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Amir H. Nosrat
Queen's University - Kingston, Ontario

Lukas G. Swan
Dalhousie University

Joshua M. Pearce
Michigan Technological University

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Simulations of Greenhouse Gas Emission Reductions from Low-Cost Hybrid Solar Photovoltaic and Cogeneration Systems for New Communities

Amir H. Nosrat[1], Lukas G. Swan[2], and Joshua M. Pearce[3*]
[1]Department of Mechanical and Materials Engineering, Queen's University, 60 Union Street Kingston, Ontario, K7L 3N6 Canada (amir.nosrat@queensu.ca)
[2]Department of Mechanical Engineering, Dalhousie University, 1360 Barrington St. Halifax, Nova Scotia, Canada, B3J 1Z1 (Lukas.Swan@dal.ca)

[3]Department of Materials Science & Engineering and Department of Electrical & Computer Engineering, Michigan Technological University, 601 M&M Building, 1400 Townsend Drive Houghton, MI 49931-1295 (pearce@mtu.edu)

***Corresponding author:** pearce@mtu.edu **ph: 906-487-1466**

Abstract

Recent work has shown that small-scale combined heat and power (CHP) and solar photovoltaic (PV) technologies have symbiotic relationships, which enable coverage of technical weaknesses while providing the potential of significant greenhouse gas emission reductions at the residential level. With the reductions in the cost of PV systems and the increasing maturity of CHP systems an opportunity exists for widespread commercialization of the technology, particularly for new construction. In order to determine the potential for this opportunity and to optimize the design of PV-CHP systems for greatest emission and cost reductions in the residential context a simulation, an optimization model has been developed using multiobjective genetic algorithms called the Photovoltaic-Trigeneration Optimization Model(PVTOM). In this paper, PVTOM is applied to emission-intensive and rapidly growing communities of Calgary, Canada. Results consistently show decreases in emissions necessary to provide both electrical and thermal energy for individual homes of all types. The savings range from 3000-9000kg CO_2e/year, which represents a reduction of 21-62% based on the type of loads in the residential household for the lowest economic cost hybrid system. These results indicate that hybrid PV-CHP technologies may serve as replacements for conventional energy systems for new communities attempting to gain access to emission-intensive grids.

Keywords: photovoltaic; cogeneration; combined heat and power; energy conservation measures; energy

Abbreviations

Φ_{CO2} : carbon dioxide emission intensity

Φ_{grid} : provincial emission intensity of the electric grid

Φ_{NOx} : nitrous oxide emission intensity

Φ_{th} : emission intensity of natural gas heating

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AL : appliance and lighting loads

CCHP: combined cooling, heat and power also referred to as trigeneration

CHREM : Canadian Hybrid Residential End-use Energy and Emissions Model

CHP: combined heat and power

DHW : domestic hot water

D : 20-year discount factor

DOC: discounted operational costs

$E_{chp,array}$: annual electric output of the CHP unit

f_{el} : amount of electricity the electric grid has provided in Wh in the event of system failure

f_{th} : amount of thermal Wh the system failed to meet

GHG: greenhouse gas

ICC: initial capital costs

PV : photovoltaic

PV-CHP: photovoltaic combined heat and power hybrid system

PVTOM: Photovoltaic-Trigeneration Optimization Model

RC : replacement costs

SC: space cooling

SD : single detached houses

SH: space heating

X : penalty function

1. Introduction:

Anthropogenic climate destabilization has evolved to be a formidable threat to human welfare, global ecosystems, and the temperate climate for which life on earth has evolved and human societies were formed [1-3]. It is now clear that an immediate reduction in greenhouse gas (GHG) emissions from energy use is necessary [2,3] and can be achieved through two strategies: (1) use fossil fuels more effectively and efficiently, and (2) use sustainable and renewable energy, which does not directly emit GHGs during energy conversion and which also tends to have low embodied and dynamic emissions [4,5]. The utilization of solar photovoltaic (PV) technology, which converts sunlight directly into electricity, is an attractive option with a number of environmental benefits [6-8]. Unfortunately, PV cells are held back by resource limitations, particularly the intermittency of solar irradiation owing to the daily solar cycle and cloudy weather conditions [9-10]. To overcome the intermittency of PV for providing constant electrical supply it has been suggested that PV can be hybridized with other sources such as fuel cells [11] and other sources of combined heat and power (CHP) [12]. Recent work has shown that small-scale CHP and PV technologies have symbiotic relationships, which enable coverage of technical weaknesses while providing the potential of significant emission reductions at the residential level [12-15]. Of these technologies the additional coupling of trigeneration (or combined cooling, heat and power (CCHP) was found to be the most effective in most applications [15]. Nearly 71% of energy consumption, and therefore emission production, occurs as stationary uses of energy in Canada [16]. Among the stationary energy users, the residential sector energy consumption behaviors are the most standardized [17]. In 2010 alone, residential buildings were responsible for 41 Mt of CO_2e [18]. With the recent reduction in the cost of PV systems [19] and the increasing maturity of CCHP [20] systems, an opportunity exists to commercialize PV-CHP and PV-CCHP systems, particularly for new construction.

In order to determine the potential for this opportunity and optimize the design of PV-CHP systems for greatest emission and cost reductions in the Canadian residential context, as well as the broader industrialized world, a simulation and optimization model has been developed using multiobjective genetic algorithms called the Photovoltaic-Trigeneration Optimization Model (PVTOM) [21]. In this paper, PVTOM is applied to newly developed Calgary, Alberta communities as case study. This case study was chosen for two reasons:

1. The province of Alberta is currently experiencing rapid growth due in large part to fossil fuel extraction [22] and these systems are expected to be implemented in new communities as opposed to existing ones.

2. The province of Alberta is known to have one of the highest grid emission intensities [16] in all of Canada, which highlights the potential for this technical application.

Results from the analysis are used to provide a synopsis of the applicability of PV-CHP systems to new communities.

2. Methodology

2.1 PVTOM

PVTOM was developed to simulate and optimize hybrid photovoltaic and trigeneration energy systems based on technical, economic, and emissions performance. PVTOM has been extensively documented elsewhere [21,24,25], but will be summarized here. PVTOM incorporates multi-objective genetic algorithms to minimize both the life cycle costs (including the capital investment, fuel costs, replacement costs over a 20 year system lifetime, and disposal costs for batteries) and GHG emissions. The GHG emissions are calculated as the carbon dioxide equivalent of the CHP unit's total emission (determined as a function of energy output) as well as any emissions produced as a result of relying on the electric grid or heating furnaces. The hybrid system only emits GHG emissions from the CHP unit. Presently, PVTOM uses the annual average GHG emission intensity of the local electricity grid, while future versions of PVTOM are intended to incorporate transmission losses and hourly emission intensities for different grids.

PVTOM requires 6 inputs for every hour of the year to simulate and optimize a PV-Trigeneration. Additionally, it requires a set of characteristics for each of the different technologies (e.g. PV, CHP, and batteries) subject to optimization. While PVTOM can upload this data for its use, it cannot provide the data beforehand. There are three primary sources for collecting input information: Generated hourly solar irradiation, as high as 5-minute resolution data for temperature, space cooling, space heating, domestic hot water, and electric end-user requirements for a case study through the CHREM, and technology specifications through literature and commercial documents. However, for the purposes of this paper, the model requires the following five inputs:

1. Hourly solar global and diffuse irradiation.
2. Hourly ambient temperature.
3. Actual or representative hourly data for household's appliance and lighting (AL) load.
4. Actual or representative hourly data for household's domestic hot water (DHW) load.
5. Actual or representative hourly data for household's space heating (SH) load.

A sixth input of space cooling (SC) would be necessary for other jurisdictions where this is significant.

The first two inputs for PVTOM have been obtained from the Meteonorm database via PVSYST 4.37 [26]. In this case, monthly irradiation data was obtained and transformed into hourly irradiation data using PVSYST's hourly synthetic irradiation generator. The last three inputs were obtained by the Canadian Hybrid Residential End-use Energy and Emissions Model (CHREM)[27, 28]. The CHREM is capable of assessing the energy demand of the four major end-use groups of the Canadian housing stock. Key features of the CHREM that enable this predictive capability are:

- The use of a statistically representative database of 16,952 unique Canadian house descriptions that include thermal envelope and plant system information. The database contains a sufficient number of unique houses to capture the range of housing characteristics found throughout Canada. Additionally, the database provides sufficient information to develop detailed thermal and electrical energy models of each unique house.
- The use of a unique "hybrid" modeling approach that relies on both statistical and engineering bottom-up modeling methods. The statistical component is used by CHREM to assess the AL and DHW energy consumption including the impacts of occupant behavior. The engineering component is used by CHREM to assess the SH and SC energy consumption based on thermodynamic and heat transfer analysis of the thermal envelope, climatic conditions, and plant equipment.
- The ability to assess impacts upon end-use energy consumption due to the implementation of advanced, alternative, and renewable energy technologies using the engineering component at an hourly or sub-hourly simulation time step.

These inputs are used to calculate the performance of PV-CHP for Calgary based on a pre-determined dispatch strategy designed to match the electric and thermal requirements of the end-user [21]. Specifically, as the thermal output of a CHP unit is larger than the electrical output, the system first prioritizes matching electrical loads and in the event that the thermal load is not met afterwards, is altered to match the thermal load. If there is excess electric power, it is first placed into the batteries, and when the case batteries are at their maximum state of charge, the electricity is dumped either onto the grid or into the ground based on whether the system is a grid-connected or stand-alone. Excess thermal power is dumped as waste heat through an exhaust. Calgary does not rely heavily on space cooling equipment during the warmer seasons. As such, there is almost no requirement for the installation of a cooling component in any comprehensive decentralized energy delivery scheme. This means that only hybrid PV and cogeneration systems will be evaluated for this case study.

The optimizer operates with eight variables that configure the system size and specifications. The variables are

1. Selection of CHP technology (from a database of CHP units)
2. Selection of PV panel technology (from a database of PV panels)
3. Selection of battery technology (from a database of battery modules)
4. Number of CHP units
5. Number of PV panels connected in series
6. Number of PV strings connected in parallel
7. Number of battery units connected in series
8. Number of battery strings connected in parallel

The performance of the system (dependent on system characteristics, temperature, solar irradiation, and end-user requirements) is summarized in a life cycle cost and annual GHG emission performance. The life cycle cost of the system is mathematically expressed as

$$F1=ICC+DOC+RC+X\cdot D \quad (1)$$

where *ICC*, *DOC*, and *RC* are, respectively, the initial capital costs, the discounted operational costs, and the replacement costs of the different components of the system across a 20-year lifespan and *X* and *D* are a penalty function and 20-year discount factor, respectively. Penalty function *X* is designed to penalize the failure of meeting either the thermal or electrical demands of the system by calculating product of the number of hours failed and the unit cost of failing to meet the energy requirements.

The annual GHG emission performance of the system is calculated as

$$F2=(\Phi_{CO2}+298\cdot\Phi_{NOx})\cdot E_{chp,array}+\Phi_{grid}\cdot f_{el}+\Phi_{th}\cdot f_{th} \quad (2)$$

where Φ_{CO2} and Φ_{NOx} is the carbon dioxide and nitrous oxide emission intensity of the CHP unit (expressed in g/Wh), $E_{chp,array}$ is the annual electric output of the CHP unit in Wh, Φ_{grid} is the provincial emission intensity of the electric grid, f_{el} is the amount of electricity the electric grid has provided in Wh in the event of system failure, Φ_{th} is the emission intensity of natural gas heating (the prevalent fuel type in Calgary), and f_{th} is the amount of thermal Wh the system failed to meet.

Cost numbers that were used for this optimization are considered to be conservative as they were derived from market research in 2011. It is assumed that costs for these technologies, particularly PV, are experiencing a price reduction with time [19] and would therefore make cost estimations more conservative.

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Buildings constructed in the near future are assumed to share similar performances compared to the most recently constructed one. This assessment, however, is beyond the scope of this article and should be further investigated.

2.2 Data Selection:

Figure 1 represents the postal map of Calgary [23]. Based on statistical information available to CHREM, postal codes T2X and T3X were selected due to a higher number of newer vintages. Within these two postal codes, there is end-user energy data available for a total of 217 available stand-alone type single detached (SD) houses constructed after 1990. While the end-uses in specific industries and businesses have specific criteria depending on utilized equipment, nearly all residential energy sector consumption is attributed to AL, SH, SC, and DHW. In order to capture a broad representation of the available houses, a two-dimensional matrix has been developed to capture high and low consumption for electric AL and SH demand. The matrix was developed as follows:

First, histograms examining the traits of AL and SH were generated to understand the distribution of consumption for each energy type. These are illustrated in Figures 2 and 3.

From the data above, a compilation of minimum, mode, and maximum values has been calculated and presented in Table 1.

In order to identify houses that meet the values above, a scatterplot was generated comparing SH to AL consumption and presented in Figure 4.

Subsequently, five sample houses were selected that matched the categories above. These five houses are used to generate the bi-dimensional matrix used for optimization in PVTOM. This matrix is presented in Table 2. Each house has representative hourly values for AL, SH, and DHW values necessary for optimization in PVTOM. Here, a range of required system specifications is provided for feasible implementation in new communities in Calgary.

3. Results

Each one of the selected representative data sets was optimized using PVTOM. In multi-objective genetic algorithms like PVTOM, there is rarely a unique solution due to the trade-off between the various variables. Table 3 is a summary for the optimized PV-CHP systems based on the selected data. The battery modules were each rated for 6V and were placed in string series. In this instance, costs and emissions directly compete against each other and therefore generate a set of solutions that range across both costs and emissions.[1] This solution set is referred to as the Pareto values, or the Pareto front when graphed with each variable serving as one axis (for problems with two objective functions only). The Pareto front for each of the houses A-E is shown in Figures 5-10.

It should be noted that the Pareto fronts for House B and C are 'staggered'. This is because the systems on the left hand side before the 'stagger' have 1 CHP system with lower costs yet higher emissions due to overuse of the CHP system. The systems after the 'stagger' on the right hand side have 2 CHP systems with higher installation costs but better matched loads that reduce overall emissions.

Considering that the Pareto values for each house traverses much more for costs than emissions, the most affordable data point was selected as the most optimal solution. Accordingly, every selected system has 1 CHP unit due to its lower lifetime cost.

1 It should be noted that this trade off only exists because the current economic system is socializing costs due to environmental damage from fossil fuel combustion.

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Market forecasts [29] for Calgary housing suggest that it is reasonable to expect average construction of 20,000 homes per year for the foreseeable futures. According to PVTOM, the average emissions savings for new Calgary homes on hybrid PV-cogeneration is roughly equal to 5,644 kg CO_2e/yr. Therefore, the theoretical emission reduction potential for residential buildings is expected to be an incremental 112 kilotons CO_2e/yr . This means that within 5 years, this potential can reach as high as 560 kilotons CO_2e/yr .

4. **Discussion**

Based on the results obtained from this study, there is a clear advantage in reducing annual GHG emissions for new households in Calgary if PV-CHP systems are adopted. As is the case with any multi-objective problem, there is a trade-off between cost and emissions dimensions. In this case, incremental emission reductions come at a substantial price. Therefore, the 'least expensive' solutions were selected as solution comparators between the different representative households. It should be noted that the exact costs were not given as PV pricing continues to decline. PVTOM optimizations must be run for current pricing in any location for actual design, however, based on the pricing data used here the overall trends are clear.

The results demonstrate two important themes. First, there is convergence amongst technology selection. The algorithm selects technologies that are efficient and deliver the highest value for the lowest costs. This calculation is based on a multitude of capital and operational costs including equipment, installation labour, maintenance, and fuel. Second, the system shows a decided advantage for both net emission and per CO_2e cost reductions for increased electrical output. This is primarily due to the higher proportion of thermal output to electrical output; CHP systems can produce thermal energy as much as twice the amount of electric energy at the same time. The system, dominated by electrical consumption, will often rely on electric output by the CHP system to maintain autonomy. With higher electric demand, the system will substantially overproduce thermally compared to thermal demand. Therefore, higher thermal and lower electrical demand will match the system's characteristic of higher thermal to lower electrical output. Pertinently, the inclusion of photovoltaic modules and connection to the grid reduces the need to turn on the CHP system at times of low electric and thermal demand (the algorithm is designed to activate the CHP system when there is a minimum demand of 50% capacity).There are additional trends displayed in the results:

1. While houses with low thermal demand can reach 50% in emission reductions, more expensive solutions for other representative houses can reach similar amounts. A synopsis is presented on Table 4.

2. For each Pareto solution set, the system emissions performance shows greater sensitivity to changes in thermal demand than to electrical demand. For example, Table 4 shows that the least expensive and most expensive solutions for House A (with low thermal and low electric demand) have only a 1 percent difference in emission mitigation. Solutions for House C, representing mode thermal and mode electric consumption, can vary as much as 34 percent.

3. The Pareto fronts for houses C, D, and E show discontinuity in emission reduction with relatively small increases in life cycle costs. This can be attributed to critical thresholds in system change where higher emission reduction can be achieved with additional capital. This system design changes include added CHP units, increased battery bank capacity, or a higher number of panels.

5. **Future Work**

This preliminary study demonstrates a strong case for further investigation of the impact of hybrid PV and CHP systems for new residential communities in Calgary. This is primarily due to the higher emission intensity of the local electricity grid that is predominantly coal-fired. Future work should investigate other building types and look at other climate locations. A comparative study with other regions would help inform policy for the ideal locations to first introduce these innovative systems for both different Canadian communities and those throughout the rest of the world. Hydro-intensive grids such as those belonging to British Columbia and Quebec may find it disadvantageous to pursue these systems in the near future because of the emissions associated with the burning of natural gas in the cogen, while communities in the Maritime region of Canada may have similar advantages for pursuing these systems. In addition, locations that need cooling during the summer would have the advantages previously determined for PV- trigen hybrid systems and should be explored. In all cases a more detailed analysis is needed to justify system ownership from the point of veiw of the consumer including optimization of all system components, and calculations of investment cost, financing, tax implications, payback time, and ROI just as with any other energy conservation measure.

This case study has prompted the following pertinent questions:

1. The study can be expanded to communal energy systems for the residential sector to gauge any benefits from economies of scale. Communal (or microgrid) systems [30] that would require larger PV, CHP, and battery installations may prove to be better suited at matching supply and demand. In particular the effect of cost on the scale of both PV and the CHP systems can be substantial. In addition, as scaling of the CHP unit is brought into consideration, the effect of partial load operation of the CHP on the efficiency and emissions must be taken into account [31,33], which will involve a refinement of PVTOM. In addition, the control strategies and configurations of such PV+CHP or PV+CCHP or trigeneration can be further refined [21,32,33]. As community scaled options are more easily compared to the conventional improvements the emissions should be compared to new combined cycle gas turbines following [33].

2. This study could be improved by using a more robust emission model that would account for the emission intensities based on different hours of the day as opposed to province-wide monthly or annual averages. Also, emission outputs accounting for different heating technologies and the manufacture of the different system components would be a strong refinement of the proposed model.

3. PV-CHP systems coupled with thermal storage should also be investigated for performance impact. It is predicted that stored thermal energy can prove to significantly reduce emission outputs by reducing the need for activating the CHP to only meet thermal requirements.

4. The large-scale physical implementation of these technologies should be investigated by planners and legal experts as issues relating to emissions, fuel distribution, technology availability, maintenance services, and grid impact are not covered by the model.

5. It should be pointed out that because the distributed generation hybrid systems described in this paper would be owned and operated by those moving into residential communities, the financing would be covered by them rather than the utilities following conventional models. To fully capitalize on this advantage policies to encourage the investment of residents in these technologies should be explored.

6. Conclusions

The results from this study demonstrates a strong case for further investigation of the impact of hybrid PV and CHP systems for new residential communities. The case study developed here for Calgary consistently showed decreases in emissions necessary to provide both electrical and thermal energy for individual homes of all types. The savings ranged from 3000-9000kg CO_{2e}/year, which represents a reduction of 21-62% based on the type of loads in the residential household for the lowest cost hybrid system. More expensive systems could offset more than 50% of emissions in all case study homes. From a planning/policy perspective, these results indicate that hybrid PV-cogen may best serve as replacements for new communities attempting to gain access to emission-intensive grids such as those in Alberta. While it may be particularly challenging to replace existing power supply networks with these technologies, it is clear that investment in energy systems for residential end-users should shift to single-use and communal sized PV-CHP systems instead of continuing to expand emission-intensive centralized power supply systems that are prevalent in these regions.

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Tables

Table 1. Minimum, mode (most common), and maximum values for AL and SH consumption values (all units in GJ)

End-use	Minimum	Mode	Maximum
Appliance and Lighting	20	27.5	35
Space Heating	55	85	110

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Table 2. Bi-dimensional matrix of select housing from new Calgary communities.

		Low		Mode		High	
		Annual AL Consumption (GJ)	Annual SH Consumption (GJ)	Annual AL Consumption (GJ)	Annual SH Consumption (GJ)	Annual AL Consumption (GJ)	Annual SH Consumption (GJ)
Space Heating	Low	21.8	55.8			35.1	52.7
		House A				House B	
	Mode			27.4	86.2		
				House C			
	High	22.3	113.4			33.8	108.7
		House D				House E	

Table 3 Technical summary of optimized PV-CHP systems for selected data

	PV Panel	PV System Size (W)	Battery Type	Battery Bank Size (Ah)	Battery Bank Voltage (V)	CHP Unit	Annual Emission Reduction (kg CO_2e/yr)	Emission Reduction Cost per kg CO_2e Reduced
House A	BP 340J	480	Trojan T-105	225	30	1 kWe (3kWth) Honda IC Engine	5280	0.50
House B	Schott EFG 310	1240	Trojan L-16P	360	42	1 kWe (3kWth) Honda IC Engine	9070	0.33
House C	BP 340J	960	Trojan T-105	225	42	1 kWe (3kWth) Honda IC Engine	3000	0.84
House D	Schott EFG 310	930	Trojan L-16P	360	54	1 kWe (3kWth) Honda IC Engine	3890	0.65
House E	BP 340J	720	Trojan T-105	225	18	1 kWe (3kWth) Honda IC Engine	6980	0.39

Preprint: Amir H. Nosrat, Lukas G. Swan, Joshua M. Pearce, Simulations of greenhouse gas emission reductions from low-cost hybrid solar photovoltaic and cogeneration systems for new communities, *Sustainable Energy Technologies and Assessments*, 8, 34-41 (2014). http://dx.doi.org/10.1016/j.seta.2014.06.008

Table 4. Summary of the effects of cost and emissions on the five representative energy profiles.

	Solution with Lowest Cost (Highest Emission)	**Solution with Highest Cost (Lowest Emission)**
House A (Low T and Low E)	51%	52%
House B (Low T and High E)	62%	66%
House C (Mode T and Mode E)	21%	55%
House D (High T and Low E)	27%	52%
House E (High T and High E)	37%	55%

T:Thermal energy consumption for space heating and water heating.

E:Electricity consumption

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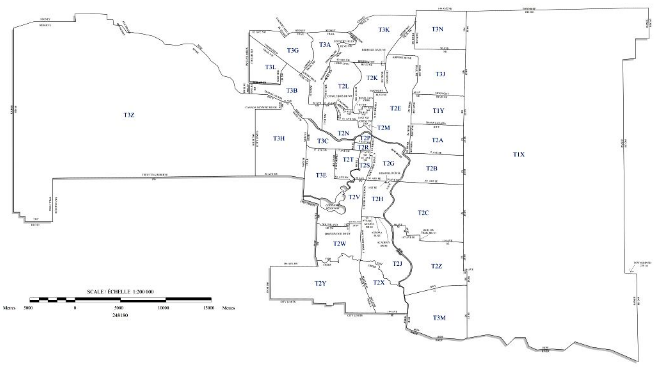
Figure Captions

Figure 1. Postal Map of Calgary [23].



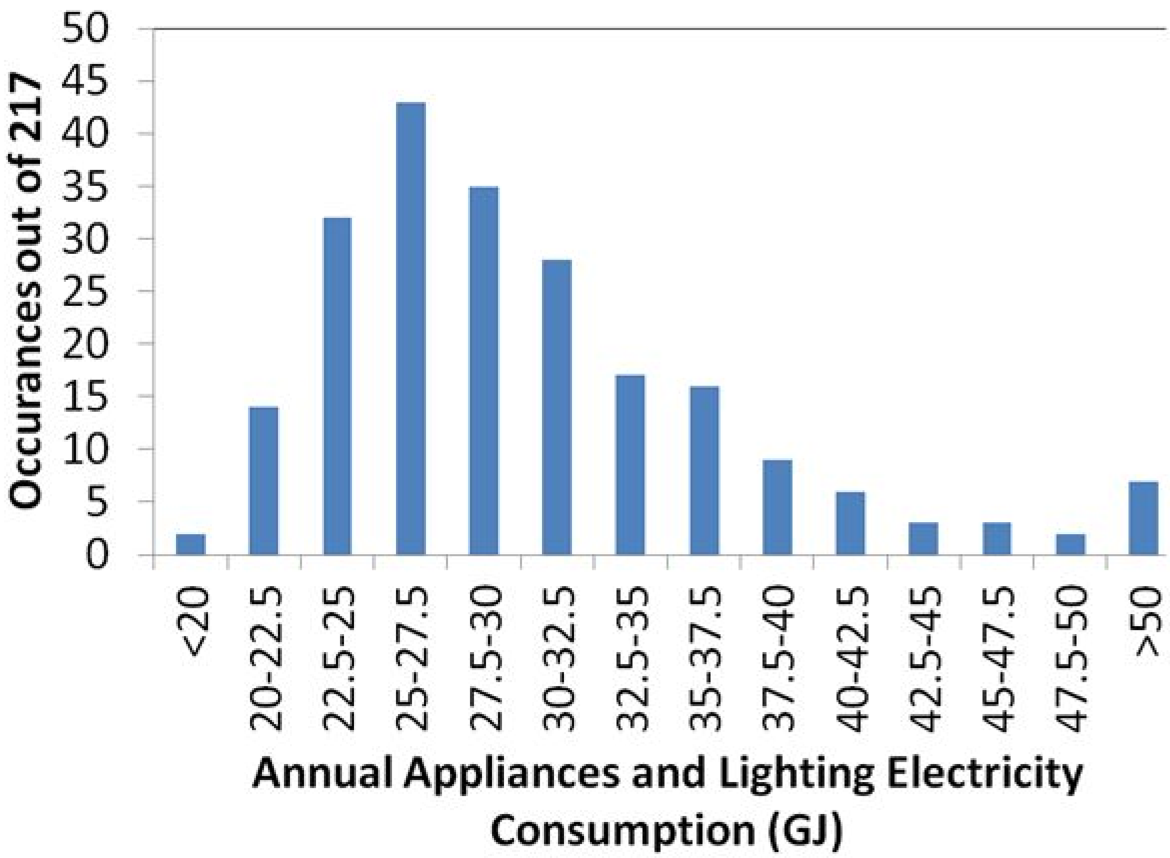


Figure 2. Distribution of household AL requirements as a function of GJ.

Preprint: Amir H. Nosrat, Lukas G. Swan, Joshua M. Pearce, Simulations of greenhouse gas emission reductions from low-cost hybrid solar photovoltaic and cogeneration systems for new communities, *Sustainable Energy Technologies and Assessments*, 8, 34-41 (2014).
http://dx.doi.org/10.1016/j.seta.2014.06.008

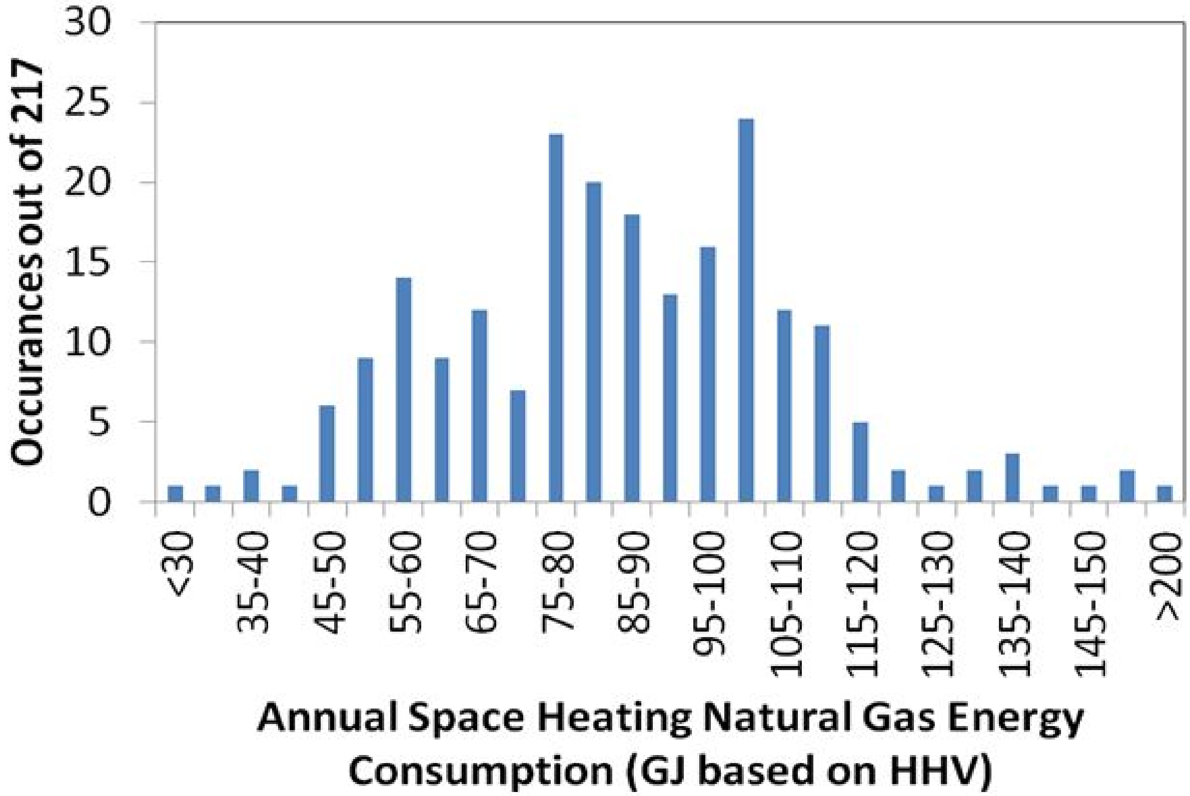


Figure 3. Distribution of household SH requirements as a function of GJ.

Preprint: Amir H. Nosrat, Lukas G. Swan, Joshua M. Pearce, Simulations of greenhouse gas emission reductions from low-cost hybrid solar photovoltaic and cogeneration systems for new communities, *Sustainable Energy Technologies and Assessments*, 8, 34-41 (2014).
http://dx.doi.org/10.1016/j.seta.2014.06.008

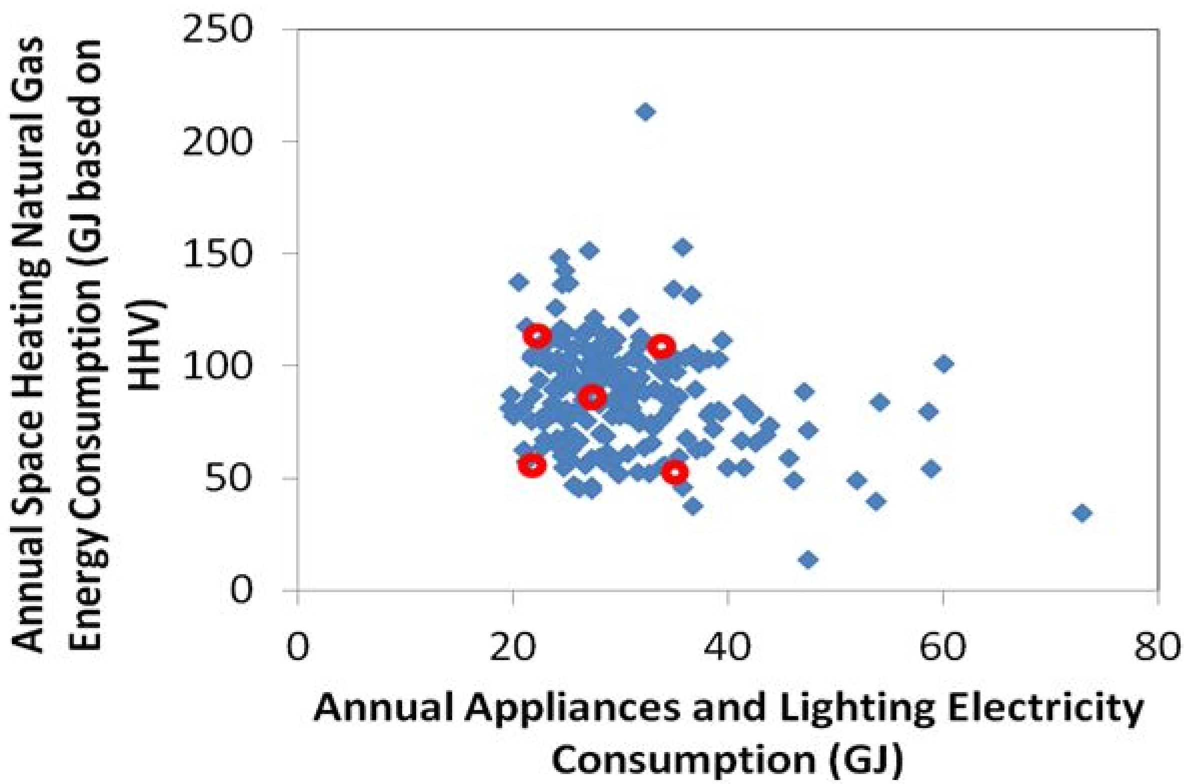


Figure 4. SH versus AL consumption. Sample houses are highlighted with red circles.

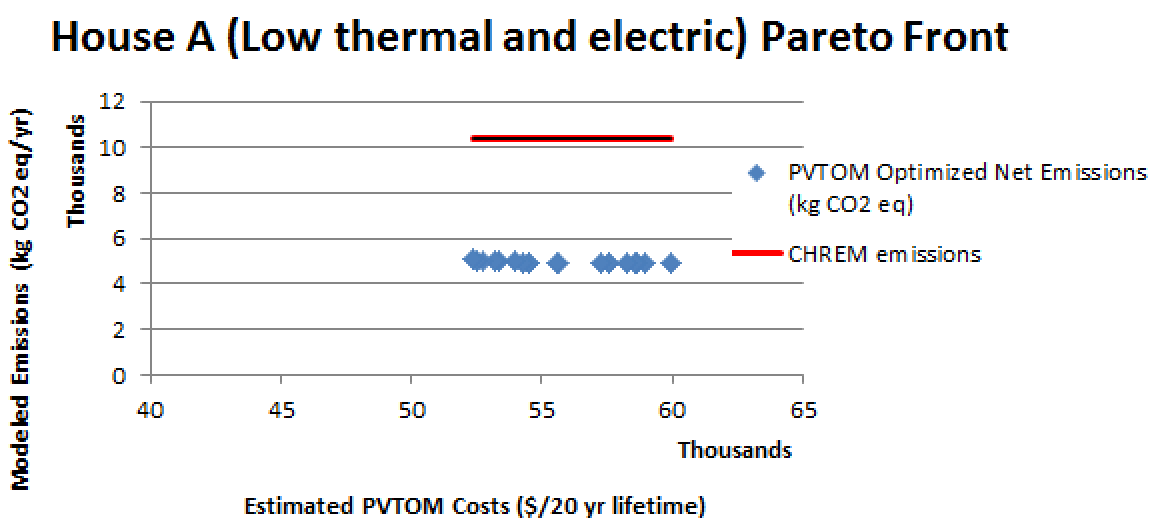


Figure 5. House A (Low thermal and low electric consumption) Pareto Front.

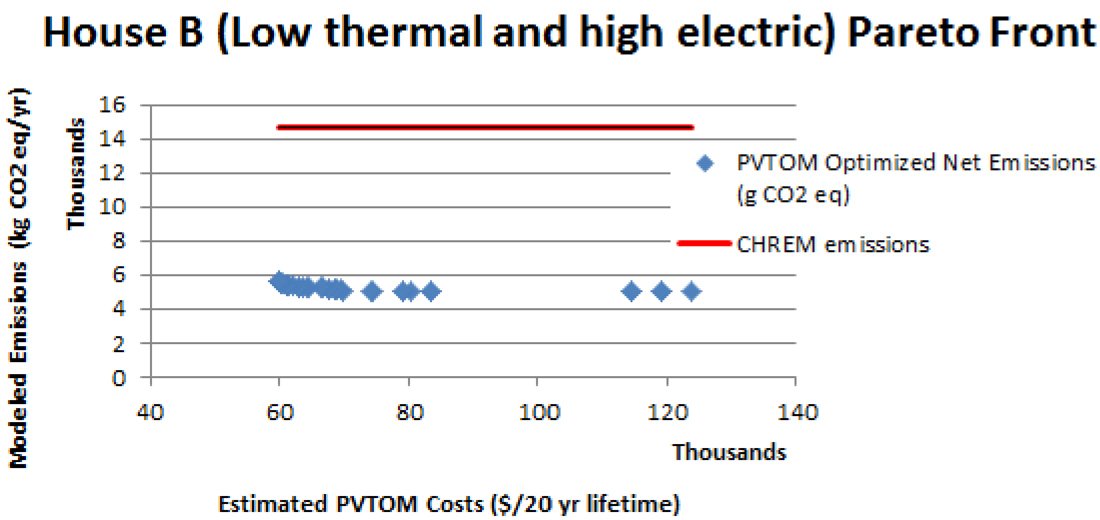


Figure 6. House B (Low thermal and high electric consumption) Pareto Front.

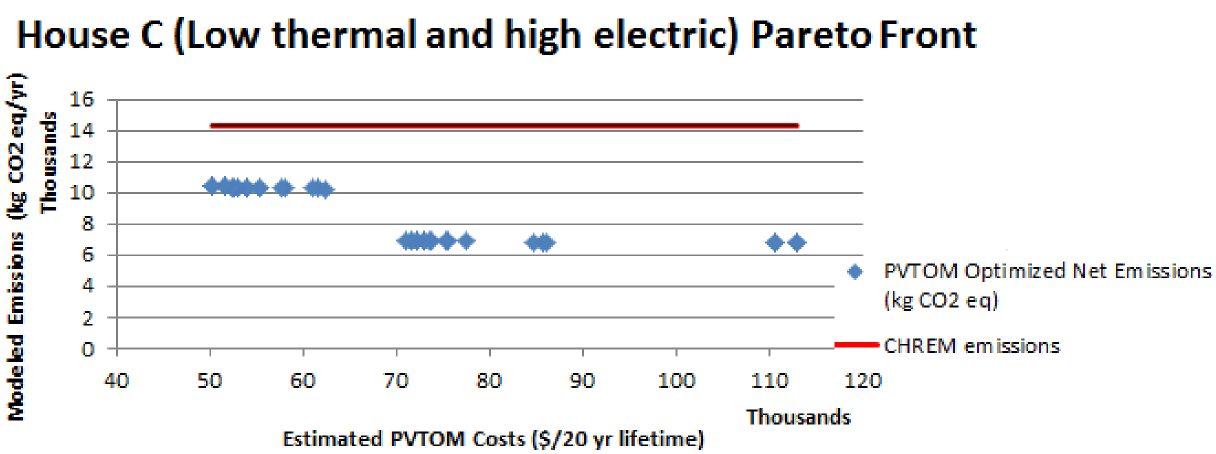


Figure 7. House C (Mode thermal and electric) Pareto Front.

Preprint: Amir H. Nosrat, Lukas G. Swan, Joshua M. Pearce, Simulations of greenhouse gas emission reductions from low-cost hybrid solar photovoltaic and cogeneration systems for new communities, *Sustainable Energy Technologies and Assessments*, 8, 34-41 (2014). http://dx.doi.org/10.1016/j.seta.2014.06.008

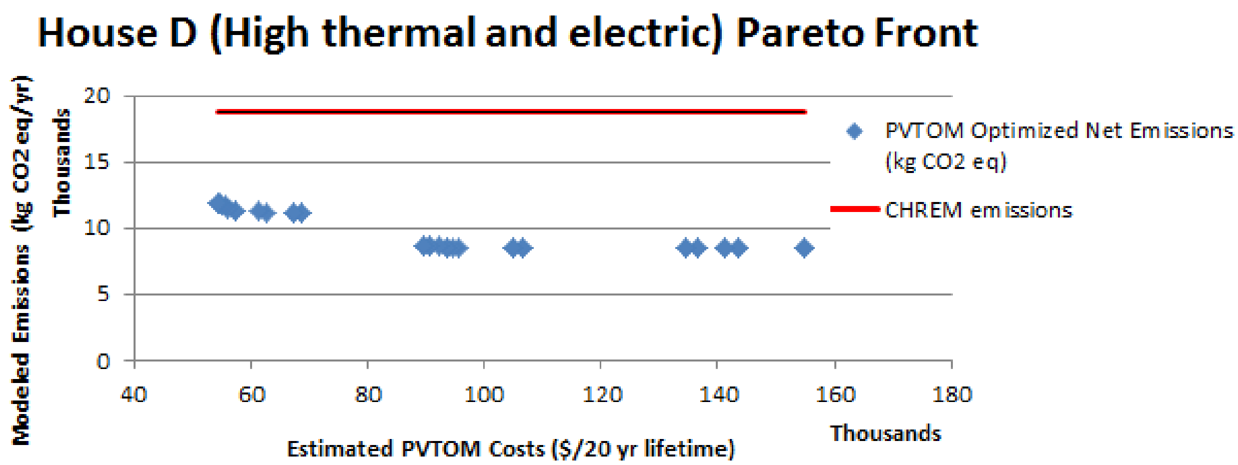


Figure 8. House D (Low thermal and high electric consumption) Pareto Front.

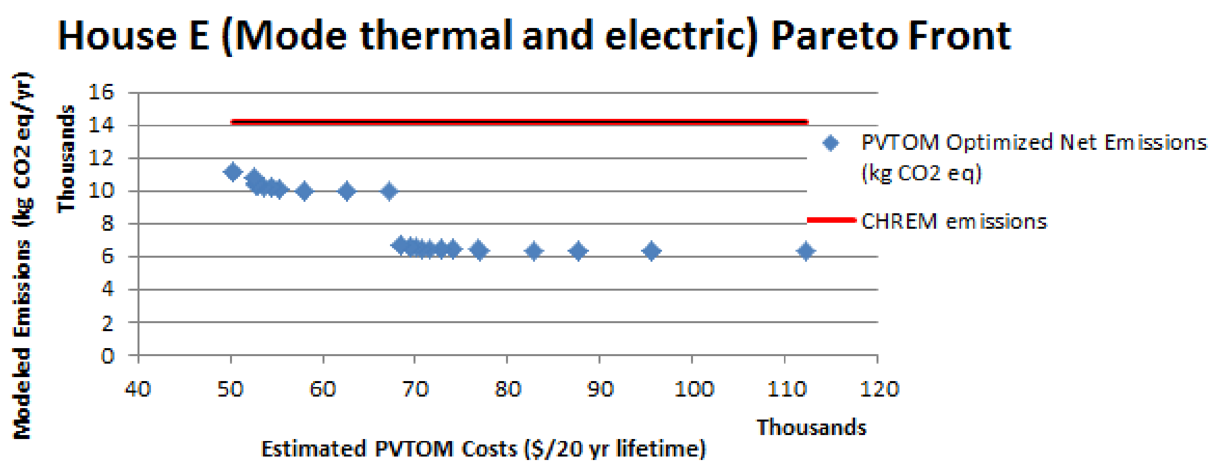


Figure 9. House E (High thermal and high electric consumption) Pareto Front.