapsis, K., 2015. Modeling and design of Net ZEBs as integrated energy systems, in: Athienitis, A.K., O'Brien, W. (Eds.), Modeling, Design, and Optimization of Net-Zero Energy Buildings. Wiley, Hoboken.

Braun, J.E., 2003. Load control using building thermal mass. Journal of Solar Energy Engineering, Transactions of the ASME 125(3), 292-301.

Buonomano, A., De Luca, G., Montanaro, U., Palombo, A., 2016. Innovative technologies for NZEBs: An energy and economic analysis tool and a case study of a non-residential building for the Mediterranean climate. Energy and Buildings 121, 318-343.

Canadian Commission on Building and Fire Codes, Construction, I.f.R.i., 2015. National Energy Code of Canada for Buildings, 2015. National Research Council, Ottawa, ON.

Delisle, V., Kummert, M., 2016. Cost-benefit analysis of integrating BIPV-T air systems into energy-efficient homes. Solar Energy 136, 385-400.

Dermardiros, V., Athienitis, A.K., Bucking, S., 2019. Energy Performance, Comfort, and Lessons Learned from an Institutional Building Designed for Net Zero Energy. ASHRAE Transactions 125(Part 1), 682-695.

ESTECO SpA, 2017. modeFRONTIER 2017R2, 2017R2 ed. ESTECO SpA, Trieste, Italy.

Guglielmetti, R., Pless, S., Torcellini, P., 2010. On the use of integrated daylighting and energy simulations to drive the design of a large net-zero energy office building, Proc. Fourth National Conference of IBPSA-USA, New York, NY.

Hachem, C., Athienitis, A., Fazio, P., 2011. Parametric investigation of geometric form effects on solar potential of housing units. Solar Energy 85(9), 1864-1877.

Hydro-Québec, 2019. Using energy more wisely in cold weather. http://www.hydroquebec.com/residential/customer-space/electricity-use/winter-electricity-consumption.html. (Accessed 2019.07.30 2019).

Jensen, S.Ø., Marszal-Pomianowska, A., Lollini, R., Pasut, W., Knotzer, A., Engelmann, P., Stafford, A., Reynders, G., 2017. IEA EBC Annex 67 Energy Flexible Buildings. Energy and Buildings 155, 25-34.

Johra, H., Heiselberg, P., Dréau, J.L., 2019. Influence of envelope, structural thermal mass and indoor content on the building heating energy flexibility. Energy and Buildings 183, 325-339.

Klein, S.A., Beckman, W.A., Mitchell, J.W., Duffie, J.A., Freeman, T.L., Mitchell, J.C., Braun, J.E., Evans, B.L., 2017. TRNSYS 18: A Transient System Simulation Program, 18 ed. Solar Energy Laboratory, University of Wisconsin, Madison, Wisconsin.

Le Dréau, J., Heiselberg, P., 2016. Energy flexibility of residential buildings using short term heat storage in the thermal mass. Energy 111, 991-1002.

Lund, P.D., Lindgren, J., Mikkola, J., Salpakari, J., 2015. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renewable and Sustainable Energy Reviews 45, 785-807.

Martin, L., March, L., 1972. Urban space and structures. Cambridge University Press, London.

Masy, G., Georges, E., Verhelst, C., Lemort, V., André, P., 2015. Smart grid energy flexible buildings through the use of heat pumps and building thermal mass as energy storage in the belgian context. Science and Technology for the Built Environment 21(6), 800-811.

Natural Resources Canada, 2012. Survey of Commercial and Institutional Energy Use - Buildings 2009, in: Efficiency, O.o.E. (Ed.). Ottawa, Canada.

Python Software Foundation, 2019. Python, 3.7.3 ed. Python Software Foundation, Beaverton, OR.

Reynders, G., Amaral Lopes, R., Marszal-Pomianowska, A., Aelenei, D., Martins, J., Saelens, D., 2018. Energy flexible buildings: An evaluation of definitions and quantification methodologies applied to thermal storage. Energy and Buildings 166, 372-390.

Reynders, G., Nuytten, T., Saelens, D., 2013. Potential of structural thermal mass for demand-side management in dwellings. Building and Environment 64, 187-199.

Rigoni, E., Ricco, L., 2011. Smoothing Spline ANOVA for Variable Screening. ESTECO, Trieste, Italy, p. 11.

Salom, J., Marszal, A.J., Widén, J., Candanedo, J., Lindberg, K.B., 2014. Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data. Applied Energy 136, 119-131.

Salpakari, J., Lund, P., 2016. Optimal and rule-based control strategies for energy flexibility in buildings with PV. Applied Energy 161, 425-436.

Torcellini, P., Pless, S., Deru, M., Crawley, D., 2006. Zero Energy Buildings: A Critical Look at the Definition, ACEEE Summer Study. U.S. Department of Energy, Pacific Grove, California, p. 12.

Tuhus-Dubrow, D., Krarti, M., 2010. Genetic-algorithm based approach to optimize building envelope design for residential buildings. Building and Environment 45(7), 1574-1581.

Yip, S., Chen, Y., Athienitis, A., 2015. Comparative Analysis of a Passive and Active Daylight Redirecting Blind in Support of Early Stage Design, CISBAT 2015. ÉPFL, Lausanne, Switzerland, pp. 229-234.

Youssef, A.M.A., Zhai, Z.J., Reffat, R.M., 2016. Genetic algorithm based optimization for photovoltaics integrated building envelope. Energy and Buildings 127, 627-636.