Stirling Engine Based Cogeneration System Retrofit Impact on the Energy Requirement and Greenhouse Gas Emissions of the Canadian Housing Stock

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Abstract:

Energy end-use and greenhouse gas (GHG) emission impact of retrofitting Stirling engine based cogeneration systems in existing Canadian houses is studied using the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM). CHREM includes close to 17,000 unique house files that are statistically representative of the Canadian housing stock (CHS). The cogeneration system performance was evaluated using a high resolution integrated building performance simulation software. It is assumed that the Stirling engine cogeneration system is retrofitted into all houses that currently use a central space heating system and have a suitable basement or crawl space. A high efficiency auxiliary boiler is included to supply heat when cogeneration unit capacity is not sufficient to meet the heating load. The GHG emission intensity factor associated with marginal electricity generation in each province is used to estimate the annual GHG emissions reduction due to the cogeneration system retrofit. The results show that cogeneration retrofit would yield substantial energy savings and GHG emission reductions in the CHS.

Keywords:

Stirling engine based cogeneration, Residential cogeneration, Residential energy consumption, Residential greenhouse gas emissions, Canadian housing stock.

1. Introduction

If widely implemented, energy saving and high efficiency energy technology retrofits in the housing stock have the potential to reduce energy consumption and greenhouse gas (GHG) emissions of the residential sector. Cogeneration (i.e. combined heat and power - CHP) systems that generate electrical and thermal energy simultaneously from a single source of fuel are of interest because of their higher efficiency compared to conventional systems that generate electricity and thermal energy in two separate processes. While the energy conversion efficiency of a cogeneration unit is close to 80% (based on the fuel's lower heating value, and the sum of thermal and electrical output), the efficiency of a conventional fossil fuel based electricity generation unit is about 30-35% [1]. Onovwiona and Ugursal [1] classified micro cogeneration units into four major categories: reciprocating internal combustion (IC) engine based, micro turbine based, fuel cell (FC) based and reciprocating external heat source Stirling engine (SE) based. As part of a comprehensive effort to evaluate the feasibility of all four types of cogeneration systems for the Canadian housing stock (CHS) to achieve or approach net-zero rating, the Stirling engine based system is considered in this work due to the high efficiency, fuel flexibility, low emissions, low noise and vibration as well as decent performance at partial load. Since the heat source for Stirling engine is external, a wide range of energy sources can be used for this application [1,2].

Several authors studied the performance of residential scale SE cogeneration systems using experimental and numerical techniques. Entchev et al. [3] conducted an experiment to assess building integration, design issues and performance characteristics of a 6.5 kW_{th} (736 W_{el}) natural gas fired SE cogeneration system installed in a demonstration house at the Canadian Centre for Housing Technology. Tests were conducted for two different setups and scenarios during the winter/spring of 2003. It was shown that the micro cogeneration system satisfied the total thermal demand of the building including space and domestic hot water (DHW) heating. While the significant portion of electricity requirement of the house was supplied through SE cogeneration system, the excess electricity was exported to the grid. Kelly and Beausoleil-Morrison [4,5] developed a simulation model to characterize the thermal and energy performance of combustion-based micro-cogeneration devices, including those that are SE based, within Annex 42 of the International Energy Agency's Energy Conservation in Buildings and Community Systems Programme (IEA/ECBCS). The IEA Annex 42 model for cogeneration systems can be used with high resolution building energy simulation tools including ESP-r, TRNSYS and EnergyPlus. The IEA/ECBCS Annex 42 cogeneration system model was validated through a set of tests to evaluate the results for different modes of operation [6,7]. Lombardi et al. [2] calibrated the IEA Annex 42 model for SE based cogeneration systems based on a comprehensive experimental study Lombardi conducted [8]. Alanne et al. [9] studied a SE based cogeneration system using the IEA Annex 42 model to evaluate and optimize strategies for the integration of this system with residential buildings. Ribberink et al. [10] modeled a SE based cogeneration system in a single detached house with average heat demand in Ontario, and found that the SE based cogeneration system yields fuel savings as well as GHG and NOx emission reductions compared to high efficiency conventional heating systems. Based on these findings, it was concluded that the SE cogeneration system is a favourable option to reduce energy consumption and GHG emissions in Ontario. Conroy et al. [11] presented a model for SE based cogeneration system. The model includes transient (start-up and shutdown) and steady state period of operations for SE. The model was validated using the measured data from a unit installed in a dwelling in Northern Ireland. The model is capable of predicting thermal and electrical energy of the cogeneration system with acceptable accuracy. González-Pino et al. [12] conducted a study to assess the operational and economic viability of SE cogeneration system in single-family houses in three different climatic zones of Spain. It was assumed that the SE cogeneration system supplied the space and DHW heating demands. A sensibility analysis was carried out to estimate the effects of initial investment costs as well as fuel and electricity price variations on the economic results. It was concluded that that SE cogeneration system might not be suitable in single-family dwellings sited in any climatic zone of Spain. However, if the capital cost decreases, the micro cogeneration system could become viable in the coldest zone of study. Bouvenot et al. [13] developed a model for SE micro cogeneration system to assess their energy performance. The model incorporates a limited number of parameters with the goal to be suitable for annual building energy simulations. The modelling approach is based on an energy balance on the device and on empirical expressions for the main inputs and outputs. Valenti et al. [14] presented an experimental and numerical analysis of 8 kW_{th} (1 kW_{el}) commercial SE cogeneration system. The results showed that the electrical and thermal efficiency (based on the higher heating value - HHV) of the SE system is close to 9% and 90%, respectively. If the cogeneration water inlet temperature rises from 30°C to 70°C, the thermal efficiency decreases to about 84%. Cacabelos et al. [15] developed a model to study the dynamic performance of a commercial micro SE cogeneration system under different mass flow inputs. A theoretical analysis was carried out to assess the performance of the engine with the variation of the heat source temperature. The simulation results conclude that an important saving could be obtained when the electrical to thermal ratio is tracked for the power or thermal demands from a dwelling.

As this brief review of literature indicates, SE based cogeneration systems present a potential for energy savings and GHG emission reductions in the residential sector depending on climate, building and system characteristics. Since no comprehensive study was conducted to evaluate the effects of large-scale implementation of SE based cogeneration systems in the Canadian residential sector so far, this study was conducted within the Smart Net-zero Energy Buildings Strategic

Research Network (SNEBRN) initiative [16] to develop detailed information regarding the potential role of SE based micro cogeneration systems to achieve the objective of converting existing Canadian houses into net/nearly zero energy buildings (NZEB).

2. Methodology

This study was conducted using a representative model of the CHS that incorporates a whole building simulation approach. The methodology used in the study is discussed below.

2.1. Modeling the Canadian housing stock

Due to the wide range of climatic, geographical and economic conditions as well as the availability and price of fuels and energy sources in different regions of Canada, the CHS exhibits a high diversity in geometry and construction materials as well as heating, cooling and ventilation systems. Thus, this study was conducted using CHREM [17,18], which is based on the Canadian Single-Detached Double/Row Database (CSDDRD) [19] and is statistically representative of the CHS.

CHREM utilizes the high-resolution building energy simulation program ESP-r [21] as its simulation engine, an integrated modeling tool for evaluation of the thermal, visual and acoustic performance as well as energy consumption and GHG emissions of buildings. ESP-r has been validated through a vast amount of research results [22]. CSDDRD was developed using the latest data available from the EnerGuide for Houses database, Statistics Canada housing surveys and other available housing databases, and consists of close to 17,000 unique houses representative of the CHS. CHREM consists of six components that work together to provide predictions of the end-use energy consumption and GHG emission of the CHS. These components are:

- The Canadian Single-Detached & Double/Row Housing Database [19],
- A neural network model of the appliances and lighting (AL) and DHW energy consumption of Canadian households [23],
- A set of AL and DHW load profiles representing the usage profiles in Canadian households,
- A high-resolution building energy simulation software (ESP-r) that is capable of accurately predicting the energy consumption of each house file in CSDDRD,
- A model to estimate GHG emissions from marginal electricity generation in each province of Canada and for each month of the year [24],
- A model to estimate GHG emissions from fossil fuels consumed in households.

As discussed in detail elsewhere [20, 25-28], the energy savings and GHG emissions reductions associated with any energy efficiency upgrade or renewable/alternative energy technology, such as cogeneration systems, can be estimated using CHREM as follows:

i. Identify houses suitable to receive the upgrade/technology: For Stirling engine cogeneration system retrofit, only houses with a basement or a mechanical room would be suitable. Therefore, a search has to be conducted in the CSDDRD to identify such houses.
ii. Modify the input files of the selected houses to add the upgrade/technology for use in the ESP-r energy simulations.
iii. Estimate the energy consumption and GHG emissions reductions (or increases) of the CHS with the adopted upgrade/technology by comparing the energy consumption and GHG emissions with the “base case” (i.e. current) values. The change in GHG emissions due to a change in electricity consumption is estimated using the marginal GHG emission intensity factors given by Farhat and Ugursal [24]. Since CSDDRD is representative of the CHS, the CHREM estimates can be extrapolated to the entire CHS using scaling factors [17,18].

CHREM has so far been used to evaluate the energy, economic and emissions performance of window and windows shading upgrade as well as solar domestic hot water (SDHW) heating, manipulation of phase change materials (PCM) and ICE cogeneration retrofit in the CHS [20, 25-28].

2.2. Modeling the SE cogeneration system

The SE cogeneration system shown in Fig. 1 is considered for retrofitting existing and eligible Canadian houses. This architecture is based on the SE cogeneration system used in IEA/ECBCS Annex 42 subtask B [5] and is capable of providing space and DHW heating as well as electricity to the house. The system includes a thermal storage tank for the purpose of allowing the SE to work for extended periods at full load and steady state to minimize fuel consumption by reducing the low efficiency operation during engine warm-up and stray losses during cool-down. The size of the cogeneration unit is selected based on the design heating load of the house and the thermal and electrical efficiencies are assumed as 80% and 10%, respectively. A cogeneration unit that just matches or is slightly undersized for the design heating load is assigned to each house, with the balance to be made up by auxiliary heat. The thermal load following method is assumed in all cases. The effect of start-up and shut-down transients are modeled according to Lombardi et al. [2] and Lombardi [8], respectively.

An auxiliary boiler is included to provide heat when the available energy in the thermal storage tank is not sufficient to meet the thermal energy demand for space and DHW heating. A hot water tank is added to the system to store high temperature water required for space and DHW heating. Two heat exchanger coils are considered in the hot water tank to heat DHW and the circulated water in the space heating radiators. The DHW heat exchanger coil is sized based on the maximum flow rate. To avoid overheating the DHW when the flow rate is less than the maximum value, a tempering valve is used to maintain the DHW temperature at 55°C. Space heating is accomplished by a hydronic system that circulates heat to radiators.

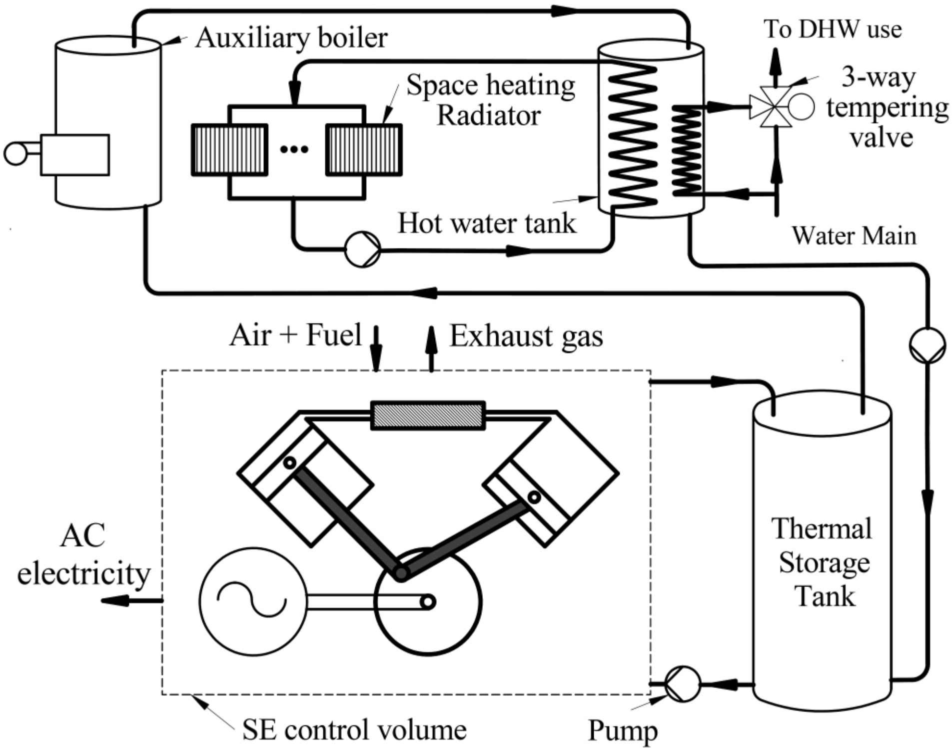

Fig. 1. Stirling engine based cogeneration system architecture.

The SE cogeneration system presented in Fig. 1 was modeled using the component models and control algorithms available in ESP-r to determine the fuel consumption of the cogeneration system. The capacity of the SE cogeneration system for each eligible house is determined according to the design heating load of the house. The building/plant model developed in ESP-r conducts an annual simulation (January 1 to December 31) with 10-minute time steps. Thus, the building model calculates the electricity as well as space and domestic hot water heating loads of the house for each

10-minute time step and passes this information to the SE cogeneration plant model. The plant model, using the performance and control algorithms, calculates the energy input/output of the cogeneration system and the auxiliary heater, as well as the electricity import/export values. The simulation is run in this fashion for the entire year, and the results are calculated and accumulated at 10-minute time steps.

The fuel used in SE cogeneration systems depends on the province. In all provinces except the Atlantic Provinces of NF, NB, NS and PE, Natural gas (NG) is widely available for residential customers. Therefore, it is assumed that in all provinces except these four, the fuel used in SE cogeneration is NG. In the four Atlantic Provinces, home heating oil is used for cogeneration.

2.3. Methodology to select houses for SE cogeneration system retrofit

The presence of a basement or mechanical room is necessary to install a SE cogeneration system in a house. Existence of mechanical room in the houses that do not have a basement is not specified in CSDDRD. Thus, two criteria are considered to evaluate the suitability of a house for SE cogeneration upgrade:

1. The presence of a basement.
2. The presence of a heating system that requires a mechanical room.

Thus, all houses that have basements, or utilize natural gas or heating oil fired heating systems, electric furnaces, or wood furnace/boilers are considered eligible for cogeneration retrofits.

Based on these eligibility criteria, 71% of the houses in the CHS were found to be eligible for the SE cogeneration system retrofit as shown in Table 1.

Table 1. Portion of houses eligible for IC engine cogeneration retrofit (% of total)

NF	NS	PE	NB	QC	OT	MB	SK	AB	BC	Canada
50	69	87	51	19	90	72	91	100	79	71

2.4. Estimation of the GHG emission intensity factor for electricity generation in each province of Canada[1]

Once the houses to be retrofitted with a cogeneration system were identified, those house files were modified to reflect the retrofit, and a batch simulation was conducted. The resulting energy consumption reflects the energy savings associated with the SE cogeneration system retrofit. Thus, the annual energy savings associated with the retrofit is determined by subtracting the energy consumption with cogeneration from the base case energy consumption.

Once the annual energy savings with the SE cogeneration system retrofit was determined, the GHG emission reductions were calculated based on the fuel type used at each dwelling. These emissions include those due to on-site fuel combustion and the emissions directly attributable to electricity production, inclusive of transmission losses.

The GHG emissions were calculated using the GHG emission intensity factor (EIF), which is the level of CO_{2e} emitted per unit input energy[2]. The GHG EIF is a function of only the type of fuel used and the efficiency of the energy conversion device used for on-site fuel combustion. However, the GHG EIF for electricity generation varies from province to province in Canada because of the different fuel mixture used in each province. Furthermore, the fuel used for base load and peak (marginal) load power plants are also different. Therefore, the base case GHG emissions due to the

[1] Provinces of Canada, from east to west, are: Newfoundland (NF), Prince Edward Island (PE), Nova Scotia (NS), New Brunswick (NB), Quebec (QC), Ontario (OT), Manitoba (MB), Saskatchewan (SK), Alberta (AB), and British Columbia (BC). NF, PE, NS and NB are collectively referred to as Atlantic Provinces (AT) while MB, SK and AB are referred to as Prairie Provinces (PR).

[2] CO_{2e} is the "equivalent CO_2" emissions from fossil fuel combustion calculated by converting all GHG emissions, such as CO and CH_4, to equivalent CO_2 emissions taking into account their global warming potentials [24].

electricity consumption of the CHS are calculated using the average GHG EIF of the regional electricity generation, while the changes in GHG emissions due to an energy upgrade is calculated using the marginal GHG EIF of the regional electricity generation. The average and marginal GHG EIFs for different provinces of Canada are given in Table 2 [24].

Table 2. The average and marginal GHG intensity factors (g CO2eq/kWh) for each province of Canada [24]

Electrical generation characteristics		Canadian provincial GHG EIF (CO_{2e} per kWh)									
		NB	NF	NS	PE	QC	OT	AB	MB	SK	BC
Annual $EIF_{Average}$		433	26	689	191	6	199	921	13	789	22
Annual $EIF_{Marginal}$		837	22	360	6				1	225	18
Monthly $EIF_{Marginal}$	Jan					23	395	825			
	Feb					0	352	825			
	Mar					0	329	795			
	Apr					0	463	795			
	May					0	501	795			
	Jun					0	514	780			
	Jul					0	489	780			
	Aug					0	491	780			
	Sep					0	455	780			
	Oct					0	458	795			
	Nov					0	379	825			
	Dec					4	371	825			
Transmission and distribution losses		6%	9%	4%	6%	4%	6%	4%	12%	6%	3%

3. Results and discussion

The CHREM estimates of current annual end-use energy consumption by the CHS and the associated GHG emissions are given in Table 3 [17]. The values presented in the table constitute the "Base Case" (i.e. current) end-use energy consumption and GHG emissions for the CHS by province and fuel type.

The SE cogeneration system shown in Fig. 1 was integrated into the eligible houses in CHREM and simulations were conducted to determine the energy end-use consumption and GHG emissions assuming that all eligible houses are retrofitted with the SE cogeneration system. The number of houses eligible for retrofit as well as the energy savings and GHG emission reductions due to the retrofits are given in Table 4. The results are discussed in detail in the following sections.

3.1. Impact of SE cogeneration system retrofit on the energy consumption of the CHS

The breakdown of annual end-use energy consumption of the houses eligible and ineligible for the SE cogeneration retrofit are given in Table 5 for each energy source and province. Electricity and fuel consumption in houses eligible for SE cogeneration retrofit are presented for existing and retrofit conditions. The energy consumption for the CHS is determined by adding the energy consumption of houses not eligible for the SE cogeneration retrofit to these data for existing and retrofit scenario, respectively. The results show that the retrofit of SE cogeneration system reduced the fuel consumption in all provinces except in the QC and OT while the electricity generation of

SE is not sufficient to supply the full demand in any region. In QC the existing heating systems are oil fired, however, due to wide availability of NG for residential customers the NG fired SE cogeneration system assumed for retrofit.

Table 3. CHREM estimates of annual energy consumption and GHG emissions for the CHS as a function of energy source [17]

	Energy (PJ)					GHG emissions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	15.2	0.0	9.6	3.3	28.1	0.12	0.0	0.67	0.8
NS	17.7	0.0	22.6	6.0	46.3	3.77	0.0	1.6	5.4
PE	1.8	0.0	4.0	1.5	7.3	0.1	0.0	0.28	0.4
NB	18.7	0.0	9.7	10.7	39.1	2.39	0.0	0.69	3.1
QC	205.3	1.0	30.3	10.4	247.0	0.36	0.05	2.14	2.6
OT	137.2	337.4	47.4	0.0	522.0	8.07	17.12	3.36	28.6
MB	18.9	33.6	0.0	0.0	52.5	0.07	1.7	0.0	1.8
SK	10.6	40.2	0.0	0.0	50.8	2.46	2.04	0.0	4.5
AB	28.3	119.8	0.0	0.0	148.1	7.56	6.08	0.0	13.6
BC	64.6	83.9	0.0	2.1	150.6	0.41	4.25	0.0	4.7
Canada	518.3	615.9	123.6	34.0	1291.8	25.3	31.2	8.7	65.3

Table 4. Energy savings and GHG emission reductions per house due to SE cogeneration retrofit

Province	No of houses eligible for retrofit	Total Energy saved (PJ)	Energy saved per house (GJ)	Total GHG reduced (Mt)	GHG reduced per house (kg)
NF	88,207	4.3	49	0.01	101
NS	205,181	8.9	43	0.55	2,655
PE	38,997	1.9	49	0.05	1,262
NB	122,070	6.8	56	0.30	2,416
QC	382,595	11.5	30	0.23	599
OT	3,082,265	120.3	39	8.81	2,859
MB	243,288	11.1	46	0.35	1,455
SK	287,895	13.9	48	0.64	2,211
AB	970,120	38.4	40	2.68	2,761
BC	877,789	28.2	32	1.03	1,175
Canada	6,298,407	245.2		14.65	

Table 5. CHREM estimates of annual energy consumption (PJ) with existing (Exist) and SE cogeneration retrofit (SER) systems in houses eligible (EL) and houses not eligible (N-E) for SE cogeneration retrofit

	Electricity			NG*		Oil*		Wood			Total		
	N-E	EL						N-E	EL		N-E	EL	
Province		Exist	SER	Exist	SER	Exist	SER		Exist	SER		Exist	SER
NF	10.9	4.3	2.4	0.0	0.0	9.6	9.9	0.6	2.7	0.0	11.5	16.6	12.3
NS	9.1	8.6	5.8	0.0	0.0	22.6	20.2	2.3	3.7	0.0	11.4	34.9	26.0
PE	0.4	1.4	1.1	0.0	0.0	4.0	3.2	0.7	0.8	0.0	1.1	6.2	4.3
NB	12.7	6.0	2.8	0.0	0.0	9.7	12.9	3.9	6.8	0.0	16.6	22.5	15.7
QC	181.7	23.6	7.1	1.0	39.2	30.3	0.0	7.5	2.9	0.0	189.2	57.8	46.3
OT	40.6	96.6	59.6	337.4	301.5	47.4	0.0	0.0	0.0	0.0	40.6	481.4	361.1
MB	12.1	6.8	3.8	33.6	25.5	0.0	0.0	0.0	0.0	0.0	12.1	40.4	29.3
SK	3.1	7.5	5.5	40.2	28.3	0.0	0.0	0.0	0.0	0.0	3.1	47.7	33.8
AB	0.0	28.3	23.7	119.8	86.0	0.0	0.0	0.0	0.0	0.0	0.0	148.1	109.7
BC	23.2	41.4	34.0	83.9	63.5	0.0	0.0	1.7	0.4	0.0	24.9	125.7	97.5
Canada	293.9	224.4	145.8	615.9	544.0	123.6	46.2	16.7	17.3	0.0	310.6	981.2	736.0

* All houses that use NG or oil as onsite fuel are eligible for cogeneration upgrade

Depending on the proportion of the houses eligible for retrofit and the type of fuels used for electricity generation and heating, the energy savings in each province is different as shown in Tables 6 and 7. These results show that retrofitting SE cogeneration in all eligible houses yields a 19% (representing 245.2 PJ/year) reduction in the end-use energy consumption of the CHS. The highest potential for energy savings is in SK, PE, AB and OT, while the lowest energy savings are in QC. This is because of the high proportion of houses that use baseboard electric convectors for space heating in QC, resulting in a relatively smaller proportion of eligible houses compared to the rest of Canada as shown in Table 1.

3.2. Impact of SE cogeneration system retrofit on GHG emissions of the CHS

The annual GHG emissions reduction in the CHS due to SE cogeneration upgrade in eligible houses is presented in Table 6 for each energy source and province. Since CO_2 emissions of biogenic material combustion will return to the atmosphere the CO_2 that was originally removed by photosynthesis, CO_2 emissions from biogenic materials are considered as a complement of the natural carbon cycle [24]. Thus the GHG intensity factor for wood is considered to be zero and emissions due to wood consumption is omitted from Tables 3 and 6. Percent GHG emission reductions due to the SE cogeneration retrofit relative to base case GHG emissions is presented in Table 7.

Due to the high efficiency of simultaneous electricity and heat generation, the SE cogeneration retrofit results the overall reduction of GHG emissions of the CHS; however, the reduction is not the same for all provinces. Because of differences in fuel mixture for electricity generation and space heating the energy savings and GHG reduction distribution are not the same in Canadian provinces. For example while the NF exhibits 15% (representing 4.3 PJ/year) energy saving due to SE cogeneration retrofit the GHG reduction is almost negligible. As shown in Table 6, wood has a significant portion (2.7 PJ) of end-use energy savings. As discussed before, the GHG EIF of the wood is assumed to be zero, thus, replacing the wood fired space heating system with oil burned SE cogeneration system increase the annual GHG emissions. However, the increase in GHG emissions is cancelled by the GHG emissions reduction due to electricity production of cogeneration system.

Table 6. Annual energy savings and GHG emission reductions due to SE cogeneration retrofits in the CHS

	Energy savings (PJ)					GHG emission reductions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	1.9	0	-0.3	2.7	4.3	0.03	0.00	-0.02	0.01
NS	2.8	0	2.4	3.7	8.9	0.39	0.00	0.16	0.55
PE	0.3	0	0.8	0.8	1.9	0.00	0.00	0.05	0.05
NB	3.2	0	-3.2	6.8	6.8	0.52	0.00	-0.23	0.30
QC	16.5	-38.2	30.3	2.9	11.5	0.03	-1.93	2.13	0.23
OT	37	35.9	47.4	0	120.3	3.78	1.71	3.32	8.81
MB	3	8.1	0	0	11.1	0.0	0.35	0.00	0.35
SK	2	11.9	0	0	13.9	0.04	0.60	0.00	0.64
AB	4.6	33.8	0	0	38.4	1.00	1.68	0.00	2.68
BC	7.4	20.4	0	0.4	28.2	0.04	0.99	0.00	1.03
Canada	78.6	71.9	77.4	17.3	245.2	5.83	3.40	5.41	14.65

The results provided in Table 7 illustrates that retrofitting SE cogeneration in all eligible houses yields a 22% (representing 14.65 Mt of CO_{2e}/year) reduction in the GHG emissions of CHS. From environmental perspective OT, BC, AB and MB show the most attractive condition for SE cogeneration retrofit.

Table 7. Annual energy savings and GHG emission reductions due to SE cogeneration retrofits in the CHS if eligible houses selected based on the criteria presented in Section 2.3

Province	Energy Savings (%)	GHG emission reductions (%)
NF	15	1
NS	19	10
PE	26	13
NB	17	10
QC	5	9
OT	23	31
MB	21	20
SK	27	14
AB	26	20
BC	19	22
Canada	19	22

4. Conclusion

The results of a comprehensive study conducted to estimate the impacts of SE cogeneration retrofits on the energy consumption and GHG emissions of the CHS were presented. The study was conducted using the CHREM, a versatile end-use and emissions energy model of the CHS. The study is part of a large-scale effort to develop approaches, incentive measures and strategies to facilitate conversion of existing Canadian houses into net zero energy buildings under Smart Net-Zero Energy Buildings Strategic Research Network.

Energy savings and GHG emission reductions are used to assess the impact of the SE cogeneration system upgrade performance in the CHS. The results of this study indicate that retrofitting existing houses in the CHS could result in 19% of energy savings and 22% of GHG emissions reductions. The suitability of SE cogeneration retrofit depends on the fuel mixture used for space heating and electricity generation as well as status of existing heating system in different provinces. Further studies are needed to study the impacts and feasibility of incorporating other energy efficiency and renewable energy technologies to achieve or approach net zero energy status in existing Canadian houses.

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Nomenclature

AB	Alberta
AL	Appliance and lighting
BC	British Columbia
CHP	Combined heat and power
CHREM	Canadian hybrid residential end-use energy and GHG emissions model
CHS	Canadian housing stock
CSDDRD	Canadian single-detached double/row database
DHW	Domestic hot water
EIF	Emission intensity factor
FC	Fuel cell
GHG	Greenhouse gas
IC	Internal combustion
MB	Manitoba
NB	New Brunswick
NG	Natural gas
NF	Newfoundland
NS	Nova Scotia
NZE	Net zero energy
ON	Ontario
PCM	Phase change material
PE	Prince Edward Island
QC	Quebec
SDHW	Solar domestic hot water
SE	Stirling engine
SK	Saskatchewan
SNEBRN	Smart net-zero energy buildings strategic research network

Subscripts and superscripts

th	Thermal
e	Equivalent
el	Electrical

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