THE FEASIBILITY OF INTERNAL COMBUSTION ENGINE BASED COGENERATION IN RESIDENTIAL APPLICATIONS

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ABSTRACT

An economic and environmental analysis on residential internal combustion engine (ICE) based cogeneration in Canada was performed. Information from three publicly available databases was used to model four houses to be used in simulation. One house per Canadian region was chosen and modeled in ESP-r. Annual simulations using the existing space and domestic hot water heating equipment were performed and these base case results were compared to the results using the ICE based cogeneration system. It was found that electricity priority control ICE based cogeneration is not economically feasible as the fuel cost exceeds that of the base case scenario. The environmental impact of ICE based cogeneration was dependant on the GHG electricity emissions factor. In provinces with high electricity GHG emissions factors (>750 gCO_2eq/kWh), the ICE system was able to reduce the GHG emissions by approximately 10%.

KEYWORDS

Building Simulation, Residential Cogeneration, ESP-r, ICE Based Cogeneration, CHP

INTRODUCTION

According to the International Energy Outlook 2006 published by the US Department of Energy, world energy demand is expected to increase by 71% between 2003 and 2030 (Energy Information Administration, 2006). In addition, all forecasts of future world energy supply (POLES, IEA, World Bank, etc.) anticipate an almost doubling of world primary energy supply between 2000 and 2020 (Pilavachi, 2002). Carbon dioxide (CO_2) emissions are expected to increase by at least the same amount as the reduced emissions achieved by using advanced technologies in developed countries will be offset by an increase in fossil fuel use for transportation and by the use of low efficiency technologies in developing countries (Pilavachi, 2002). Current world energy demand is met primarily by fossil fuels – oil with 39% of the total share, natural gas at 23%, coal at 24%, nuclear at 7% and others including renewable sources at 8% (Doman, 2004) and fossil fuel dependence is expected to be 90% by 2020 (Pilavachi, 2002).

In Canada, between 1990 and 2003, secondary energy use – the energy used to heat and cool homes and workplaces, to operate appliances, vehicles and factories – increased 22 percent, from 6950 to 8460 petajoules (PJ) (NRCan, 2005). Consequently, secondary energy-related GHG emissions increased 23% from 410 to 500 megatonnes (Mt) (NRCan, 2005). As Figure 1.1 indicates, over 17% of this energy use was in the residential sector contributing 16% of the total secondary energy-related GHG emissions (NRCan, 2005).

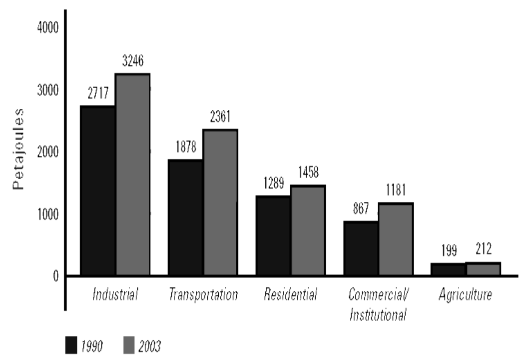

Figure 1: Energy Use by Sector, 1990 and 2003 (Petajoules) (NRCan, 2005)

In response to increasing GHG emissions resulting from increasing energy demand and consequent fossil fuel use, Canada has agreed, under the Kyoto Protocol, to reduce its annual GHG emissions to levels 6% below that of 1990 by 2012. Published by the Government of Canada, the Action Plan 2000 outlines Canada's commitment to reduce GHG emissions by approximately 65 Mt per year during the commitment period of 2008-2012 with 10% of the reductions expected to come from the residential sector (Government of Canada, 2000).

COGENERATION

Cogeneration, also known as combined heat and power (CHP), is defined as the simultaneous production of electrical or mechanical energy and useful thermal energy from a single energy stream such as oil, coal, natural or liquefied gas, biomass or solar (ASHRAE, 2000). Cogeneration is a well-proven technology that has been used for over 125 years. Its first appearance was in industrial plants in the 1880s when steam was the primary source of energy in industry and electricity was just surfacing as a product for both power and lighting (Knight and Ugursal, 2005).

While cogeneration can provide thermal and electrical energy at higher efficiencies than conventional methods, many applications still involve the burning of fossil fuels resulting in combustion products that are harmful to the environment. The combustion products obtained from the burning of fossil fuels include carbon dioxide (CO_2), oxides of nitrogen (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), unburned hydrocarbons and particulates (Onovwiona & Ugursal, 2006). However, due to the increased efficiency of cogeneration systems, less fuel has to be used in order to produce the same amount of useful energy, resulting in lower GHG emissions using cogeneration when compared to conventional generation methods. Figure 2 illustrates the difference between conventional genearation and cogeneration.

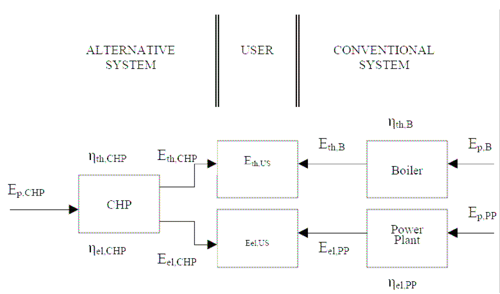

Figure 2: Conventional Generation and Cogeneration (Possidente et al., 2006)

Currently, there are several cogeneration systems available for use in residential buildings including reciprocating internal combustion engine (ICE) (spark ignition – natural gas, propane, gasoline, landfill gas, or compression ignition – natural gas, diesel) based systems, micro gas turbine based systems, fuel cell based systems and Stirling engine based systems (Onovwiona & Ugursal, 2006).

Reciprocating internal combustion engines are well suited to residential cogeneration due to their robust and well-proven technology (Knight and Ugursal, 2005). They are commercially available over a wide range of sizes, can utilize a wide variety of fuels and operate with high (>80%) availability making them well suited to numerous cogeneration applications including residential cogeneration (Knight and Ugursal, 2005). The reciprocating internal combustion engine based cogeneration system has several key advantages over competing technologies (i.e. fuel cell, micro-turbine and Stirling engine based cogeneration systems) including low capital cost, reliable onsite energy, low operating cost, ease of maintenance and wide service infrastructure (Onovwiona & Ugursal, 2006).

BUILDING SIMULATION AND ESP-R

Building simulation is a powerful tool used to aid in the assessment of renewable energy technologies in buildings. With respect to both environmental impacts and economics, it is important that critical design decisions can be tested and analyzed using building simulation (Hensen et al., 1993). Due to the progression of computing power, as well as the increasing demand for detailed thermal performance assessments, users regularly employ comprehensive, dynamic thermal appraisal tools which are able to handle the complexity of design (Hensen et al., 1993). Currently, there is a plethora of building simulation software available. For information on the abilities of some of the available software, refer to (Crawly et al., 2005).

ESP-r is a transient building energy simulation program developed and maintained by Energy Systems Research Unit (ESRU) at the University of Strathclyde (ESRU, 2002). It is an integrated modelling tool for the simulation of the performance of buildings in terms of thermal, visual and acoustic performance as well as the assessment of the energy use and gaseous emissions associated with the environmental control system and constructional materials (ESP-r, 2000). ESP-r's capabilities have expanded to include thermal behaviour as well as electrical, fluid, acoustic and visual performance (ESP-r, 2000)

ESP-r is a comprehensive modelling and simulation tool. ESP-r's approach is markedly different from traditional methods in that it aims to represent all relevant phenomena, and to process these phenomena simultaneously so that the inter-relationships are preserved (Clarke, 1994). This is achieved by establishing sets of conservation equations for different spatial regions and arranging for the integration of these equations over time (Clarke, 1994). Finally, the theories upon which heat transfer and fluid flow within ESP-r are based and the numerical techniques used are detailed in (Hensen, 1991).

DETERMINATION OF TEST HOUSE MODELS

To investigate the economic feasibility and environmental impacts of residential cogeneration in Canada a group of houses were modeled using the open-source building simulation program, ESP-r. Information from three publicly available Canadian databases was used to generate the models in ESP-r. The 1993 Survey of Household Energy Use (SHEU) database (Statistics Canada, 1993) contains detailed information on 8767 houses, representing more than seven million low-rise, single-family dwellings in Canada and is the most comprehensive and statistically representative survey on household energy use in Canada (Statistics Canada, 1993). The database contains weighting factors for each house which quantify the number of houses each entry in the SHEU database represents in Canada. Information regarding the house size, occupancy, number of storeys, number of doors and windows, space heating equipment and fuel type and temperature set points are available in SHEU and this information was used to model the test houses in ESP-r. The information available in SHEU was not sufficient to develop ESP-r models, thus to augment the information in SHEU, data from the EnerGuide for Houses database and the New Housing Survey database is used.

The EnerGuide for Houses (EGH) database is a management information tool and central depository for tracking residential energy evaluations and measuring benefits from the energy evaluations delivered across Canada (Blais et al., 2005). The database contains more than 165,000 houses rated across Canada, containing more than 162 information fields per house detailing information on its physical characteristics and energy use (Blais et al., 2005). Information including efficiency levels for space heating and domestic hot water equipment and insulation values for the main walls, ceiling and foundation were taken from this database, as this information is not available in SHEU.

The 1994 New housing survey (NHS) was conducted by Criterion Research Corp. between September 1995 and February 1996 for Natural Resources Canada surveying 2300 participants from all provinces except Prince Edward Island (NRCan, 1997). The NHS database details information such as house orientation and relative window distribution, information not available in SHEU or EGH databases.

The scope of the project is limited to simulating single detached dwelling, thus all attached houses (including row, duplex, low and high rise apartments) were taken out of the databases. In addition, only houses heated by either natural gas or oil were considered, as they would have the infrastructure required to implement a cogeneration system. For this purpose, homes heated by electricity were not considered in this analysis. Houses heated by propane and wood have also been taken out of the databases as houses using these fuels are not widespread enough (<15%) to be considered representative. Lastly, because the SHEU database does not contain any houses from the Northern Territories including the Yukon Territories, the Northwest Territories and Nunavut, these territories will not be considered in the analysis.

The SHUE, EGH and NHS databases were classified into categories according to region, namely, Western, Praries, Central and Atlantic Region. Table 1 details the provinces that make up the four Canadian Regions.

Table 1: Canadian Regions

REGION	PROVINCES
Western	British Columbia
Prairies	Alberta
	Saskatchewan
	Manitoba
Central	Ontario
	Quebec
Atlantic	New Brunswick
	Nova Scotia
	Prince Edward Island
	Newfoundland

The databases were further classified by vintage, namely, before 1941, 1941-1960, 1961-1977, 1978 and later; and by space heating fuel type, either natural gas or oil. The NHS database was classified on the basis of region only as there were not enough entries to allow for further classification.

To determine the most representative group per region based on vintage and space heating fuel type, the SHEU weighing factors for each group were summed. The group with the highest sum of weighting factors became the representative group for the region. Table 2 lists the reuslts of the classification process.

Table 2: Regional Test Houses

REGION	CITY	VINTAGE	SPACE HEATING FUEL
Western	Vancouver	1961-1977	Natural Gas
Prairies	Calgary	1961-1977	Natural Gas
Central	Toronto	1978 and later	Natural Gas
Atlantic	Halifax	1961-1977	Oil

MODELING AND SIMULATION

Once the representative groups were chosen, the average characteristics for each group, including house size, insulation levels, space and DHW heating equipment, and occupancy were calculated. Once all of the characteristics were determined, the houses were modeled in ESP-r. Tables 3 lists the main characteristics used to develop the house models.

Table 3: Test House Characteristics

Simulation City	Vancouver	Calgary	Toronto	Halifax
Size (m^2)	116	116	163	116
# of Storeys	1	1	2	1
Main Wall RSI	1.75	1.91	2.28	1.84
Foundation RSI	1.82	1.25	1.79	0.83
Ceiling RSI	3.91	4.23	5.06	3.19
Furnace Fuel	NG	NG	NG	Oil
Furnace η (%)	77	75	82	79
DHW Fuel	NG	NG	NG	Oil
DHW η (%)	51	55	56	56
# of Occupants	3	3	3	3
Glazed Area$_{2P}$ (m^2)	6.72	7.12	9.49	8.70
Glazed Area$_{1P}$ (m^2)	12.25	-	-	-
ACH	8.07	4.32	4.56	6.84

The first simulations, called the base case simulations, were run to determine how much energy the houses required and their associated GHG emissions while using the conventional equipment. The results of the base case simulations were then compared to the results when the conventional equipment was replaced by an ICE based cogeneration system. Figure 3 illustrates the ICE based cogeneration system configuration modeled in ESP-r using the ICE model developed by Onovwiona et al. (2007).

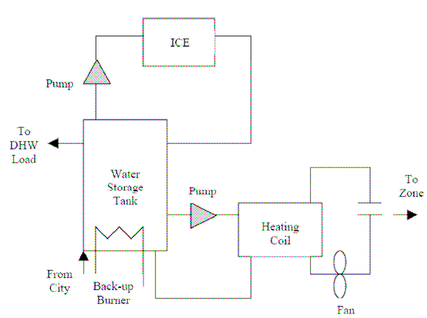

Figure 3: ICE based Cogeneration System Configuration

The ICE based cogeneration system was operated in electricity priority control mode in which the system's electrical output followed the electrical demand of the house. Any additional electricity was imported from the electrical grid. The thermal energy produced by the ICE system was stored in the hot water storage tank, and the back-up burner was controlled using on/off control with a six degree temperature band around the required DHW supply temperature of 55ºC. Heat was dumped from the hot wtaer storage tank when the temperature in the tank reached 85ºC to prevent the water from boiling. An air heating coil fed by the hot water storage tank was used to meet the space heating demand of the house. Both the heating coil pump and the supply fan were controlled using on/off control, and were actuated when the temperature in the main zone fell below the set point temperature.

Figure 4 illustrates the DHW draw profile used in the simulations (Lopez, 2001).

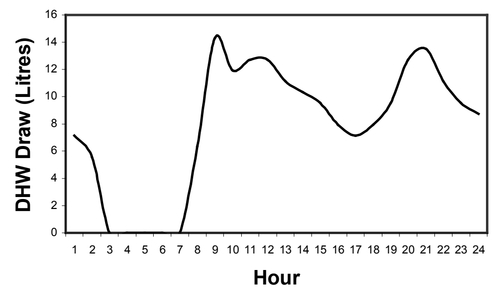

Figure 4: Daily DHW Draw Profile

Figure 5 illustrates seasonal averaged daily electicity load profiles for the test house in Vancouver. The seasons are defined as winter spaning from December to February, spring from March to May, summer from June to August and fall from September to November. Data from BC Hydro was used to determine the shape of the load curve (Good et al., 2004) while the magnitude of the load profiles were determined using the estimates provided by Aydinalp et al. (2002) who used Neural Networks (NN) to estimate the end-use energy consumption of Canadian single-family households, specifically for the entries in the SHEU database. Similar curves were developed for each of the four test houses and were used in simulation.

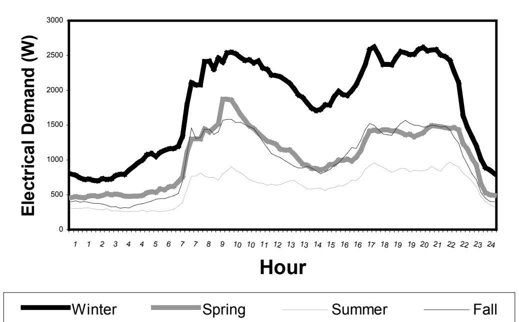

Figure 5: Electricity Load Profile

Four different ICE based cogeneration systems were simulated. Table 4 details the ICE capacities and thermal storage capacities used in the simulations.

Table 4: Cogeneration System and Thermal Storage Capacities

SYSTEM	ICE CAPACITY (kW)	THERMAL STORAGE CAPACITY (kg)
1	1	300
2	2	450
3	1	300
4	2	450

SIMULATION RESULTS

Tables 5 - 7 detail the fuel and electricity prices and electricity emissions factors used in this study.

Table 5: Fuel Costs

LOCATION	FUEL	COST	UNIT
Vancouver	Natural Gas[1]	40.77	¢/m³
Calgary	Natural Gas[1]	38.68	¢/m³
Toronto	Natural Gas[1]	49.27	¢/m³
Halifax	Oil[2]	71.40	¢/L
	Propane[2]	96.50	¢/L

Table 6: Electricity Prices

LOCATION	COST (¢/KWh)
Vancouver[3]	6.33
Calgary[4]	7.71
Toronto[5]	10.00
Halifax[6]	10.13

Table 7: Electricity Emissions Factors (Environment Canada, 2006)

LOCATION	gCO_2eq/kWh
Vancouver	24
Calgary	861
Toronto	222
Halifax	759

Table 8 details the annual base case simulation results for each of the four regional test houses. Note that fuel consumption values are in m³ for natural gas and litres for oil.

Table 8: Regional Test Houses – Base Case Annual Simulation Results

Simulation City	Vancouver	Calgary	Toronto	Halifax
$Demand_{el}$ (kWh)	17659	10867	9793	10127
$Demand_{SH}$ (GJ)	62.2	61.3	30.9	54.8
Furnace η (%)	77.3	74.9	82.4	78.7
Fuel for SH	2251	2317	1060	1897
$Demand_{DHW}$ (GJ)	11.7	11.8	11.8	11.8
DHW η (%)	51.1	55.0	55.6	56.0
Fuel for DHW	678	627	618	613
Total Fuel	2929	2944	1678	2510
$Cost_{el}$ ($)	1118	838	979	1026
$Cost_{Fuel}$ ($)	1194	1139	827	1792
$Cost_{tot}$ ($)	2312	1976	1806	2818
GHG_{el} (tonnes)	0.42	9.36	2.17	7.69
GHG_{th} (tonnes)	5.44	5.46	3.11	7.11
GHG_{tot} (tonnes)	5.86	14.82	5.29	14.80

The economic feasibility of ICE based cogeneration was evaluated by determining the difference in cost of electricity and fuel (for space and domestic hot water heating) when using ICE based cogeneration compared to the conventional systems. The difference in cost was calculated using Equation (1) where a positive value indicates a reduction in cost.

$$\Delta \cos t = \frac{\cos t_{BC} - \cos t_{ICE}}{\cos t_{BC}} \times 100\% \qquad (1)$$

The environmental impact asscociated with using ICE based cogeneration was assessed by caluculating the difference in GHG emissions (including CO_2, N_2O and CH_4) produced using ICE based cogeneration and comparing this to the base case results. The difference in GHG emissions was calculated using Equation (2) where a positive value indicates a GHG reduction.

$$\Delta GHG = \frac{GHG_{BC} - GHG_{ICE}}{GHG_{BC}} \times 100\% \qquad (2)$$

Table 9 - 12 details the cost and GHG changes using ICE based cogeneration.

[1] http://www.energyshop.com/es/homes/gas/gas-prices.cfm
[2] http://www.mjervin.com/WPPS_Public.htm
[3] http://www.bchydro.com
[4] http://www.customerchoice.gov.ab.ca/Rates-Current.pdf
[5] http://www.oeb.gov.on.ca
[6] http://www.nspower.ca

Table 9: Western Region - ICE Based Cogeneration Annual Simulation Results

SYSTEM	Δ COST (%)	Δ GHG (%)	η_{el} (%)	η_{CHP} (%)
1	-13.9	-56.4	23.2	60.5
2	-14.4	-56.9	23.2	60.7
3	-36.2	-122.0	21.0	42.7
4	-36.2	-122.1	21.0	42.7

Table 10: Prairie Region – ICE Based Cogeneration Annual Simulation Results

SYSTEM	Δ COST (%)	Δ GHG (%)	η_{el} (%)	η_{CHP} (%)
1	-11.1	12.2	22.4	53.4
2	-10.9	12.4	22.4	53.3
3	-27.5	12.7	19.0	36.5
4	-29.7	11.2	19.0	36.5

Table 11: Central Region – ICE Based Cogeneration Annual Simulation Results

SYSTEM	Δ COST (%)	Δ GHG (%)	η_{el} (%)	η_{CHP} (%)
1	-26.4	-50.2	21.2	48.2
2	-25.6	-49.2	21.2	48.2
3	-66.1	-110.5	17.2	33.5
4	-66.3	-110.7	17.2	33.6

Table 12: Atlantic Region – ICE Based Cogeneration Annual Simulation Results

SYSTEM	Δ COST (%)	Δ GHG (%)	η_{el} (%)	η_{CHP} (%)
1	-133.5	10.1	21.6	48.1
2	-135.6	9.2	21.6	48.3
3	-201.8	0.5	17.4	34.2
4	-202.6	-0.1	17.5	34.3

DISCUSSION

The economic viability of the ICE based cogeneration system in terms of fuel costs is dependent on the provincial fuel and electricity prices. The ICE based cogeneration system displaces grid-imported electricity in place of increased fuel consumption, thus the economics are favourable in provinces with relatively high electricity prices and relatively low fuel prices. In addition, the differences in fuel costs between the base and ICE based cogeneration cases in Halifax are considerably higher compared to the remaining cities because, due to the unavailability of natural gas, the ICE based cogeneration system was fuelled by propane, the most expensive of the fuels used in this study.

The potential reductions in GHG emissions using the ICE based cogeneration system compared to the base case is dependent on the local electricity emissions factor. It was determined that in location where the electricity emissions factor was greater than 750 gCO_2eq/kWh, using the ICE based cogeneration system results in a net GHG reduction.

Currently, there is very little data regarding the performance of cogeneration in residential applications in Canada. Much of the data available is from Europe and is based on fuel cell based systems. Specifically, there have been several studies published in recent years investigating the feasibility of residential cogeneration. Peacock and Newborough (2005) investigated the potential economic and CO_2 emissions savings using Stirling engine and fuel cell based cogeneration in the UK while Hawkes et al. (2007) concentrated on SOFC based cogeneration in the UK. De Paepe et al. (2006) investigated the potential cost and CO_2 emissions reductions using ICE, fuel cell, and Stirling engine based cogeneration in Belgium, in both single detached and terraced houses. Several Italian studies (Santangelo and Tartarini, 2007), (Possidente et al., 2006), and (d'Accadia et al., 2003) have investigated the reduction in cost and CO_2 emissions using ICE, fuel cell (PEMFC and SOFC), and Stirling engine based cogeneration systems and Dorer et al. (2005) investigated the potential economic savings and CO_2 reductions in single and multi-family dwellings in Switzerland using PEMFC and SOFC based cogeneration. In Canada, Entchev et al. (2004) investigated the performance of Stirling engine based cogeneration and Alanne et al. (2006) investigated the financial viability of SOFC based cogeneration in single-family dwellings. Currently, there is no published data on the performance of ICE based cogeneration in residential applications in Canada, thus there is no data available to verify the simulation results presented in the paper against. In addition, the results presented in this work agree with the results obtained by Onovwiona (2005), the developer of the ICE based cogeneration model used in this work.

CONCLUSION

As can be seen in Tables 9 - 12, electricity priority controlled ICE based cogeneration is not economically feasible. The heat generated during non-space heating months is not utilized, thereby reducing the annual average CHP efficiency. In provinces with high electricity emissions factors (>750 gCO_2eq/kWh), using ICE based cogeneration results in GHG reductions of approximately 10%. The 1kW ICE system coupled to the 300 kg thermal storage tank performs the best with respect to electrical and CHP efficiency. The 2 kW system operated at part load more often compared to the 1 kW system resulting in a lower annual average electrical efficiency. The increased thermal storage capacity was not fully utilized leading to a decrease in the annual average CHP efficiency.

To more fully quantify the potential impacts of using ICE based cogeneration in residential applications in Canada future work should involve exploring different ICE control schemes. Operating under a thermal load following scheme or constant output with electrical storage are scenarios that should be investigated. In addition, optimizing the control strategies used on the auxiliary equipment (ie: pumps, fan) could potentially improve overall system performance.

NOMENCLATURE

Symbols	
E	power (kW)
η	efficiency (%)
Subscript	
1P	single glazing
2P	double glazing
B	boiler
BC	base case
CHP	combined heat and power
el	electric
ICE	ICE case
p	primary
PP	power plant
th	thermal
Abbreviations	
ACH	air change per hour
DHW	domestic hot water
NG	natural gas
SH	space heating

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