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An Approach Towards Achieving Net-Zero Energy Buildings Based on a Stochastic Tenant Model

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Abstract: *During the simulation-aided net-zero energy building design process, there are uncertainties related to occupancy schedules, occupant behavior, and the corresponding effect on thermal and electrical loads in buildings. As a result, designers' assumptions about occupant-related energy use may have a significant impact on equipment sizing and associated capital cost. This paper examines the potential of using stochastic tenant models (occupancy, lighting, and plug loads) in order to understand the relationship between uncertainty from occupants' behavior and photovoltaic (PV) system sizing to achieve NZE. Using the medium Canadian office reference building model as a case study, it was found that uncertainty of occupants for sizing PV is very expensive if the objective is to be highly confident that the building will achieve NZE. The results revealed that each incremental percentage point of certainty becomes increasingly expensive as we increase the confidence that PV is adequately sized to achieve NZE.*

Keywords: *net-zero energy, occupant behavior, stochastic occupant modelling, photovoltaic system sizing*

1. INTRODUCTION

Nowadays many countries are encouraging and pursuing net-zero energy (NZE) buildings to promote sustainable development. Based on the climate, different passive design techniques could be applied along with the choice of the appropriate renewable energy system to generate the required annual energy demand (Athienitis & O'Brien, 2015; AbuGrain & Alibaba, 2017). In Canada, National Research Centre (NRC) have been focusing on developing design guidelines in order to achieve NZE (NRC, 2017). During early design stages, architects/ and engineers often use whole building energy simulation tools to predict annual energy demand to achieve NZE. However, during the design process, there are several major sources of uncertainty, including occupant behavior, occupancy, and the corresponding effect on thermal loads in buildings (Wei , Jones , & de Wilde, 2014; de Wilde, 2014; Yan, et al., 2015).

Previous studies have focused on studying the effect of occupant behavior in NZE. Barthelmes et al. (2016) considered different occupant behavior lifestyles (low, standard, and high consumer) and household composition (family of four people, old couple, and young couple) in a residential NZE building in Italy. They found that the energy consumptions vary from –83% for the low consumer scenario up to +76% for the high consumer compared to the basic standard consumer scenario. The results of their study revealed that the building energy performance is heavily dependent on the type of post-occupancy household arrangements. Brahme et al. (2009) found that conservative occupant behavior could cause a reduction to the energy consumption by approximately 50% to the typical assumption (i.e. design point) in high-efficiency residence. While, the energy consumption could increase by 50% by using wasteful assumption with respect to typical occupant assumptions. Carpino et al. (2017) used national and local statistical data to generate different scenarios (number of components of a family, and different occupant behaviors) to evaluate the influence of user pattern on the energy consumption in Mediterranean climatic condition. Becchio et al. (2016) found that the calculated energy consumption of a high-performance building in Italy during design stage (based on typical occupant assumptions) was higher than the measured data (realistic occupant behavior) by 50%, 19%, and 16% for space heating, DHW, and electricity use, respectively. Gill et al. (2010) observed the same discrepancies in the energy consumption of a residential buildings in the United Kingdom but with different values for space heating (51%), electricity use (37%), and DHW (11%). Nord et al. (2018) evaluated the change in the energy performance of a zero-emission building (ZEB) located in Norway based on occupant behavior to analyze the electricity grid stress. Standard schedules, well-defined profiles based on thorough statistical analysis, and voltaic modelling methods were used. 31 scenarios for different occupant behaviors were analyzed. It was found that the change in

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occupant behavior resulted in grid stress variance from −5% to +13% compared to the reference case based on the standard values. It was also found that the occupant behavior might change the annual energy balance reliability by 20%. A study by Judd et al. (2013) evaluated the way occupants interact with green office buildings and opportunities to optimize their behavior to further reduce energy use, led by Pacific Northwest National Laboratory (PNNL).

The above-mentioned studies reported that the design evaluations of zero-energy often do not match the real performance in terms of indoor environmental quality and annual energy use. These discrepancies could be due to: 1) peculiar users' interactions with building components (such as windows and blinds), and 2) uncertainty of building simulations in relation to input data and occupants' behavior (Stazi & Naspi, 2018).

Such discrepancies could yield to uncertainties in: 1) determining how much energy is required by consumers, and 2) sizing of renewable energy system (such as solar photovoltaic (PV) systems) to generate the amount of electricity required to achieve zero-energy building (Skunpong & Plangklang, 2011). In the context of sizing off-grid PV systems (which typically utilize battery back-up systems), designers prefer to design for the "worst-case" scenario (i.e. constant occupancy schedules and accounting for maximum potential electricity usage from lighting and equipment) (CSRA, 2010; Carpino, Mora, Arcuri, & De Simone, 2017). This could yield to oversizing of the PV system. Oversizing PV system might help in accounting for change in climate, degradation of building components/systems, and change in building function/space use (Carpino, Mora, Arcuri, & De Simone, 2017). Oversizing the PV system can cause the inverter to operate at its maximum capacity for a larger percentage of the time and the solar system will produce more energy during times of low solar radiation (JSTOR, 2014). Furthermore, the cost-benefit analysis of oversizing is a function of the PV system costs (in both materials and labor), inverter costs and other balance-of-system costs in addition to the life-cycle costs. Moreover, oversizing PV system will require an increase of PV array size which could be an issue regarding the limited PV surface area on roof /walls (Torcellini, Pless, Deru, & Crawley, 2006).

The aim of this paper is to understand the relationship between uncertainty from occupants' behavior and sizing PV system to achieve net-zero energy. The definition of net-zero energy used in this study is net zero source energy. Net-zero source energy (NZE) means that on-site renewable energy generation meets or exceeds the building energy demand during a typical year (Carpino, Mora, Arcuri, & De Simone, 2017). The main contribution of this paper is to demonstrate a method for sizing PV systems on the basis of a probabilistic model in order to understand the relationship between certainty of achieving NZE and the cost premium of improving certainty. The paper commences with the framework describing: 1) the probabilistic tenant model, 2) the building energy model, and 3) the application of the developed probabilistic tenant models on the parametric building energy model. The paper then discusses the PV design approach in terms of sizing and cost-effective analysis. Next, the simulation results are provided. Finally, the paper follows with recommendations and guidelines for modelling occupants to support the design of Canadian net-zero energy office buildings.

2. FRAMEWORK

This section commences with describing the developed probabilistic tenant model based on realistic data measured in a multi-tenant office building. This is followed by a description of the parametric building energy model of a medium Canadian office building. Office buildings were selected in this study as there is a diversity in occupant behavior such as arrival and departure time, switching on/off lighting and equipment, changing thermostat set-point, and opening/closing blinds and windows (O'Brien, Gunay, Tahmasebi, & Mahdavi, 2016). Finally, the application of the developed tenant model to the parametric building model is addressed to tackle the current topic of PV system sizing to achieve NZE. EnergyPlus v8.7 was selected as the energy simulation tool in the current study. Figure 1 shows the framework of the current study.

2.1 Tenant modelling approach

As mentioned above, relying on conservative assumptions regarding occupancy and behavior as well as power densities may cause oversizing of PV system. Table 1 and Figure 2 shows standard values and schedules for the above domains that are typically used for office spaces in building simulation, respectively. It should be noted that many of the standard values and schedules are based on data that were collected three decades ago (Deru, et al., 2011).

In the context of modern Canadian office buildings that are equipped with fixed windows, the occupants' and their behavior have the greatest influence on energy consumption and thermal loads through their use of lighting and plug loads. To build stochastic tenant models (where a tenant refers to a group of occupants occupying a given space), electricity data from a 17-storey office tower was collected. They data have a frequency of hourly and cover lighting and receptacle (plug) loads separately from January 1, 2016 to March 31, 2017.

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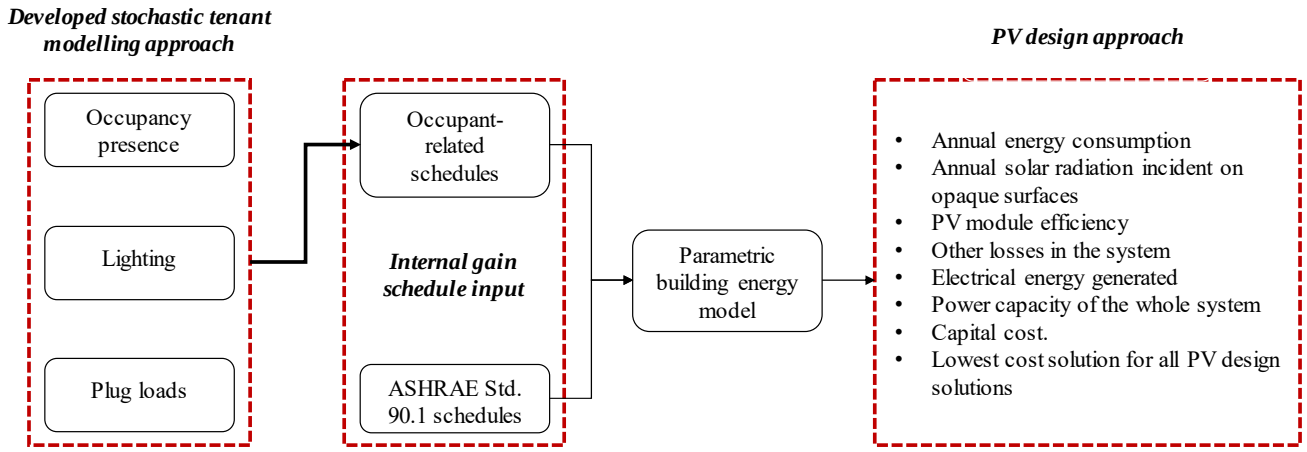
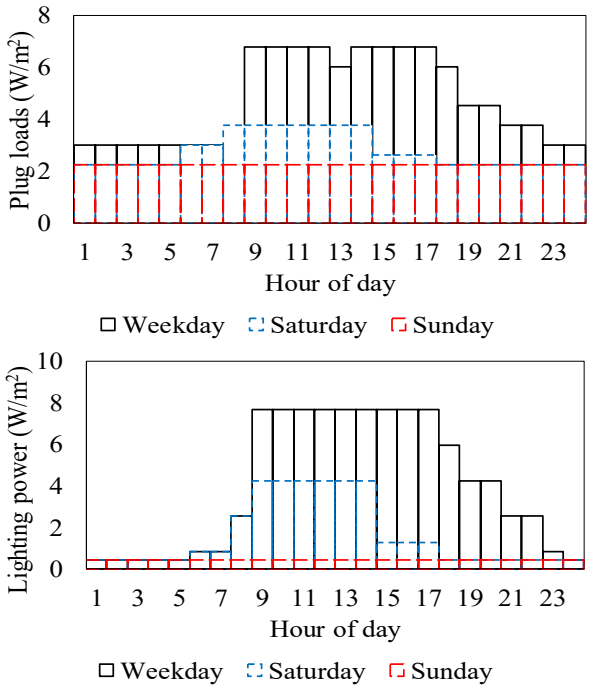


Figure 1: The proposed framework to understand the relationship between uncertainty from occupants' behavior and sizing PV system to achieve NZE

Table 1: Typical internal gain assumptions used for office spaces

Domain	Assumptions
Occupancy (occupant presence)	0.054/m^2 at 140 W/person (Deru, et al., 2011; American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE), 2017)
Office equipment (plug loads)	7.5 W/m^2 (Deru, et al., 2011)
Lighting	8.5W/m^2 (ANSI/ASHRAE/IESNA, 2016)



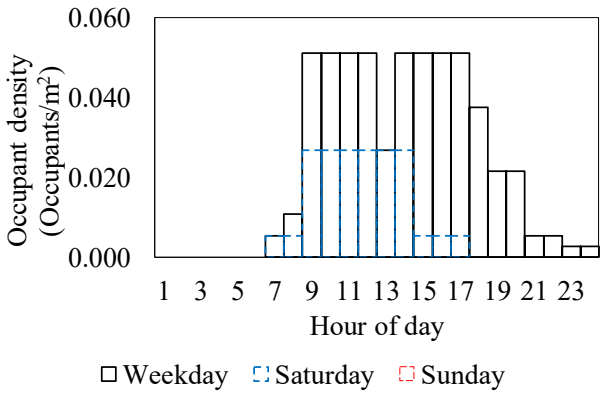


Figure 2: Commonly used default schedules for: plug loads (top), lighting power (middle), and occupant density (bottom) (Deru, et al., 2011)

The objective was to develop a model that could generate synthetic tenant schedules that were still based on the original dataset.

Based on visual inspection of the data, the data from each tenant and day type (weekday, Saturday, Sunday/holiday) were fit to simple five-segment profile shown in Figure 2a. A sample of the original data for a single tenants' weekday plug loads and corresponding model fit are shown in Figure 2b and 3c, respectively. Among the 17 tenants, the mean MAE between the model fit and the raw data is 0.24 W/m^2 for the weekday plug loads and 0.41 W/m^2 for the weekday lighting loads. Weekend and holiday values of MAE were lower. Table 2 summarizes the distribution (assumed Gaussian) of coefficients for the 17 tenants.

While seasonal variation in the data is not significant, day-to-day variation is non-negligible. Inter-day variability was quantified and included in the model. For simplicity, the mean values of the standard deviation for the inter-day variation is summarized in Table 3.

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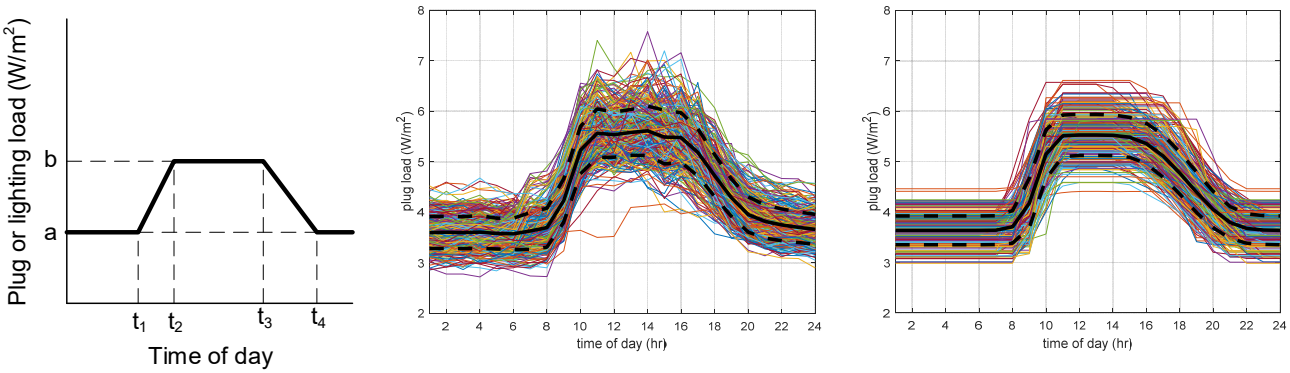

Figure 3: (a) the generic model form for daily plug and light load; (b) sample daily profiles for one year's worth of weekday plug loads in a single tenant office; and, (c) the modelled tenant, showing the standard error range.

Table 2: Summary of model coefficients for the 17 tenants

	Plug						Light					
	Weekday		Saturday		Sunday/Holiday		Weekday		Saturday		Sunday/Holiday	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
a	3.59	1.23	3.46	1.23	3.45	1.24	0.79	0.57	0.36	0.52	0.38	0.50
b	5.85	1.81	3.67	1.37	3.70	1.33	4.90	1.61	1.33	0.89	1.51	0.73
t_1	7.43	0.85	8.10	1.41	7.58	1.11	6.80	0.71	8.21	0.92	7.66	1.14
t_2	10.43	0.62	10.54	1.66	10.91	0.69	8.94	0.65	11.09	1.11	10.34	1.82
t_3	16.19	1.20	14.94	1.89	16.52	2.00	18.83	1.41	16.13	1.69	18.19	2.38
t_4	21.49	1.41	20.45	2.25	21.98	1.72	24.00	0.00	21.90	1.89	23.41	1.16

Table 3: Standard deviation of day-to-day variation of parameters

	Plug			Light		
	Weekday	Sat.	Sun./hol.	Weekday	Sat.	Sun./hol.
a	0.25	0.259	0.267	0.464	0.359	0.357
b	0.503	0.370	0.620	0.240	1.16	1.48
t_1	0.563	2.16	2.13	0.554	2.18	1.86
t_2	0.668	1.93	1.93	0.562	2.07	1.80
t_3	1.21	2.84	2.73	1.51	4.03	3.77
t_4	1.11	2.24	2.21	1.00	2.20	2.20

As per the method described by O'Brien et al. (2016), correlations between tenant model parameters are often significant and should be preserved from the raw data to model application. For instance, it was found that the weekday daytime plug loads are closely correlated to the weekday nighttime plug loads. Using a correlation matrix, the generation of synthetic tenants preserved the correlations from the original tenants' data. Finally, to obtain annual hourly schedules for lighting and plug loads, the procedure in Figure 4 is followed. MATLAB code was written to generate the schedules and output them to a CSV file, where they can be read using EnergyPlus' *Schedule:File* object.

Unfortunately, concurrent occupancy (i.e., occupant presence) data was not available from the building. Previous field studies by Gunay et al. (2016) showed that plug loads and occupancy are strongly correlated. To estimate occupancy, Gunay et al.'s (2016) correlation between occupant density (OD) and plug load density (PLD) was used, as follows.

$$OD = \max(0.00703 \cdot PLD - 0.0222, 0) \quad (1)$$

Occupant density is expressed in occupants per m^2 and plug load density is expressed in W/m^2. The model and its validation is discussed in greater detail in O'Brien, Abdelalim, & Gunay (2018).

2.2 Building model description

The medium office reference building that complies with the National Energy Code of Canada for Buildings (NECB) for the Toronto climate zone was selected for the purpose of testing the proposed framework (NRC, 2015). The new Toronto Canadian Weather for Energy Calculations (CWEC) annual weather data file was used for annual simulations. It is based on typical weather data measured during the period 1998 to 2014.

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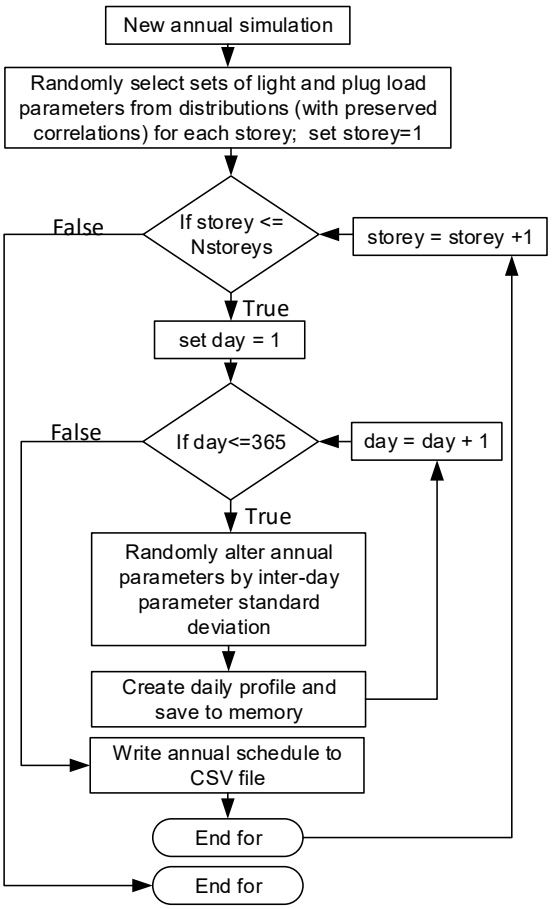

Figure 4: High-level flow chart of annual plug and light power schedules

Some modifications were made to the reference model to improve the feasibility of achieving NZE. Three categories of energy-related measures were applied to the model: passive design, heating ventilation and air conditioning (HVAC) system, and power generation from renewable energy source. For the passive design techniques, the thermal performance of windows and opaque envelop components were enhanced. The values for the thermal resistance for walls, roof, floor, and windows were obtained from previous studies in the literature and practical values that are relevant to commercial buildings (Pikas, Thalfeldt, & Kurnitsk, 2014; Costlow, et al., 2015). Moreover, the window-to-wall ratio was reduced from 48% to 30%. For the HVAC system, the heating and cooling equipment (i.e. boilers, chillers, and cooling towers) were replaced by ground source heat pump (GSHP) due to its high efficiency (Deng, Wang, & Dai, 2014). The coefficient of performance (COP) of the closed loop GSHP used for heating and cooling are 3.8 and 4.5, respectively (NRC, 2017). Normalized performance curve was used to describe the heat pump performance as recommended by EnergyPlus in modeling water-to-air heat pump. Moreover, a ground heat exchanger with 120 boreholes and depth of 76.2 m was selected based on pilot simulations and previous studies on similar sized-sized commercial buildings (Fisher & Rees, 2005; NRC, 2017). Figure 5 and Table 4 show the key characteristics of the medium office building model used in the study. Typical schedules and power densities assumptions as shown in Table 1 and Figure 2 above were used for the base case model. The purpose of using ASHRAE Standard 90.1 schedules and assumptions is to compare them to the generated realistic occupant profiles and loads to achieve NZE. Finally, for the power generation, PV system design approach is discussed in detail in Section 3.

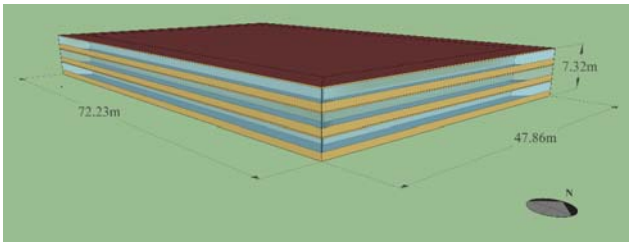

Figure 5: Medium Canadian office reference building model

2.3 Application of the developed tenant models

This section describes the simulation approach and the application of the developed tenant models to the parametric energy model to understand the relationship between uncertainty from occupants' behavior and sizing PV system to achieve NZE. The simulation approach in this study entails a Monte Carlo simulation to explore a wide range of operating conditions at the floor level based on the proposed method explained in Section 2.1. A large number of annual energy simulations (1000) were performed with randomly generated profiles (for plug loads, lighting, and occupancy density for each floor), as per the above tenant modelling approach, to allow the distribution to converge. The values for the annual electrical energy consumption for each run was then used to determine the sizing of the PV system. By using the standard schedules and assumptions, the annual electrical energy demand was approximately 1.23 GWh (30.3% equipment, 23.3% lighting, 14.4% heating, 9.1% cooling, 13% fans and 9.9% for pumps). The lighting and equipment recoreded the highest energy consumption which shows how the occupant behavior can have a signficant impact on the building's energy demand. By applying the generated stochastic schedules, the annual electrical energy consumption was significantly reduced. Figure 6 shows the annual electrical energy demand for the medium office building using stochastic and standard schedules and assumptions. Moreover, it shows the percentile (90, 95, 99, and 99.9%) of the distribution to achieve NZE. For instance, to have a 99% probability of achieving net-zero energy, the renewable energy would have to be sized to generate 1.06 GWh per year.

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Table 4: Medium Canadian office reference building model detail summary

General	Floor Area (m^2)	10,351
	No. of stories	3
	No. of thermal zones (4 perimeter zones and 1 core zones/floor)	15
	Window to wall ratio (WWR) for all orientations	30%
Building Envelope U-value ($W/m^2.K$)	Roof	0.145
	Walls	0.191
	Below grade floor	0.277
Window properties	U-value (double glazed (6mm) with 12.5 mm air gap: clear from inside and tinted with low-e from outside)	1.086
	SHGC	0.283
Infiltration Rates	Flow per exterior surface area ($m^3/s\text{-}m^2$)	0.00025
HVAC air loop	Each cardinal direction (i.e. East, West, North, and South) is served with a separate air handling unit with demand control ventilation. The air distribution system is single duct with VAV (variable-air-volume). An energy recovery wheel is also installed in the air loop.	
Outdoor air flow	Outdoor air flow/person	0.0025 m^3/s-person
	Outdoor air flow/zone floor area	0.0003 $m^3/s\text{-}m^2$
Space Cooling	Ground source water to air heat pump with COP of 4.5. The building relies on free outdoor cooling when the outdoor temperature is between 12 and 22°C	
Space Heating/Hot water	Ground source water to air heat pump with COP of 3.8. Ground heat exchanger with 120 boreholes and depth of 76.2 m.	
Thermostat settings	heating/cooling setpoints are 22°C to 24°C, respectively.	heating/cooling setbacks are 18°C to 28°C, respectively.

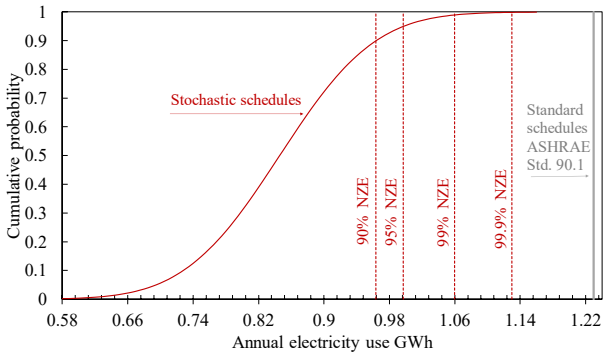

Figure 6: Annual electrical energy demand for the medium office building using stochastic vs. standard schedules

3. PV DESIGN APPROACH

This section disccuses the PV system design approach and the capital costs. Monocrystalline silicon PV cells were used in this study because they: 1) are high-purity silicon: results in having the highest efficiency rates among other solar cells, 2) are space efficient: generate highest power outputs with least amount of space, and 3) tend to perform better than other solar cells at low-light conditions (IRENA, 2012). The first step to size the PV system is to obtain the annual electrical energy consumption, annual solar radiation incident on surface, and net surface area (i.e. excluding fenestration surface areas) of the required surface to install PV. The annual electrical energy demand was determined based on the input schedules and assumptions (as in Figure 6). Table 5 shows the total net surface area of the opaque envelop components and the total annual solar radiation incident on roof, South, West, East, and North walls. The annual solar radiation incident on the above surfaces was obtained from EnergyPlus using the annual weather data file described in Section 2.2. It should be noted that the annual solar radiation is not exactly the same for every year.

The tilt angle of the solar module installed on the roof was set to zero (i.e. not tilted) to avoid shading that could be caused by other modules, which could reduce the amount of solar radiations. Moreover, to avoid shading on the solar modules, this require reducing the number of PV modules (to increase the horizontal distance between modules), and hence reduce the total power capacity of the PV system. Furthermore, it was found that the total annual solar radiation on the horizontal surface on the roof was less than that on a tilted surface (i.e. β=30°) by approximately 7%.

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Table 5: Opaque net surface area and total annual solar radiation incident

Surface	Net surface area (m^2) (i.e. excluding fenestration surface areas)	Annual solar radiation incident (kWh/m^2)
Roof (horizontal β=0)	3450	1373
South wall	370	1093
West wall	245	878
East wall	370	824
North wall	245	414

The second step is to estimate the total generated electrical energy and power capacity of the system. The total generated electrical energy from the PV system is estimated using Equation (2), following the RETScreen methodology (NRCan, 2017). The power capacity of the whole system is calculated as shown in Equation (3).

$$\textit{PV system generated electrical energy [kWh]} = \sum A_i \times I_i \times \eta \times PR \quad (2)$$

$$\textit{Power capacity of the whole PV system [kWp]} = \sum 1 \frac{kW}{m^2} \times [A_i] \times \eta \quad (3)$$

where, A is the net surface area of the surface, I is the total annual solar radiation incident on surface, η is the PV module efficiency, PR is the performance ratio or coefficient for losses, and the subscript i represents roof and walls for each cardinal directions (i.e. S, W, E, and N). The coefficient for losses includes inverter losses (assumed 5%), temperature coefficient of the PV module efficiency (0.4%/°C), DC cable losses (2%), AC cable losses (2%), shading (3%), losses at weak irradiation (5%), and losses due to dust or snow (2%) (Skunpong & Plangklang, 2011). The 1 kW/m^2 is the solar irradiance based on standard testing condition (STC) for most of the PV panels (NRCan, 2017). The nominal operating cell temperature for Monocrystalline solar cells is 45°C, while the STC specifies the cell temperature as 25°C (NRCan, 2017). Thus, the difference between the nominal and cell temperatures was multiplied by the temperature coefficient of the module efficiency.

To quantify the capital cost of the PV system, the following costs should be determined: PV module, inverter, structural and supply chain cost, installation labor, permitting and inspection, and other related costs. For the PV module cost, the price varies based on the manufacturer and brand (IRENA, 2012). For instance, the price of a PV module with a higher performance (in terms of power output and efficiency) could be less than that with a lower performance. Moreover, the prices of PV modules with same specifications are not consistent among different brands. Thus, a wide range of average Monocrystalline PV module efficiency and the corresponding PV module cost ($/Wp) were obtained from online solar wholesaler for different companies as shown in Figure 7. Other costs such as equipment, labor, and other related costs as mentioned above were estimated to be $2.45/W (NREL, 2017). While, the total PV system cost is calculated as in Equation (4).

$$\textit{Total PV system cost [\$] = Power capacity of the whole PV system} \times \textit{(PV module cost +2.45)} \quad (4)$$

In the current study, the main approach is to size the PV system by using a parametric sweep of all designs to determine the lowest cost solution for a given annual energy generation level. For that purpose, a MATLAB script is written including four steps: 1) systematically and simultaneously vary PV module efficiency (10 to 26%) and PV area on each of the opaque surfaces, 2) compute the PV system capacity and estimated annual electrical energy generation, 3) compute the total cost, and 4) estimate the pareto front by finding lowest cost solution for all PV design options. The PV array area on a given surface was allowed to vary between 0 and the total opaque surface area. Modules were modelled as being flush on the surface (not tilted relative to the surface). For simplicity, PV array area was considered continuous (i.e., individual modules were not modelled).

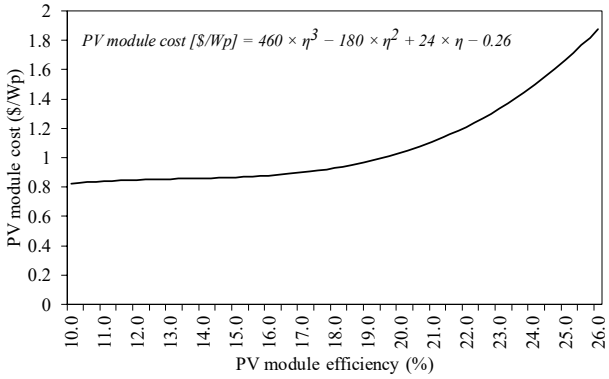

Figure 7: Relationship between PV module efficiency and the corresponding cost

4. RESULTS AND DISCUSSION

In order to achieve NZE, typical schedules and assumptions as well as stochastic occupant related-loads generated from the developed tenant modeling approach were used to determine the annual energy demand. Using the design approach in Section 3, a total of 24,577 PV design solutions were evaluated, as shown in Figure 8**Error! Reference source not found.**. The maximum annual energy output (i.e. installing PV modules with an efficiency of 26% on all opaque envelope components including roof and walls) is 1.18 GWh with a total cost of $5.29M. This

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design option results in producing 96.5% of the building energy consumption on an annual basis using ASHRAE Std. schedules and assumptions. Torcellini, et al. (2006) claimed that for buildings with more than three stories, the generated electricity from PV could be insufficient to cover the annual energy demand due to limited surface area of roof and walls. However, they claimed that it is possible for the PV system to cover the annual energy demand if the loads are substantially reduced. Table 6 shows the PV design solution to achieve NZE based on the lowest capital cost. Table 7 summarizes the probability of achieving NZE and the total PV system capital cost using default ASHRAE and stochastic schedules.

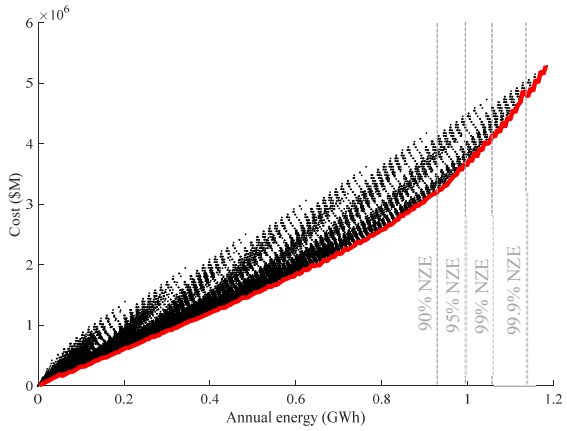

Figure 8: Annual electrical energy generated and total PV system cost. Black dots represent each design solution, while the red line follows the lowest cost solution for any given required level of annual PV energy output. The dotted lines represent the percentile of achieving NZE for the building with a stochastic occupant model.

Table 6: The required PV module efficiency and PV array size to achieve NZE based on the lowest capital cost

Probability of achieving NZE (%)	PV module efficiency (%)	Area of opaque surfaces that are covered with PV modules (m²)				
		Roof	South	West	East	North
90	23	3450	370	82	-	-
95	23	3450	370	245	163	-
99	25	3450	370	245	82	-
99.9	26	3450	370	245	163	-

The results revealed that the occupant behaviour has a significant impact on the annual energy demand – particularly for net-zero energy buildings, for which the envelope and HVAC are high-efficiency. This is due to the diversity of occupants' in terms of their presence, switching on/off lights, installed lighting capacity, and equipment (desktop computers or laptops) use and type. Compared to the typical default assumptions and schedules, the required PV array size to achieve NZE significantly decreased when a data-driven stochastic model was simulated. In general, depending on the climate of interest, the internal gains from occupants, lights, and equipment may also cause a significant change in HVAC energy.

Table 7: The percentile of achieving NZE using default and stochastic schedules

Probability of achieving NZE (%)	Stochastic schedules			ASHRAE schedules	
	Annual energy demand (GWh)	Lowest PV system cost	Incremental PV system cost increase*	Annual energy demand (GWh)	PV system cost (produce 95.5% of the building energy
90	0.96	$3.4M	-	1.23	$5.29M
95	1	$3.6M	5.5%		
99	1.06	$4.1M	12.2%		
99.9	1.13	$4.8M	14.6%		

** The incremental PV system cost represents the increase in cost to go from 90 to 95%, 95 to 99%, and 99 to 99.9%.*

In order to study the feasibility of achieving NZE for the annual energy demand range (0.59 to 1.17 GWh) obtained from the 1000 runs, it is essential to consider the capital and maintenance cost of the PV array. The results revealed that by installing more PV modules rather than increasing the module efficiency results in lower capital cost because of the increased cost of higher efficiency modules. However, the maintenance cost of PV modules with a higher efficiency (to achieve 99.9% NZE) is less than that to maintain a bigger PV array size. As a result, some building components could be upgraded in order to achieve NZE instead of installing more PV modules or increasing their efficiencies such as: 1) improve building envelope thermal performance, 2) install more efficient light bulbs, and 3) install more efficient heating and cooling systems.

5. CONCLUSIONS AND FUTURE WORK

The main contribution of this paper is to size the PV system based on a probabilistic model in order to understand the relationship between certainty of achieving NZE and the cost premium of improving certainty. The results revealed that uncertainty of occupants for sizing PV is costly if the objective is to be highly confident that the building will achieve NZE. Each incremental percentage point of

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certainty (as shown in Figure 8 and Table 7) becomes increasingly more expensive as we attempt to approach 100% certainty. For instance, the difference in the required PV array size to go from 90 to 95% (5.5%) is much less than going from 95 to 99% (12.2%) and from 99 to 99.9% (14.6%). Moreover, by increasing the PV array size may requite us to rely on more efficient modules or sub-optimal surfaces. The developed tenant modeling approach was tested on a medium office building with three floors to account for inter-tenant diversity. By increasing the number of stories, this will require more energy and hence increasing the PV system capacity (Torcellini, Pless, Deru, & Crawley, 2006). However, the inter-tenant diversity will cause the building-level energy use uncertainty to decrease for buildings with more tenants. As illustrated by the current study, reduced uncertainty can have a significant benefit to PV system cost.

One of the limitations of the current study is that it treated occupant-related loads (i.e. lighting and plug loads) as an uncontrollable boundary condition. This paper focused on the uncertainty from occupant behavior alone, future work should simultaneously consider other sources of uncertainty such as construction quality, weather, faults, and unanticipated space uses. Also, it should be noted that not achieving net-zero energy is relatively inconsequential for grid-tied buildings, but an energy shortfall would be considerable more problematic for an off-grid building.

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7. REFERENCES

AbuGrain, M., & Alibaba, H. (2017). Optimizing Existing Multistory Building Designs towards Net-Zero Energy. *Sustainability*(doi:10.3390/su9030399).

American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE). (2017). *Handbook - Fundamentals.* Atlanta, GA: ASHRAE.

ANSI/ASHRAE/IESNA. (2016). *Standard 90.1-2016: Energy standard for buildings except for low-rise residential buildings.*

Athienitis, A., & O'Brien, W. (2015). *Modeling, Design, and Optimization of Net-Zero Energy Buildings* (ISBN: 978-3-433-03083-7 ed.).

Barthelmes, V., Becchio, C., & Corgnati, S. (2016). Occupant behavior lifestyles in a residential nearly zero energy building: Effect on energy use and thermal comfort. *Science and Technology for the Built Environment, 22*, 960-957.

Becchio, C., Bello, C., Corgnati, S., & Ingaramo, L. (2016). Influence of occupant behaviour lifestyle on an Italian social housing. *In: Proceedings of the 71st Conference of the Italian Thermal Machines Engineering Association (ATI2016).* Turin, Italy.

Brahme, R., Neill, Z., Sisson, W., & Otto, K. (2009). Using existing whole building energy tools for designing net-zero energy buildings Challenges and workarounds. *Proceedings of the 11th International IBPSA Building Simulation Conference.* Glasgow, UK.

Carpino, C., Mora, D., Arcuri, N., & De Simone, M. (2017). Behavioral variables and occupancy patterns in the design and modelling of Nearly Zero Energy Buildings. *BUILD SIMUL*(Doi: https://doi.org/10.1007/s12273-017-0371-2), 875-888.

Costlow, J., Kelly, S., Rezeli, J., Lavine, D., Dieme, R., Kaplan, S., . . . Boccella, C. (2015). *A NET-ZERO APPROACH FOR SMALL OFFICE BUILDINGS.* Sustainable energy fund.

CSRA. (2010). *Renewable Energy Options Feasibility Study – Starr Ranch/Longhorn Munitions Superfund Site.* Washington, DC 20460: U.S. Environmental Protection Agency.

de Wilde, P. (2014). The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction, 41*, 40-49.

Deng, S., Wang, R., & Dai, Y. (2014). How to evaluate performance of net zero energy building - A literature research. *Energy, 71*, 1-16.

Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., . . . Crawley, D. (2011). *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock.* National laboratory of the U.S. Department of Energy, Office of Energy.

Fisher , D., & Rees, S. (2005). Modeling Ground Source Heat Pump Systems in a Building Energy Simulation Program (ENERGYPLUS). Montréal, Canada: International IBPSA Conference.

Gill, Z., Tierney, M., Pegg, I., & Allan, N. (2010). Low-energy dwellings: The contribution of behaviours to actual performance. *Building Research & Information, 38*, 491-508.

IRENA. (2012). *RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES: Solar Photovoltaics.* The International Renewable Energy Agency (IRENA).

JSTOR. (2014, September). *Oversizing PV arrays: How far should you go?* (ReNew: Technology for a Sustainable Future, No. 128, The off-grid issue) Retrieved 11 16, 2017, from http://www.jstor.org/stable/renetechsustfutu.128.30

Judd, K., Zalesny, M., Sanquist, T., & Fernandez, N. (2013). *The Role of Occupant Behavior in Achieving Net Zero Energy: A Demonstration Project at Fort Carson.* Oak Ridge, TN: U.S. Department of Energy .

Nord , N., Tereshchenko, T., Qvistgaard, L., & Tryggestad, I. (2018). Influence of occupant behavior and operation on performance of a residential Zero Emission Building in Norway. *Energy and Buildings, 159*(https://doi.org/10.1016/j.enbuild.2017.10.083), 75-88.

NRC. (2015, January 19). *National Energy Code of Canada for Buildings*. (Natural Resources Canada (NRCan)) Retrieved December 5, 2017, from https://www.nrc-cnrc.gc.ca/eng/publications/codes_centre/2015_national_energy_code_buildings.html

NRC. (2017, May 3). *Intelligent Net-zero Energy Buildings*. (NRC) Retrieved 11 16, 2017, from http://www.nrcan.gc.ca/energy/funding/current-funding-programs/eii/16074

NRC. (2017). *Natural Resources canada: Ground-Source Heat Pumps (Earth-Energy Systems)*. Retrieved 12 5, 2017, from http://www.nrcan.gc.ca/energy/publications/efficiency/heating-heat-pump/6833

NRCan. (2017). *RETScreen*. Retrieved December 18, 2017, from http://www.nrcan.gc.ca/energy/software-tools/7465

NREL. (2017). *U.S. Solar Photovoltaic System Cost Benchmark Q1 2017.* National Renewable Energy Laboratory .

O'Brien, W., Abdelalim, A., & Gunay, B. (2018). Development of an office tenant electricity use model and its application for right-sizing HVAC equipment. *Journal of Building Performance Simulation*.

O'Brien, W., Gunay, H. B., Tahmasebi, F., & Mahdavi, A. (2016). A preliminary study of representing the inter-occupant diversity in occupant modelling. *Journal of Building Performance Simulation*(https://doi.org/10.1080/19401493.2016.1261943), 1-18.

Pikas, E., Thalfeldt, M., & Kurnitsk, J. (2014). Cost optimal and nearly zero energy building solutions foroffice buildings. *Energy and Buildings, 74*, 30-42.

Skunpong, R., & Plangklang, B. (2011). A Practical Method for Quickly PV Sizing. *Engineering Procedia, 8*, 120-127.

Stazi, F., & Naspi, F. (2018). *Impact of Occupants' Behaviour on Zero-Energy Buildings.* ISBN 978-3-319-71867-5: Springer International Publishing, DOI: 10.1007/978-3-319-71867-5.

Torcellini, P., Pless, S., Deru, M., & Crawley, D. (2006). Zero Energy Buildings: A Critical Look at the Definition. Pacific Grove, California: A national laboratory of the U.S. Department of Energy Office of Energy Efficiency & Renewable Energy.

Wei , S., Jones , R., & de Wilde, P. (2014). Driving factors for occupant-controlled space heating in residential buildings. *Energy and Buildings, 70*, 36-44.

Yan, D., O'Brien, W., Hong, T., Feng, X., Gunay , H., Tahmasebi, F., & Mahdavi, A. (2015). Occupant behavior modeling for building performance simulation: Current state and future challenges. *Energy and Buildings, 107*, 264-278.