Using Performance Simulation in the Commissioning and Monitoring of a Net-Zero Energy Home

Yannick Allard[*]**, Michaël Kummert, Michel A. Bernier**

École Polytechnique de Montréal, Département de génie mécanique

Case postale 6079, succursale centre-ville, Montréal (Québec) H3C 3A7, Canada

[*] Corresponding Author, yannick.allard@polymtl.ca

Abstract

Abondance Montréal is a net-zero energy "triplex", a typical 3-unit apartment building in Montreal. This paper reports the lessons learned during the commissioning phase of the building and in setting up the monitoring system. As-built numerical simulation is used to assess performance against design specifications, without having to wait for measured yearly performance results. Commissioning results are used to validate and fine-tune the simulation inputs. This allows detecting and remedying operating problems that are not critical but lead to a degradation of the energy performance. After the commissioning phase, a detailed monitoring system is implemented to allow a full performance assessment and to provide data for calibration of the design simulations. Comparison between design simulation and recorded performance is compared to simulation outputs.

1. Introduction

The "EQuilibrium Sustainable Housing Demonstration Initiative" [1] is a national project led by the Canada Mortgage and Housing Corporation (CMHC) which aimed at helping local teams to design and build 15 net-zero energy homes throughout Canada. These net-zero energy homes produce as much energy from renewable sources as the amount of energy they use, on a kWh basis. The building analyzed in this paper was designed by the "Abondance Montréal" team, who decided to take on the challenge of net-zero energy in an urban environment. The triplex (a typical 3-unit apartment building in Montreal) relies on drastic reduction of energy demand for space heating and appliances, highly efficient Heating, Ventilation and Air Conditioning (HVAC) systems and building-integrated solar energy devices (thermal and photovoltaic). The construction of the building was completed in 2009 and the photovoltaic system was installed in April 2010. This paper reports the lessons learned during the commissioning phase and in setting up the monitoring system.

2. Using calibrated simulations for energy performance assessment: literature review

Uncalibrated simulations of buildings and mechanical systems are widely use in estimating building energy performance. This modeling procedure may result in major differences (7%-73%) between estimation and measured electrical consumption [2]. Calibrating building simulation with measured data results in more accurate models that can then be used to perform continuous commissioning, assess design changes, etc. Most studies are based on iterative calibration with monthly energy bills for calibration [3], and very limited information has been published on simulation calibration for small multifamily building using TRNSYS. The International Performance Measurement and Verification Protocol (IPMVP) was used as a guideline in establishing the base of the measuring and verifying (M&V) Plan [4].

3. The net-zero energy triplex

3.1. Building site

The project location was selected based on availability and accessibility by public transportation. The building is integrated within the local urban grid, which means that the orientation is not optimum for passive solar gains. Only the East and West façades have good access to daylight. The North wall is a party wall with an adjacent building, and the South wall will be completely shaded by an adjacent building. This choice reflected the aim of the Design Team to deliver a project that could be repeated in non-optimal locations for solar buildings.

Fig. 1. Triplex Abondance

3.2. Building envelope

The building envelope has a thermal resistance of 7.9 $m^2 \cdot K/W$ for walls and 12.3 $m^2 \cdot K/W$ for the roof. The fenestration is composed of heat mirror (low-e) triple glazing filled with krypton, with an overall U-value of 1.35 $m^2 \cdot K/W$, mounted on an aluminum frame with a thermal break. The glazed area fraction is 40 % on the south-west façade and 35 % for the north-east wall. The building air infiltration rate is 0.5 ACH @ 50 Pa, which is 5 times better than the local energy efficiency standard for houses.

3.3. HVAC

The Abondance Triplex is divided vertically in three apartments of 96.6 m^2 each and one mechanical/storage room located in the basement. The air-based heating and cooling system includes one Ground Source Heat Pump (GSHP) and one Heat Recovery Ventilator (HRV) per housing unit (3 GSHPs and 3 HRVs in total). The 3 systems are independently controlled by thermostats located in each housing units. Ventilation can operate according to 3 modes depending on weather conditions (heating, cooling and free cooling). The free cooling mode was added as a result of the design simulations [6] in order to cancel the cooling demand during mild weather. Fig. 2 shows that the free cooling mode allows to operate without cooling or heating when the daily average temperature is between 7 °C and 20 °C. This mode mainly consists in deactivating the HRV and supplying a large amount of fresh air to the building using the main heat pump fans (see Fig. 3).

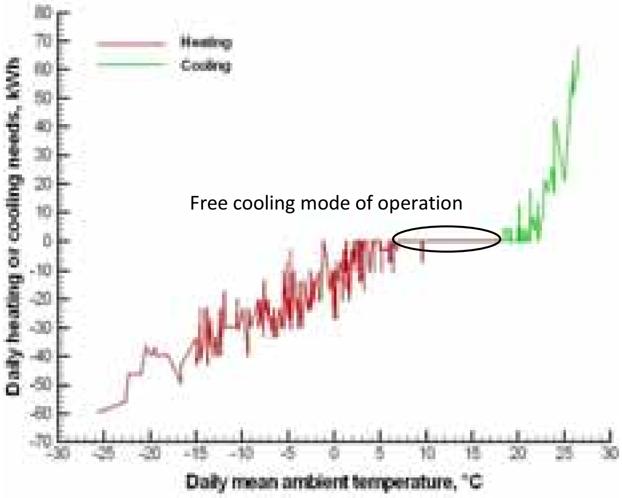


Fig. 2. Daily energy needs as a function of daily ambient temperature

3.4. Domestic hot water

Domestic hot water (DHW) is provided by a hybrid system, presented in Fig. 4, which combines drain (grey) water heat recovery (GWHR), GSHP desuperheaters, solar thermal collectors, and electrical auxiliary backup [5]. A recirculating pump is also installed to ensure instant hot water availability at all floors. The solar collector area is oversized to maximize the winter solar fraction. The design simulations estimated a renewable fraction of 0.73 (see Equ. 1 below for a definition).

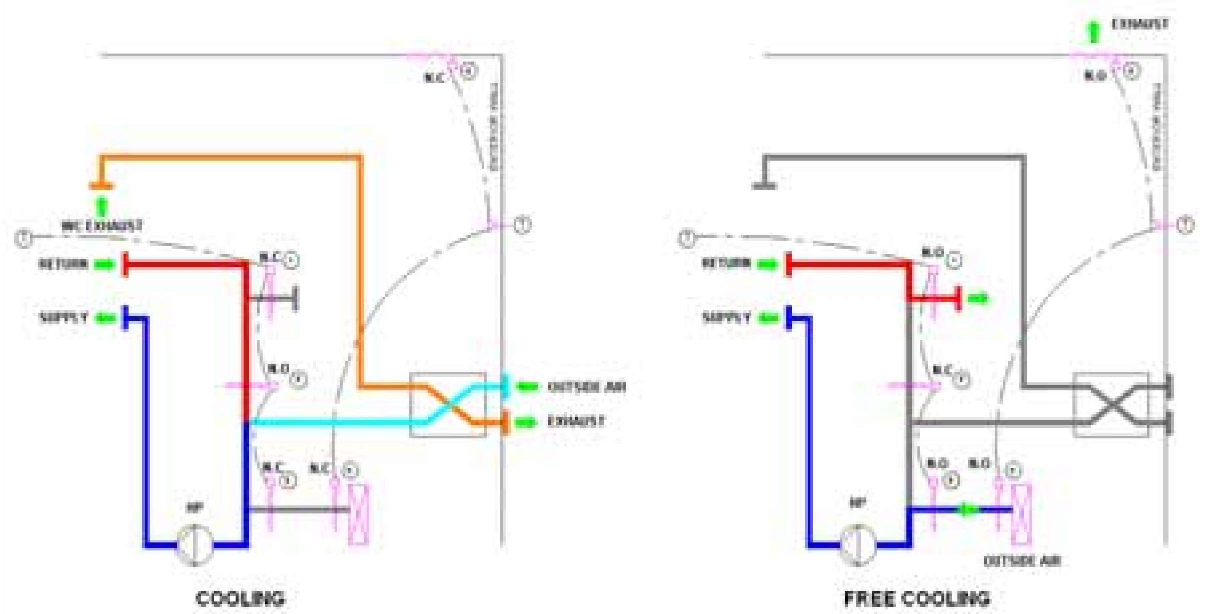


Fig. 3. Ventilation modes

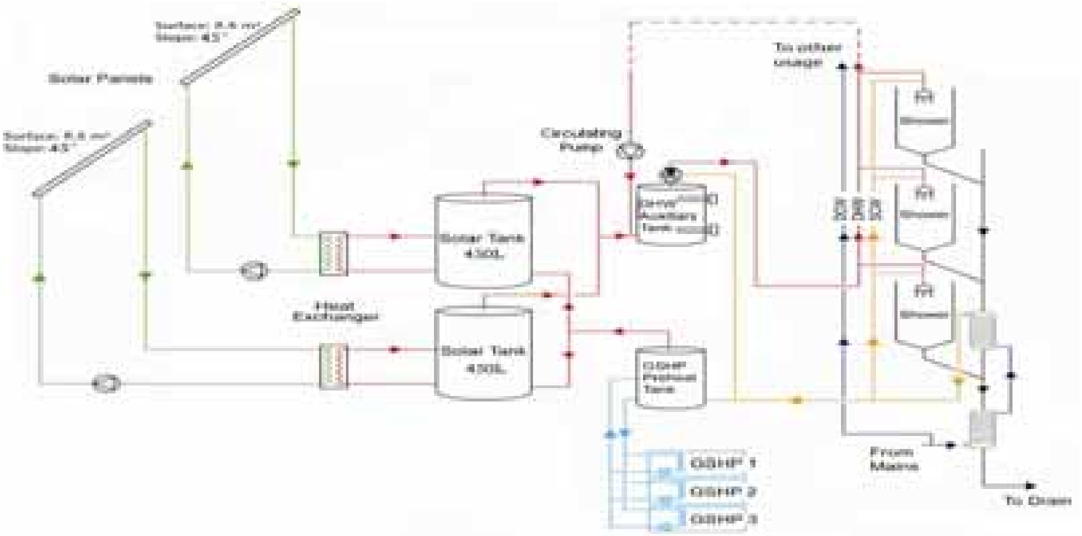


Fig. 4. Hybrid DHW system

3.5. Electrical system

Local renewable electricity is produced by photovoltaic (PV) panels located on the roof. Urban planning regulations in the area mandate flat roofs so the PV panels were installed on a metal structure tilted at 30° above the flat roof. The structure and PV panels leave enough headroom and provide shading for the roof terrace. The azimuth angle was imposed by the urban grid, it is 23° East of South. The produced electrical power is either used locally or fed into the grid. The utility company (Hydro-Québec) offers net-metering for renewable energy generated by small producers, so that the cost of electricity from the grid and to the grid are the same (net metering).

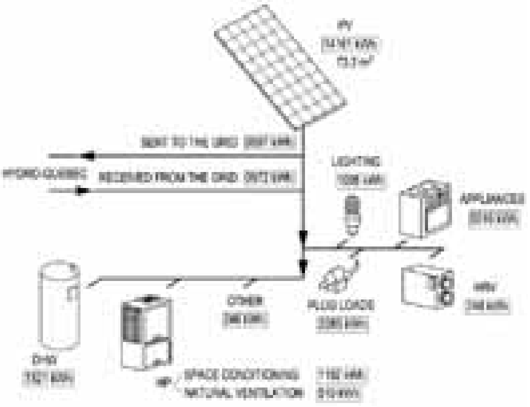


Fig. 5. Annual electrical energy distribution for design simulation [6]

The design simulations assumed a PV array with 60 PV panels (97.9 m^2) and the estimated production is 14100 kWh per year. The amount of electricity exchanged with the grid is estimated at 10000 kWh (imports and exports must be equal according to the net-zero energy definition). The numbers obtained in the as-built configuration are presented below. The overall energy balance of the system is presented in Fig. 5, where we can also note that 62 % of the energy is used by appliances and plug loads. This high percentage results from the use of a superior envelope design, efficient heat recovery on ventilation, and high-efficiency ground source heat pumps, which reduce the electrical energy consumption of HVAC systems significantly (reduction by a factor 5 compared to the base case). The building design and energy performance simulation results are described in detail in [6].

4. Commissioning phase

Commissioning of the building and HVAC system (including the domestic hot water system) was performed during building construction and in the beginning of occupation. The detailed commissioning phase highlighted and allowed to remedy main problems with the system.

After building insulation was completed, air infiltration and thermography tests were performed. These test allowed noticing minor air infiltration around the windows and doors, which was expected at that stage, as interior lining still had to be installed. The measured infiltration rate was exceptionally good at 0.5 ACH at 50 Pa. No unexpected thermal bridges were identified on infrared images shown in Fig. 6. Notice that the walls of a neighbouring building, at the far right of the picture, have the same color (hence the same temperature) as the Triplex windows – in other words the thermal resistance of the high-performance triple glazing is as high as standard construction walls.

Fig. 6. Air infiltration and thermography tests [7]

Because of the highly insulated and airtight building envelope, the design simulations had showed that the cooling energy use would be unacceptably high unless free-cooling was added to the system configuration. A series of dampers with their dedicated controls were added to implement the principle of operation represented in Fig. 3. However, it quickly became apparent that the controls of the motorized dampers used for free cooling were not operating correctly. Performing additional tests allowed identifying that control temperature set points of the damper were the cause of this problem. After modification, the system seems to be working correctly.

The DHW recirculation pump was not present in design simulations. It was added as an afterthought, which caused two issues. First, the performance of the hybrid DHW system is degraded, as shown by as-built simulations (see below). Secondly, the addition of a recirculation pump made the design of the mixing thermostatic valve more complex. In the early days of operation, the manager of the installation reported significant problems in the DHW loop and decided to shut off the cold water supply to the thermostatic mixing valve after different trial-and-error attempts to solve the problem. However, the solar thermal system can deliver water at 85°C so this is not a long-term solution. The commissioning phase identified the problem that the cold water supply valve was closed, but a short test could not confirm the thermostatic valve malfunction. This issue will be investigated during the monitoring phase, and the security of having continuous performance assessment was a key argument in convincing the building manager to re-activate the cold-water supply.

5. As-built simulation

The system configuration and selected components have been slightly modified compared to the final design simulations because of various reasons such as budget constraints, limited availability from local suppliers. Therefore, the original TRNSYS simulation input files were adapted to reflect the final configuration. These as-built simulations will allow to quantify the impact of last-minute design changes on the energy performance of the building (including whether or not the building still is a net-zero energy house). They will also be used and calibrated in the detailed monitoring and performance assessment phase. Simulations were divided in two majors subsystems: Domestic Hot Water system and building envelope with its HVAC systems.

5.1. Domestic hot water

The DHW system simulations realized during the design phase are presented more in detail in [5]. The system configuration has been updated to reflect changes in the selected equipment:

- two smaller GWHR units were used instead of one, due to available vertical space in the mechanical room;
- a different solar thermal system including a Natural Convection Heat Exchanger (NCHE) was installed.

The renewable energy fraction is used to compare the as-built and design simulations. The renewable fraction is defined as:

$$F_{ren} = 1 - \frac{Q_{aux} + W_{pumps} + W_{GSHP}}{Q_{DHW}} \quad (1)$$

Where Q_{aux} is the electrical energy provided by water heater, W_{pump} is the overall consumption of the various pumps in the system, W_{GSHP} is the additional energy used by the compressor of the GSHP in heating mode to feed the desurperheater and finally, Q_{DHW} is the annual consumption of DHW (287 L/day at 55°C) for all 3 units.

The monthly results comparing these simulations, presented in Table 1, show that these changes led to a small increase of the renewable energy fraction (~8%).

Table 1. Monthly renewable fraction for As-built and Design simulation

Month	Q_{DHW} (kWh)	W_{GSHP} (kWh)	Pump energy consumption (kWh)			Q_{AUX} (kWh)	F_{ren} As-Built	F_{ren} Design
			Desuper. Pump	Solar Pump	W_{pumps}			
Jan	580	22	17	1	18	157	0,659	0,673
Feb	550	18	13	2	15	78	0,800	0,788
Mar	665	8	6	2	8	124	0,788	0,784
Apr	580	1	1	2	3	61	0,888	0,801
May	440	0	0	3	3	29	0,927	0,810
Jun	410	0	3	3	6	6	0,972	0,798
Jul	340	0	8	3	11	4	0,956	0,772
Aug	290	0	5	3	7	12	0,932	0,736
Sep	275	0	1	2	3	14	0,940	0,752
Oct	395	2	1	2	3	80	0,784	0,725
Nov	430	9	7	1	8	180	0,543	0,575
Dec	545	20	15	1	16	205	0,557	0,583
Total	**5500**	**80**	**76**	**26**	**102**	**950**	**0,794**	**0,732**

The most significant changes is the introduction of a circulating pump for the DHW loop in order to provide hot water instantaneously at all points-of-use. Simulation results presented in Table 2 show that this addition has a significant impact on the energy performance of the hot water system.

Table 2. Monthly renewable fraction for with and without recirculation configuration

Month	Without Hot Water Recirculation			With Hot Water Recirculation		
	Q_{AUX} (kWh)	Recirculation Pump (kWh)	F_{ren}	Q_{AUX} (kWh)	Recirculation Pump (kWh)	F_{ren}
Jan	157	0	0.659	266	0.6	0.471
Feb	78	0	0.800	171	0.5	0.630
Mar	124	0	0.788	223	0.5	0.639
Apr	61	0	0.888	145	0.5	0.742
May	29	0	0.927	122	0.5	0.714
Jun	6	0	0.972	85	0.5	0.778
Jul	4	0	0.956	72	0.5	0.755
Aug	12	0	0.932	96	0.5	0.641
Sep	14	0	0.940	101	0.5	0.619
Oct	80	0	0.784	179	0.5	0.532
Nov	180	0	0.543	287	0.5	0.293
Dec	205	0	0.557	315	0.5	0.354
Total	**950**	**0**	**0,794**	**2062**	**6**	**0,591**

As we can see in Fig. 4, the water going through the recirculation loop can only be heated by the auxiliary electric water heater. Even if solar heat is available, electricity is used to compensate piping losses, which results in a 25% reduction of the renewable fraction. The energy input in the last DHW tank (auxiliary electric) has more than doubled.

The recirculating pump was installed for comfort reasons and to save water, but it leads to a significant decrease in the energy performance for DHW preparation. The calibrated model and online monitoring will be used to assess possible improvements through reduced operating times and other control strategies.

5.2. Building envelope and HVAC

The differences between design simulations and actual building envelope and HVAC system are:

- measured air infiltration rate of 0.5 ACH@50Pa is better than the estimated one of 0.8 ACH@50Pa;
- wall layers and building orientation have been corrected to represent real building characteristics (differences came from minor details and simulation input errors);
- the single 100-m borehole containing 2 U-tubes has been replaced by two 70-m boreholes containing one U-tube each (local installers are not familiar with multiple U-tubes per borehole);
- PV panels had to be sourced from a different supplier to meet the requirements of a funding agency. A total of 60 panels rated at 230 Wp were installed instead of the original 62 panels rated at 205 Wp. The installed PV panels have a lower efficiency, which resulted in a larger PV array.

Table 3. Result summary – Electrical consumption

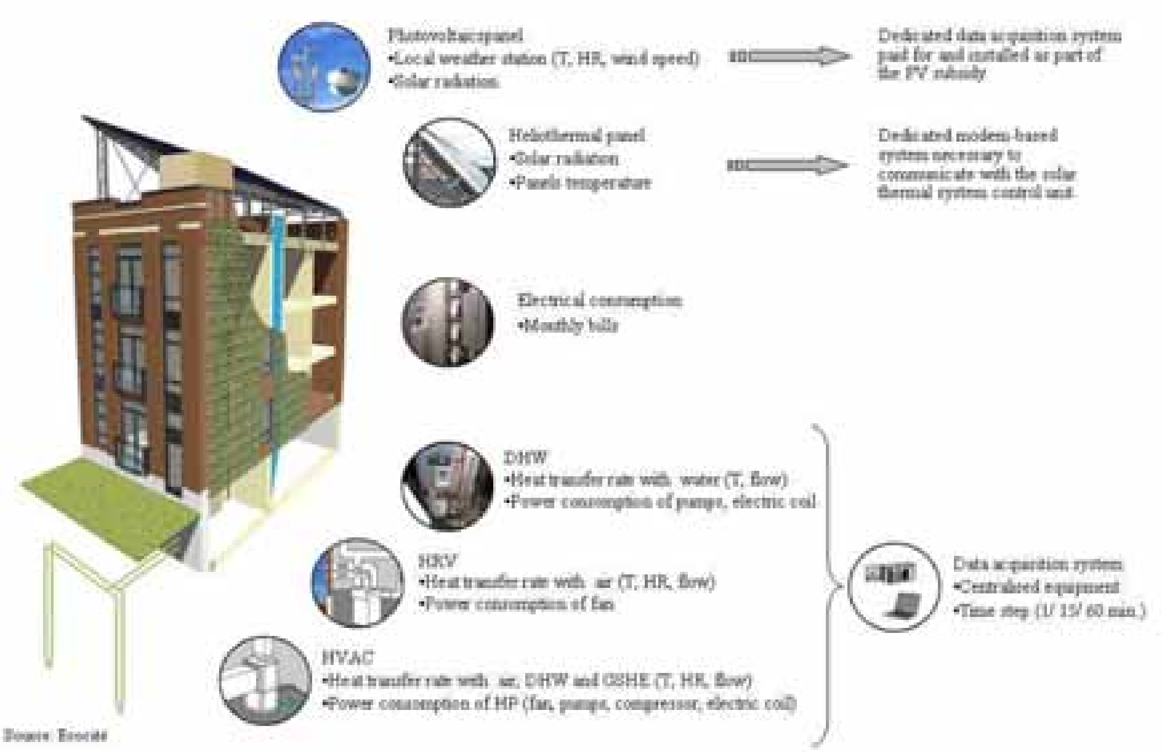
	As-Built (kWh/year)	Design (kWh/year)
HRV	907	931
HP	1910	1509
DHW	2250	1521
Lighting	1095	1095
Appliances	5516	5516
Plug load	3285	3285
Pumps	57	246
Total	**15020**	**14103**
PV output	**15092**	**14161**
Net Zero Energy	**YES**	**YES**

Table 3 shows the yearly electricity use of the building and the yearly net output of the PV array. It can be seen that the increased PV production compensates the higher electricity consumption and that the net-zero objective is still attained. Mainly, two sectors are responsible for the augmentation of electrical consumption: the recirculation loop of the DHW system and the HP which is directly related to building heating (and cooling) load and the efficiency of the ground source heat exchanger.

6. Lessons learned in installing the monitoring system

The monitoring system was not specified by the design team. As often in similar projects, different actors were involved in designing and providing funding for the different subsystems, which resulted in a fractioned monitoring system. The main objective of the monitoring is to assess whether or not the net-zero energy target is met, which can be done very easily based on monthly electricity bills. But this would not provide any information on how well (or how poorly) the different subsystems perform. This requires a much more complex data acquisition system. The monitoring devices that were installed to track the performance of all the subsystems (PV, heat pumps, solar thermal, HRV) were combined. Additional data loggers were added to the system and a PC-based centralized data logging system was connected to the different subsystems in place. This allowed recording all system variables at the same time (see Fig. 7).

In total, about a hundred sensors collect data with various time intervals. First of all, a local weather station takes readings on dry bulb temperature, humidity ratio, wind speed and solar radiation at every hour. Then, measures associated with PV and HVAC systems are recorded every 15 minutes and every minute for DHW system. The measuring frequency is mainly based on the time constant of measured phenomena, and it should also match the time step of the simulations being calibrated. Measurement of energy fluxes for these various systems are calculated from basic measurements (temperature, humidity ratio, air/water flow, produced/consumed electrical energy).



Source: Ecocité

Fig. 7. Monitoring system

7. Discussion and conclusions

The commissioning phase and early monitoring results have already delivered improvements to the day-to-day building operation. The long-term online monitoring will be instrumental in resolving the last question marks or problems related to the operation of this complex HVAC and DHW system.

As-built simulations allowed to quantify the impact of last-minute design changes on the energy performance of the building. In this case, addition of a DHW recirculation pump would have resulted in missing the net zero energy target if the PV array had not been increased at the same time.

Monitoring is time- and money-consuming. But in net zero energy projects, where initial investment is significant, measurement equipment represents a small fraction of the initial cost, and it is the best guarantee that the complex systems will operate according to the specifications and that their performance will be maintained or improved. Moreover, time and money can be saved by specifying the monitoring equipment at the design stage. Furthermore, all sensors should be connected to one data acquisition system in Fig. 7.

While we can reasonably expect that as-built simulations have delivered results that are closer to the actual building performance, these simulations still need to be calibrated to the actual equipment performance, the actual control strategies and the actual user behaviour. This will deliver “as-operated”, and not only “as-built”, calibrated simulations. User behaviour in particular is one of the main unknowns in building performance simulation and it will play a key role in deciding whether or not the Abondance Triplex is a net-zero energy building. The detailed monitoring system and the calibrated simulations will ensure that useful lessons are learned from the actual building operation and that these lessons can be applied to designing other similar buildings.

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