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The financial viability of an SOFC cogeneration system in single-family dwellings

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Abstract

In the near future, fuel cell-based residential micro-CHP systems will compete with traditional methods of energy supply. A micro-CHP system may be considered viable if its incremental capital cost compared to its competitors equals to cumulated savings during a given period of time. A simplified model is developed in this study to estimate the operation of a residential solid oxide fuel cell (SOFC) system. A comparative assessment of the SOFC system vis-à-vis heating systems based on gas, oil and electricity is conducted using the simplified model for a single-family house located in Ottawa and Vancouver. The energy consumption of the house is estimated using the HOT2000 building simulation program. A financial analysis is carried out to evaluate the sensitivity of the maximum allowable capital cost with respect to system sizing, acceptable payback period, energy price and the electricity buyback strategy of an energy utility. Based on the financial analysis, small (1–2 kW_e) SOFC systems seem to be feasible in the considered case. The present study shows also that an SOFC system is especially an alternative to heating systems based on oil and electrical furnaces.

Keywords: Residential buildings; Financial analysis; Solid oxide fuel cell (SOFC); Micro-CHP

1. Introduction

The energy supply of a single-family house consists of the supply of electricity and the supply of heating and cooling energy. Traditionally, electricity demand is satisfied by purchasing the required electricity from the grid. In Canada, the most common heating methods are electrical baseboard heating, district heating, oil heating, gas heating, ground and air source heat pumps and central heating based on wooden fuel. The percentage of different heating energy supply types for single-family houses in Canada in 1996–2002 is presented in Table 1.

Due to micro-CHP technologies, the ability of single-family houses to be self-supporting, in terms of both electricity and heat, is possible for the near future. Fuel cells can be regarded as one of the most promising cogeneration technologies due to their favorable characteristics under a regime of pollution reducing policies and deregulation of the electricity market. Although there is growing interest in residential scale fuel cell cogeneration systems, they are still not widely recognized as serious competitors with traditional energy supply methods due to technological difficulties and high capital costs.

The objective of present study is to find out the maximum allowable capital cost of a solid oxide fuel cell (SOFC) system that makes the system competitive with traditional supply of electricity and heating systems utilizing gas, oil and electrical furnaces. The sensitivity of the capital cost is investigated with respect to system size, acceptable payback period, energy price and the electricity buyback strategy of an

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Abbreviations: CANMET, Canada Centre for Mineral and Energy Technology; CCHT, Canadian Centre for Housing Technology; CHP, combined heat and power; CMHC, Canada Mortgage and Housing Corporation; CSA, Canadian Standards Association; CWEC, Canadian Weather for Energy Calculations; DHW, domestic hot water; GST, Canadian Goods and Services Tax; HVAC, heating; ventilation and air-conditioning; NRCan, Natural Resources Canada; PEMFC, polymer electrolyte membrane fuel cell; SOFC, solid oxide fuel cell

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Nomenclature

a	constant parameter
A_{sto}	heat transfer area of heat storage tank (m^2)
b	constant parameter
c	constant parameter
c_{e}	purchasing price for electricity (C\$ kWh^{-1})
c_{es}	buyback electricity price for CHP generators (C\$ kWh^{-1})
c_{pr}	purchasing price for primary energy (C\$ kWh^{-1})
c_{sto}	specific heat capacity of heat storage tank ($\mathrm{J\,kg^{-1}\,{}^{\circ}C^{-1}}$)
$C_{\mathrm{I,SYS}}$	investment cost of SOFC system (C\$)
$\Delta C_{\mathrm{I,CHP}}$	incremental capital cost of CHP (C\$)
$\Delta C_{\mathrm{I,m}}$	incremental maintenance cost (C\$)
$\Delta C_{\mathrm{I,ma}}$	annual incremental maintenance cost (C\$ a^{-1})
$E_{\mathrm{e,0}}$	annual electricity consumption in base case ($\mathrm{kWh\,a^{-1}}$)
$E_{\mathrm{pr,0}}$	annual primary energy consumption in base case ($\mathrm{kWh\,a^{-1}}$),
$E_{\mathrm{ep,CHP}}$	annual amount of purchased electricity in CHP case ($\mathrm{kWh\,a^{-1}}$)
$E_{\mathrm{es,CHP}}$	annual amount of electricity into the grid ($\mathrm{kWh\,a^{-1}}$)
$E_{\mathrm{pr,CHP}}$	annual primary energy consumption in CHP case ($\mathrm{kWh\,a^{-1}}$)
K_{sto}	tank loss coefficient of heat storage tank
n	length of payback period (a)
P_{e}	electrical power demand (kW)
$P_{\mathrm{e,CHP}}$	electrical output of micro-CHP system (kW)
$P_{\mathrm{e,p}}$	purchased electrical power (kW)
$P_{\mathrm{e,s}}$	electrical power delivered to grid (kW)
$P_{\mathrm{in,CHP}}$	electrical input to micro-CHP system (kW)
$P_{\mathrm{in,f}}$	electrical input to the furnace system (kW)
r	interest rate (%)
S_{CHP}	savings of CHP (C\$)
t	time (h)
T_{min}	minimum temperature of heat storage tank (°C)
T_{sto}	temperature of heat storage tank (°C)
T_{max}	maximum temperature of heat storage tank (°C)
ΔU_{max}	maximum capacity of heat storage tank (kWh)
ΔU_{sto}	energy contained by heat storage tank (kWh)
V_{sto}	volume of heat storage tank (m^3)

Greek letters

Φ_{hs}	heat flow lead to heat sink (kW)
Φ_{th}	thermal load of the space heating of a building (kW)
$\Phi_{\mathrm{in,DHW}}$	thermal input to the DHW system (kW)
$\Phi_{\mathrm{in,hd}}$	thermal input to heat distribution system (kW)
$\Phi_{\mathrm{l,CHP}}$	loss heat flow of micro-CHP system (kW)
$\Phi_{\mathrm{l,DHW}}$	loss heat flow of the DHW system (kW)
$\Phi_{\mathrm{l,f}}$	loss heat flow of backup furnace (kW)
$\Phi_{\mathrm{l,hd}}$	loss heat flow of the heat distribution system (kW)
$\Phi_{\mathrm{l,int}}$	loss heat flow of electrical interface (kW)
$\Phi_{\mathrm{l,sto}}$	tank loss (kW)
$\Phi_{\mathrm{pr,CHP}}$	primary energy input of micro-CHP system (kW)
$\Phi_{\mathrm{pr,f}}$	primary energy input of backup furnace (kW)
$\Phi_{\mathrm{th,CHP}}$	thermal output of micro-CHP system (kW)
$\Phi_{\mathrm{th,DHW}}$	thermal load of the DHW heating (kW)
$\Phi_{\mathrm{th,f}}$	thermal output of backup furnace (kW)
$\Delta\Phi$	surplus or shortage heat flow (kW)
η_{DHW}	efficiency of the DHW system
$\eta_{\mathrm{e,CHP}}$	electrical efficiency of micro-CHP system
η_{hd}	efficiency of the heat distribution system
$\eta_{\mathrm{th,f}}$	thermal efficiency of backup furnace
$\eta_{\mathrm{tot,CHP}}$	total efficiency of micro-CHP system
$\eta_{\mathrm{tot,f}}$	total efficiency of backup furnace system
ρ_{sto}	density of heat storage ($\mathrm{kg\,m^{-3}}$)

energy utility. A case study is carried out for two locations in Canada.

2. Methodology

2.1. General description

This study has been carried out in two phases. The first phase is dedicated to the modelling and simulation of energy supply systems. The HOT2000 building simulation program [2], available from Canada Centre for Mineral and Energy Technology (CANMET), is first used to estimate the energy requirements when electricity is purchased from grid and heat is generated by gas, oil or electrical furnace. Because HOT2000 does not offer tools for simulating the operation of an SOFC-based energy supply system, a simplified model is developed and applied in Microsoft Excel, to estimate the energy requirements in this modified case on the basis of results provided by the HOT2000 simulation.

In the second phase, the results of the simulation are used to estimate the savings (and thus maximum incremental costs) in the case of energy supply based on an SOFC system. A payback analysis is also incorporated to evaluate the sensitivity of maximum allowable capital cost of an SOFC system with respect to changes in system size, interest rate, payback period, additional maintenance cost, electricity price, fuel price and the buyback rate of electricity.

2.2. System description

In the present study, the reference heating system incorporates a furnace with forced-air circulation system. Three conventional furnace types are investigated that differ from each other only due to their different primary energy. A high-efficiency (efficiency 93%) natural gas fired furnace, an oil furnace (efficiency 85%) and an electrical furnace (efficiency 100%) are considered. The domestic hot water (DHW) system is equipped with a standard 190 L storage tank, and it utilizes the same primary energy as the main heating system. All the electricity is purchased from the grid. The operation

Table 1
Distribution of heating methods in Canada in 1996—2002 [1]

Heating energy source	1996 (%)	1997 (%)	1998 (%)	1999 (%)	2000 (%)	2001 (%)	2002 (%)
Gas	48.0	46.5	45.5	46.0	46.3	44.9	46.2
Electricity	33.6	34.7	36.7	36.2	35.8	37.7	36.7
Oil	11.0	10.6	9.9	9.9	9.5	9.0	8.6
Wood	6.4	7.1	6.8	7.0	7.5	7.4	7.4
Other[a]	1.0	1.1	1.1	0.9	0.9	1.0	1.1
Total	100	100	100	100	100	100	100

[a] Propane, coal and steam.

of these systems is modelled using HOT2000 simulation program.

Basically, an SOFC system is considered to be the same as the system equipped with a gas furnace. The additional component is an SOFC module containing a fuel cell stack, an air handling unit, a fuel processing unit and a 1000 L seasonal heat storage tank (operational temperature difference between 75 and 95 °C) that is used to handle the excess heat and to deliver the heat to the heat distribution and DHW systems. If the amount of excess heat is more than the capacity of heat storage, a heat dump valve is used. The gas furnace is included in this system as a backup heat source. The system is connected to the electricity grid by an interface that makes it possible to feed the excess electricity into the grid. A model is described in the following sections that can be used to evaluate the operation of this system based on the energy requirement data predicted by the HOT2000 program. A schematic diagram of the modelled system is presented in Fig. 1.

2.3. System modelling

2.3.1. Hourly simulation

The HOT2000 simulation gives an estimate of monthly heat and electricity consumption. In order to properly evaluate the operation of an SOFC system, an hourly simulation is required. In present study, the monthly space heating energy consumption given by HOT2000 was converted to hourly loads by means of “degree hours”, using local hourly outdoor temperatures presented in the weather file by Canadian Weather for Energy Calculations (CWEC) [3]. The relative heat demand of DHW and the relative demand of occupant driven electricity (including lighting and appliances) were used to convert monthly requirements to hourly basis, as presented in Fig. 2. The monthly consumptions of heat and electricity were distributed evenly for each day.

2.3.2. Heat demand

The space heating load of a building depends on heat losses through the envelope of the building, heat losses through ventilation and air leakage and thermal gains. The thermal flow to the heat distribution system is (see also: Fig. 1)

$$\Phi_{\mathrm{in,hd}} = \frac{\Phi_{\mathrm{th}}}{\eta_{\mathrm{hd}}} = \Phi_{\mathrm{th}} + \Phi_{\mathrm{l,hd}} \qquad (1)$$

where $\Phi_{\mathrm{in,hd}}$ is the thermal flow to the heat distribution system, Φ_{th} the space heating load, $\Phi_{\mathrm{l,hd}}$ the heat loss of the heat distribution system and η_{hd} is its efficiency.

The thermal load for the DHW system depends on both the amount of hot water consumed in the building and the temperatures of the cold and hot water. The thermal flow to the DHW system is

$$\Phi_{\mathrm{in,DHW}} = \frac{\Phi_{\mathrm{th,DHW}}}{\eta_{\mathrm{DHW}}} = \Phi_{\mathrm{th,DHW}} + \Phi_{\mathrm{l,DHW}} \qquad (2)$$

where $\Phi_{\mathrm{in,DHW}}$ is the thermal flow to the DHW system, $\Phi_{\mathrm{th,DHW}}$ the thermal load for the DHW system, $\Phi_{\mathrm{l,DHW}}$ the heat loss of the DHW system and η_{DHW} is its efficiency.

In the present study, the heat flows both to the DHW and to the space heating systems are predicted using HOT2000 building simulations.

2.3.3. Seasonal heat storage tank

In this study, the seasonal heat storage tank is assumed to be a cylindrical tank. For the sake of simplicity, the contents of the tank is assumed to be fully mixed. The energy balance of the seasonal heat storage tank can be expressed as follows:

$$\Phi_{\mathrm{th,CHP}} + \Phi_{\mathrm{th,f}} - \Phi_{\mathrm{in,hd}} - \Phi_{\mathrm{in,DHW}} - \Phi_{\mathrm{hs}} - \Phi_{\mathrm{l,sto}} = \rho_{\mathrm{sto}} V_{\mathrm{sto}} c_{\mathrm{sto}} \frac{\mathrm{d}T_{\mathrm{sto}}}{\mathrm{d}t} = \frac{\mathrm{d}U_{\mathrm{sto}}}{\mathrm{d}t} \qquad (3)$$

where $\Phi_{\mathrm{th,CHP}}$ is the thermal flow from the micro-CHP system, $\Phi_{\mathrm{th,f}}$ the thermal flow from a backup gas furnace, Φ_{hs} the thermal flow to the heat sink, $\Phi_{\mathrm{l,sto}}$ the loss heat flow from the storage, V_{sto} the volume of the tank, c_{sto} and ρ_{sto} are the specific heat capacity and a density of the contents of the tank, respectively.

Table 2
The states of operation of the heat storage tank

State of operation	T_{sto}	ΔU_{sto}	$\Phi_{\mathrm{th,f}}$	Φ_{hs}
(1) Using backup furnace	$=T_{\mathrm{min}}$	=0	>0	=0
(2) Charging the storage	$T_{\mathrm{min}} \le T_{\mathrm{sto}} \le T_{\mathrm{max}}$	$0 \le \Delta U_{\mathrm{sto}} \le \Delta U_{\mathrm{max}}$	=0	=0
(3) Using heat sink	$=T_{\mathrm{max}}$	$=\Delta U_{\mathrm{max}}$	=0	>0
(4) Discharging the storage	$T_{\mathrm{min}} \le T_{\mathrm{sto}} \le T_{\mathrm{max}}$	$0 \le \Delta U_{\mathrm{sto}} \le \Delta U_{\mathrm{max}}$	=0	=0

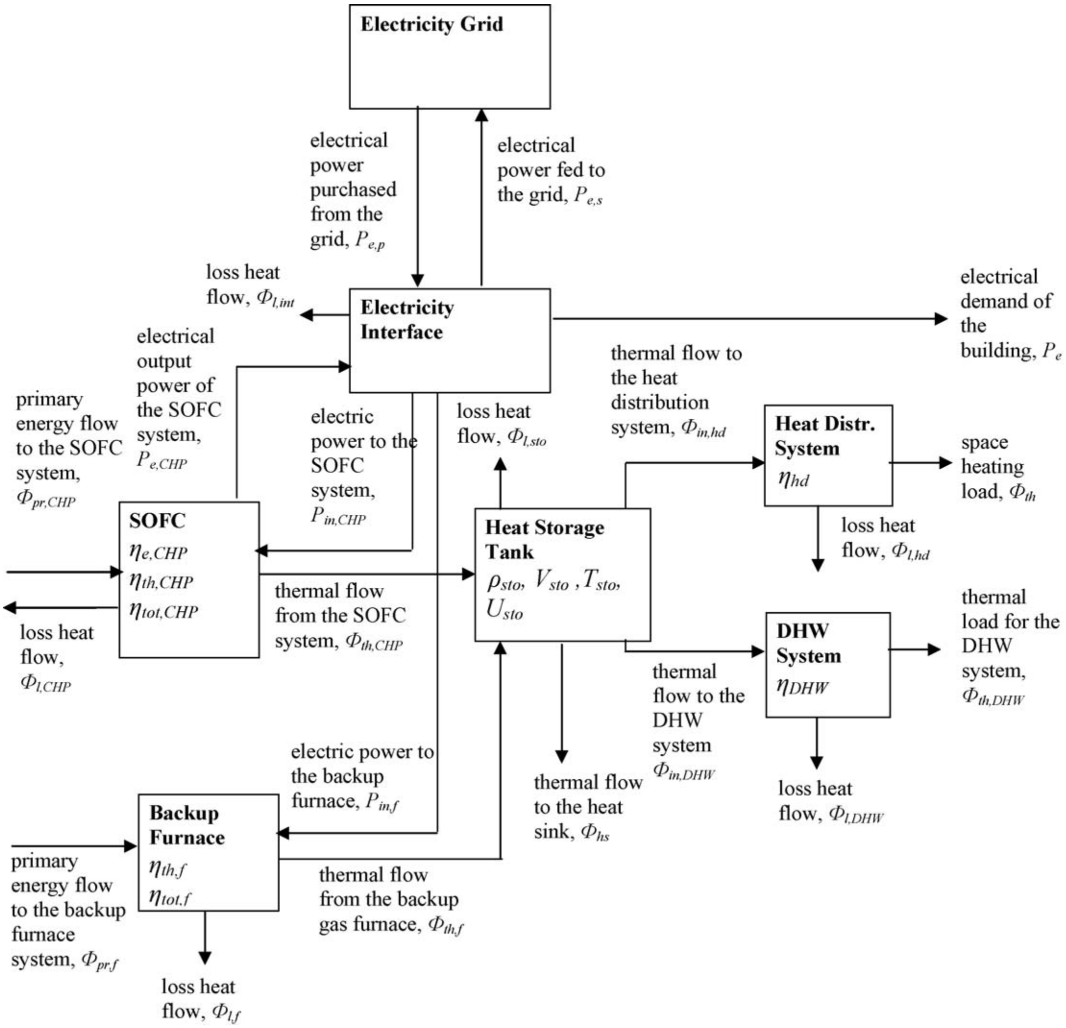

Fig. 1. The schematic diagram of the modelled system.

At time *t*, the contents of the heat storage tank is at temperature T_{sto} and its energy contents is U_{sto}. The need to use heat sink, i.e. a heat exchanger that leads heat to the ambience occurs when an SOFC system generates more heat than is the amount of heat consumed by the building plus the amount of heat that can be stored in the heat storage tank.

In the present study, the amount of contents in the tank is assumed to remain constant during the operation. Therefore, the amount of energy stored in the tank only depends on the temperature of the tank and can be expressed as follows:

$$\Delta U_{\text{sto}} = \rho_{\text{sto}} V_{\text{sto}} c_{\text{sto}} (T_{\text{sto}} - T_{\text{min}}) \tag{4}$$

where ΔU_{sto} is the amount of thermal energy in the tank and T_{min} is the minimum allowable storage temperature.

The allowable range of storage temperatures is dictated by factors like the boiling temperature of the contents in the tank and the minimum temperature that is required to distribute heat from the tank to spaces and to the DHW system. In the present study, the tank is assumed to be filled with water and the operation temperature is assumed to vary between 75 and 95 °C.

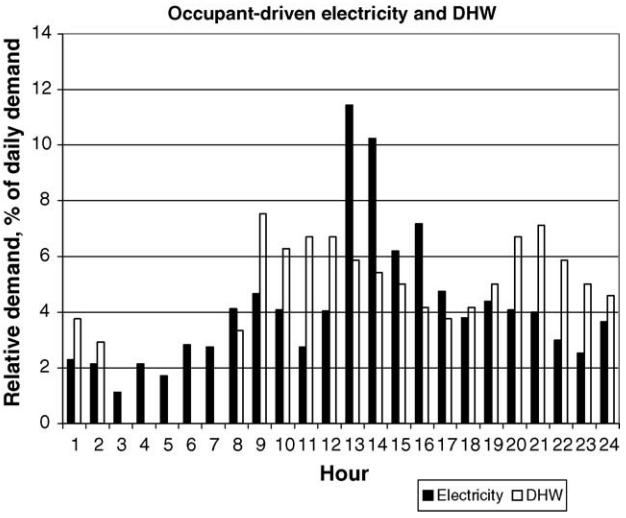

Fig. 2. Hourly distribution of electricity and DHW demand [4].

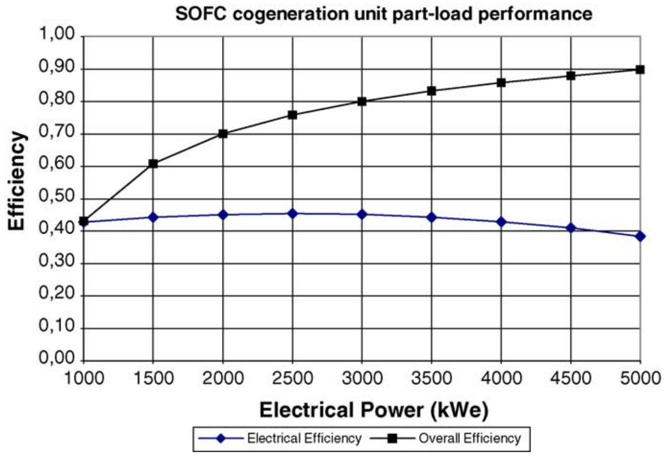

Fig. 3. The part-load performance of reference SOFC fuel cell [6].

When the storage temperature varies between $T_{\min}$ and $T_{\max}$, and $\Delta U_{\max}$ is the capacity of the tank, the states of operation of the tank can be classified as is presented in Table 2.

Assuming that the index number 0 refers to the past time step and index number 1 to the present time step, the operation of the storage tank is modelled using the following procedure:

(1) Estimate $\Phi_{\mathrm{l,sto}}$

Let the initial temperature be $T_{\mathrm{sto}}(0)$ that is arbitrarily selected between $T_{\min}$ and $T_{\max}$. The storage tank heat loss is approximately:

$$\Phi_{\mathrm{l,sto}}(1) = K_{\mathrm{sto}} A_{\mathrm{sto}} (T_{\mathrm{sto}}(0) - T_{\mathrm{amb}}) \tag{5}$$

where K_{sto} is the tank loss coefficient that takes into account the heat transfer by convection, conduction and radiation from the water inside the tank to the ambient air and A_{sto} is the heat transfer area of the tank. K_{sto} is the specific feature of a tank, but, for instance, Kribus uses the value $1.0\,\mathrm{W\,m^{-2}\,K^{-1}}$ in an example calculation and that is the reference value used in present study as well [5].

(2) Calculate the surplus or shortage of heat $\Delta\Phi$

The amount of surplus (i.e. $\Delta\Phi > 0$) or shortage (i.e. $\Delta\Phi < 0$) of heat is estimated on the basis of energy balance, by means of:

$$\Delta\Phi(1) = \Phi_{\mathrm{th,CHP}}(1) - \Phi_{\mathrm{in,hd}}(1) - \Phi_{\mathrm{in,DHW}}(1) - \Phi_{\mathrm{l,sto}}(1) \tag{6}$$

(3) Determine ΔU_{sto}, $\Phi_{\mathrm{th,f}}$ and Φ_{hs}

The amount of energy stored in the tank at time 0, $\Delta U_{\mathrm{sto}}(0)$, is calculated on the basis of the initial temperature $T_{\mathrm{sto}}(0)$, using the Eq. (4).

In the case of thermal shortage ($\Delta\Phi < 0$),

- $\Phi_{\mathrm{hs}}(1) = 0$ always;
- if $\Delta U_{\mathrm{sto}}(0) \geq \Delta\Phi(1)$, then $\Delta U_{\mathrm{sto}}(1) = \Delta U_{\mathrm{sto}}(0) - \Delta\Phi(1)$;
- otherwise $\Delta U_{\mathrm{sto}}(1) = 0$ and $\Phi_{\mathrm{th,f}} = \Delta\Phi(1) - \Delta U_{\mathrm{sto}}(0)$.

In the case of thermal surplus ($\Delta\Phi > 0$),

- $\Phi_{\mathrm{th,f}}(1) = 0$ always;
- if $\Delta U_{\mathrm{sto}}(0) + \Delta\Phi(1) \leq \Delta U_{\max}$, then $\Delta U_{\mathrm{sto}}(1) = \Delta U_{\mathrm{sto}}(0) + \Delta\Phi(1)$;
- otherwise $\Delta U_{\mathrm{sto}}(1) = \Delta U_{\max}$ and $\Phi_{\mathrm{hs}} = \Delta\Phi(1) - \Delta U_{\mathrm{sto}}(0)$.

(4) Determine new storage temperature T_{sto}

The new storage temperature is calculated on the basis of the amount of energy stored in the tank. It is defined as:

$$T_{\mathrm{sto}}(1) = T_{\mathrm{sto}}(0) + \frac{\Delta U_{\mathrm{sto}}(1)}{c_{\mathrm{sto}} \rho_{\mathrm{sto}} V_{\mathrm{sto}}} \tag{7}$$

The new storage losses can now be estimated using the new storage temperature. The procedure is then applied to each time step, until the desired time range has been considered.

2.3.4. Backup gas furnace

The energy balance of the backup gas furnace in steady-state operation is expressed as follows:

$$\Phi_{\mathrm{pr,f}} + P_{\mathrm{in,f}} - \Phi_{\mathrm{th,f}} - \Phi_{\mathrm{l,f}} = 0 \tag{8}$$

where $\Phi_{\mathrm{pr,f}}$ is the primary energy flow to the backup furnace system, $P_{\mathrm{in,f}}$ the electric power to the furnace system, $\Phi_{\mathrm{th,f}}$ the thermal flow from the furnace and $\Phi_{\mathrm{l,f}}$ is the heat loss from the furnace.

The required primary energy flow is defined as:

$$\Phi_{\mathrm{pr,f}} = \frac{\Phi_{\mathrm{th,f}}}{\eta_{\mathrm{th,f}}} \tag{9}$$

where $\eta_{\mathrm{th,f}}$ is the thermal efficiency of the furnace. Hence, the heat loss of the furnace is:

$$\Phi_{\mathrm{l,f}} = (1 - \eta_{\mathrm{th,f}})\Phi_{\mathrm{th,f}} \tag{10}$$

The electric power to the furnace system can then be expressed as follows:

$$P_{\mathrm{in,f}} = \frac{\Phi_{\mathrm{th,f}}}{\eta_{\mathrm{tot,f}}} - \Phi_{\mathrm{pr,f}} \tag{11}$$

where $\eta_{\mathrm{tot,f}}$ is the total efficiency of a furnace system.

2.3.5. SOFC-based micro-CHP system

The energy balance of a micro-CHP system in steady-state operation is expressed as follows:

$$\Phi_{\mathrm{pr,CHP}} + P_{\mathrm{in,CHP}} - \Phi_{\mathrm{th,CHP}} - P_{\mathrm{e,CHP}} - \Phi_{\mathrm{l,CHP}} = 0 \tag{12}$$

where $\Phi_{\mathrm{pr,CHP}}$ is the primary energy flow to the system, $P_{\mathrm{in,CHP}}$ the electric power to the system, $\Phi_{\mathrm{th,CHP}}$ the thermal flow from the system, $P_{\mathrm{e,CHP}}$ the electrical output power of the system and $\Phi_{\mathrm{l,CHP}}$ is the heat loss from the system.

The performance of a micro-CHP system is commonly defined by a given electrical output power, the electrical efficiency and the overall (total) efficiency. Electrical efficiency depends on both the features of the micro-CHP technology and the operational conditions. Thus, a reference technology is required. In the present study, the 5 kW SOFC cogeneration unit of “Fuel Cell Technologies Ltd.” is applied [6].

The relation between the electrical efficiency and the electrical output power can be determined either by simulating the electrochemical process occurring within a fuel cell, or based on experimental studies. For the sake of simplicity, a parametric relation between the efficiency and the output is applied in the present study, by expressing it as:

$$\eta_{\mathrm{e,CHP}} = aP_{\mathrm{e,CHP}}^2 + bP_{\mathrm{e,CHP}} + c \tag{13}$$

where $\eta_{\mathrm{e,CHP}}$ is the electrical efficiency of the SOFC system and a, b and c are constant parameters. The required primary energy flow now can be estimated by:

$$\Phi_{\mathrm{pr,CHP}} = \frac{P_{\mathrm{e,CHP}}}{\eta_{\mathrm{e,CHP}}} \tag{14}$$

The following useful simplifications are made for the prediction of the performance of an SOFC system in an approximate way:

(1) the electrical power demanded by ancillaries (pumps, fans, etc.) of a cogeneration plant is about 6% of the electrical output power of the plant [7];
(2) the operating temperature of an SOFC system does not change significantly in part-load, thus making it reasonable to assume skin losses constant as well.

The latter argument implies that if the overall efficiency of an SOFC system is known at certain operational conditions, the heat loss can be estimated as follows:

$$\Phi_{\mathrm{l,CHP}} = (1 - \eta_{\mathrm{tot,CHP}})\Phi_{\mathrm{pr,CHP}} \tag{15}$$

where $\eta_{\mathrm{tot,CHP}}$ is the overall efficiency of an SOFC system. The performance curve of the reference fuel cell is presented in Fig. 3.

Based on these assumptions, the thermal output of the SOFC system can be evaluated using Eq.(12). A micro-CHP system can be operated using various control strategies, by following either thermal or electrical loads, or by aiming at satisfying both of them either fully or partially. In the present study, the SOFC system was selected to be run constantly at its full power (100%) for the following reasons [8]:

(1) 100% operation is associated with the best possible overall efficiency;
(2) frequent shutdowns of an SOFC system are not reasonable due to thermal stresses that significantly decrease the lifetime of a fuel cell stack;
(3) the turndown of about 70% load in practical cases causes a heat leak that is more than the amount of heat generated by the SOFC system itself.

2.3.6. *Electricity interface*

The energy balance of the electricity interface in steady-state operation is expressed as follows:

$$P_{\mathrm{e,CHP}} + P_{\mathrm{e,p}} - P_{\mathrm{e}} - P_{\mathrm{in,CHP}} - P_{\mathrm{in,f}} - P_{\mathrm{e,s}} - \Phi_{\mathrm{l,int}} = 0 \tag{16}$$

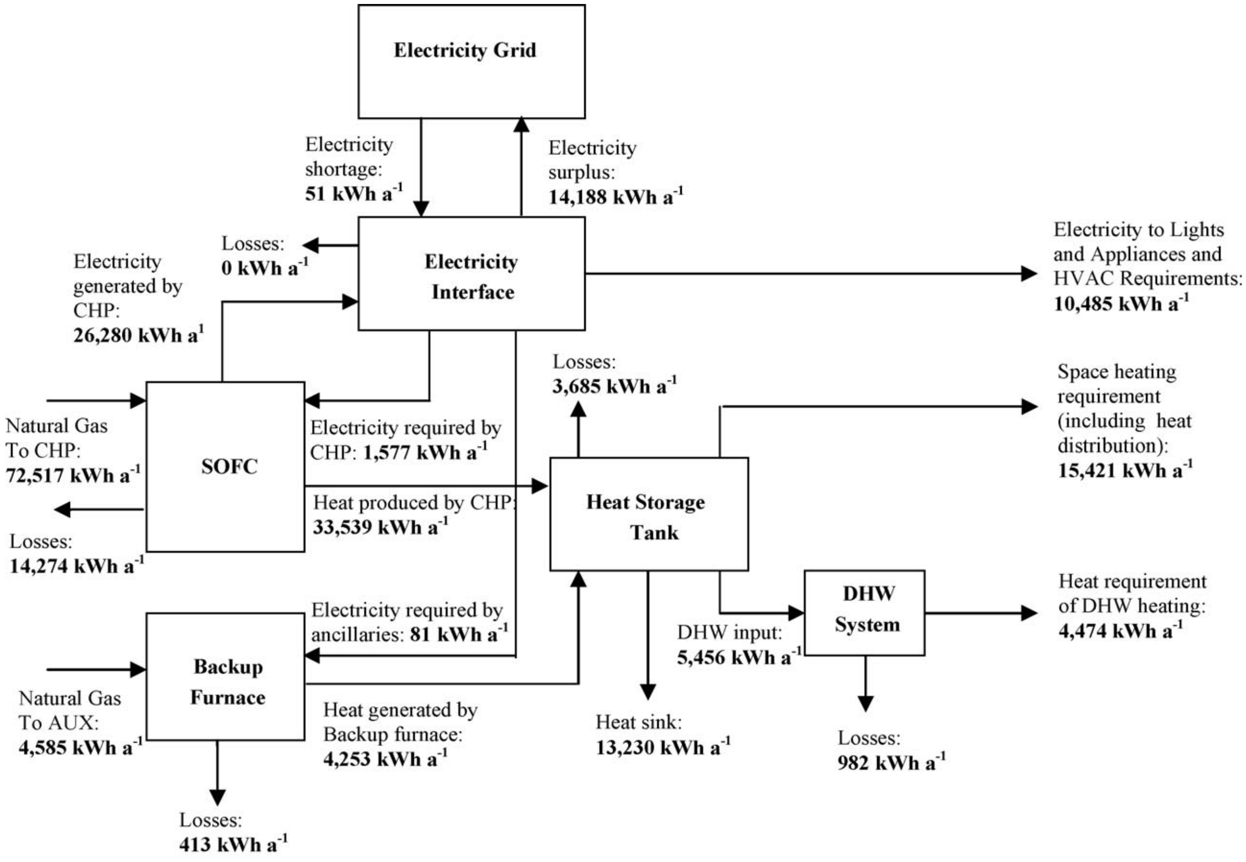

Fig. 4. The energy balance of a micro-CHP system containing 3 $\mathrm{kW_e}$ SOFC.

where P_e is the electrical demand of the building, $P_{e,p}$ the electrical power purchased from the grid, $P_{e,s}$ the electrical power fed to the grid and $\Phi_{l,int}$ is the heat loss from the interface.

In the present work, the steady-state operation of the interface is assumed. Consequently, the interface does not store heat, the temperature remains constant and the heat loss can be regarded as constant as well. On the other hand, the interface operates at the temperature that is close to the ambient temperature. Hence, the heat loss can be considered insignificant.

The need to purchase electricity from the grid occurs if the micro-CHP system generates less electricity than is required to meet the electrical demand of the building and to cover the losses of the interface. The need to feed electricity to the grid occurs if the micro-CHP system generates more electricity than is required to meet the electrical demand of the building and to cover the losses of the interface. Both the surplus and the shortage of electricity can be defined on the basis of the Eq. (16).

2.4. Financial viability analysis

An investment in a micro-CHP system can be considered barely financially viable with respect to the investment in a competing system, if the discounted incremental cost of the micro-CHP system equals to discounted cumulated savings during a given period of time. This condition is satisfied if:

$$\Delta C_{I,CHP} - S_{CHP} = 0 \tag{17}$$

where $\Delta C_{I,CHP}$ is the incremental cost of the micro-CHP system and S_{CHP} is cumulated discounted savings of the micro-CHP system. Because the capital cost of a micro-CHP system cannot be negative, it is also required that $\Delta C_{I,CHP} \geq 0$.

The discounted incremental cost of a micro-CHP system occurs, mainly because:

- there is the cost of acquisition of a micro-CHP system;
- the service life of micro-CHP system may be shorter;
- the micro-CHP system may require additional maintenance.

On the other hand, potential savings may occur in the case of micro-CHP, because

- the overall system efficiency is improved;
- the backup gas furnace may be smaller than the furnace in the reference case;
- some compensation is possible against the electricity fed into the grid.

The incremental cost of a micro-CHP system is given as follows:

$$\Delta C_{I,CHP} = C_{I,SYS} + \Delta C_{I,m} \tag{18}$$

where $C_{I,SYS}$ is the capital (investment) cost of a micro-CHP system (heat storage tank is included into the package for the sake of simplicity) and $\Delta C_{I,m}$ is the discounted incremental maintenance costs during the given time period.

The discounted incremental maintenance costs during the given time period can be expressed as:

$$\Delta C_{I,m} = \frac{(1+r)^n - 1}{r(1+r)^n} \Delta C_{I,ma} \tag{19}$$

where r is the interest rate, n the length of a time period and $\Delta C_{I,ma}$ is the annual incremental cost of maintenance. In the present work, the annual incremental cost of maintenance is considered to remain constant during the entire time period. Furthermore, the maintenance costs of the competitors (gas and oil furnaces, electrical furnace) are assumed to be equal.

In the present study, the backup furnace system is considered to be the same size as the furnace system in the reference case. This is reasonable, because the energy supply has to be able to satisfy the peak demand when the micro-CHP system is down. On the other hand, there is not a significant difference in capital costs between oil, gas and electricity fired furnace systems. Hence, all the savings are associated with the energy bill during the given period of time. The savings can be defined as:

$$S_{CHP} = \frac{(1+r)^n - 1}{r(1+r)^n} \left[c_e E_{e,0} + c_{pr} E_{pr,0} - (c_e E_{ep,CHP} \right. \\ \left. - c_{es} E_{es,CHP} + c_{pr} E_{pr,CHP}) \right] \tag{20}$$

where $E_{e,0}$ and $E_{pr,0}$ are the annual electricity and primary energy consumptions in the reference case, respectively, c_e and c_{pr} are the purchasing prices for electricity and primary energy, respectively, c_{es} the buyback price of electricity, $E_{ep,CHP}$ the annual amount of electricity to be purchased, $E_{es,CHP}$ the annual amount of electricity a fed into the grid and $E_{pr,CHP}$ is the primary energy consumption in the case of micro-CHP.

3. Computational study

3.1. The experimental building

The experimental building is a two-floor, four-bedroom single-family house with about 240 m^2 heated area, including the basement, as built for the test houses of the Canadian Centre for Housing Technology (CCHT) in Ottawa [9]. The building represents a commonly encountered modern Canadian energy-efficient sub-urban wood frame construction home, following the requirements of the R-2000 energy efficiency standard[1] [10]. The building is equipped with a gas furnace and a forced-air heating system.

The full basement is assumed to be heated. Thus, the total heated area is approximately 240 m^2, and the heated volume is 665 m^3. The set-point temperature is 21 °C in the first and second floors and 19 °C in the basement throughout the year. The house is occupied by two adults and two children, 50% of the total time, sensible internal heat gain from occupants being 2.40 kWh per day. The electricity use for lighting and appliances

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[1] R-2000 is a series of technical requirements for new home performance to improve the energy efficiency and the reduction of greenhouse gas emissions in Canada's new housing stock.

Table 3
Energy prices in Ottawa and Vancouver

	Ottawa	Vancouver
Electricity (C$ kWh^{-1})	0.110	0.069
Gas (C$ kWh^{-1})	0.053	0.049
Oil (C$ kWh^{-1})	0.061	0.061

is 24 kWh per day and the use of hot water is 225 L per day. The ventilation operates continuously, at the rate of 70 L s^{-1}.

3.2. Energy simulations with HOT2000

The present HOT2000 model is a simplified model of the building and it was created using the Version 9.21 of HOT2000, following the R-2000 requirements. In this model, a rectangular plan shape and a habitable space in one single zone are assumed. The model has been built utilizing previous models of the same building, created by Purdy and Beausoleil-Morrison using ESP-r [11] and Gough using the Version 7.10 of HOT2000 [12]. Each heating option was investigated for two different climatic zones: Ottawa and Vancouver.

3.3. Energy simulations applying the SOFC model

The model was applied to investigate five SOFCs with capacities of 1, 2, 3, 4 and 5 kW$_e$. The efficiency of the DHW system was assumed to be 82% (the HOT2000 default value for an electrical DHW system). This is reasonable because there is no significant distance between the heat storage tank and the DHW tank in the SOFC case, and therefore, the tank heat loss is comparable to that of the electrical DHW system.

When an SOFC system runs at constant power, the amount of excess heat is considerable during the warm season. In the present study, heat storages as large as 3000 L were investigated, but the benefit of increasing the size from 1000 to 3000 L proved to be insignificant. Thus, the 1000 L tank was selected due to its smaller space requirement, capital costs and tank heat loss.

3.4. The financial viability analysis

In the present study, the energy price was considered as a single value that is expressed as a monetary value per purchased kWh. Thus, it was simply defined by dividing the annual energy bill by the annual amount of consumed energy, on the basis of the residential rate schedules provided by Hydro Ottawa [13], Enbridge Gas Ltd. [14], BC Hydro [15] and Terasen Gas [16]. The prices were valid in May 2005 and they are presented in Table 3.

The change of ±15% in the reference energy prices was considered in the present study. This range proved to be reasonable on the basis of the consumer price index presented by Statistics Canada [17]. For example, during the time period from November 2001 to November 2002 the price of energy increased by 14% in Canada according to that index. On the other hand, the price of energy was 36.2% higher in November 2002 than it was in 1997. Thus, the estimated range is slightly conservative.

The compensation received by a small electricity producer for the excess electricity fed into the grid depends on the so-called "net metering policy" of the energy utility. According to Canada Mortgage and Housing Corporation (CMHC) [18], net metering policies can be classified as follows:

(1) Simple net metering—Both the electricity fed into the grid and the electricity taken from the grid is measured within a billing period. A customer does not receive any monetary compensation for the net excess electricity fed into the grid, but he pays the retail rate for the net electricity shortage that is supplied during the billing period using the grid.
(2) Full net metering with buyback—Both the electricity fed into the grid and the electricity taken from the grid is measured within a billing period. A customer receives the retail rate or less (i.e. buyback rate) for each kWh of electricity fed into the grid. This monetary compensation is received also in the case when the net excess electricity occurs during the billing period.

Because a customer does not receive any monetary compensation in the case of simple net metering, it is obvious that in this case the buyback rate of electricity is 0% of the electricity price presented in Table 3. The full net metering is not presently exercised in Canada, and it is unlikely that it will be in use in the near future. Thus, any exact reference can not be given at the moment for the buyback rates in the case of full net metering. Assuming that the buyback rate is related to the energy charge that covers about 55% of the annual electricity bill in the case concerned in the current study, the buyback rate of electricity was allowed to vary in the range from 0 to 50% of the electricity prices presented in Table 3.

A micro-CHP system is an integrated part of the HVAC system of a house. Hence, it is not considered a source of significant incremental maintenance costs in the present study. The possibility of incremental maintenance cost is taken into account by estimating the maximum allowable capital costs of an SOFC system in the case when the incremental maintenance cost is C$ 0.01 kWh$_e^{-1}$a^{-1}. The previous number can be inferred from the maintenance cost data for various micro-CHP technologies, presented by Onovwiona and Ugursal [19].

An acceptable payback period in the context of house construction industry is usually relatively short. On the other hand, a longer payback period may be acceptable, for example, in the context of political decision-making that, in turn, affects the governmental support of the introduction of new, sustainable energy technologies. In the present study, payback periods of 5, 10, 15 and 20 years are examined considering the real interest rates of 3 and 10%. The real interest rate represents an interest rate excluding the effect of inflation. The interest rate of bank loans is based on the real interest rate.

All the monetary values presented in this study are in Canadian dollars. The Canadian Goods and Services Tax (GST) is not included in to the prices, unless otherwise mentioned.

3.5. Results

3.5.1. Energy consumption

The annual energy consumption with oil, gas and electric heating on the basis of HOT2000 simulations is presented in Table 4. The annual energy profile for each size of SOFC predicted using the model developed in this work is presented in Table 5. The space and DHW heating energy consumptions are the same as presented in Table 4 for the gas furnace system. The modelled energy balance of the 3 kW_e SOFC system for the house located in Ottawa is presented in Fig. 4.

As seen in Tables 4 and 5, and in Fig. 4, the annual heat loss is significant when an SOFC system with more than 2 kW_e capacity is considered. Because of the warmer climate, the annual heating energy consumption of the house located in Vancouver is only about 60% of that of the house located in Ottawa, making the application of an SOFC system in Vancouver more challenging than it is in Ottawa. Small differences between the energy consumptions of base systems can be explained by their different efficiencies.

3.5.2. Annual savings in energy costs

The annual savings (+) or losses (−) in energy costs, when an SOFC system is used instead of competing energy supply methods are presented in Table 6 where the “Buyback Price 0%” refers to the reference price of purchased electricity.

The main conclusion that can be derived from these results is that annual savings occur only when the design power of the SOFC system is not more than 3 kW_e. The best savings are achieved when the SOFC system is compared with the electrical furnace system. Gas is about 10% and electricity is almost 40% cheaper in Vancouver than they are in Ottawa. Hence, the operational environment for an SOFC system in Vancouver is more unfavorable also from the economic point of view. Therefore, further discussion of the results focus on the case of Ottawa unless otherwise mentioned.

3.5.3. Effect of payback period

The effect of payback period on the maximum allowable capital costs of an SOFC system in Ottawa is presented in Fig. 5. The maximum allowable capital cost is significantly improved by the extension of the payback period. However, the extension of payback period does not change the order of preference amongst the energy supply solutions.

3.5.4. Effect of electricity buyback price

The maximum allowable capital costs of an SOFC system against buyback price of electricity for payback periods 5 and 10 years are presented in Fig. 6. As to be expected, the greater the buyback rate of electricity is, the more feasible it is to select a large system to produce as much electricity as possible. This effect is only perceived, however, when the SOFC system is compared with the electrical furnace. Systems with 3 kW_e capacity proved to be barely viable when the buyback rate was increased to 50% of the electricity price. The buyback rate has only a minor effect on the viability of 1 kW_e systems, the order of preference amongst the energy supply solutions does not change.

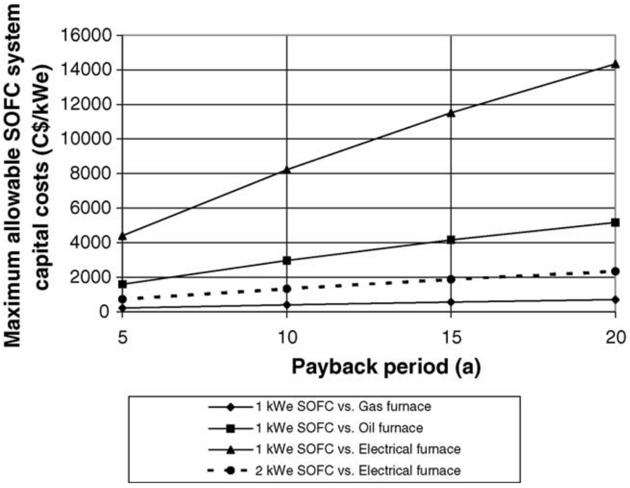

Fig. 5. The effect of payback period on allowable capital costs of an SOFC system.

3.5.5. Effect of electricity price

The maximum allowable capital costs of the SOFC system against the electricity price with payback periods of 5 and 10 years are presented in Fig. 7. The rise of the electricity

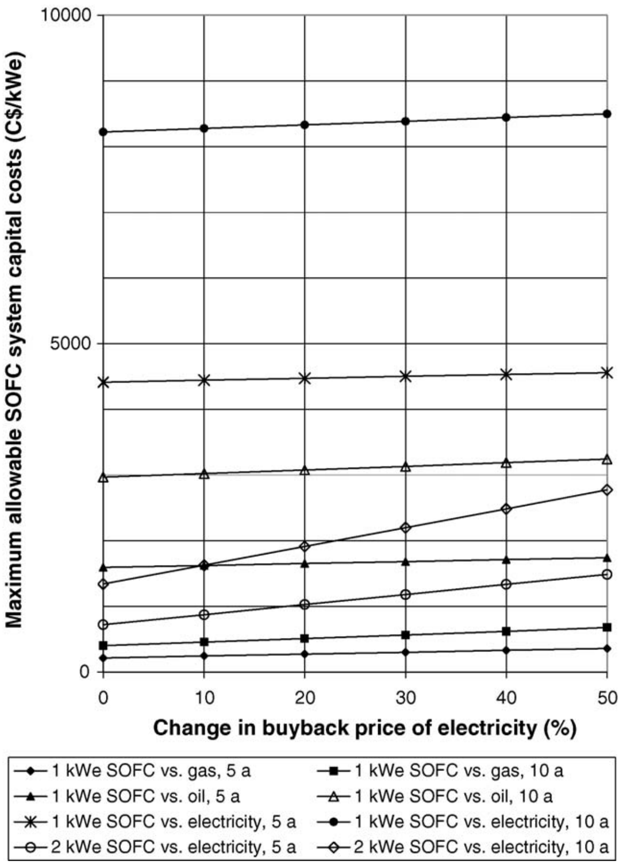

Fig. 6. The effect of buyback price on allowable capital costs of SOFC system.

Table 4
Energy consumption of the case building on the basis of HOT2000

	Gas furnace	Oil furnace	Electric furnace
Ottawa			
Space heating (kWh a^{-1})	15421	15589	15319
DHW heating (kWh a^{-1})	4474	4474	4474
Total primary input (kWh a^{-1})	24207	26317	20476
Total electricity[a] (kWh a^{-1})	10779	10760	10808
Vancouver			
Space heating (kWh a^{-1})	7638	7714	7653
DHW heating (kWh a^{-1})	4243	4243	4243
Total primary input (kWh a^{-1})	15487	16602	12713
Total electricity[a] (kWh a^{-1})	10362	10352	10380

[a] Does not include electricity used to heating in the case of electric furnace.

price has a positive effect on the viability of an SOFC system. SOFC systems with electrical power of 2 kW_e become competitive if the electricity price is no more than 10% under the reference price. Also in this case, the best scenario is realized if the SOFC system is compared with the electrical furnace system and as much electricity is generated as possible.

3.5.6. *Effect of natural gas price*

The maximum allowable capital costs of the SOFC system against the natural gas price with payback periods of 5 and 10 years are presented in Fig. 8. The reduction of the natural gas price has a positive effect on the competitiveness of an SOFC system. This scenario emphasizes the status of an SOFC system as a competitor of the heating systems based on electricity and oil, but because of improved system efficiency, the same trend is seen also when an SOFC system is compared with the traditional gas furnace system.

3.5.7. *Effect of oil price*

The maximum allowable capital costs of a 1 kW_e SOFC system against oil price for payback periods 5, 10, 15 and 20 years are presented in Fig. 9. As to be expected, the rise of the oil price has a positive effect on the status of an SOFC system as a competitor of the oil furnace system.

3.5.8. *Effect of interest rate*

The effect of interest rate on the maximum allowable capital cost of an SOFC system is presented in Fig. 10. The effect of interest rate becomes more significant as the payback period becomes longer, and the annual savings of an SOFC system becomes greater. The viability of an SOFC system with respect to the electrical furnace is strongly affected by the interest rate and the required payback period. If the interest rate is low and a long payback period is allowed, then the viability of an SOFC system is significantly better than it is in the case when only a short payback period is allowed. The effect of interest rate is an

Table 5
Energy profiles of the case building on the basis of SOFC analysis

	1 kW_e	2 kW_e	3 kW_e	4 kW_e	5 kW_e
Ottawa					
SOFC electrical output (kWh a^{-1})	8760	17520	26280	35040	43800
SOFC thermal output (kWh a^{-1})	11180	22359	33539	44719	55898
SOFC primary input (kWh a^{-1})	24172	48344	72517	96689	120861
Backup thermal output (kWh a^{-1})	13943	8467	4253	1616	349
Backup primary input (kWh a^{-1})	15031	9127	4585	1742	376
Total primary input (kWh a^{-1})	39203	57472	77101	98431	121237
Total electricity input (kWh a^{-1})	11276	11679	12143	12618	13120
Electricity shortage (kWh a^{-1})	3140	714	51	0	0
Electricity excess (kWh a^{-1})	624	6536	14188	22422	30680
Net electricity (kWh a^{-1})	−2516	5823	14137	22422	30680
Vancouver					
SOFC electrical output (kWh a^{-1})	8760	17520	26280	35040	43800
SOFC thermal output (kWh a^{-1})	11180	22359	33539	44719	55898
SOFC primary input (kWh a^{-1})	24172	48344	72517	96689	120861
Backup thermal output (kWh a^{-1})	6065	1785	99	0	0
Backup primary input (kWh a^{-1})	6538	1924	107	0	0
Total primary input (kWh a^{-1})	30710	50269	72623	96689	120861
Total electricity input (kWh a^{-1})	10858	11302	11796	12319	12845
Electricity shortage (kWh a^{-1})	2863	672	36	0	0
Electricity excess (kWh a^{-1})	765	6890	14520	22721	30955
Net electricity (kWh a^{-1})	−2098	6218	14484	22721	30955

Table 6
The annual savings of the SOFC system in energy costs

	Buyback price		Electricity price		Gas price		Oil price	
	0%	50%	−15%	+15%	−15%	+15%	−15%	+15%
Ottawa								
SOFC vs. gas								
1 kW_e SOFC	+51	+85	−75	+177	+169	−68	+51	+51
2 kW_e SOFC	−645	−285	−811	−479	−382	−907	−645	−645
3 kW_e SOFC	−1605	−825	−1782	−1428	−1188	−2023	−1605	−1605
4 kW_e SOFC	−2723	−1490	−2901	−2545	−2137	−3309	−2723	−2723
5 kW_e SOFC	−3924	−2236	−4102	−3746	−3157	−4690	−3924	−3924
SOFC vs. oil								
1 kW_e SOFC	+372	+407	+247	+498	+682	+63	+133	+612
2 kW_e SOFC	−323	+37	−489	−157	+131	−777	−563	−83
3 kW_e SOFC	−1283	−503	−1460	−1107	−674	−1892	−1523	−1044
4 kW_e SOFC	−2401	−1168	−2579	−2223	−1624	−3178	−2641	−2161
5 kW_e SOFC	−3602	−1915	−3779	−3424	−2644	−4560	−3842	−3362
SOFC vs. electricity								
1 kW_e SOFC	+1031	+1066	+567	+1496	+1341	+722	+1031	+1031
2 kW_e SOFC	+336	+696	−168	+841	+790	−118	+336	+336
3 kW_e SOFC	−625	+156	−1140	−109	−16	−1234	−625	−625
4 kW_e SOFC	−1742	−509	−2258	−1226	−965	−2520	−1742	−1742
5 kW_e SOFC	−2943	−1256	−3459	−2427	−1985	−3901	−2943	−2943
Vancouver								
SOFC vs. gas								
1 kW_e SOFC	−230	−204	−308	−152	−118	−343	−230	−230
2 kW_e SOFC	−1042	−803	−1142	−941	−785	−1299	−1042	−1042
3 kW_e SOFC	−2099	−1596	−2206	−1991	−1677	−2521	−2099	−2099
4 kW_e SOFC	−3281	−2494	−3389	−3174	−2681	−3881	−3281	−3281
5 kW_e SOFC	−4472	−3400	−4579	−4364	−3693	−5250	−4472	−4472
SOFC vs. oil								
1 kW_e SOFC	+15	+41	−63	+93	+242	−212	−137	+166
2 kW_e SOFC	−797	−558	−897	−696	−425	−1168	−948	−645
3 kW_e SOFC	−1854	−1351	−1961	−1746	−1317	−2390	−2005	−1702
4 kW_e SOFC	−3036	−2249	−3144	−2929	−2322	−3751	−3188	−2885
5 kW_e SOFC	−4227	−3155	−4334	−4119	−3334	−5120	−4378	−4075
SOFC vs. electricity								
1 kW_e SOFC	−111	−85	−321	+99	+116	−338	−111	−111
2 kW_e SOFC	−923	−684	−1156	−690	−551	−1294	−923	−923
3 kW_e SOFC	−1980	−1477	−2219	−1740	−1443	−2516	−1980	−1980
4 kW_e SOFC	−3162	−2375	−3402	−2922	−2448	−3876	−3162	−3162
5 kW_e SOFC	−4353	−3281	−4593	−4113	−3460	−5245	−4353	−4353

insignificant factor from the point of view of viability when an SOFC system is compared with other than the electrical furnace system or when the capacity of the SOFC system is more than 2 kW_e.

3.5.9. Effect of incremental maintenance cost

The effect of the incremental maintenance cost on the competitiveness of an SOFC system is presented in Fig. 11. The effect of incremental maintenance becomes more significant as the payback period becomes longer, and the capacity of an SOFC system becomes larger. The order of preference amongst the energy supply solutions does not change due to this factor.

3.5.10. Multivariate effects

The simultaneous effect of changing more than one variable was not widely examined in the present study. However, the maximum allowable capital cost of an SOFC system was determined for two scenarios. The tendency of energy prices to change to similar directions is taken into account.

The first scenario refers to the shortage of energy, thus being “optimistic” from the point of view of distributed energy generation. This scenario is possible, for example, due to natural disasters or political conflicts that harm the existing energy infrastructure thus limiting the availability of energy. The energy price then increases and some governmental support to the energy generation is also possible, for example, in the form of an interest subsidy. A short payback period is not necessarily required in this kind of situations. The “pessimistic” scenario reflects strong competition on energy market. The energy prices are “dumped”, the interest rate is high and only short payback periods are acceptable.

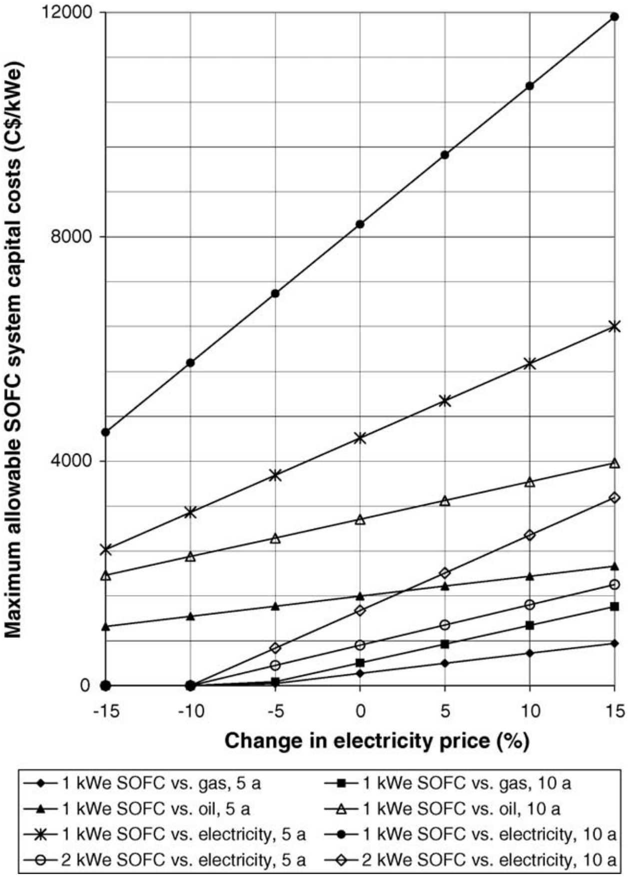

Fig. 7. The effect of electricity price on allowable capital costs of SOFC system.

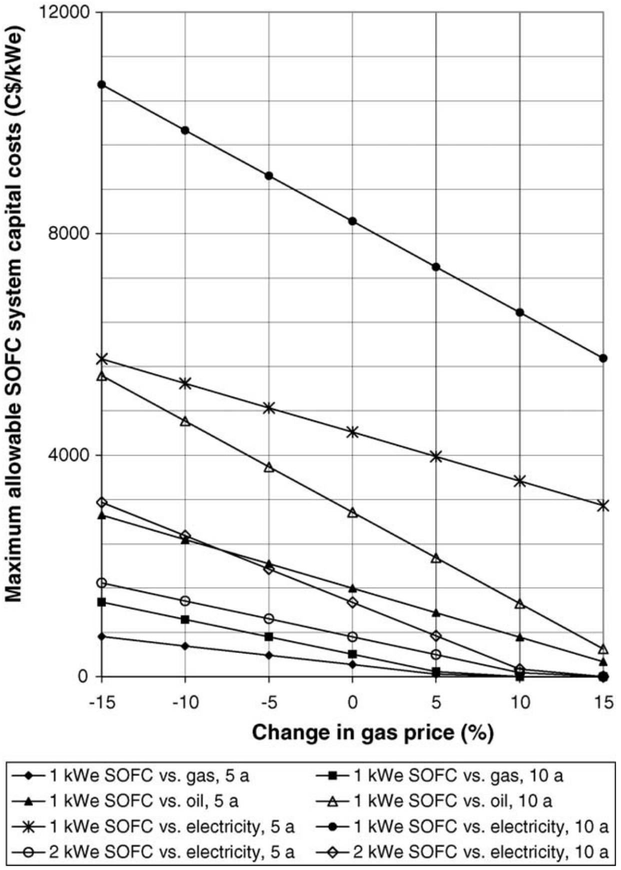

Fig. 8. The effect of gas price on allowable capital costs of SOFC system.

Table 7
The maximum allowable capital costs of an SOFC system in optimistic and pessimistic scenarios

	Ottawa		Vancouver	
	Optimistic	Pessimistic	Optimistic	Pessimistic
Definition of scenario				
Change in electricity price (%)	+15	−15	+15	−15
Change in gas price (%)	+5	0	+5	0
Change in oil price (%)	+15	−15	+15	−15
Buyback price (%)	50	0	50	0
Payback period (a)	20	5	20	5
Interest rate (%)	3	10	3	10
Max capital costs (C$ kW_e^{-1})				
1 kW_e vs. gas heating	2383	0	0	0
1 kW_e vs. oil heating	9301	24	2707	0
1 kW_e vs. electrical heating	19837	2009	693	0
2 kW_e vs. gas heating	0	0	0	0
2 kW_e vs. oil heating	2023	0	0	0
2 kW_e vs. electrical heating	7290	0	0	0
3 kW_e vs. gas heating	0	0	0	0
3 kW_e vs. oil heating	0	0	0	0
3 kW_e vs. electrical heating	2169	0	0	0
4 kW_e vs. gas heating	0	0	0	0
4 kW_e vs. oil heating	0	0	0	0
4 kW_e vs. electrical heating	0	0	0	0
5 kW_e vs. gas heating	0	0	0	0
5 kW_e vs. oil heating	0	0	0	0
5 kW_e vs. electrical heating	0	0	0	0

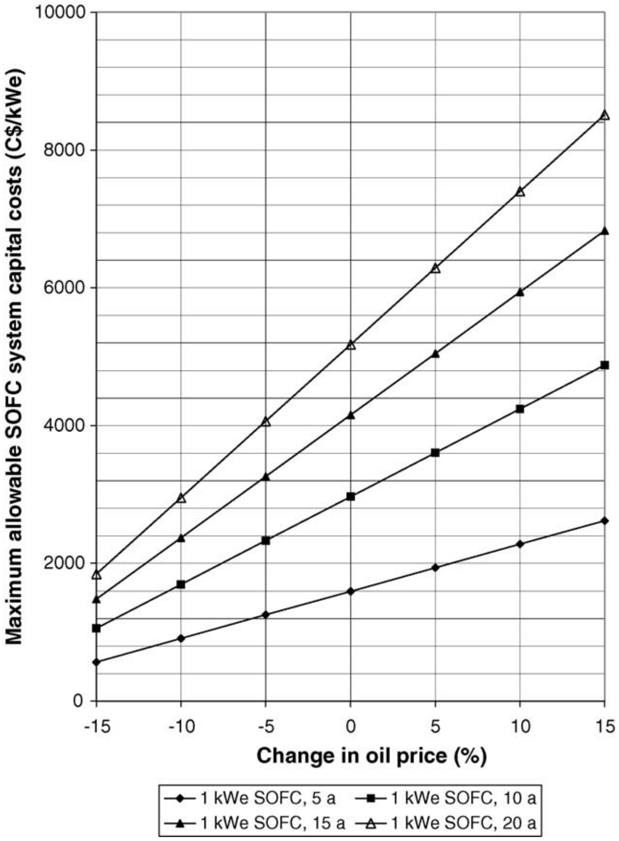

Fig. 9. The effect of oil price on allowable capital costs of SOFC system.

The descriptions of these two scenarios as well as the maximum allowable capital costs of an SOFC system in these scenarios are presented in Table 7. One should note in Table 7 that if the maximum allowable capital cost is more than 0, then the viability of that system is clear. The main conclusion that can be made on the basis of these results is that when the design power is more than 3 kW_e, the SOFC system does not become feasible even in “optimistic” conditions.

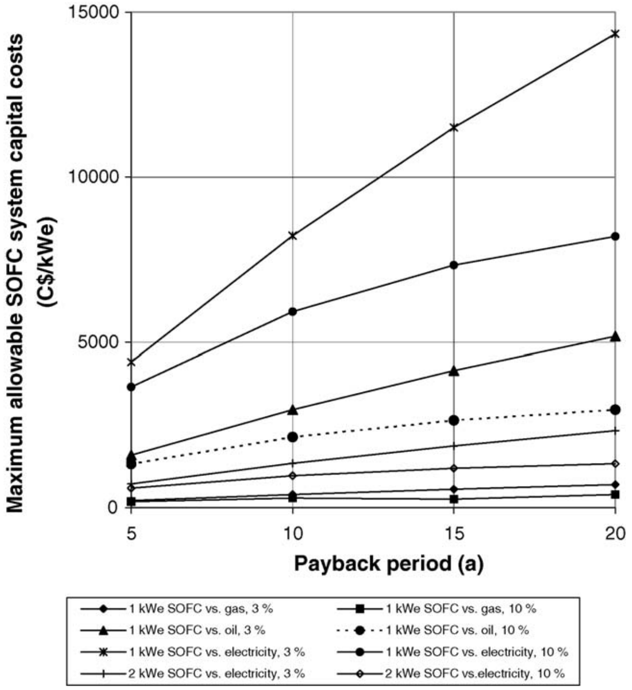

Fig. 10. The effect of interest rate on allowable capital costs of SOFC system.

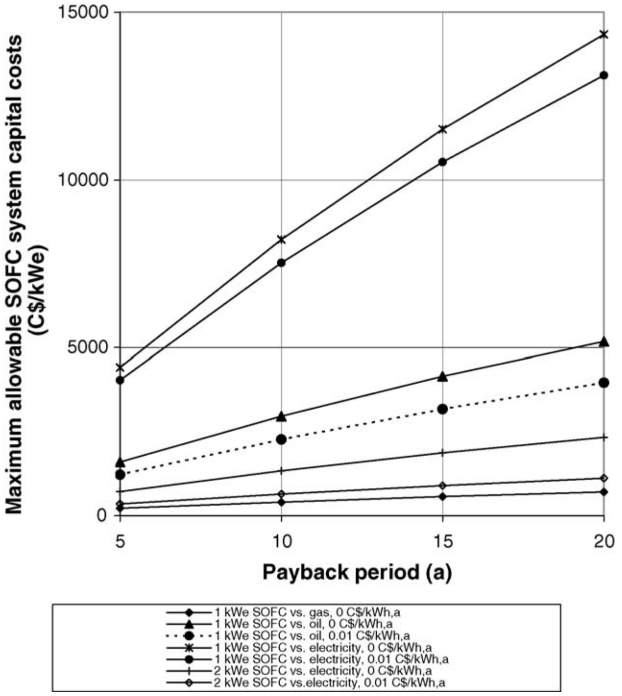

Fig. 11. The effect of incremental maintenance costs on allowable capital costs of SOFC system.

4. Conclusions

This paper presents a point of view to the introduction of SOFC-based micro-CHP technologies as the energy source of residential buildings in Canada. The viability of an SOFC system as an energy supply method for a single-family house was investigated on the basis of a financial analysis. The HOT2000 building simulation program was used to predict the space and domestic hot water heating energy requirements of a modern energy efficient house located in Ottawa and Vancouver. A simplified model was developed to estimate the operation of an SOFC system on the basis of the energy requirement predictions provided by HOT2000. Because the operation of an SOFC system is modelled in a simplified way and because the economic evaluation of an SOFC system in the residential scenario still is based on many assumptions, the results should be interpreted with a critical eye.

The study showed that if an SOFC system runs on constant power, the only justifiable electrical power output is 1–2 kW_e. The main reason is that the significant amount of waste heat makes the operation infeasible and also unacceptable from the environmental point of view in the case of larger units. The SOFC system especially proved to be a competitor of electrical and oil furnaces. One should remember, however, that residential customers more likely select electric baseboards instead of an electric furnace when they want to use electricity as the source of heat. The significance of the SOFC system as the competitor of the gas heating system seems to be minimal. Due to the low energy price and the temperate climate in British Columbia, an SOFC system did not prove to be an option in Vancouver.

The SOFC technology should be compared with other micro-CHP technologies in order to make final conclusions about its competitiveness. According to Onovwiona and Ugursal [19], the installed plant costs of residential cogeneration systems such as combustion engines, Stirling engines and micro-turbines vary between approximately US\$ 1500 and 4000 $\mathrm{kW_e^{-1}}$. Therefore, the rule of thumb is that the maximum allowable capital costs of the SOFC technology from the point of view of its viability with respect to other micro-CHP technologies varies between US\$ 1500 and 4000 $\mathrm{kW_e^{-1}}$ (approximately C\$ 1800 and 4800 $\mathrm{kW_e^{-1}}$), depending on which technology the SOFC system is compared with. One has to remember, however, that the costs of operation of the competing micro-CHP technologies affect the viability of an SOFC system and they should be determined before conclusions.

The viability of an SOFC system also should be estimated by reflecting it to the actual price of the system. According to Onovwiona and Ugursal, in 2002 the total installed cost of a 10 $\mathrm{kW_e}$ polymer electrolyte membrane fuel cell (PEMFC), a 200 $\mathrm{kW_e}$ PEMFC and 100 $\mathrm{kW_e}$ SOFC was US\$ 5500 $\mathrm{kW_e^{-1}}$ (approximately C\$ 6600 $\mathrm{kW_e^{-1}}$), US\$ 3600 $\mathrm{kW_e^{-1}}$ (approximately C\$ 4300 $\mathrm{kW_e^{-1}}$) and US\$ 3500 $\mathrm{kW_e^{-1}}$ (approximately C\$ 4200 $\mathrm{kW_e^{-1}}$), respectively. The investment cost of a small, 1–2 $\mathrm{kW_e}$ SOFC system will obviously be at least C\$ 7000 $\mathrm{kW_e^{-1}}$ and probably more. According to the results of the present study this means in brief that an SOFC system only remains the competitor of the electrical furnace system.

The use of an SOFC technology as the method of energy supply in single-family houses is somewhat limited due to its inflexibility to shutdowns and turn-offs. An SOFC-based micro-CHP system should be able to better cope with the thermal excess and to avoid significant heat leaks. This problem could be avoided by improving the utilization of waste heat, for example, by producing cold using absorption chiller.

In future studies, we are going to pay attention to the construction economics and environmental issues. We are going to leave the technical parameters of micro-CHP technologies open to be examined by a sensitivity analysis. Our aim will be to outline the required trends of development of residential micro-CHP systems and their integration into the residential sector.

Acknowledgements

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