OPTIMIZATION OF NET-ZERO ENERGY SOLAR COMMUNITIES: EFFECT OF UNCERTAINTY DUE TO OCCUPANT FACTORS

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Abstract

This paper applies an energy optimization methodology to evaluate the impact of occupant factors on the net-energy consumption or generation of a community of net-zero energy or near net-zero energy homes located in Montreal, Quebec. The building simulation software EnergyPlus was used for energy simulations and Canadian national statistics were used to model occupant behaviour. Results showed that diversifying building designs can decrease the impact of variability of occupant behaviour and reduce peak loads.

Introduction

This paper presents an optimization methodology for a net-zero energy (NZE) community which accounts for the impact of energy-related behaviour on the net-energy consumption and peak electrical loads of a community. A NZE community is defined as a community which generates as much on-site renewable energy as it consumes over a year. Variability in end-user energy consumption, which depends on the number of occupants per home, financial situation, age, and other factors, is an important aspect to take into account in a community energy system simulation model. Despite the difficulty of accounting for user behaviour, passive and active solar strategies can aid in mitigating its impact by reducing the electricity demand from the grid. Thus, there is a need to estimate the impact of energy-related behaviour on a community of NZE homes.

In this study, the effects of three types of occupant behaviour were considered: i) variations in heating set points, ii) variations in cooling set points, and iii) electricity consumption for lighting, domestic hot-water (DHW), appliance usage and their corresponding internal gains. Since the end-user electrical demand can only be estimated, this investigation used consumption profiles derived from Canadian national statistics of energy use in households [1]. Profiles were based on percentages of national energy consumption and were scheduled using normal distributions during occupied hours. It was assumed that a home with high appliance loads would also consume a proportionately large amount of electricity for DHW and lighting.

Due to the vast number of possible design combinations, an optimization methodology was used to facilitate the identification of individual building designs used to form the community with constrained orientations and footprint areas. An optimization approach ensures that energy conservation measures have been fully exploited prior to sizing building integrated energy generation using photovoltaics (PV) on the near-south facing roof surface. The impact of variable user behaviour was conducted on these pre-optimized home designs. For this paper, it was assumed that community sizes had equal ratios of all orientations ranging from -45 to 45 degrees of due south. Such orientations were selected to allow for acceptable passive solar performance and to consider communities in variable configurations. Diversifying building orientations has the notable property of reducing peak loads in communities [2, 3]. It is understood that an all south-facing community would have higher PV generation due to energy generation limited to roof-top area only.

The optimization methodology used in this study consists of a hybrid algorithm, a deterministic-evolutionary approach [4]. The objective of the optimization search is to maximize the amount of electricity generation of each individual home by reducing heating and cooling loads through passive solar design while maximizing electricity generation through PV. Since each home in the community is optimized for electricity generation, and since the total electricity generated is just the linear sum of electricity generated from each home, the electricity generated for a community will also be optimal. This assumption may not be true for community with centralized thermal storage and energy generation. The energy model used for building simulation was calibrated using monitored data from an existing near net-zero energy home [5, 6].

A net-zero energy community in Montreal, Canada, is used as a design case study. Montreal has approximately 4500 heating degree days (18°C reference) and 1 kW of PV facing due south at a 45 degree angle approximately generates 1200 kWh of electricity per year. Although results are specific to Montreal, the methodology can be applied to measure the impact of energy related behaviour on any NZE community.

Methodology

Rather than modeling the interactions among buildings in the whole community, a myriad of design alternatives for a single home are considered, while constraining orientations, footprint areas and user load consumption. This simplification is applied to reduce the size of the design space while still obtaining meaningful results. Centralized thermal storage or thermal energy sharing between homes is not considered in this study. Also, it is assumed that shading and infrared radiant exchanges between homes is not significant.

Seven different orientations, ranging from -45 to 45 degrees from due south, were used to model the orientation of houses in variable community shapes. It was assumed that homes are appropriately placed such that there is no loss in performance due to shading. Since communities rarely are composed of only one house size, three footprint areas were used: 100 m^2, 200 m^2 and 300 m^2 distributed across two above-ground floors. Heat loss through basements is considered, although basements are not considered as a portion of the footprint area. The remaining design parameters used in the optimization study are presented in Table 1. Note that individual houses were allowed to have heating and cooling systems, using electric powered heat pumps with an average coefficient of performance equal to three, as large as necessary to maintain set points during occupied periods.

Table 1. Definition of Optimization Variables used for Home Designs

Design Variable	Units	Low	High	Increments	Description
wall_ins	m^2 °C/W	3.5	12	8	Thickness of Wall Insulation
ceil_ins	m^2 °C/W	5.6	15	8	Thickness of Ceiling Insulation
base_ins	m^2 °C/W	0	7	8	Thickness of Basement Wall Insulation
slab_ins	m^2 °C/W	0	2.32	4	Thickness of Slab Insulation
aspect	--	0.7	2.2	16	Width to length ratio of building
ovr_south	m	0	0.45	4	Width of Southern Window Overhangs
int_loads	--	1	3	1	Occupant load profile (1: 50%, 2: 60%, 3: 70%)
roof_slope	deg	30	45	4	Roof slope
pv_eff	%	6	14	8	PV efficiency
pv_area	%	0	80	8	Percent of PV on roof
wwr_s	%	1	80	8	Window to Wall Ratio South (also N,E,W)
GT_s	--	1	4	1	Glazing type (also N,E,W)
set_heat	°C	18	25	4	Heating Setpoint (18 implies radiant floor)
set_cool	°C	25	28	4	Cooling Setpoint (28 implies NV)
FT	--	1	2	1	Window Framing Type (1:Wood, 2:Vinyl)
blind_irr	W/m^2	0	1000	4	Incident Solar Radiation for Blind Deployment
slab_th	m	0.1	0.2	8	Concrete Slab Thickness (Thermal Storage)
vwall_th	m	0	0.35	8	Concrete Wall Thickness (Thermal Storage)
zone_mix	L/s	0	400	4	Air Recirculation Rate between thermal zones
infil	ACH	0.025	0.179	8	Natural Infiltration Rate (ambient pressure)

The design of each home was performed using an optimization algorithm by constraining the floor area, orientation and user load consumption pattern to given values. This ensured that all homes were designed to improve their performance by modifying blind control, window-to-wall ratios (WWR) and sizing of thermal storage for solar gains regardless of their specified orientation and footprint area. Electricity generation using PV was restricted to the roof of the home. Consumption schedules were created by normal distributions of electricity use during occupancy in the mornings, evenings and weekends. It was assumed that a high consumer of electricity for appliances was also a proportionately high consumer of electricity for DHW and lighting.

From the optimization data, equal ratios of orientations and footprint areas were selected to form each community size. A single home, facing due south, was used to compare net-energy consumption and peak loads against. Population sizes of 21 homes, 35 homes, 49 homes and 98 homes were used for the study. For all optimized home designs, heating set points (HSP) of 18ºC, cooling set points of 28ºC (CSP) and electricity consumption equivalent to 50% of Canadian national averages was used [1]. The 50% target was selected as it most closely matched monitored data of a near NZE home located near Montreal [5, 6].

For evaluations of the impact of user behaviour, uniform distributions were used for stochastic sampling. Heating set points were allowed to take values of 18 to 21ºC with a step-size of one degree. Cooling set points were allowed to vary from 25 to 28ºC, with similar step-sizes. Electricity consumption profiles, relative to Canadian national averages, of 50, 60 and 70% were used [1].

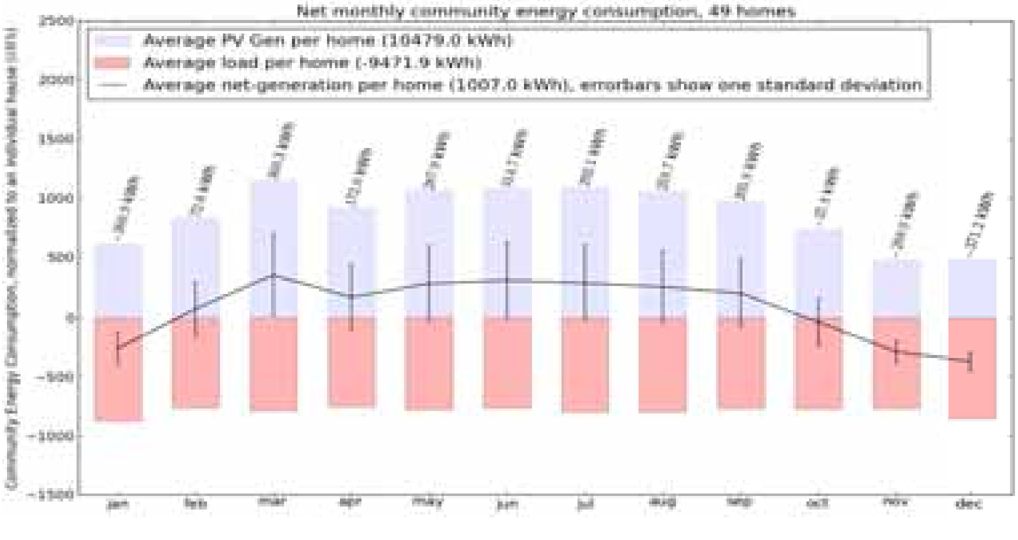
Peak loads of the community were analyzed at 15 minute intervals for each house in the community. After the entire community was simulated, the dataset was post-processed to determine peak loads of the community.

Results

For the first part of the study, an estimate of how much electricity a community of net-zero or near net-zero energy homes could produce was made assuming occupants used the lowest heating set point, the highest cooling set point and 50% of the national average for electricity consumption.

Figure 1 shows the average PV and building loads as simulated for a community of 49 homes, normalized to one home. It will be shown later that the size of the community does not greatly affect this profile. A rule of thumb of about 1000 kWh of electricity generation, on average, per home in the community can be used if occupants consistently practice the extreme limits of energy conservation. It is noted that the community only consumed electricity for four months of the year.

Fig. 1 Base case net-generation capacity of a community of 49 houses, normalized to a single home, using 18C heating set point, 28C cooling set point and 50% of national average user loads. Values indicate electricity use (+ if generation)



This exercise was conducted again, but this time using randomized HSP, CSP and user loads, see Figure 2. Note that the shape of the averaged consumption/generation profile (black line) is similar, but the baseline loads have shifted. Occupant factors alone have converted the community from an energy producer, to an energy consumer with a normalized average of 800 kWh of electricity consumption per household. Note that homes generated electricity for seven months of the year, but generation was not significant enough to offset winter loads.

To measure the relative impact of randomizing HSP, CSP and user loads separately on variable community sizes, simulations were initiated 200 times, averaged and normalized to a single home, as shown in Table 2.

Fig. 2 Net-generation capacity of a community of 49 houses, normalized to a single home, using randomized heating set points [18, 21C], cooling set points [25, 28C] and national average user loads [50%, 70%]

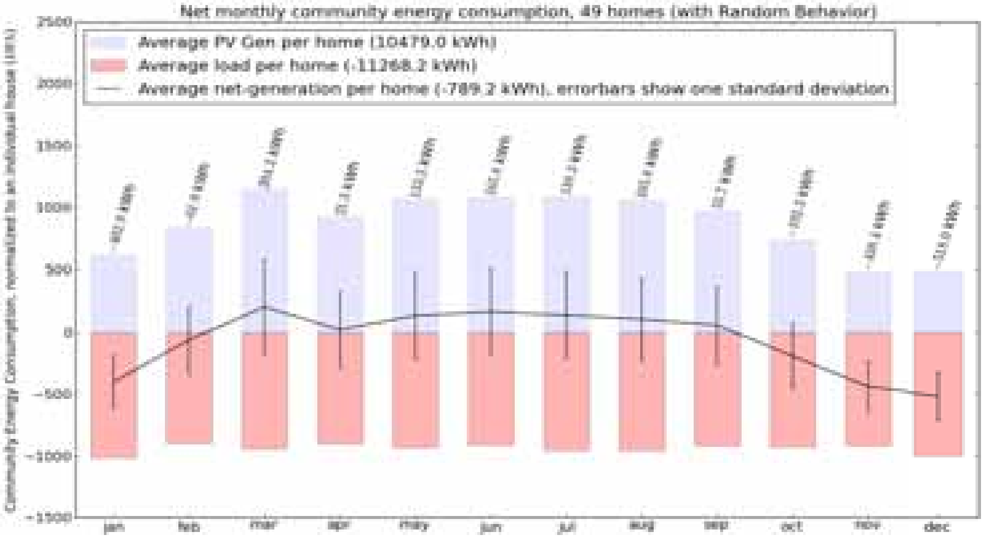


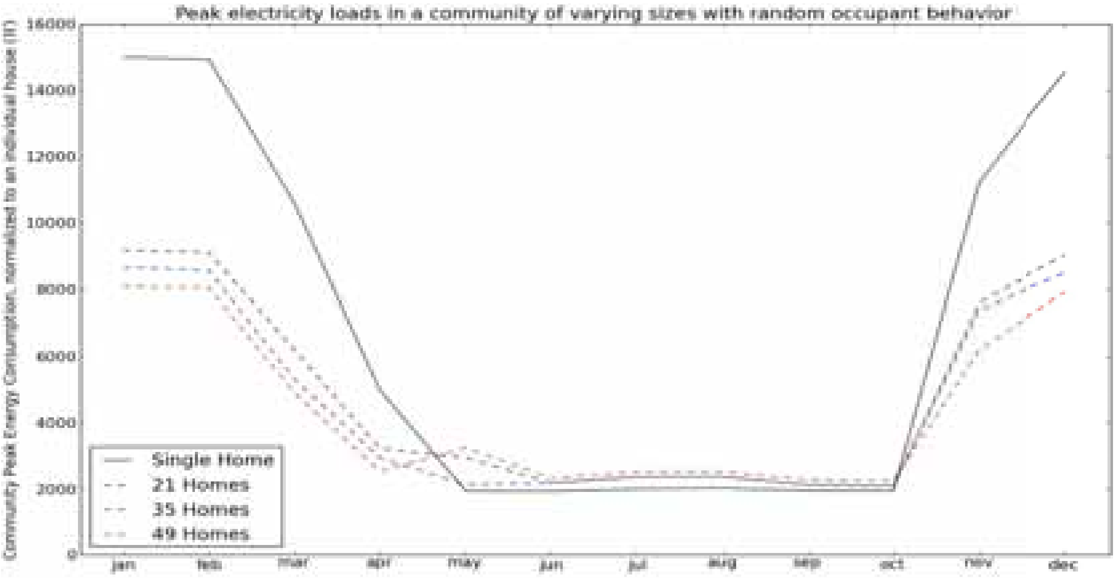
Table 2. Average net-generation capacity (kWh) and variation using a 95% confidence internal of a community of varying size, normalized to a single home, using randomized heating set points [18, 21C], cooling set points [25, 28C] and national average user loads [50%, 70%]

Number of Homes	**Varied Internal Loads (kWh)**	±	**Varied HSP (kWh)**	±	**Varied CSP (kWh)**	±	**Combined (kWh)**	±
1	-425	4306	1193	285	1366	68	-392	3923
21	-882	896	752	88	957	31	-1213	854
35	-945	722	751	69	965	23	-1146	747
49	-874	629	754	51	951	21	-1183	570
98	-929	401	753	37	951	15	-1201	483

From Table 2, the impact of electricity consumption through appliances, lighting and DHW far outweighs the impact of HSP and CSP. It should be noted that this effect alone can turn a net-zero community into an energy consuming community. Variability in HSP and CSP is not enough to affect the net-generation status of the community. The effect of random behaviour on a community tends to increase rapidly at first, due to homes being oriented away from south, but plateaus for larger community sizes. As one might expect, the impact of energy-related behaviour on the average electricity consumption of each home was found to be independent of community size, since averages fall within simulated variance extremes. However, the variability of net-electricity consumption tends to diminish with increasing community size. This is a consequence of the central limit theory of statistics which states that for any distribution, variance will tend to zero as the sample size increases. That is, statistical artefacts tend to cancel each other out for large sample sizes and averages tend to real mean values. This notion is important to understand when sizing centralized energy generation equipment to make a community of homes net-zero energy. Although the impacts of occupant behaviour on a single net-zero energy home are significant and highly unpredictable, the net impact of occupant behaviour, from a community perspective, becomes increasingly more predictable as the community size increases.

The effect of occupant behaviour not only diminishes with regards to variability of net-annual energy consumption, but also with regards to peak loads. Figure 3 shows the maximum peak power usage of the entire community over the year using 15 minute intervals, normalized to a single home, for randomized occupant behaviour. Peak loads in the community are dominated by the heating season. Note in Figure 3 that a single building requires almost 15 kW of power, whereas, by diversifying building orientation, floor areas and design, this can be reduced by 50% for larger community sizes. Peak loads of the community, normalized to a single home, tend to decrease as the community size increases. The combination of on-site generation and diversification of peak load timing can be used by community designers to flatten peak loads of a community. Note that a single home has slightly lower peak loads in the summer months than a community of homes due to its direct south orientation and thus improved PV output.

Fig. 3 Peak electricity usage of a community of varying sizes, normalized to a single home, using randomized heating set points [18, 21C], cooling set points [25, 28C] and national average user loads [50%, 70%] based on 15 minute intervals



Conclusion

This paper estimates the importance of energy-related occupant behaviour on the electricity consumption of a community. Pre-optimization of home designs was performed to ensure conservation measures, such as passive solar design, was fully exploited to reduce the electricity consumption of the home at various orientations and footprint areas. EnergyPlus was used for building energy simulations [7]. Some of these initial homes were near net-zero and other were net-positive energy, but the summation of both resulted in slightly net-positive energy communities.

Parametric analysis using random samplings was used to estimate the impact of energy related occupant behaviour on the variability of energy consumption and peak community electricity loads. It was found that random occupant behavioural factors can easily convert the community into a consumer of energy over an annual period.

To identify which occupant factors impact energy performance the most, repeated community simulations were performed with randomized occupant behaviour. Communities of NZE homes with variable orientations have several notable properties under variable occupant behaviour: i) they mitigate variability due to occupant effects, and ii) they reduce the peak load of the community, as normalized to a single home. These factors are important to understand and estimate as they have implications for sizing on-site energy generation.

Occupant behaviour, primarily in the form of appliance, lighting and DHW loads, can greatly deteriorate the performance and net-energy generation of a community of NZE homes. Estimating such behaviour stands as a major challenge in the design of NZE homes and requires further location specific research.

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