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Techno-economic evaluation of internal combustion engine based cogeneration system retrofits in Canadian houses – A preliminary study

S. Rasoul Asaee [a,*], V. Ismet Ugursal [a], Ian Beausoleil-Morrison [b]

[a] Department of Mechanical Engineering, Dalhousie University, Halifax, NS B3H 4R2, Canada
[b] Sustainable Building Energy Systems, Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, ON K1S 5B6, Canada

HIGHLIGHTS

- Performance of IC engine cogeneration for Canadian housing is evaluated.
- Primary energy saving index was used for energetic evaluation.
- Greenhouse gas reduction index was used for environmental evaluation.
- Tolerable capital cost was used to evaluate economic performance.
- Impact of thermal storage capacity on cogeneration system performance was studied.

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ABSTRACT

A preliminary techno-economic evaluation of retrofitting reciprocating internal combustion engine based cogeneration into existing Canadian houses for the purpose of achieving or approaching net-zero energy rating is presented. Primary energy and electricity consumption, associated greenhouse gas emissions and tolerable capital cost are used as indicators. A whole building simulation model was used to simulate the performance of a commonly used cogeneration system architecture with thermal storage in "typical" single storey houses located in Halifax, Montreal, Toronto, Edmonton and Vancouver, representing the five major climatic regions of Canada. The system is assumed to sell excess electricity to the grid at the purchase price. A high efficiency auxiliary boiler is included to supply heat when cogeneration unit capacity is not sufficient to meet the heating load. The effect of thermal storage capacity, interest rate and acceptable payback period on the overall performance was evaluated through a sensitivity analysis. The findings suggest that internal combustion engine based cogeneration provides a promising option to achieve net-zero energy rating for Canadian houses, and therefore more detailed studies focusing on the entire Canadian housing stock are needed.

1. Introduction and literature review

The Canadian residential sector is responsible for 17% and 16% of the national energy consumption and greenhouse gas (GHG) emissions, respectively [1]. Therefore, reducing residential energy consumption will have a substantial contribution to the efforts to reduce overall energy consumption and GHG emissions in Canada. In this respect, research on technologies that would approach or achieve net-zero energy rated buildings has gained impetus [2]. 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% [3]. In contrast to photovoltaic and wind systems, the ability to control the electricity generation is a key benefit of CHP systems, providing an opportunity to achieve net zero energy status for residential applications [4]. Onovwiona and Ugursal [3] classified microcogeneration units into four major categories: reciprocating internal combustion (IC) engine based, microturbine based, fuel cell (FC) based and reciprocating external heat source Stirling engine (SE) based. As part of a

* Corresponding author at: Department of Mechanical Engineering, Dalhousie University, 5269 Morris Street, Halifax, NS B3H 4R2, Canada. Tel.: +1 (902) 494 3165; fax: +1 (902) 423 6711.
E-mail address: asaee@dal.ca (S.R. Asaee).

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Nomenclature

ACS	net annual cost savings due to energy upgrade (C$)
C	specific heat of water (kJ/kg °C)
C_{EE}	cost of electrical energy (C$)
C_{PE}	cost of primary energy (C$)
EC	energy cost (C$)
GER	GHG emission reduction index (decimal)
GHG_{CHP}	GHG emissions from combined heat and electricity generation
GHG_{CONV}	GHG emissions from separate heat and electricity generation
HDD	heating degree days (°C)
i	interest rate (decimal)
n	acceptable payback period (year)
PES	primary energy savings index (decimal)
$q_{gen,ss}$	heat generated by the cogeneration system in one hour (kJ/h)
$t_{op,ss}$	hours of steady state operation (h)
TCC	tolerable capital cost (C$)
V_t	tank capacity (m^3)
ΔT_{tank}	tank temperature range (°C)

Greek symbols

ρ	density of water (kg/m^3)
$\eta_{th,CHP}$	heat efficiency of the cogeneration
$\eta_{th,conv}$	efficiency reference value for separate heat production
$\eta_{EE,CHP}$	electrical efficiency of the cogeneration
$\eta_{EE,conv}$	efficiency reference value for separate electricity production

Abbreviations

CHP	combined heat and power
CHREM	Canadian Hybrid Residential Energy End-use and Emissions Model
CHS	Canadian housing stock
CSDDRD	Canadian Single-Detached and Double/Row Database
C$	Canadian dollar
DHW	domestic hot water
FC	fuel cell
GHG	greenhouse gas
HHV	higher heating value
HWT	hot water tank
IC	internal combustion
NB	New Brunswick
NL	Newfoundland and Labrador
NG	natural gas
NPCC	Northeast Power Coordinating Council
NS	Nova Scotia
PEI	Prince Edward Island
SE	stirling engine

comprehensive effort to evaluate the feasibility of all four types of cogeneration systems for the Canadian housing sector to achieve or approach net-zero rating, the IC engine based system is considered in this work due to the mature technology, fuel adaptability and ubiquitous presence of IC engines in the market.

In an IC engine based cogeneration system the engine is connected to an electricity generator and recovered heat from the engine is supplied to the building to satisfy the thermal energy requirement for the space and domestic hot water (DHW) heating. Usable heat is mainly recovered from engine jacket cooling water, exhaust gas and lube oil cooling water. Thermal storage in the form of one or more water tanks is incorporated into the cogeneration system to increase the duration of the high-efficiency steady state operation of the engine. Where possible (based on electric utility company policies), a cogeneration system may use the grid as electrical storage to export and import electricity when the electricity generation of the CHP unit is not equal to the building demand.

Thermal and electrical load following operating strategies are commonly used with IC engine based cogeneration systems. In both strategies, the IC engine operation period is governed by the energy requirement of the building and storage capacity. To be able to accurately simulate the performance of the cogeneration plant it is therefore necessary to integrate CHP electricity and heat generation with building energy requirements through a whole building simulation method. Thus, numerous studies of IC engine based cogeneration systems conducted using whole building simulation approach have been reported in the literature. For example, Onovwiona et al. [5] developed a parametric model that can be incorporated into a building energy simulation program to evaluate the techno-economic performance of residential scale reciprocating IC engine based cogeneration systems. The model includes IC engine, water based thermal energy and battery based electrical energy storage system as well as required control algorithms. Simulation results showed that size of the system components (IC engine, thermal and electrical storages) as well as control scenario significantly affect overall cogeneration system performance. Beyer and Kelly [6] studied the performance of an IC engine based domestic cogeneration system for different UK housing types using a model that was validated by comparing the results of simulations with actual measurement data. Various operating strategies for the cogeneration system, with and without thermal storage, were considered. The presence and size of thermal storage were found to have significant effects on the performance of microcogeneration system. Aussant et al. [7] modeled a series of test case houses using a building performance simulation program and studied the efficiency and economic performance of residential scale IC engine based cogeneration system in Canada. Electrical and thermal loads, climatic conditions and construction characteristics of the house were found to have strong influence on the overall performance of the microcogeneration system. Also, it was found that GHG emissions increased with the cogeneration system if the provincial electricity emission factor was lower than 400 gCO_2eq/kW h. Rosato et al. [8] conducted a study to evaluate energetic, economic and environmental performance of natural gas (NG) fed reciprocating IC engine based microcogeneration system integrated to a three storey multifamily house located in Naples, Italy. Investigation was carried out for thermal and electrical load following strategies, and the cogeneration system performance was contrasted to that of a conventional system generating heat and electricity separately. The results showed primary energy and operating cost savings as well as reduction of GHG emissions. It was concluded that compared to the electrical load following strategy, the heat load following is more beneficial in terms of primary energy consumption and GHG emissions but not operating cost.

There are also numerous experimental studies focusing on the performance of IC engine based residential cogeneration systems. For example, Possidente et al. [9] conducted an experimental study to evaluate the energetic, economic and environmental performance of three different microcogeneration systems (electric power $\leqslant$15 kW). They used primary energy consumption, CO_2 emissions and payback period as indicators, and compared the performance of the cogeneration systems to that of conventional