PERFORMANCE ASSESSMENT OF RESIDENTIAL COGENERATION SYSTEMS IN CANADA USING A WHOLE-BUILDING SIMULATION APPROACH

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ABSTRACT

A performace assessment study has been performed on the application of Stirling engine (SE) and Solid Oxide Fuel Cell (SOFC) residential cogeneration systems in single family detached houses in Canada. Detailed mathematical component models, calibrated with measured data from prototypes, were combined into the whole-building simulation program ESP-r with synthetic electricity and domestic hot water demand profiles from calibrated event based generators to realistically forecast the Greenhouse gas emission reduction and efficiency improvement of these new technologies.

Simulation models and calibration methods are described. Simulation results for different locations across Canada and for cases with variations of the energy demand of the house are presented and discussed. Finally, conclusions and recommendations for potential improvements of the residential cogeneration systems are given.

KEYWORDS

Residential cogeneration, fuel cell, Stirling engine, emission reduction

INTRODUCTION

Residential cogeneration is generally believed to hold a promise of increased efficiencies, reduced greenhouse gas emissions, and reduced peak-load and grid dependence through on-site co-production of heat and power. Numerous simulation activities have been performed over the last decade to quantify the advantages of the application of cogeneration systems based upon an Internal Combustion Engine (ICE), a Stirling engine (SE), an Organic Rankine Cycle (ORC), a Polymer Exchange Membrane Fuel Cell (PEMFC), or a Solid Oxide Fuel Cell (SOFC) in houses. A literature review by Dorer et al. (2006) summarizes a total of over 75 publications. Many of these have been based upon a simplified performance-map approach that decouples the performance of the cogeneration unit from that of the rest of the building. However, until recently a comparison of the outcome of these simulation studies to the test results of the actual application of the cogeneration units in real houses has not been possible due to the early stage of development of most residential cogeneration technologies and/or the limited availability of prototype units.

Results from early field trials

In the UK a field trial of proptotypes of residential cogeneration systems was initiated in 2003 by the Carbon Trust. Prototype residential cogeneration systems were installed in representative homes in the UK gradually through 2004 and 2005 and an interim report on the preliminary results of the field trial was published at the end of 2005 (Carbon Trust, 2005). The conclusion on these very early findings was that the "*performance is not as encouraging as had been hoped based on published, modelled performance of the technology at the outset of the trial*". The interim report states as reasons for the disappointing results:

- The actual, real-world efficiency of the units are lower than assumed by existing modelling exercises.
- The amount of electicity generated is much lower than forecasted.
- Electricity exported out of the building is considerably higher than expected.

The lower efficiency and lower amount of electricity production were concluded to be related to the design and operation of the prototype units. The intermittent heat demand of the house did not interact well with the operational behaviour of the units, which is characterized by relatively long warm-up periods due to the high thermal mass of the units. During this warm-up phase no electricity is produced, and a lot of heat is absorbed in the units to bring them to their operating temperatures. Most of this heat cannot be usefully recovered. In a separate field study, Entchev et al. (2004) noted many of the same performance characterisitcs with a SE cogeneration system. These effects are not captured with decoupled performance-map models.

The mismatch in electricity export appears to be related to a common modelling assumption that the typical electricity demand in homes during a half-hour is similar to the average demand in that half-hour. The field trial data clearly show that this is incorrect. The domestic electricity consumption profile is much better characterised by a baseload of 100-500 W with short very high peaks (up to 10 kW) superimposed on this baseload. This baseload power consumption is generally (much) lower than the power production by the cogeneration unit, resulting in considerble export of excess power. Hawkes and Leach (2005) have demonstrated the that use of such coarse temporal precision in modelling can lead to significant errors.

It seems that some of the modelling studies used to forecast the performance of the prototypes in the Carbon Trust field trial overestimated the performance of the residential cogeneration and its carbon reduction due to the use of oversimplified assumptions on the operation of the cogeneration unit as well as on the energy demand pattern of the house it was placed in.

Objectives of current study

The current study sets out to realistically forecast the efficiency improvement and carbon emission reduction of Stirling Engine (SE) and Solid Oxide Fuel Cell (SOFC) residential cogeneration systems applied in single detached houses in Canada. The study does this by using:

- Detailed mathematical models to simulate the performance of the cogeneration devices (Ferguson and Kelly 2006; Beausoleil-Morrison et al. 2006a). These are system-level models that consider the thermodynamic performance of all components that consume energy and produce electrical and thermal output. These models are integrated with those of associated HVAC components, controls, and the building.
- Component models for SE and SOFC residential cogeneration systems that were calibrated using detailed measured performance data of prototype SE and SOFC cogeneration devices.
- A house model that is based upon the Test House of the Canadian Centre for Housing Technology (CCHT), which was previously modeled and validated thoroughly.
- Realistic electric and domestic hot water (DHW) load profiles generated by event based profile generators that used measured data for defining the characteristic draws of electricity and DHW.
- On the margin displaced greenhouse gas (GHG) emissions of central power production.
- The well-validated ESP-r whole building simulation program run with small time steps (100 seconds).

The work presented here is part of Canada's contribution to Annex 42 "The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC + COGEN-SIM)" of the International Energy Agency (IEA) implementing agreement on Energy Conservation in Buildings and Community Systems program (ECBCS). The performance assessment methodology developed within Annex 42 and described by Dorer and Weber (2007) is used in this study.

SIMULATION MODELS AND INPUTS

The performance of residential cogeneration systems depends strongly on country-specific and local conditions. The heat load of the house varies with building practices and climate, while occupant behaviour determines electricity and DHW loads. The efficiency improvements and reduction of GHG emissions due to the application of residential cogeneration depend on the power production structure and the chosen reference technologies. This means that the outlook for the application of residential cogeneration may vary significantly between (parts of) countries and conclusions from application studies may not be valid for other regions or countries.

The Canadian setting

Most houses in Canada have a wood based structure resulting in houses with a low thermal mass. Almost 60% of houses in Canada are single detached houses with an average floor area of 141 m^2 (Anon. A). This house type is used in this study.

Canada is a very large country with in general a continental climate, characterized by both a cold winter and a hot summer. Regional differences on the performance of the residential cogeneration are investigated by performing simulations for a number of locations across Canada.

Canada's extensive natural gas grid reaches form Québec City in the east to Vancouver in the west. Most major metropolitan areas are serviced by natural gas, making this the fuel of choice for the residential cogeneration systems.

Most houses in Canada are heated by a forced air furnace, where heated air is transported to various rooms in the house through a ductwork system. A state of the art condensing furnace with an Annual Fuel Utilization Efficiency of 96.3% (based upon the higher heating value, HHV) is taken for the reference technology (Anon. B).

Domestic hot water is predominantly heated in storage vessels by natural gas or electricity. Water heating efficiencies of 85% (HHV) are obtained for natural gas fired water heaters operating continuously (Anon. B). However, normal intermittent operation will result in a maximum annual average efficiency of only 62% (HHV) due to stand still losses. A simple one node water tank model with an annual 62% efficiency (HHV) is used in the simulations. A built-in natural gas burner serves as a back-up burner for preparing DHW.

The average Canadian household consumes approximately 6600 kWh of *non-HVAC* electricity (Anon. A). *HVAC* electricity is the power consumed by Heating, Ventilation, and AirConditioning equipment. The average daily DHW consumption is around 230 l/day. Event based profile generators are used to make load profiles that match the demands of the average household living in a one family single detached house.

In Canada the power production has historically been a provincial responsibility. Major differences in geographical conditions have resulted in a large variation in the provincial power production mix, ranging from a (vast) majority of hydropower in Québec and British Columbia to an almost exclusive use of coal in Alberta and Saskatchewan. The application of residential cogeneration systems at various location in Canada was investigated to identify the differences in displaced GHG emissions for various provinces.

Stirling engine model

In 2003 a WhisperTech Stirling Combined Heat and Power (CHP) unit was tested in the CCHT test house (Bell et al. 2003). The unit was used to heat water for space heating and DHW. The WhisperTech unit was run to operate in a heat load following mode keeping the water temperatures in storage vessels within a certain band. The engine was controlled to always perform complete operating cycles (warm-up, normal operation, shutdown, and inoperation) and was not allowed to restart before the full shutdown phase had ended. Normal operation in these cycles equalled operation at full load (700 W electric and around 6 kW heat output).

The data gathered during this testing was used to calibrate the model (i.e. establish its inputs) of Ferguson and Kelly (2006). This calibration procedure is documented in (Ferguson 2006).

Unfortunately, no data was available for continuous part load operation or warm restarts as would be required for an electricity load following mode. In this study, the use of the model is therefore restricted to heat load following scenarios at full load.

Solid Oxide Fuel Cell model

A series of experiments were conducted with a prototype SOFC cogeneration system from Fuel Cell Technology (FCT). These data were used to calibrate the model of Beausoleil-Morrison et al. (2006a). The calibration procedure is described in Beausoleil-Morrison et al. (2006b).

The test program included the characterization of the electrical and thermal output at varying loads, cooling water temperatures and flows. Unfortunately, the start-up and cool down behaviour of the SOFC unit could not be calibrated due to a lack of data.

The FCT SOFC has a nominal (and maximum) net electrical output of 2.7 kW and a thermal output of around 3 kW. Although the SOFC prototype has part load capabilities, the efficiency of the unit would decrease dramatically at part loads below 85%, as a supplementary heater needs to be operated to keep the SOFC stack at its desired temperature. For the simulations it was decided to operate the unit continuously at its nominal operating conditions. However, a three-month summer stop was introduced, as no significant heat demand was foreseen during this period matching the magnitude of SOFC heat production.

SE and SOFC systems

The system layout of the Stirling engine and SOFC residential cogeneration systems is very similar. The cooling water of the cogeneration unit is used to heat water in a storage vessel. This storage vessel provides DHW and warm water for the fan-coil unit that heats the house. The storage tank has a backup burner. A schematic overview of the SE and SOFC cogeneration systems is given in Figure 1.

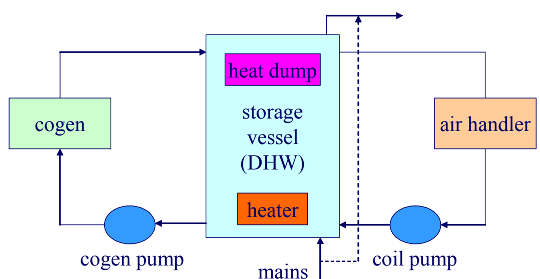

Figure 1 Schematic overview of the SE and SOFC residential cogeneration systems

The simulated SE system is controlled in a heat load following mode. The SE is started when the temperature of the water in the storage vessel drops below 60 °C. The engine will operate until its outgoing cooling water will reach a temperature of 80 °C. The corresponding temperature of the storage vessel will then be around 73 °C for the pump flow rate used in this study. The back-up burner will be activated when the tank temperature falls below 50 °C.

The SOFC system will be in continuous operation all year except for the period June through August. The SOFC unit will then be inoperative and all heat load will be supplied by the back-up burner in the hot water tank. When the SOFC heat supply will cause the water tank temperature to reach 92 °C, heat is dumped from the tank until the storage temperature has dropped to 90 °C. In the current study a rather ficticious heat dump facility is used that simply removes the appropriate amount of energy from the energy balance of the water tank model. The heat dump facility is foreseen to be upgraded to an external cooling loop with pump and fan coil unit in the near future. This upgrade would also allow the electricity consumption of pump and fan to be included in the simulations.

The balance of plant equipment of both cogeneration systems is assumed to be standard equipment. The power consumption of the cogeneration cooling loop pump is 80 W. The heating coil loop pump draws 100W, while the heating coil fan uses 200 W electric.

The thermostat set points for space heating are 21 °C from 8 to 24 hr and 18 °C from 0 to 8 hr.

House models

Four house models have been used in this study. All models are based upon the CCHT test house. This house was built conform the R2000 standard for energy efficient building and has a floor area of 210 m^2. This house ('ccht') is representative of new single detached housed built in Canada. The resulting space heating demand of this house is 39.7 GJ (after casual gains have been taken into account and using weather data for Ottawa for 2004).

The 'ccht141' house model combines the building characteristics of the ccht house with the floor area of the average Canadian single detached house (141 m^2). The ccht141 house is the base case model for this study and requires 27.8 GJ for space heating.

Two variants of the ccht141 model were made by adjusting the insulation level and the air tightness of the house. The 'ccht141_avg' house has a heat load equal to that of the average existing single detached house in Canada (71.3 GJ). Demonstrated aspects of an even more energy efficient way of building have been implemented in the 'ccht141_future' model, that has a very small resulting heat load (8.2 GJ).

Demand profiles for electricity and DHW

Realistic high resolution (5 minute time step) synthetic electric and DHW profiles have been produced using event based profile generators developed by the National Research Council of Canada (NRC) and Annex 26 of the IEA Solar Heating and Cooling Program.

Both generators have been calibrated using measured data from characteristic draws. More details on the NRC generator for electricity profiles can be found in Knight et al. (2007). For the Annex 26 DHW profile generator the reader is referred to Jordan and Vajen (2001).

Casual gains

Most electricity used by a household ends up as heat in the house. In the simulations 80% of the electric load is added as heat (casual gain) to the house. The remainder represents the external lighting and e.g. the hot exhaust of an electrically heated clothes dryer.

All space heating and DHW supply equipment is assumed to be located in a part of the house that does not belong to the heated zones. Heat losses from furnace, SE, and SOFC system (including hot water storage tank) are not taken as a source of casual gain in the house.

The occupants of the house were assumed to provide 200 W of heat continuously.

Performance metrics

The performance of the SE and SOFC residential cogeneration systems is first expressed in the GHG emission reduction they achieve in comparison to the reference situation of separate heat and power production using best available heating technology (condensing hot air furnace and high efficient water heater) and central power production. Secondly, the efficiency of the cogeneration systems in producing heat and power, and in providing the requested energy services to the house are investigated.

Greenhouse gas emissions

The reduction of GHG emissions has been calculated taking into account the displaced emissions of central power production plants on a temporal basis. Two methods have been applied:

The first method uses a correlation between the publicly available Hourly Ontario Electricity Price (HOEP) and the on-the-margin fuel source for central power production in Ontario that would be displaced by cogeneration power production. This method was developed in a recent project at Natural Resources Canada and is described in (Mottilo et al. 2006). The majority of cases have been simulated using climate data for Ottawa for 2004 and the corresponding displaced emission data from the 'HOEP' method.

A second method is used in the comparison of the simulation results for different locations across Canada (Montréal, Ottawa, Calgary, Vancouver). The PERRL study (ICF Consulting 2003) presents monthly data on displaced emissions per province. Climate data for standard 'cwec' reference year have been used for all locations in this comparison.

Upstream fuel cycle emissions (i.e. the emissions for getting the primary energy from its source to the house or power plant) are taken into account in the GHG emissions reduction calculations.

Efficiencies

Efficiencies are defined on three levels: the cogeneration *unit*, the cogeneration *system*, and the house.

The efficiencies for the cogeneration *unit* present the efficiency of the conversion of natural gas into electricity and heat. The net cogeneration efficiency ($\eta_{HHV,cogen\text{-}net}$) is defined as:

$$\eta_{HHV,cogen-net} = \frac{P_{net} + Q_{gross} - Q_{dump}}{Q_{fuel-cogen}} \quad (1)$$

in which P_{net} is the net AC power output of the cogeneration unit, Q_{gross} the gross heat output of the cogeneration unit, Q_{dump} the heat dumped from the storage tank, and $Q_{fuel\text{-}cogen}$ the energy content (HHV) of the fuel consumed by the cogeneration unit.

Similarly, the net electric cogeneration efficiency ($\eta_{HHV,cogen-net-elec}$), the gross cogeneration heat efficiency ($\eta_{HHV,cogen-gross-heat}$), and the net cogeneration heat efficiency ($\eta_{HHV,cogen-net-heat}$) are defined:

$$\eta_{HHV,cogen-net-elec} = \frac{P_{net}}{Q_{fuel-cogen}} \quad (2)$$

$$\eta_{HHV,cogen-gross-heat} = \frac{Q_{gross}}{Q_{fuel-cogen}} \quad (3)$$

$$\eta_{HHV,cogen-net-heat} = \frac{Q_{gross} - Q_{dump}}{Q_{fuel-cogen}} \quad (4)$$

The efficiencies of the cogeneration *system* (cogeneration unit *plus* balance of plant (BOP) equipment) will differ from those of the cogeneration unit alone. Heat losses from the storage tank and power consumed by the system's pumps will reduce the efficiency. The use of the back-up burner will also influence the efficiency.

The net cogeneration system efficiency ($\eta_{HHV,system-net}$) is defined as

$$\eta_{HHV,system-net} = \frac{P_{net} + E_{SH} + E_{DHW} - P_{BOP}}{Q_{fuel-cogen} + Q_{fuel-bb}} \quad (5)$$

with E_{SH} and E_{DHW} being the thermal energy supplied to meet the space heating demand of the house (after casual gains have been accounted for) and the domestic hot water demand, respetively. P_{BOP} is the electricity draw of the balance of plant equipment. Only the power for the two pumps (see Figure 1) is taken into account, since the fan of the air handler unit would have to be present in a furnace anyway. $Q_{fuel-bb}$ is the energy content (HHV) of the fuel consumed by the back-up burner in the storage tank.

The net system electric efficiency ($\eta_{HHV,system-net-elec}$) and net system heat efficiencies ($\eta_{HHV,system-net-heat}$) are defined similarly:

$$\eta_{HHV,system-net-elec} = \frac{P_{net} - P_{BOP}}{Q_{fuel-cogen} + Q_{fuel-bb}} \quad (6)$$

$$\eta_{HHV,system-net-heat} = \frac{E_{SH} + E_{DHW}}{Q_{fuel-cogen} + Q_{fuel-bb}} \quad (7)$$

The house efficiency ($\eta_{HHV,house-net}$) is the overall efficiency of meeting the demand for (non-HVAC) electricity, space heating, and DHW of the house.

$$\eta_{HHV,house-net} = \frac{E_{El-non-HVAC} + E_{SH} + E_{DHW}}{Q_{fuel-cogen} + Q_{fuel-bb} + PE_{grid}} \quad (8)$$

$E_{el-non-HVAC}$ is the non-HVAC electricity demand of the house, PE_{grid} is the required primary energy (natural gas or coal) input to the central power plant for supplying the amount of electricity imported by the house. PE_{grid} is negative for a net export of electricity to the grid.

Central power production is rated at 51% (HHV) for a natural gas fired combine cycle, and at 32% (HHV) for coal based power production. A 92% distribution efficiency is taken into account for grid electricity. All efficiencies are based upon primary energy inputs to the house or to the power plants. No upstream efficiency losses are considered.

For reference cases, similar efficiencies can be defined by replacing the fuel input of the cogeneration unit by the fuel input of the furnace in equation 5-8.

SIMULATION RESULTS AND DISCUSSION

SE and SOFC base cases

The SE system is operated in a cyclic mode. At full load, $\eta_{HHV,cogen-net-elec}$ is 8.4%, $\eta_{HHV,cogen-net-heat}$ is 74.4%, totalling 82.8% for $\eta_{HHV,cogen-net}$. However, start-stop losses decrease this number to an annual average net cogeneration efficiency of 78.9% (7.0% electric and 71.9% heat). The pumps of the SE system absorb approximately 20% of the SE power production. Heat losses from the storage tank cause the $\eta_{HHV,cogen-net-heat}$ to drop to 60.8%. The resulting $\eta_{HHV,system-net}$ is 66.2%, substantially lower than the equivalent full load efficiency.

The SOFC residential cogeneration system is run continuously at full load, with a $\eta_{HHV,cogen-net-elec}$ of 23.6% and a $\eta_{HHV,cogen-gross-heat}$ of 25.4%. However, 38.3% of the heat output of the SOFC can not be used and needs to be dumped, decreasing $\eta_{HHV,cogen-net-heat}$ to 15.6% and $\eta_{HHV,cogen-net}$ to 39.3%.

The SE net house efficiencies are only a little lower than those for the reference case. For the SOFC system, the difference is bigger. Table 1 presents the efficiencies for the SE and SOFC systems and (where appropriate) for the reference case.

Table 1 Performance of base case SE and SOFC residential cogeneration systems compared to the reference case.

	Reference base case (%)	SE base case (%)	SOFC base case (%)
$\eta_{HHV,cogen-net-elec}$		7.0	23.6
$\eta_{HHV,cogen-gross-heat}$		71.9	25.4
$\eta_{HHV,cogen-net-heat}$		71.9	15.6
$\boldsymbol{\eta_{HHV,cogen-net}}$		**78.9**	**39.3**
$\eta_{HHV,system-net-elec}$		5.4	22.3
$\eta_{HHV,system-net-heat}$		60.8	14.8
$\boldsymbol{\eta_{HHV,system-net}}$	**(80.4)**	**66.2**	**37.1**
$\eta_{HHV,house-net-coal}$	46.5	45.3	42.0
$\eta_{HHV,house-net-nat.gas}$	61.7	57.3	33.6

Emission reduction for locations across Canada

The fuel source for central power production that is displaced by the cogeneration system's electricity production heavily influences the potential for GHG emission reduction. The second column of Table 2 presents the annually averaged emission factors of the displaced fuel sources (ICF Consultancy 2003) in case all the non-HVAC power of the house would be supplied by the cogeneration unit for different locations across Canada.

A similar emission factor $GHG_{f,cogen}$ can be defined for the cogeneration cases

$$GHG_{f,cogen} = \frac{GHG_{total,cogen} - GHG_{SH+DHW,ref}}{P_{net} - P_{BOP,extra}} \qquad (9)$$

in which $GHG_{total,cogen}$ is the total GHG emission due to the natural gas consumption of the cogeneration unit, $GHG_{SH+DHW,ref}$ the combined GHG emission of the furnace and the water tank for the reference case, and $P_{BOP,extra}$ the *additional* electricity consumption for BOP equipement of the cogeneration system over that for the reference system. The nominator in Equation 9 represents the GHG emissions attributed to the electricity production, while the denomenator equals the reduction of electricity import from the grid in comparison to the reference case. The application of residential cogeneration systems will reduce the GHG emissions if the emission factor of the cogeneration system ($GHG_{f,cogen}$) is lower than that for the central power production it displaces, and vice versa. The emission factors for the SE and the SOFC system are also given in Table 2.

Table 2 clearly shows that the potential for emission reduction is mainly determined by the specific central power production technology (hydro, natural gas, coal) locally used.

Table 2 Annual average GHG emission factors for on-the-margin central power production, and SE and SOFC residential cogeneration systems.

	GHG emission factor (kg/kWh)		
	Central power production	$GHG_{f,cogen}$ SE system	$GHG_{f,cogen}$ SOFC system
Montréal	0.186	0.951	0.746
Ottawa	1.067	0.957	0.749
Calgary	0.480	0.941	0.751
Vancouver	0.379	1.038	0.802

Emission reduction using the HOEP method

The HOEP method provides temporal information on the on-the-margin fuel source. For the reference case, the annual average emission factor for displaced grid electricity is 0.850 kg/kWh. This indicates that the cogeneration power production would primarily displace emissions from a coal-fired power plant (1.076 kg/kWh) and to a lesser extent electricity production based on natural gas (0.461 kg/kWh) and hydro (0.0178 kg/kWh).

A number of variations on the base cases have been simulated for the SE and SOFC systems (and for the corresponding reference cases) to investigate the relative importance of the demand for electricity, space heating, or DHW, and the temperature of the storage tank on the performance of the cogeneration systems. Table 3 presents the variation in input parameters for the different cases and the main results per case.

Using HOEP and climate data for 2004, the use of SE residential cogeneration systems hardly has any impact on the house emissions. GHG emission reductions would range from +1% for the ccht141_avg house (high space heating load) to -2% for the ccht141_future house (very low space heating load).

All SOFC cases show a reduction in GHG emissions. Variation of heat load (low to high) results in a 5% - 16% emission reduction. An 8 - 22% reduction is calculated for varying the electricity demand of the house (from high to low).

Reduction of primary energy use

The application of the SE and SOFC cogeneration systems has also been assessed in light of their potential to reduce the amount of primary energy (natural gas) needed for the energy demands of the house. In this assessment, grid electricity has been assumed to be produced by a natural gas fired combined cycle power plant.

The results for the different SE cases do not vary substantially relative to each other, due to the low amount of electricity produced. All SE systems perform slightly less than the reference systems. The SE cases consume between 5% and 10% more natural gas than the reference cases. A gap that could likely be bridged by improvements to the BOP plant of the system (i.e. improved insulation of the storage tank and the use of high-efficient pumps). However, the performance of the SE unit itself needs to be improved considerably before the system can significantly outperform the reference system of condensing furnace and high efficient hot water heater.

The continuous full load operating strategy has a major influence on the performance of the SOFC residential cogeneration system. For the base case the electricity production is roughly two times the power consumption of the house. All SOFC cases show a (large) net power export to the grid. For all cases there is also more heat produced than can be used. Despite the summer stop, still between 20% and 60% of the heat output of the SOFC has to be dumped. This heat represents between 6 and 15% of the cogeneration unit's energy input. The performance of the SOFC system is therefore better for cases that have a higher demand for space heating or DHW.

Even a lower storage temperature does not increase the efficiency, because the benefit of lower heat losses from the storage tank is completely annulled by a higher heat dump due to the smaller heat storage capacity.

Due to the very low system efficiency, the SOFC cases require a 50% to 120% higher natural gas input than the reference cases. Major improvements to the SOFC prototype are required before the system will be able to reduce natural gas consumption.

PRELIMINARY CONCLUSIONS AND RECOMMENDATIONS

New models for simulating the performance of residential cogeneration devices have been developed and calibrated. This paper demonstrates their application for assessing the performance of prototype SE and SOFC devices in Canadian housing.

For the prototype devices investigated, the emission reduction potential is mainly determined by the displaced emissions of the grid. Application of the prototype SOFC system in Ontario would substantially reduce the GHG emissions of the house despite a very low system efficiency of 37%. The prototype SE system has a higher system efficiency but negligible emission reduction when applied in Ontario. The prototpye cogeneration units in this study would cause GHG emissions to increase when applied in Québec, Alberta, and British Columbia.

The prototype SE system consumes between 5% - 10% more natural gas than the reference system, a difference that may already be bridged by reducing storage heat losses and BOP power consumption . The SOFC needs 50% - 120% additional natural gas input compared to the reference system, partly due to the necessity to dump excess heat. Improvements to both SE and SOFC prototype systems are possible that will allow the systems to reduce the primary energy input to the house and have substantial GHG emission reductions.

The capacity of the SE unit is rather small for Canadian single detached houses, the SOFC capacity is too large (assuming continuous operation).

The importance of performing detailed simulations with small time steps was demonstrated by this study. For the SE cogeneration system, stand-still losses and HVAC electricity reduced the net electric system efficiency to only 64% of full load efficiency. The net heat efficiency was 81% of full load efficiency.

FUTURE WORK

The results described in this study are part of a larger performance assessment study on SE and SOFC residential cogeneration, which will be reported in an IEA/ECBCS Annex 42 publication at a later time.

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Table 3 Main results for SE and SOFC simulation cases (HOEP method, Ottawa, 2004)

Variation of		Em. reduction (%)	Prim. en. reduction (%)	$\eta_{HHV,system-net-elec}$ (%)	$\eta_{HHV,system-net-heat}$ (%)	$\eta_{HHV,system-net}$ (%)	Heat dumped (%)	$GHG_{f,cogen}$ (kg/kWh)
SE cases	**base case**	**-1.3**	**-7.7**	**5.4**	**60.8**	**66.2**	**0.0**	**0.950**
Storage temperature [1]	50 – 63	-0.7	-5.8	4.9	64.2	69.1	0.0	0.900
(°C)	55 – 73	-0.9	-6.9	5.4	61.9	67.3	0.0	0.907
Electricity demand [2]	4837	-1.6	-10.1	5.5	62.0	67.5	0.0	0.929
(kWh/y)	13044	-1.0	-5.5	5.2	59.2	64.5	0.0	0.980
Space heating dem. [3]	8.2	-1.6	-6.3	4.7	53.8	58.5	0.0	1.088
(GJ/y)	39.7	-0.5	-7.4	5.6	64.2	69.8	0.0	0.869
	71.3	1.1	-6.6	5.6	69.6	75.1	0.0	0.778
DHW demand [4]	9.5	-1.8	-8.1	5.3	59.5	64.8	0.0	1.008
(GJ/y)	21.2	-0.8	-7.3	5.4	62.6	68.0	0.0	0.895
SOFC cases	**base case**	**14.3**	**-83.4**	**22.3**	**14.8**	**37.1**	**38.3**	**0.757**
Storage temperature [1]	50 – 70	13.5	-84.4	22.2	14.8	37.0	46.3	0.760
(°C)	50 – 80	14.0	-83.7	22.3	14.8	37.1	42.2	0.758
Electricity demand [2]	4837	21.8	-96.9	22.1	16.6	38.7	33.8	0.741
(kWh/y)	13044	8.3	-69.4	22.4	12.7	35.1	44.6	0.778
Space heating dem. [3]	8.2	5.0	-120.2	22.6	8.0	30.6	60.4	0.827
(GJ/y)	39.7	15.8	-71.4	21.7	18.6	40.3	32.9	0.731
	71.3	16.3	-51.8	19.9	27.1	47.0	23.2	0.685
DHW demand [4]	9.5	12.5	-91.0	22.4	13.2	35.7	42.2	0.771
(GJ/y)	21.2	16.1	-74.4	22.0	17.1	39.1	33.5	0.740

[1] Storage temperature reference case: 50-60°C; SE base case: 60-73°C; SOFC bae case: 50-90°C
[2] Base case electricity demand: 8160 kwh/y
[3] Base case space heating demand: 27.8 GJ/y
[4] Base case DHW demand: 14.4 GJ/y