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Energy Performance, Comfort, and Lessons Learned from an Institutional Building Designed for Net Zero Energy

Vasken Dermardiros
Student Member ASHRAE

Andreas K. Athienitis, PhD, PE
Fellow ASHRAE

Scott Bucking, PhD, PE
Associate Member ASHRAE

ABSTRACT

This paper examines the early performance of the Varennes Library, a building designed for net-zero annual energy balance in Varennes, near Montréal, Canada. It produces electricity from a 110.5 kWp building-integrated photovoltaic (BIPV) system where heat is also recovered from a section of the array and used to preheat the outdoor air intake. The building's many architectural and mechanical features were integrally designed to achieve the net zero energy target over a five-year averaging period with several key decisions made at the early design stage. These include the shape, area, and orientation of the roof that maximizes electricity production from the BIPV (part BIPV/T [building-integrated photovoltaic/thermal with heat recovery]) system and a design layout that promotes daylight penetration and natural ventilation/free cooling during the cooling season. In the first year after inauguration, an operational energy use intensity (EUI) of 24.8 kBtu/ft^{2}y (78.1 kWh/m^{2}y) was achieved and has since been reduced to 22.20 kBtu/ft^{2}y (70.0 kWh/m^{2}y). Considering renewables production, the net-energy use intensity (EUI) is 4.60 kBtu/ft^{2}y (14.5 kWh/m^{2}y). This is a 95% EUI reduction over the national institutional average and can be further reduced with additional (ongoing) commissioning efforts. Suggested improvements in operation include ensuring the electricity production is optimized and any faults corrected, dimming electric lighting when daylight is sufficient, extending the hours of natural ventilation, and better utilization of the hydronic radiant slab for thermal storage using predictive controls. This paper discusses the process followed in the design of the library, its key features, its early performance, and some of the lessons learned.

INTRODUCTION

Leading researchers and policymakers envision a future of net zero energy (NZE) buildings: buildings producing at least as much energy from renewable sources as they use in a year (ASHRAE 2008, CEC 2016, NBI 2016, SNEBRN 2016). Net zero provides an objective target for high-performing buildings, promoting an integrated approach to energy efficiency and renewables—the path toward net zero is more important than achieving the target. In the future, buildings that are currently near NZE can become NZE or net positive energy buildings as more advanced controls and higher efficiency equipment replaces depreciated ones. Thermal and electrical storage solutions can be added to better seize opportunities for load shifting.

The role of NZE and high-performing buildings will be paramount in the near future as more building-integrated decentralized renewables are connected to the grid. Such buildings may be highly instrumented and may act as regulators of demand to aid the utility by relying on energy flexibility concepts such as optimally controlling their thermal and/or electrical storage systems (Denholm and Hand 2011; Jensen et al. 2017; Lund et al. 2015; Moslehi and Kumar 2010). Renewable energy sources such as solar and wind are highly variable and can impose a burden on the grid when demand is low.

This paper presents the performance of a NZE library built in the city of Varennes (near Montréal), Québec, Canada. The library is the first institutional Canadian NZE building (designed as net zero but the energy balance will be performed over five years beginning in 2016, while improvements are also being implemented). Table 1 summarizes its key features. Figure 1 shows pictures of the exterior, and Figure 2 shows a schematic cross-sectional area highlighting architectural and

Vasken Dermardiros is a PhD candidate and **Andreas K. Athienitis** is a professor in the Department of Building, Civil and Environmental Engineering at Concordia University, Montréal, Québec, Canada. **Scott Bucking** is an assistant professor of Building Information Modelling in the Department of Civil and Environmental Engineering and the Azrieli School of Architecture and Urbanism at Carleton University, Ottawa, Ontario, Canada.

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Table 1. Varennes Library Key Features

Architectural	
Site	Varennes, Québec, Canada
ASHRAE climate zone	6
Net floor area, ft^2 (m^2)	22,600 (2100)
Width/depth, ft (m)	180/56 (5(5.3/17.1)
Roof tilt, degrees	37
Window type, S	Double-glazed argon low-e wood-frame
Window type, N/E/W/skylight	Triple-glazed argon low-e wood-frame
Window-to-wall ratio, S/N/E/W,%	30/10/20/30
Shading, S, fixed louvers	6.5in. (165 mm) wide, 20° tilted toward window 10 in. (250 mm) center-to-center (c/c), 4in. (100 mm) from glass
U-factor, window, S, Btu/h·ft^{2}°F (W/m^2K)	0.45 (2.56)
SHGC, window, S	0.58
U-factor, window, N/E/W/skylight	0.32 (1.82)
Solar heat gain coefficient (SHGC), window, N/E/W/skylight	0.47
R-value, wall, h·ft^{2}°F/Btu (m^2K/W)	29.0 (5.1)
R-value, roof, h·ft^{2}°F/Btu (m^2K/W)	47.7 (8.4)
Mechanical	
Main system, type	Centralized dedicated outdoor air system (DOAS) modulated based on CO_2
Main system, features	Ground source heat pump (GSHP), energy recovery ventilator (ERV), solar thermal recovery
Distribution system, first floor	four-pipe fan coil, overhead diffuser
Distribution system, second floor	four-pipe fan coil, underfloor air distribution (UFAD), displacement diffuser
Distribution system, S/E/W perimeter	Radiant slab, 5 in. (125 mm) thick, heat+cool
Cathedral area, second floor	Ceiling fans
Natural ventilation	Motorized windows
BIPV/T area, ft^2 (m^2) (No. units)	1860 (173) (66)
BIPV/T maximum air volume, cfm (L/s)	2420 (1140)
Domestic water	Low-flow fixtures
Electrical	
On-site photovoltaic (PV), nominal capacity, kWp	110.5
PV panel, unit capacity (W) and No. units	260, 425
Inverter capacity, kW (kW/unit) (No. units)	100 (10) (10)
Lighting, typical type, controls	T8 fluorescent, 1–2 tube luminaires, digital addressable lighting interface (DALI) system
Lighting power density (LPD), W/ft^2 (W/m^2)	0.71 (7.64)
Other features	Electric vehicle (EV) charging station (2 cars), no coffee machines, no vending machines, no refrigerated water fountains

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Figure 1 *Varennes Library tagged images. (1) entrance, southwest view; (2) north façade; (3) south façade; (4) second floor, facing west, (5) second floor, middle section, facing south; (6) ground floor facing south; (7–8) mechanical room; (9) south façade; (10) official opening ceremony, from left to right: Dr. Konstantinos (Costa) Kapsis, Dr. Andreas K. Athienitis, Major Martin Damphousse, Vasken Dermardiros, and Remi Dumoulin. (A) forced convected BIPV and BIPV/T area; (B) naturally convected BIPV portion (out of view); (C) west façade, vine supports; (D) two car charging station; (E) skylights on northern roof; (F) fixed exterior louvers, solar shading; (G) geothermal boreholes; (H) ceiling fans; (I) motorized windows; (J) displacement ventilation integrated to bookshelves/stacks; (K) underfloor ventilation diffuser; (L) hydronic radiant slab; (M) geothermal heat pumps; (N) BIPV/T heat into air-handling unit (AHU); (O) AHU.*

mechanical features. We use the site energy NZE definition from Torcellini et al. (2006), which considers the energy boundary to be at the site level.

The paper is contains the following sections: Conception and Construction, Energy Consumption and End-Use Breakdown, Energy Production, Occupant Comfort, Recommended Improvements to Achieve Net Zero, and Summary and Discussion.

CONCEPTION AND CONSTRUCTION

The city of Varennes is an off-island suburb of Montréal (latitude 45°N). With its growing population, the city was in need of a new library to replace its aging one. From 2010 to 2011, a team consisting of municipal representatives, CanmetENERGY researchers, and academics and industry partners was formed and adopted an integrated design process (IDP) through several design charettes. Since the beginning, the objective was to make the library the first NZE institutional building in Canada with a building-integrated solar system. The Natural Sciences and Engineering Research Council of Canada's (NSERC) Smart Net-Zero Energy Buildings Research Network (SNEBRN) was represented by a team from Concordia University who guided the development of the overall energy concept for a two-story, 22,600 ft^2 (2100 m^2) building. Two key concepts determined the overall shape of the building and the integration of the technologies:

1. The design team estimated the annual energy consumption of a highly energy-efficient library around 22.20 $\text{kBtu/ft}^2\text{y}$ (70 $\text{kWh/m}^2\text{y}$), resulting in an energy consumption of about 501,600 kBtu (147,000 kWh) per year. To reach site net zero energy with solar electricity generated by a PV system optimally tilted and oriented

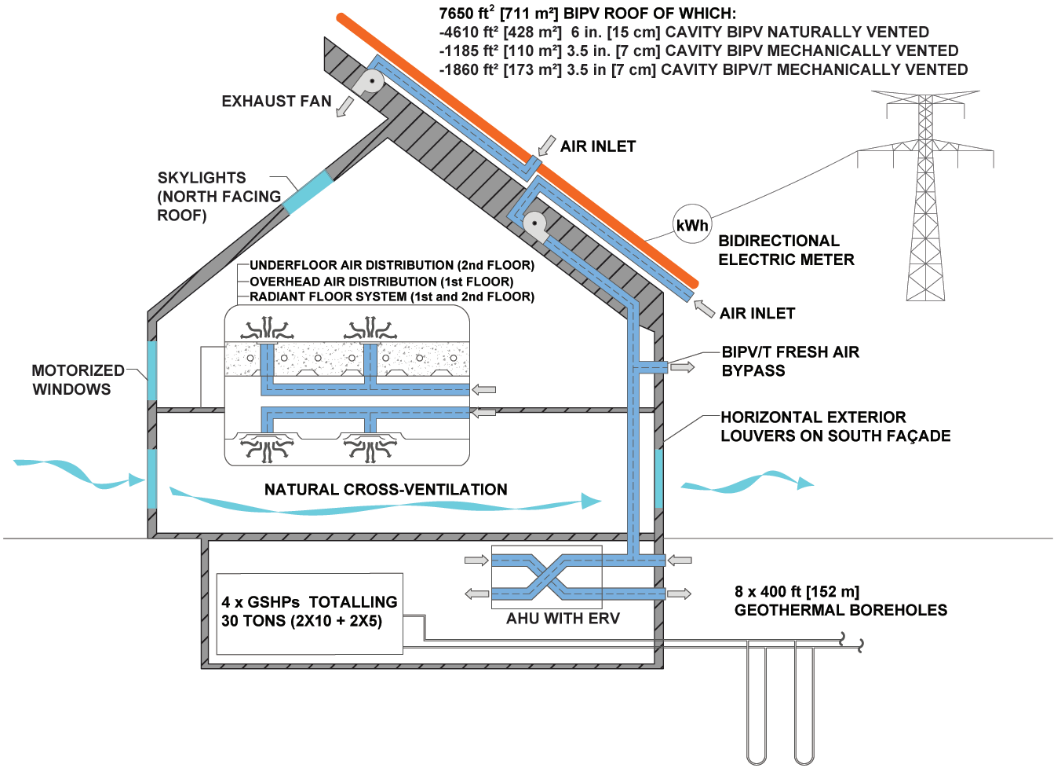

Figure 2 *Varennes Library schematic.*

due south, we would need a 110 to 120 kW system that would generate about 1200 kWh/y per kW installed based on well established solar potential maps from National Resources Canada (NRCan) and our own measured data (Athienitis and O'Brien 2015). This would require a roof area of 7500 to 8600 ft^2 (700 to 800 m^2).

2. The depth of the building would have to be 65 to 110 ft (6 to 10 m) to promote deep daylight penetration (Athienitis and O'Brien 2015) and night free-cooling through motorized windows on opposite façades.

The 15 early design charettes served to develop a common vision for the net zero energy building and to implement it into a practical design for the local climate. The SNEBRN group aimed to educate the architects and engineers (selected after a competition organized by the municipality) on new energy efficiency and solar technologies. Through better integration of the different building subsystems, system components would function more efficiently and therefore could be sized smaller. During the early design charettes, key energy features were decided: (1) the roof slope was set to be close to a 40º inclination and directed due south to optimize PV production while reducing snow accumulation; (2) all façades would receive triple-glazed, low-e, argon-filled, wood-framed windows to minimize thermal losses in winter, and the south façade would have double-glazed, low-e, argon-filled windows to increase passive solar gains; (3) windows sizes are to be optimally selected to have sufficient views to the exterior but not have excessive heat gains or losses or lead to visual discomfort; (4) the target for lighting was set to <0.65 W/ft^2 (<7 W/m^2) (combined with task lighting) and dimmable in conjunction with daylight; and (5) the use of a ground-source heat pump and BIPV/T systems to reduce energy consumption for heating while potentially being able to export excess heat to heat the neighboring public pool in summer or houses in winter. To condition the space, the design team selected a radiant slab for both heating and cooling on the southern perimeter of the building and an underfloor air displacement (UFAD) system for the rest of the upper floor; the first floor uses overhead diffusers. Outdoor air was to be supplied by a dedicated outdoor air system (DOAS) based on the occupancy determined by CO$_2$ readings throughout the space. The finalized building energy use intensity (EUI) was estimated at 26.95 kBtu/ft^{2}y (85 kWh/m^{2}y). The actual amount was 24.8 kBtu/ft^{2}y (78.1 kWh/m^{2}y) the first year following its inauguration (June 1, 2016, to May 31, 2017), and has since been reduced to about 22.20 kBtu/ft^{2}y (70.0 kWh/m^{2}y). Considering renewables production, the net EUI is around 4.60 kBtu/ft^{2}y (14.5 kWh/m^{2}y). See Figure 3 for a chart tracking the gross EUI and net EUI, considering renewables production over time, with a one-year sliding window showing results prior to the inauguration as well. The Canadian average commercial/institutional building in the category that includes libraries consumes 105 kBtu/ft^{2}y (330 kWh/m^2) of energy (major

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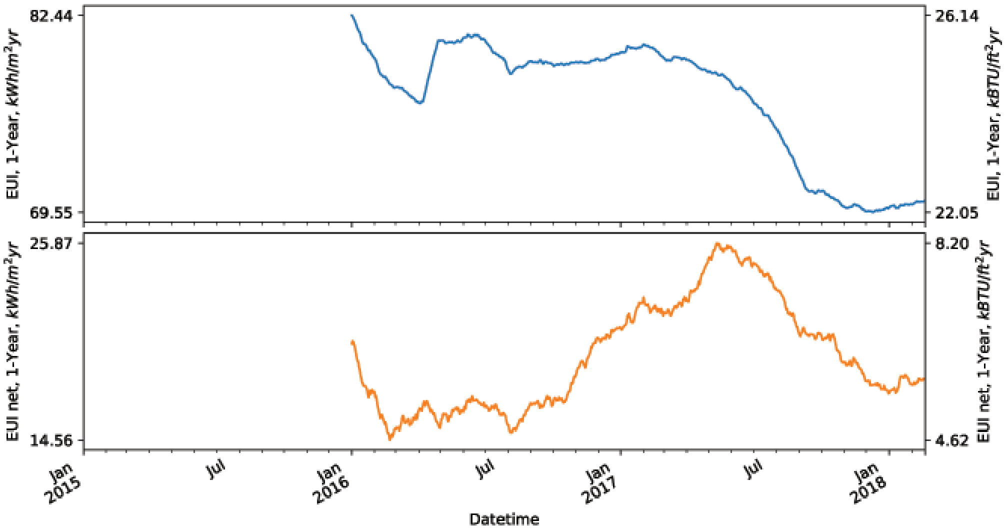

Figure 3 *Energy use intensity (EUI) over time on a one-year sliding window. Each point on the chart represents the EUI value for the previous one-year period. (Top) gross EUI; (Bottom) net EUI including photovoltaic panel production.*

fuels) (NRCan 2014). A U.S. national public assembly building[1] in a "very cold/cold" climate consumes 82.4 kBtu/ft^{2}y (260 kWh/m^{2}y) of major fuels, which include electricity, natural gas, fuel oil, and district heat from which 42.31 kBtu/ft^{2}y (133.4 kWh/m^{2}y) of electricity is consumed. (EIA 2016) The Varennes Library is 100% electrical, using geothermal heat pumps as a main heating/cooling source, so its electricity consumption cannot be directly compared with buildings that are heated with fossil fuels.

The secondary objectives were for Varennes to use the project to transfer acquired knowledge to the building design sector, convince other municipalities to adopt IDP, reduce the perception about high-performing having a higher life-cycle cost, and educate and showcase to the public about the library's various net-zero energy enabling technologies, particularly their integration.

The library was inaugurated on May 16, 2016, achieved Leadership in Energy and Environmental Design (LEED®) Gold certification, won an Award of Excellence 2014 in Real Estate for Innovation from the Urban Development Institute of Quebec (Macogep 2014), and won an Award of Excellence from the Association of Consulting Engineering Companies of Canada (ACEC 2016).

The library cost $8 million ($354/ft^2) (Canadian and U.S. dollars on parity at the time), not including architectural, engineering and construction professional fees, profit, and overhead. (Bibliothèque de Varennes 2018). To compare, the Bibliothèque du Boisé, another LEED Gold library built in Montréal around the same year, cost $22.6 million (64,130 ft^2, $352/ft^2). (Bibliothèque du Boisé 2018) Finally, the estimated cost of a U.S. library, unionized and not including professional fees, is $118.80/ft^2 ($1278.30/m^2) (RSMeans 2013).

ENERGY CONSUMPTION AND END-USE BREAKDOWN

Like any building, a NZE building is not necessarily a high-performing building or immune to poor operational practices. Poor operational practices, such as using incorrect outdoor air and thermostat settings and unaccounted occupant behavior could combine to increase energy use by up to 50% to 60% more than necessary (NBI 2013). The challenges can be addressed during the design and operation stages of a building.

Performance verification includes carrying out routine maintenance on the mechanical equipment to assure peak performance and efficiency. Commissioning also includes updating the controls to better match occupancy. This does not require purchasing new equipment and can be a cost-effective solution for most existing buildings. To better understand how the library is running, we look at its energy consumption and break it down by end-use.

The energy breakdown is shown in Table 2 for the period between June 1, 2016, and May 31, 2017. During a portion of that period, although individual luminaires are addressable and dimmable, lighting was running on a fixed schedule and at full intensity. The lighting power has since been reduced through dimming. Fan and pump power take up a significant portion due to the radiant slab systems requiring circulation pumps and the fan coil units having each their own fans. The Other category includes plug loads such as computers, book check-out counter, etc. From the beginning, the energy design team decided to exclude energy-intensive equipment such as

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[1] A library falls under the "public assembly" building definition. See Tables C10 and C20 for major fuel and electrical consumption data by climate region in the survey data (EIA 2016).

refrigerated vending machines, water fountains, and coffee makers. The building manager is proactive and is always tweaking the system to reduce energy use. Looking at the middle subplot of Figure 4, we can see the yearly consumption of the building dropping.

The building automation system (BAS) has been logging data since November 2014, however, the building was not fully functional then and not all equipment was installed and commissioned. Unfortunately, there are gaps and corrupted data due to misreads or controller restarts.

Table 2. End-Use Breakdown and Energy Use Intensity (EUI)

Category	Energy, kWh (% of total)
Consumption	163,920 (100%)
Lights	40,980 (25%)
Heating/Cooling	47,540 (29%)
Pumps	32,780 (20%)
Fans	32,780 (20%)
Other	9840 (6%)
Production	110,150 (67%)
Difference	53,770 (33%)

Data from June 1, 2016 to May 31, 2017: First year after inauguration.

ENERGY PRODUCTION

The library has a 110.5 kW roof-mounted BIPV array. From the total 7650 ft^2 (711 m^2) (425 panels) PV area, 4610 ft^2 (428 m^2, 258 panels) are naturally vented through a 6 in. (150 mm) air gap between the PV panels and metal roofing. The remaining 3040 ft^2 (280 m^2, 167 panels) are fan-assisted and vented through a narrower 2.8 in. (70 mm) air gap. Airflow behind the panels serves to reduce overheating and to increase production efficiency. From a 1860 ft^2 (173 m^2) (66 panels) portion of the forced air area, heat from the PV panels is recovered through outdoor air flowing in the cavity under the panels that is used as outdoor air; this airflow to the outdoor air intake is controlled through variable-speed fans during the heating season (see Figure 2). This system is known as BIPV/thermal (BIPV/T) as it produces useful heat in addition to electricity. As an example, for a typical cold, sunny day, 748 kBtu (220 kWh) can be harvested as solar heat (see Figure 5). On average, 23,320 kBtu (6835 kWh) have been harvested per heating season (November to April). On approximately 50% of the occupied time the BIPV/T system harvested more than 6825 Btu/h (2 kW) of heat and 14% of the occupied time above 34,120 Btu/h (10 kW) of heat. The BIPV/T portion covers 16% of the roof; if the whole roof were BIPV/T, 6.5 times more heat could theoretically be recovered and potentially fed to a thermal microgrid to assist neighboring buildings in heating. The BIPV/T system was designed to maintain an air velocity within the air channel near 200 fpm (1 m/s) as it was found to be a good compromise between maximizing heat transfer while reducing pressure loss

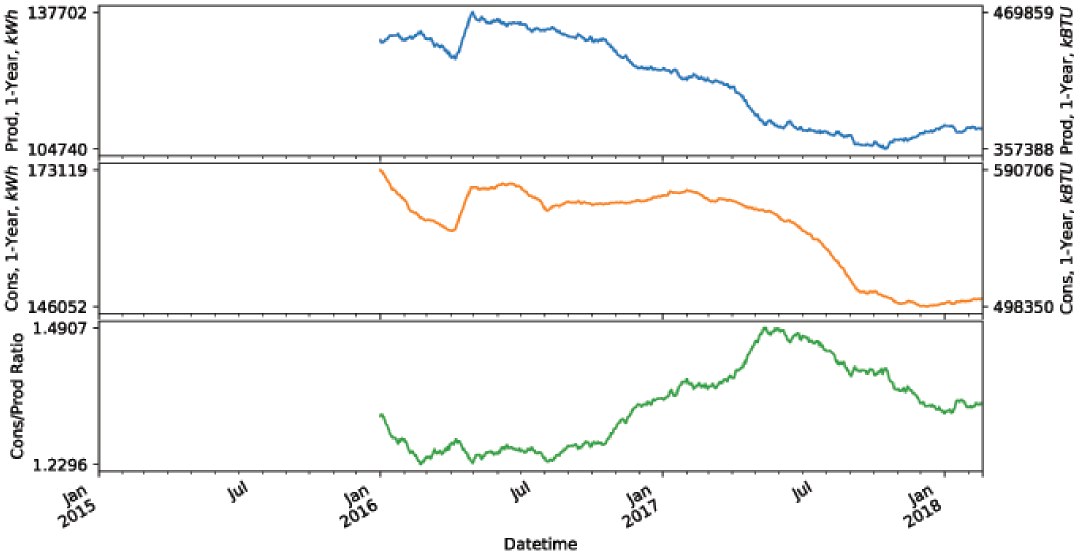

Figure 4 *One-year sliding window for (top) production, (middle) consumption, and (bottom) ratio of production over consumption; when the ratio production over consumption reaches at most 1, net zero is achieved. Each point on the chart represents the total value for the previous one-year period. Production μ: 121,060 kWh, σ^2 :10,710; consumption μ: 161,740 kWh, σ^2 : 8296.*

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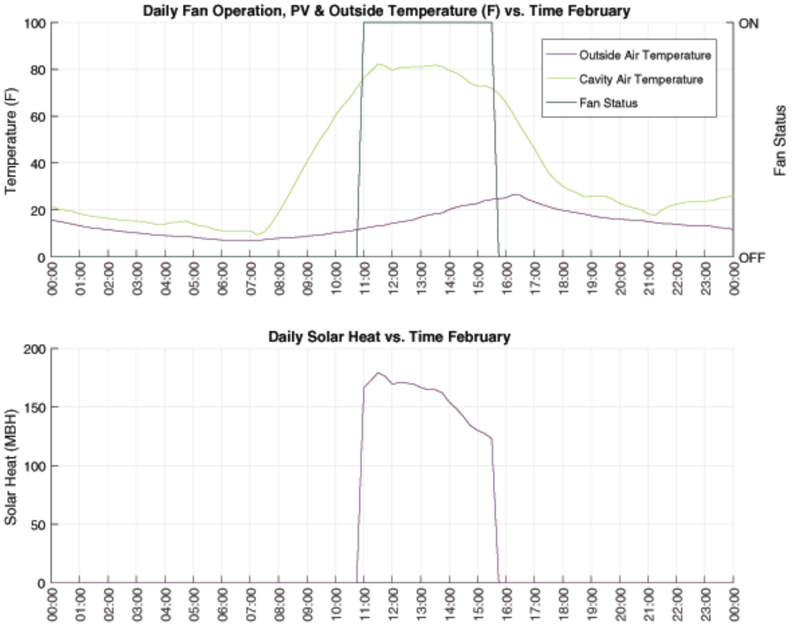

Figure 5 *BIPV/T performance in winter.*

(Candanedo 2010). In summer, the mechanical ventilation under the panels is turned on for a minimum of 30 min whenever the air at the end of the cavity reaches 77°F (25°C). This air is exhausted directly to the outside because there is no need to harvest heat during summer.

Ten 10 kW inverters convert the direct current (DC) output from the PV system to alternating current (AC) to be used by the building or exported to the grid. The inverters were slightly undersized with the aim to achieve higher yields during average days. The daily peak production for the whole history of the building is plotted in Figure 6 and shows that the installed 110.5 kW power was never achieved due to losses in wiring and conversion. Tracking the peaks, past June 2015, they reach a maximum of 90 kW. Similarly, past May 2016, the daily peaks do not surpass 80 kW. After a site visit, we noticed that two inverters were not functioning and a third one was functioning erratically. These inverters were connected to larger strings of PVs. Poorly functioning inverters have since been replaced. We suspect the inverters are breaking down because of a combination of a much larger production than their rated 10 kW caused overloading, the maximum power point tracker (MPPT) had failed, the PV strings were not wired correctly, and/or the inverter settings were incorrect and led to failures. A dedicated controller has been installed since February 2017 to monitor the individual inverters; only aggregate amounts were logged beforehand. We can observe similar trends by looking at the daily energy production in Figure 7.

A net daily energy balance is shown in Figure 8. This figure demonstrates when the library is net consuming versus net-producing. In winter and summer, the building consumes approximately 400 kWh daily, whereas during the shoulder seasons, it exports around 200 kWh daily. Taking the same period used in the end-use breakdown (June 1, 2016 to May 31, 2017), we plot in Figure 9 the load duration curve. This figure shows the hourly net power demand sorted from net consuming to net producing. By intercepting the curve with the *x*-axis, the number of hours where the library is net-consuming can be determined. For the given period, 6784 hours (77%) are net consuming and the remaining 1976 hours (23%) are net positive.

Excess electricity is sold to the grid and compensated up to 50 kW as per the agreement with the utility. As can be seen from Figure 9, by intercepting the curve with –50 kW and integrating the area between the curve and the intercept line, we determine that 642 kWh of energy was exported *pro gratis*. There are no batteries installed and therefore the library is incentivized to consume its electricity on-site and/or sell its electricity to clients plugging their electric vehicles to the library's charging station.

OCCUPANT COMFORT

The library conditions its interior space using overhead diffusers on the first floor and underfloor displacement diffusers on the second floor. Some of the spaces have their own terminal four-pipe fan coil unit to provide local conditioning. The remaining zones are conditioned using 5 in. (125 mm) thick hydronic radiant slabs. Outdoor air is supplied by a DOAS, which is modulated based on each zone's CO_2 concentration down to a minimum rate dictated by the Codes (ASHRAE 2016, NRCC 2010) when the space is occupied.

To assess the thermal comfort in the library, we will examine three spaces representing north and south perimeter zones and a central core zone. The air temperatures are binned in 0.9°F (0.5°C) intervals outside of the base range between

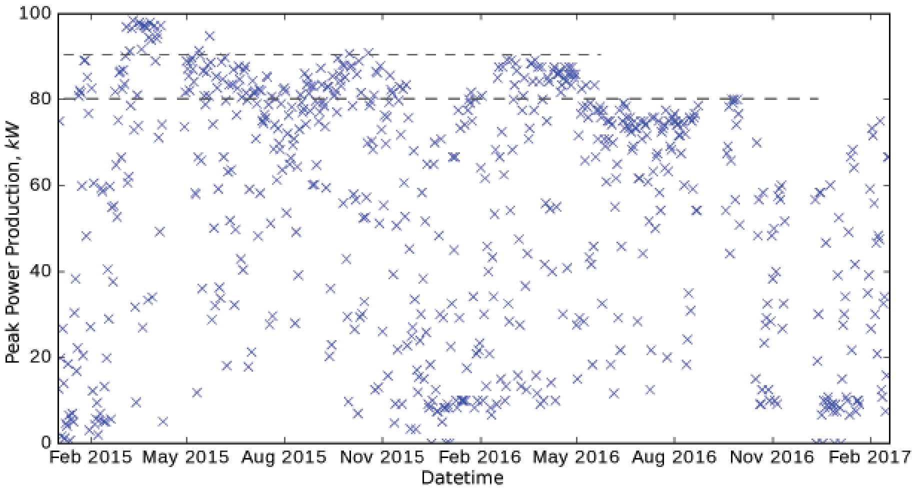

Figure 6 *Daily electrical peak power production. Around June 2015, the peak no longer crosses 90 kW, and around May 2016, the peak no longer crosses 80 kW. A new controller was installed on February 2017 to monitor individual inverters.*

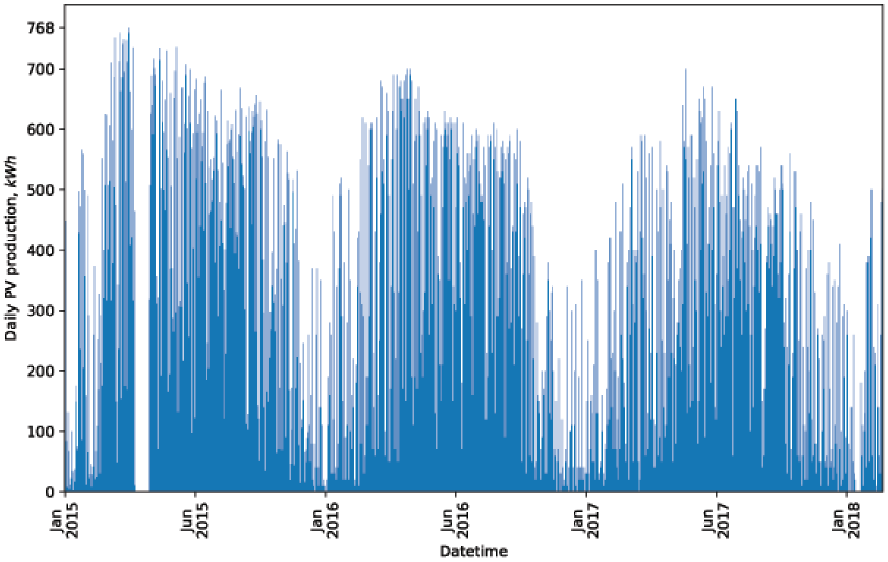

Figure 7 *Daily electrical energy production.*

69.8°F to 75.2°F (21°C to 24°C) (see Table 3). The binning was performed on all the data available and only for periods when the library was occupied. The core zone is within the temperature range for 64% of the time. The south zone tends to be warmer and the north zone cooler. Early in the design process, the library committee agreed to extend the comfortable upper bound to 78.8°F (26°C) because there are motorized windows and people will tolerate warmth given increased outdoor air and air movement (Taleghani et al. 2013). Given the relaxed requirements, the core zone is within acceptable limits 85% of the time and the perimeter zones for more than 73% of the time.

The motorized windows are opened when the exterior air temperature is between 55.4 to 71.6°F (13 to 22°C), and if there is a need for outdoor air and if it is not raining. The windows are open approximately 9% of the time.

Visual comfort is achieved with fixed exterior louvers (See Figure 1F and Table 1). They have been designed to block direct sun from occupants' eyes and to reflect the light towards the ceiling. Being a passive solution, they require no maintenance. On the west façade, vine vegetation will block direct sun during the summer to limit glare and excess solar gains. Small amounts of visual glare are possible in the early morning and late afternoons on the east and west façades, respec-

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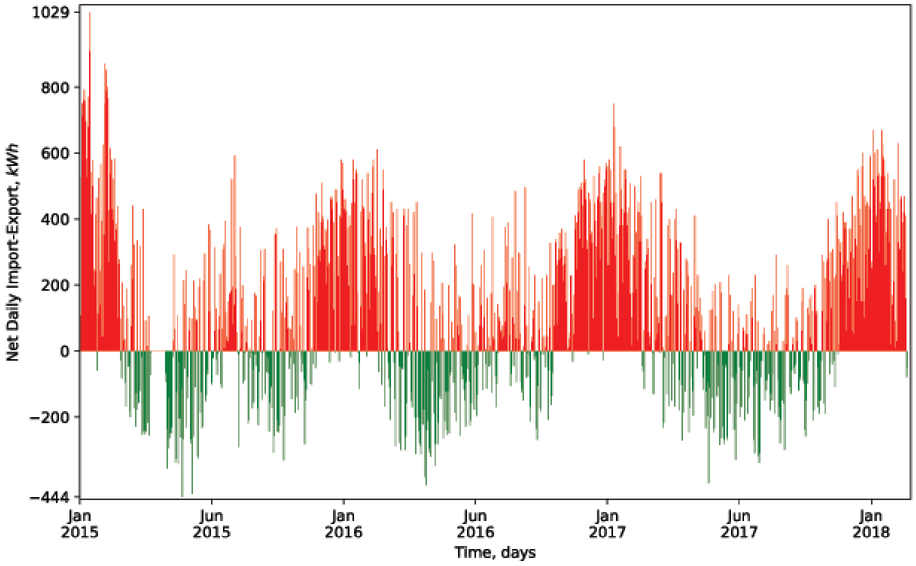

Figure 8 *Net daily electrical energy balance.*

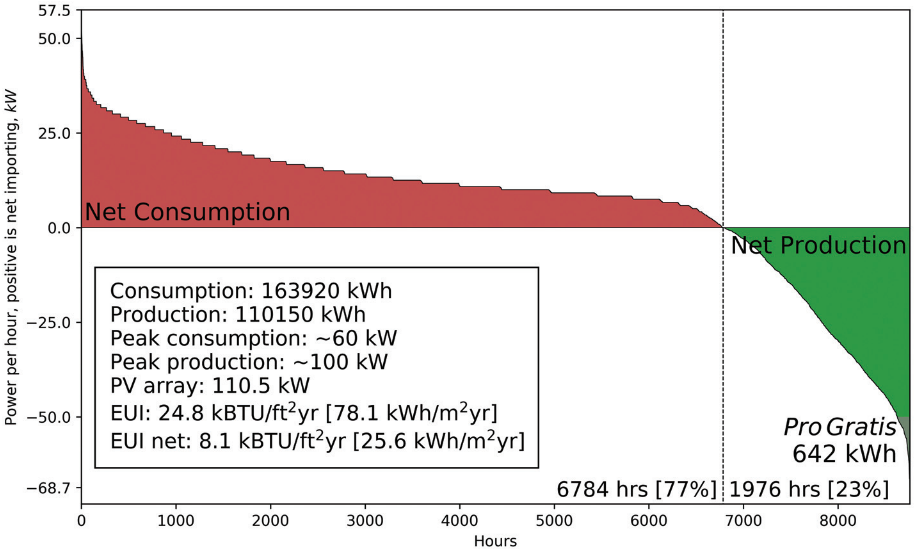

Figure 9 *Electrical load duration curve. Data from June 1, 2016 to May 31, 2017, first year after inauguration.*

tively. The skylights are on the northern portion of the roof and admit diffuse light.

Occupancy awareness and adapting better energy habits are encouraged with an energy dashboard at the main lobby showing the library's consumption and production for the past hours, days, and months.

RECOMMENDED IMPROVEMENTS TO ACHIEVE NET ZERO

The library has many features favorable to achieve the NZE target.

Production

Whether or not the PV panels of the library should be cooled mechanically was an interesting question to address to improve the net energy balance of the library. In theory, fan-assisted cooling of the PV panels should fulfill two objectives: maintaining the panels below their critical operating temperature of 185°F (85°C), as per IEC Standard 61215-1:2016 (IEC 2016) and maximizing the electrical efficiency of the panels. Given the availability of cavity air temperature data for the fan-assisted portion of the roof, it was possible to calibrate a simple model to see the effects of different cooling strategies

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Table 3. Temperature Bins for Three Spaces near the North and South Perimeters and Core Zone

Range, °F (°C)	Core	South	North
63.5–64.4 (17.5–18)	0.02	0.59	0.28
64.4–65.3 (18–18.5)	0.23	0.82	0.74
65.3–66.2 (18.5–19)	0.55	1.58	1.10
66.2–67.1 (19–19.5)	1.11	2.56	2.57
67.1–68.0 (19.5–20)	2.46	3.95	3.59
68.0–68.9 (20–20.5)	4.09	5.06	7.09
68.9–69.8 (20.5–21)	5.88	6.19	11.12
69.8–75.2 (21–24)	63.65	43.76	49.40
75.2–76.1 (24–24.5)	15.12	11.35	13.40
76.1–77.0 (24.5–25)	5.24	10.85	7.76
77.0–77.9 (25–25.5)	0.90	6.69	2.06
77.9–78.8 (25.5–26)	0.43	3.55	0.40
78.8–79.7 (26–26.5)	0.18	2.26	0.32
79.7–80.6 (26.5–27)	0.11	0.57	0.10
80.6–81.5 (27–27.5)	0.06	0.15	0.05
81.5–82.4 (27.5–28)	0.00	0.04	0.02
82.4–83.3 (28–28.5)	0.00	0.03	0.00
69.8–78.8 (21–26)	84.90	72.66	72.62

Data from February 20, 2016, to February 20, 2018

for a typical warm sunny day on the PV panel temperature and on their efficiency. The thermal network developed by Charron and Athienitis (2006) was used with actual solar and meteorological data for September 1, 2015. Three scenarios were studied. The first case represents the existing installation with fans operating at cavity temperatures over 77°F (25°C) and a 2.8 in. (70 mm) air cavity. The second scenario looks at how the temperature of the panel would vary if no mechanical ventilation was provided for a 2.8 in. (70 mm) air cavity. The last shows the panel temperature behavior when no fan-assistance is provided for a 6 in. (150 mm) cavity. For the natural ventilation, it was found through the initial calibration of the model that the convective heat transfer within the cavity corresponded to an internal air velocity of 60 fpm (0.3 m/s). This value was kept constant throughout the naturally vented analysis.

The results for a warm day in September are summarized in Figure 10. Under no circumstances are the panels reaching their critical operating temperature. Besides, the electrical efficiency of the panel does not benefit enough to justify the fan energy consumption; the fan should only be used as an overheating preventative measure. In other words, the PV system will not generate more electricity with the fans running than when they are off. Two conclusions can be drawn from this simple analysis. First, if the heat from the BIPV/T is not used, then ventilating the roof is not worthwhile, i.e., the gain in electrical efficiency by mechanically cooling the panels is not more than the input fan energy. Second, the naturally vented, larger 6 in. (150 mm) cavity was a better design option in terms of net energy use, maintenance, and complexity. This is what was installed under the majority of the library's PV system. We are currently installing sensors on the panels to further analyze the as-built performance of the BIPV and BIPV/T portions of the roof to measure PV surface temperatures instead of relying on a model.

Lighting

When the library was first opened, the lighting was set to a minimum of 80 foot-candles (fc) (800 lux) everywhere. Since then, lighting was reduced following Illuminating Engineering Society (IES) guidelines (DiLaura et al. 2011). Two main tasks are conducted in a library: office work and reading and browsing the library book shelves/stacks. IES recommends 30 to 50 fc (300 to 500 lux) for office work and library reading and 20 to 50 fc (200 to 500 lux) for library shelves (DiLaura et al. 2011). However, when lighting was reduced, occupants complained that it was too dim, possibly because of strong contrast between the daylit areas and the book stacks.

The library is open to employees well before it is opened to clients. During that period, the lighting in areas designated for clientele can be switched off or sparsely lit. Photosensors dim luminaires when daylight is present. Lastly, some T8 fluorescent ballasts have started to fail. The building manager seeks to replace the luminaires with LED types because they last longer, are more economical to operate, can be dimmed efficiently, and do not contain harmful elements like mercury.

Natural Ventilation

Yuan (2016) proposed a window-opening strategy based on exterior air water content and temperature (Figure 11). The ambient air is acceptable if the admitted air does not raise the indoor air relative humidity above 70% at 71.6°F (22°C). In her study, she allows ambient air down to 46.4°F (8°C) to be admitted for precooling when the building is unoccupied, by applying a nighttime free-cooling strategy.

Applying the proposed ranges to the library, we note a window opening rate increase from 9.0% to 9.4% going from the current control program to Yuan's most conservative scenario: see Yuan Case 1 in Table 3, where the exterior conditions are closest to interior conditioned air. By increasing the range of acceptable air, window use can be increased to almost 29%. However, the lower bound 46.4°F (8°C) air should only be considered in unoccupied hours, otherwise it will lead to thermal discomfort near the windows. By using longer natural ventilation and nighttime precooling strategies during the cooling season, the cooling load can be reduced.

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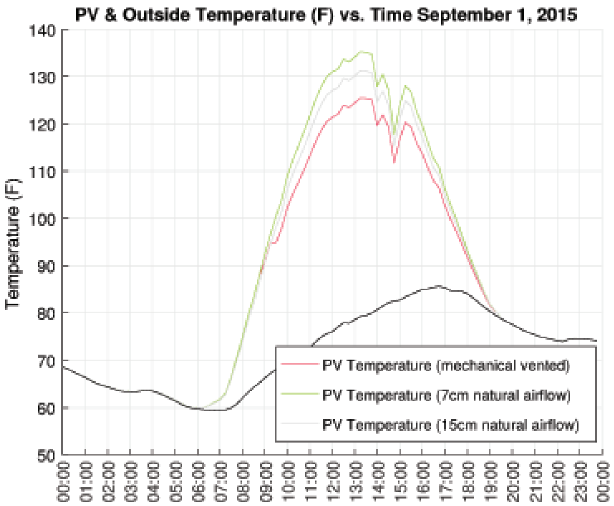

Figure 10 *BIPV/T performance in summer. PV temperatures shown for cases: (1) mechanically vented, (2) 2.8 in. (7 cm) gap, naturally vented, and (3) 6 in. (15 cm) gap, naturally vented.*

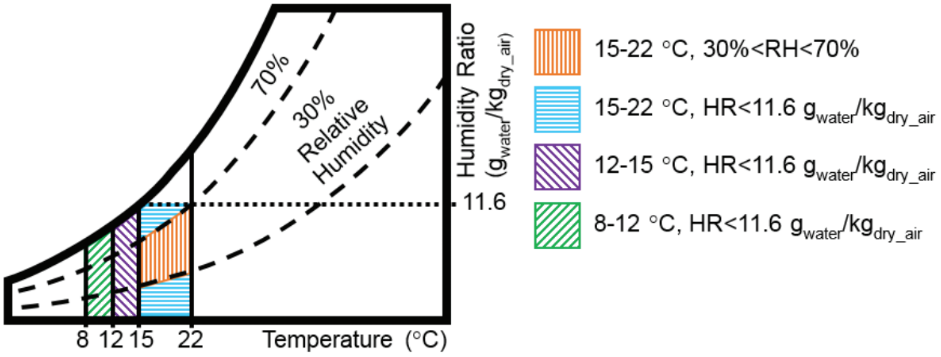

Figure 11 *Natural ventilation operating range (Yuan 2016).*

The challenge of natural ventilation is to be able to use it alongside the HVAC system to reduce the overall energy use.

Radiant Slab Precharge

The current controls function based on two modes: heating or cooling. If the building is in cooling mode, no heating is supplied, and vice versa. There are opportunities to reduce the overall energy consumption of a zone with radiant slabs by either preheating or precooling in anticipation of a future load, such as occupancy or solar gains. We have completed a preliminary study (Dermardiros et al. 2017) on how to apply an optimization-based model-based predictive control (MPC) strategy on the radiant slab. Based on a model of the radiant slab and on future forecasts, MPC will determine the operational trajectory the system needs to follow to minimize a cost function. For a case where heating is needed in the morning and cooling in the afternoon, it is possible that the lowest energy optimal is to cool the slab in the morning in anticipation of solar gains at noon but use the diffusers for heating in the morning. This strategy was found by the optimization routine. The method also dramatically reduced the peak electrical demand by as much as 50% by preemptively cooling the slab instead of simply reacting to solar gains as is the current case. The strategy is to be applied to validate the savings.

Ground Source Heat Pump Ground Interactions

The building's heating and cooling is supplied from four ground-source heat-pumps (GSHP) connected to eight 400 ft (152 m) deep boreholes with a cooling capacity of 30 tons. Preliminary heat interactions with the ground revealed a yearly imbalance in the range of –220,000 kBtu (–65,000 kWh), which signifies that the ground is heating over time, i.e., the building is cooling dominated. How this imbalance will play a role in the future capacity of the geothermal system will be monitored. Natural ventilation and better radiant slab control strategies can mediate the

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Table 4. Natural Ventilation Current Use and Potential Use (Yuan 2016)

Cases	Conditions		% in Effect	% if Combined	
Yuan	Closed		71.40		
1	59.0°F–71.6°F (15°C–22°C)	30–70% rh	9.43		
2	59.0°F–71.6°F (15°C–22°C)	W < 11.6 g/kg	6.09	15.52	(1+2)
3	53.6°F–59.0°F (12°C–15°C)	W < 11.6 g/kg	5.61	21.13	(1+2+3)
4	46.4°F–53.6°F (8°C–12°C)	W < 11.6 g/kg	7.47	28.60	(1+2+3+4)
Current	Closed		90.96		
	55.4°F–71.6°F (13°C–22°C)	outdoor air need	9.04		

Windows automatically close upon rain detection. Psychometric data determined from BAS data using Bell et al. (2014). Data from February 20, 2016 to February 20, 2017.

effects. Installation of motorized shades can reduce solar gains and diminish cooling loads.

Demand Reduction

The Varennes Library does not have batteries to store the excess electricity for later use. Instead, electricity is sold back to the grid. With the increasing number of energy producing buildings, grid instability can be caused because of load mismatches. Ideally, the building should export electricity into the grid during peak hours or avoid importing electricity during those times. In localities with time-of-use (TOU) pricing, the optimal economical model will apply demand reduction strategies during peak hours. Currently, the International Energy Agency (IEA) Task 67 (Jensen et al. 2017) and ASHRAE Technical Committee (TC) 7.5 “Smart Building Systems” are working on solutions.

In Quebec, the grid’s peak demand occurs during the winter since most small to medium commercial buildings and residential buildings are electrical resistance heated. In Figure 12, the library’s power demand is plotted along with the grid’s for a very cold February day. The library’s demand curve follows a 9:00 a.m. to 9:00 p.m. schedule where the heating is turned on at around 6:00 a.m. The grid experiences a peak from 6 a.m. to 9 a.m. and from 5 p.m. to 9 p.m. With predictive controls and by using the radiant slab’s thermal mass, the library can reduce its peak demand during the two peak periods.

SUMMARY AND DISCUSSION

The Varennes Library demonstrated that it is possible to build a high-performing net zero energy building without significant cost increases by using an integrated design process and optimizing the solar collection area and building shape at the early design stages. With an installed PV array of 110.5 kW, small footprint, and highly efficient architectural and mechanical system and features, the library has the potential to reach net zero. The challenges are primarily related to optimizing operation and are presently being addressed. Poorly functioning inverters had caused a production loss but have been replaced and inverters are now monitored individually. Thermal comfort is satisfied for most of the time, but can be improved through better utilization of the radiant slabs and underfloor ventilation system. The motorized windows are used approximately 9% of the time, however, a recent study suggests a much larger operational period. Other smaller issues can be solved with routine maintenance. The role of net zero energy buildings will be paramount in the near future as more decentralized renewables are introduced onto the grid, which may lead to grid stability and energy availability mismatch issues. Buildings such as the Varennes Library are highly instrumented, sometimes have access to thermal and electrical storage solutions, and will need to actively act as regulators of demand to aid the utility by relying on energy flexibility concepts.

Implementation of the proposed improvements including MPC strategies to control the radiant slab leading to demand reduction strategies, and a deeper analysis of the BIPV/T system are currently underway and will be published in follow-up papers.

Considering alternatively the source energy NZE definition over site energy (Torcellini et al. 2006), the energy boundary is extended to the source production level. In Quebec, the strong majority of electricity comes from hydroelectric dams. The primary energy factor (PEF) for hydroelectricity is 1.50 (CEN 15603 2008), the Canadian average PEF is 1.98, and on-site PV production has a PEF of 1.00 (Energy Star 2018). Each unit of electricity consumed on-site originating from PVs displaces a unit of electricity purchased from the utility, therefore making the on-site production be worth 1.50 to 1.98 times its value at the source level. The bottommost chart in Figure 4 shows that the ratio between consumption and production is between 1.23 and 1.49. Applying the hydroelectricity PEF to the production, the building becomes net zero at the source level.

Looking back on the project and on the design charettes, the early challenges came from convincing the different professional domains that the design will perform through examples: mostly institutional and residential, not enough

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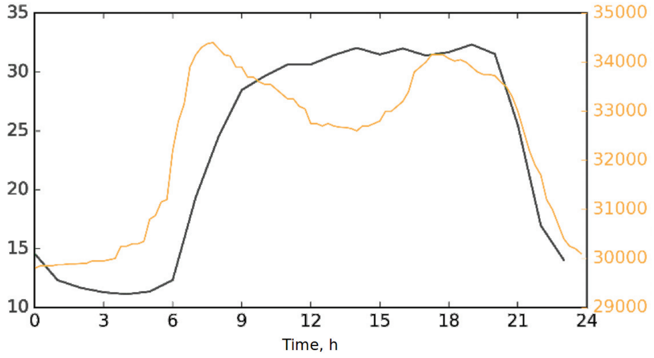

Figure 12 *Library electrical demand and grid demand for an extreme winter day, Hydro-Québec data from (Laperrière and Brassard 2011).*

commercial. If there was an easy-to-use, fast, and parametric tool or method to estimate the energy use for various design options, this could have guided and facilitated the process for the actual design.

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