MODULAR AND OFFSITE CONSTRUCTION
MAY 21-24 2019 FAIRMONT BANFF SPRINGS HOTEL BANFF, AB, CANADA

Toward Community Generation: Energy Simulation and Performance Evaluation of Multi-family Solar PV Settings for Energy-efficient Homes in Edmonton, Canada

Hadia Awad[1], Mustafa Gül[2*], and Mohamed Al-Hussein[3]

[1] *Post-doctoral Fellow, Department of Civil and Environmental Engineering, University of Alberta*
[2] *Associate Professor, Department of Civil and Environmental Engineering, University of Alberta*
[3] *Professor, Department of Civil and Environmental Engineering, University of Alberta*
[*] *Corresponding author's e-mail: mustafa.gul@ualberta.ca*

ABSTRACT

The integration of renewable micro-generation systems into residential buildings, particularly solar photovoltaic (PV) distributed energy generation, is emerging rapidly as an effective method of mitigating the housing impact on greenhouse gas emissions. However, the application of solar PV micro-generation is confronted with several challenges: (a) the average system self-consumption does not exceed 25% in cold-climate regions; (b) most of the energy generated during daytime, peaking in the summer, is exported to the grid; and (c) rebates from the surplus generated energy exported to the grid are at a lesser rate than that of the imported energy. Due to relatively poor economics paralleled with the solar PV application, governments and policy makers envision the value of considering the integration of renewable energy sources at the community level rather than individual behind-the-meter applications, since this strategy can leverage the system self-consumption and increase its social impacts and economics. In this regard, this research aims to simulate and compare the overall performance of two scenarios of a sustainable community of 42 townhouse units. In the first scenario, each unit is connected to a behind-the-meter solar PV system of 3.3-kWp. In the second scenario, all units are connected to a large 140-kWp solar PV system. Historical data from one typical house has been collected (ongoing since 2015). Monte Carlo simulation technique is applied to ensure the stochasticity of the diverse household users. The hourly energy consumption and generation data is simulated using Simphony.NET® simulation engine based on the real-time data collected in Edmonton, Canada. Then, the load-match is identified as well as grid interaction indicators and system economics resulting from both scenarios. Results indicate that the application of community generation can significantly mitigate the imported and exported energy compared with individual behind-the-meter system generation due to the improved system self-consumption.

KEYWORDS

Community shared solar; Load-match-driven design; Monte Carlo simulation; Solar PV optimization; Long-term monitoring; Energy-efficient community simulation

INTRODUCTION

As the residential solar PV applications within net-zero energy homes (NZEHs) and energy-efficient homes (EEHs) gain market penetration, maintaining the safety, reliability, and affordability of the electricity distribution grid becomes an increasingly challenging task, especially in high-latitude regions. Individual behind-the-meter residential solar PV systems are confronted with several challenges (Awad et al., 2017b; Awad and Gül, 2018a, 2018b) such as PV mismatch in winter months, PV penetration (Hoke et al., 2012) in summer months, and poor economics in general. In this regard, governments and stakeholders seek alternative solutions that can possibly improve the economics of distributed energy generation such as the implementation of community shared solar PV systems. However, this concept is relatively novel and research should be conducted to examine several aspects of this application (Nadkarni and Hastings-simon, 2017). In this context, this paper focuses on developing a systematic framework that simulates and optimizes community shared solar associated with NZEHs and EEHs. The research presented in this paper aims to address the grid-wise quantification of the implications associated with the community shared solar advances in both NZEHs and EEHs. Community shared solar has been defined by several researchers (Augustine, 2015; Hicks and Ison, 2018; Jones et al., 2017; Shakouri et al., 2015; Walker and Devine-Wright, 2008; Wiseman and Bronin, 2013): one comprehensive definition of which is provided by Augustine (2015) as *"a solar photovoltaic project that delivers energy and/or economic benefit to multiple customers"*. In addition to the environmental benefits of community generation, there are several economic and social benefits such as development of local and small businesses, job creation, public acceptance, citizen involvement, rational use of energy, and social cohesion and regeneration (Romero-Rubio and de Andrés Díaz, 2015). Currently, there are more than fifty commercial solar PV design and simulation tools, as reviewed by Jakica (2018) and Sharma et al. (2014). However, there are only a few tools that support, with limitations, the simulation, design, and analysis of large-scale community shared solar applications (Shakouri et al., 2017). For example, PVsyst (2012) is a deterministic application that is widely used for the purpose of designing and simulating grid-tied standalone solar PV systems. On the other hand, the stochasticity and uncertainties associated with solar energy systems fall short of this type of application (Shakouri et al., 2017). For interested readers, additional details on the advantages and disadvantages of these tools are described in a study by Shakouri et al. (2017).

Challenges associated with community shared solar

Worldwide, the application of community shared solar is rapidly gaining popularity. For example, a study by Leuphana University (2013) reveals that, as of 2012, 46% (34 GW) of the installed renewable energy capacity in Germany was owned by citizens (from urban areas and farmers), whereas the remainder belonged to energy suppliers (12%) and institutional and strategic investors (42%) (Leuphana University, 2013; Romero-Rubio and de Andrés Díaz, 2015). It can thus be concluded that there is strong potential for the implementation of community shared solar applications among citizens and communities. On the other hand, community shared solar is also associated with challenges (Jones et al., 2017). The application of community solar itself does not contribute to community resilience (Jones et al., 2017). For example, while the community solar arrays generate electricity to support the energy demands of the community and can be independent from the grid, when the grid is impacted by a power outage, the community solar facility is no more resilient than other fully-grid-supported communities. In their book chapter, Jones et al. (2017) recommended that future researchers target the technological and market forces in the implementation of community shared solar advances and to involve the community members along with policymakers, local utilities, and third-party suppliers to achieve the local energy goals.

Research gap and objectives

As the world begins to consider the centralization of distributed energy sources and the decentralization of the utility grid and also prepare for the smooth transition from fossil-based energy sources to renewable energy sources, it is critically important to investigate the grid-wise implications of the community-scale application of net-zero energy homes (NZEH) in comparison with the equivalent application of energy-efficient homes (EEH). This matter has not often been addressed in previous studies, especially in northern climates. One of the focus areas of the present research is to develop a generic and systematic framework that analyses, simulates, and optimizes community dwellings equipped with community shared solar PV systems, using statistical distributions. The specific objectives and contributions of this study are to: (1) identify the various energy demand patterns resulting from EEH and NZEH prototypes located in northerly latitudes; (2) develop a systematic model that simulates the household energy demand of multiple dwellings (community) based on statistical data (probabilistic distributions) by using data from one dwelling or a few dwellings by means of Monte Carlo simulation technique; (3) based on the energy demand patterns, develop an optimization framework which aims to identify the optimum community-shared solar PV system design in terms of layout and system size, and thereby quantify the improvements incurred by the optimised system against the current practice; and (4) quantify the energy performance measures of the simulated community scenarios in terms of hourly energy demand, energy generation, load match, and grid interaction.

METHOD

This research is carried out by means of three primary stages: (1) data collection, (2) random simulation, and (3) PV layout optimization and options analysis. First, long-term historical energy performance data (ongoing since 2015) is collected at a one-minute temporal resolution, which includes energy loads, generation, and grid interaction. This data is used to generate probabilistic distribution curves for each hour of the day and month of the year. In order to simulate the household energy demand of an entire community containing multiple units, it is preferred to consider the random selection of demand activities rather than deterministic demand activities in order to convey the stochasticity and uncertainties of multiple users' behaviour. Then, the load-match and grid-interaction (LMGI) measures proposed by Salom et al. (2014) are used to quantify the LMGI indicators and to identify the net-zero balance of the community under investigation. A Monte Carlo simulation prototype is then developed to represent the hourly-interval energy demand. Further, an optimization model developed by Awad and Gül (2018) is used to identify the optimum load-match-driven design of community-scale PV system layout and size for both EEHs and NZEHs. In the present research, a systematic hybrid framework previously developed by Awad et al. (2017a, 2017b) and Awad and Gül (2018) is applied in order to combine the inputs from real-time data with an analytical model. It is thus possible to estimate the energy aggregate of a given PV system at any layout placement and at the desired temporal resolution, which will then be used as a variable in the optimization model in order to identify the optimum system layout and size. Finally, options analysis is carried out by conducting a pairwise comparison between two scenarios: (1) small single PV system per household, and (2) large system connected evenly to the entire community, and two household types: (a) EEH, and (b) NZEH.

Historical Household Energy Performance of Existing Dwellings

Historical data collected from 11 houses in Edmonton (Table 1) is analysed to investigate the energy performance of each house type (energy-efficient and net-zero), as well as the performance of various configurations of installed solar PV systems, with the focus on the net-zero balance, load-match, and grid interaction indicators of each house. It can be observed from Table 1 that the average PV system size for EEHs and NZEHs is 3.08 kWp and 13.39 kWp, respectively, since, unlike EEHs, NZEHs are required to achieve a yearly net-zero goal. Thus, the large PV sizing of NZEHs reflects the high electrical energy demand to be compensated on a yearly basis. Further information on the characteristics and performance of EEHs and NZEHs can be found in Li et al. (2016), Awad et al. (2017b) and (Awad and Gül, 2018a, 2018b).

Table 1. List of monitored NZEHs (denoted with N-#####) and EEHs (denoted with E-#####).

Type	Data Collection Starting Date	Tilt (°)	Azimuth (°)	System Size (kW_p)	Latitude (° N)	Heating system	DHW heating
E-18356	20-May-15	27	182	3.640	53.62545	NG/ F[1]	NG
N-18366	29-May-15	27	195	10.92	53.51095	ASHP[2]	EHP[3]
E-18360	30-May-15	30	180	2.080	53.42344	NG/ F	NG
E-18357	2-Jun-15	30	201	2.080	53.62550	NG/ F	NG
E-18371	10-Jun-15	30	180 (2) – 270 (6)	2.080	53.40846	NG/ F	NG
E-18364	22-Jun-15	30	201	2.080	53.42183	NG/ F	NG
E-18358	23-Jun-15	34	130	2.080	53.62808	NG/ F	NG
N-18374	20-Aug-15	27	152	14.715	53.41930	ASHP	EHP
N-18361	26-Nov-15	10	165	13.455	53.51288	ASHP	EHP
E-18367	23-Apr-16	27 (19) – 30 (7)	180 (19) – 270 (7)	6.760	53.47755	NG/ F	NG
N-18365	17-Jun-16	23	180	14.280	53.52306	ASHP	EHP

[1]NG/F: natural gas / furnace; [2]ASHP: electric air source heat pump; [3]EHP: electric heat pump.

Simulation of Energy Demand

Due to the limited availability of data and for the interest of replicability, providing a generalised framework with less dependency on local data, Monte Carlo simulation technique, also known as random simulation, is used in order to simulate the energy demand of an entire community with minimal input (i.e., historical energy demand from one or a few households). The use of probabilistic simulation supports the running of the several consecutive iterations of the simulation model to mimic the electrical energy demand of as many households as desired by the user. Simphony.NET® (Hajjar and Abourizk, 1996) simulation platform is used to simulate the energy demand profiles of the community dwellings based on the Monte Carlo random sampling technique. In order to simulate the energy generation of a given solar PV system, an analytical model is developed to determine the power output at any two-way tilted surface as discussed explicitly in Awad and Gül (2018). Then, generalised reduced gradient (GRG) nonlinear optimization algorithm (Lasdon et al., 1974) is employed to identify the optimal PV system layout and size. For interested readers, detailed information on the optimization model structure is given in the study by Awad et al. (2017b) and Awad and Gül (2018a, 2018b). The optimization model focuses on finding a solution that maximises the self-consumption of a given solar PV system through the load-match-driven design criterion in order to maximise the load-match indicator considering that

$$f_{load} = f(\theta, \alpha_s) \quad (1)$$

Here, the objective function, taken from Lasdon et al. (1974), is defined as

$$\text{maximise } f(\theta, \alpha_s) \quad (2)$$

and subject to $0° \leq \theta_o \leq 90°, 90° \leq \alpha_{s_o} \leq 270°$ (3)
where f_{load} represents the load-match indicator; θ represents the optimum PV system's tilt angle, α_s represents the PV system's azimuth angle, θ_o represents the optimum PV system's tilt angle; and $\alpha_{s,o}$ represents the optimum PV system's azimuth angle. It is assumed that the 0° and 90° tilt angles are horizontal and vertical placements, respectively. Similarly, 90° and 270° azimuth angles are east- and west-oriented placements, respectively.

RESULTS

A site under planning and design for a sustainable community located in Edmonton (53.44˚ N, 113.53˚ W) is investigated in this section. It is assumed that this future community consists of 42 dwellings and is connected to either a (1) behind-the-meter single rooftop PV system connected to each individual dwelling or (2) larger-sized PV system connected to the entire community as a whole unit. The site location and suggested housing layout is presented in Figure 1. Since several years' worth of data is collected from 11 homes, a significantly large population of instances will then be used to determine the probability distribution of each hour of the day and month of the year, which will in turn be used to run the random sampling of several dwellings within the community. Figure 2 presents a screen shot of the January simulation model in which each of the grey-coloured tasks (squares) represents an hour of the day. Each task runs 42 times to select 42 random samples, where each run represents one of the community dwellings, and these samples are collected and analysed later. As can be seen in the upper right section of the screen shot, each month is run in a separate scenario and statistics are then collected after all months are simulated. To avoid negative and/or unrealistic values, most of the data bins are fitted into either beta, gamma, or triangular distributions.

Figure 1. Proposed layout of a hypothetical community.

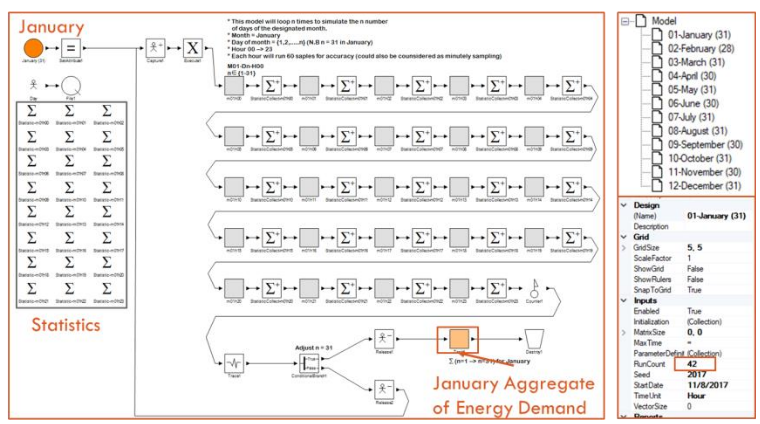

Figure 2. Screen shot of the Monte Carlo simulation model for January.

Detailed comparisons of the current practice and suggested solutions for EEH and NZEH communities are provided in Table 2 and Table 3. In general, it is found that the average PV sizing per dwelling is approximately 5.83 kW_p and 11.41 kW_p. For the system economics, a fixed electricity rate of 9.05 ¢/kWh and a renewable energy credit (REC) of 3.9 ¢/kWh is assumed. Administrative and grid-operation fees are also assumed to be at a flat rate of $5.67/month and $18.92/month, respectively, based on the local energy retailer fees. The PV system price is also assumed to be $3.00/Wp. Although in the case of EEHs, natural gas is used as an energy source for heating, the gas rates are not included in the calculations.

The layout placement solutions provided by the optimization framework for both cases (EEH and NZEH) are indicative of the nature of the household energy demand for the given community type. For example, NZEHs consume significantly larger amounts of electricity, and, in addition, the high electricity demand is clustered in the winter months to meet mechanical system demand. Because the altitude of the sun in winter is relatively low in Edmonton, a higher-than-typical tilt angle is proposed by the optimization framework— approximately 56° (about 3° higher than the local latitude). In both cases—EEH and NZEH communities—the azimuth angle is found to be approximately 195°, a value that is considerably similar to the conclusions of Litjens et al. (2017). The reasoning behind this given solution is that the energy loads peak in the late afternoon hours (especially on weekdays). The given solution also adheres to the research findings previously observed by Awad et al. (2017b), where the optimum tilt angle, azimuth angle, and system size for a single EEH located in Edmonton are concluded to be 38.9° and 189.8°, and 4.94 $kW_{p,}$ respectively. First, the optimization framework suggests increasing the PV system size of the EEH community from 129.36 kW_p to 244.92 kW_p in order to achieve the entire community's electricity net-zero balance; however, in case of the NZEH community, it is suggested to down-size the PV system from 560.28 kW_p to 479.18 kW_p while the net-zero balance can still be achieved.

Table 2. Total EEH community optimization results.

Iteration	W/out Solar	Current Practice		Suggested Solution		Implied Changes
State		(Scenario 1)		(Scenario 2)		Suggested Solution vs. Current Practice
		Total	Average	Total	Average	
Index		$S_{1,t}$	$S_{1,\mu}$	$S_{2,t}$	$S_{2,\mu}$	$(S_2 - S_1)/S_1$
System Size (kW_p)	-	129.36	3.08	244.92	5.83	89.33%
System's Generating Capacity (kWh/kW_p)		174,636	4,158	330,642	7,872	89.33%
Tilt Angle (°)	-	18.5	18.5	50.1	50.1	
Azimuth Angle (°)	-	Variable	Variable	194	194	
Yearly Exported (kWh)	-	49,023	1,167	221,306	5,269	351.44%
Yearly Imported (kWh)	315,080	238,375	5,676	218,563	5,204	−8.31%
Imported/Exported Balance (kWh)	−315,080	−189,352	−4,508	2,743	65	−101.45%
Yearly Generation (kWh)	-	125,728	2,994	317,823	7,567	152.79%
Yearly Loads (kWh)	315,080	315,080	7,502	317,899	7,569	0.89%
Load/Generation Balance (kWh)	−315,080	−440,808	−10,495	−635,722	−15,136	44.22%
On-site Solar Energy Use (kWh)	-	76,705	1,826	99,336	2,365	29.50%
On-site Solar Energy Use (%)	-	61.01%	61.01%	31.26%	31.26%	−48.77%
Yearly LM	-	39.90%	39.90%	99.98%	99.98%	150.54%
System Initial Cost ($)	$0.00	$388,080	$9,240	$734,760	$17,494	89.33%
Imported Grid Electricity ($/year)	$28,514	$21,573	$514	$19,780	$471	−8.31%
Export Revenue ($/year)	$0.00	$1,912	$46	$8,631	$206	351.44%
Balance ($/year)	$28,515	$19,661	$468	$11,149	$265	−43.29%
Balance Inc. Admin. Fees (%/year)	$28,810	$19,956	$475	$11,444	$272	−42.65%

Second, the layout placement has proven its effectiveness in designing a solar PV system on both the individual (Awad et al., 2017b) and the community levels. For example, it can be seen that in the EEH community, increasing the system size by 89.33% while installing the solar PV system at the proper layout placement (50.1˚-tilt and 194˚-azimuth) can improve the net-zero balance by 101.45% and can also improve the PV system's self-consumption by 29.50%. On the other hand, in the NZEH community, it is noticed that by reducing the system size by 14.47% while installing the solar PV system at the proper layout placement (55.7°-tilt and 195.8°-azimuth) can achieve net-zero balance, which has not been achieved with the larger PV system in the first scenario, and can also improve the PV system's energy generation by 8.20%.

Table 3. Total NZEH community optimization results.

Iteration	W/out Solar	Current Practice		Suggested Solution		Implied Changes
State		(Scenario 1) Total	Average	(Scenario 2) Total	Average	Suggested Solution vs. Current Practice
Index		$S_{1,t}$	$S_{1,\mu}$	$S_{2,t}$	$S_{2,\mu}$	$(S_2 - S_1)/S_1$
System Size (kW_p)	-	560.28	13.39	479.18	11.41	−14.47%
System's Generating Capacity (kWh/kW_p)	-	756,378	18,009	646,893	15,402	−14.47%
Tilt Angle (°)	-	18.5	18.5	55.7	55.7	
Azimuth Angle (°)	-	Variable	Variable	195.8	195.8	
Yearly Exported (kWh)	-	382,437	9,106	444,308	10,579	16.18%
Yearly Imported (kWh)	315,080	426,244	10,149	440,675	10,492	3.39%
Imported/Exported Balance (kWh)	−315,080	−43,807	−1,043	3,633	87	−108.29%
Yearly Generation (kWh)	-	578,348	13,770	625,789	14,900	8.20%
Yearly Loads (kWh)	315,080	622,156	14,813	622,156	14,813	0.00%
Load/Generation Balance (kWh)	−315,080	−1,200,504	−28,583	−1,247,944	−29,713	3.95%
On-site Solar Energy Use (kWh)	-	195,911	4,665	181,481	4,321	−7.37%
On-site Solar Energy Use (%)	-	33.87%	33.87%	29.00%	29.00%	−14.39%
Yearly LM	-	92.96%	92.96%	100.00%	100.58%	7.57%
System Initial Cost ($)	$0.00	$1,680,840	$40,020	$1,437,540	$34,227	−14.47%
Imported Grid Electricity ($/year)	$28,515	$38,575	$918	$39,881	$950	3.39%
Export Revenue ($/year)	$0.00	$14,915	$355	$17,328	$413	16.18%
Balance ($/year)	$28,515	$23,660	$563	$22,553	$537	−4.68%
Balance Inc. Admin. Fees (%/year)	$28,810	$23,955	$570	$22,848	$544	−4.62%

CONCLUSION

In conclusion, it is found that community shared solar PV systems that are distributed evenly among the community members are effective for facilitating a net zero site energy balance for the entire community. Two types of communities are simulated using a data-driven approach. It is found that, in general, the optimum layout placement of the proposed solar PV system for the EEH and NZEH communities is found to be [50.1°-tilt, 194°-azimuth] and [55.7°-tilt, 195.8°-azimuth], respectively, for the location of this study: Edmonton, Canada (53.44˚ N, 113.53˚ W). This finding also conforms to the findings found in Awad et al. (2017b) and Litjens et al. (2017). The proposed framework is systematic and can be used for simulations of both individual households and communities of any given size. Findings from this study are informative for academics and land developers and can easily be implemented for future research and in practice at the pre-planning phase in order to achieve more efficient net-zero communities and/or community generation applications. Local storage practices are also highly recommended for consideration as another step toward flattening the load-generation balance and stimulating on-site energy utilisation. As a limitation, the impact of some solar PV aspects such as the system components, typology, brand, technology, and inverter type are not discussed in detail in the current study. Future works will include these aspects as additional measures in the optimization model. Future work will focus on multi-array layout placement at multiple orientations for maximised self-consumption. In light of worldwide endeavors towards mitigating GHG emissions resulting from buildings, other community shared components will be considered in future work such as community energy storage and district heating systems.

ACKNOWLEDGEMENTS

This research has been conducted at the University of Alberta within the scope of a project entitled, “Integrating solar PV systems into residential buildings in cold-climate regions” (Grant number CRDPJ 461824-14). The authors would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) for their funding of this project and the industrial partner, Landmark Group of Companies, for their financial support as well as data supply and guidance.

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