# Economic premises for SOFC cogeneration in Finnish households

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## SUMMARY

In this paper, we present the economic analysis of a solid-oxide fuel-cell (SOFC) micro-cogeneration plant in a single-family low-energy house in Finland. Here, we implement a new solid-oxide fuel-cell (SOFC) model in the dynamic building simulation software “IDA – Indoor Climate and Energy” to obtain a match between energy demand and supply. In our computational study, we first estimate the break-even values for both the buyback price of electricity and plant investment that make an SOFC plant financially viable in a comparison with a water-based gas boiler heating system without cogeneration. Second, we determine the sensitivity of break-even prices in terms of the electrical power, overall efficiency and two operational strategies. Our results suggest that the optimal operation would encompass a constant run with electrical power no more than 1 $kW_e$. In the above case, the break-even buyback price would remain less than 0.04 EUR $kWh^{-1}$, provided that the overall efficiency exceeds 80 %.

## INTRODUCTION

Buildings account for 40% of final energy use, providing a major challenge to the whole energy system. Several studies suggest that the introduction of distributed energy generation would promote the transition to a sustainable energy system (e.g. [1-2]). A solid-oxide fuel cell (SOFC) can be considered a promising alternative to the traditional energy supply for residential buildings due to its general advantages, such as noiselessness and low emissions [3].

The success of new technology in the market presumes, however, that the technology is financially viable with respect to conventional technologies. The key economic drivers are capital costs, energy import and export prices, and plant lifetime [4]. Earlier studies imply that savings in a comparison with traditional residential energy supply solutions may be difficult to obtain by employing solid-oxide fuel cells, partly because of their high capital costs and also due to the high amount of non-utilizable thermal energy (e.g. [5]). The economic key factors that apply to fuel cells, however, strongly depend on the local operational environment and several issues between climatic conditions and taxation policy. A good example is the buyback price of electricity (i.e. the monetary compensation a producer receives for the electricity fed into the grid), which is largely not yet established.

The objective of this study is to evaluate the financial viability of SOFC cogeneration in a low-energy single-family house in Finland. First, we estimate the break-even values for both the buyback price of electricity and plant investment that make an SOFC plant financially viable in a comparison with a water-based gas boiler heating system without cogeneration. Second, we determine the sensitivity of break-even prices in terms of electrical power, overall efficiency and two operational strategies.

## METHODS

The applied methodological framework consists of i) creating the hourly electrical and thermal demand profiles of a case building using the advanced building simulation software IDA – Indoor Climate and Energy (IDA-ICE), ii) estimating the hourly electrical and thermal supply profiles of an SOFC plant using the new mathematical model of SOFC implemented in the IDA–ICE and iii) post-processing of the simulation results and conducting an economic analysis in MicroSoft Excel.

IDA-ICE provides an advanced tool for the dynamic simulation of heat transfer and airflows in buildings, allowing the modelling of multi-zone buildings, internal and solar gains and outdoor climate. The software is widely used in Scandinavia both in commercial and research use. It has been developed by the Royal Institute of Technology and the Swedish Institute of Applied Mathematics, reported in detail by Björsell et al. [6] and Shalin [7] and well tested in several studies, e.g. Achermann et al. [8] and Travesi et al. [9].

The SOFC model is based on the principles in Beausoleil-Morrison et al. [10] and is implemented in the IDA–ICE using the modelling language “Neutral Model Format (NMF)”, reported by Sahlin et al. [11,12]. Here, the “dynamics” of a 3 $kW_e$ SOFC system is modelled as a modified PI-controller, which drives the fuel-cell system at a limited power change rate. The user provides parameter values manually. Inputs to the system are given by flow rates of fuel, water and air. Outputs are electricity, exhaust gas and heat losses from the surfaces. The model structure with relevant parameters is presented in Figure 1.

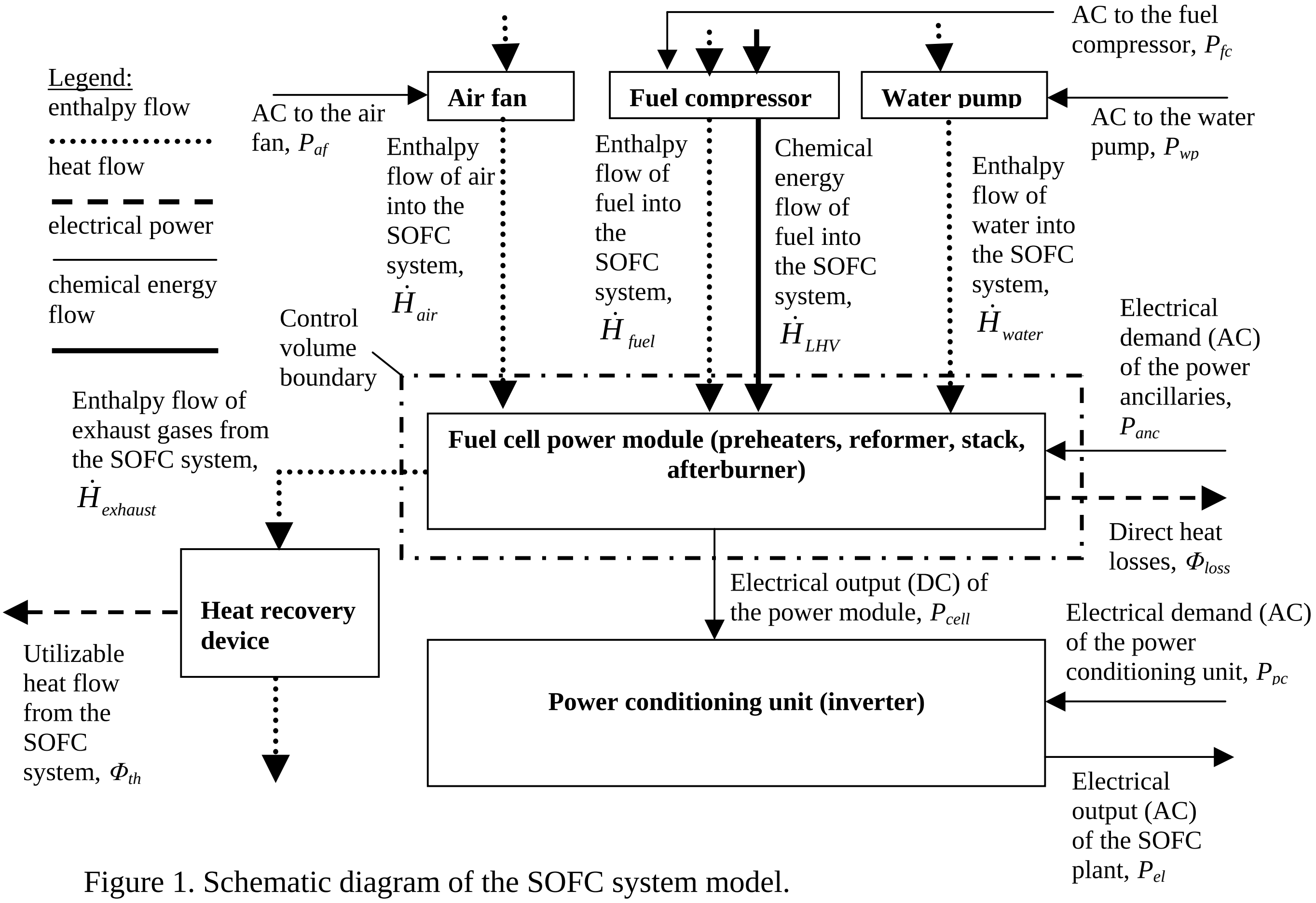

Figure 1. Schematic diagram of the SOFC system model.

The electrical output (DC) of the power module $P_{cell}$ is given by Eq. (1)

$$P_{cell} = \eta_{e,stack}\dot{n}_{fuel}LHV = \eta_{e,stack}\dot{H}_{LHV} \qquad (1)$$

where $\eta_{e,stack}$ is the electrical efficiency, $\dot{n}_{fuel}$ is the molar flow of fuel [mol/s] and $LHV$ is the lower heating value of the fuel. In the present model, the electrical efficiency of the power module $\eta_{e,stack}$ as the function of expected electrical output power is expressed as a polynomial

$$\eta_{e,stack} = (e_{2,\eta}P_{cell}^{2} + e_{1,\eta}P_{cell} + e_{0,\eta})(1 - d_{stops}n_{stops}) \cdot \left(1 - MAX\left[\int_{0} dt - t_{threshold}, 0\right] \cdot L\right) \quad (2)$$

where $e_{2,\eta}$, $e_{1,\eta}$ and $e_{0,\eta}$ are polynomial coefficients obtained by experiments. The term "1-$d_{stops}n_{stops}$" is an expression for the degradation of the fuel cell power module's electrical efficiency as a result of stop-start cycling, $n_{stops}$ is the number of stops and parameter $d_{stops}$ is a user-input that represents the fractional performance degradation. The "$L$-term" represents the degradation of electrical efficiency as a consequence of operation. The time integral indicates the current time of operation, i.e. the accumulated time from the initial system start. $L$ is a fixed, user-defined value that represents the fractional degradation related to operation time and $t_{threshold}$ is a given time when the operational degradation is expected to start.

The energy balance of the power module is

$$\dot{H}_{fuel} + \dot{H}_{air} + \dot{H}_{water} + \dot{H}_{LHV} + P_{anc} = P_{cell} + \dot{H}_{exhaust} + \Phi_{loss} \qquad (3)$$

where $H_{fuel}$, $H_{air}$, and $H_{water}$ are the enthalpy flows into the power module by the fuel, air and water, respectively, $H_{LHV}$ is the chemical energy flow into the system by the fuel, $H_{exhaust}$ is the heat flow out of the system by the exhaust gases, $P_{anc}$ and $P_{cell}$ are the electrical draw of ancillaries and the electrical output of the power module, respectively, and $\Phi_{loss}$ is the loss heat flow out of the power module.

The enthalpy flows in Eq.(3) are defined as

$$\dot{H}_{i} = \dot{n}_{i}h_{i} \qquad (4)$$

where $n_i$ is the $i$-th molar flow [mol s$^{-1}$] and $h_i$ is the corresponding specific enthalpy [kJ/mol]. The relation between temperature $T$ and specific enthalpies is given by the Shomate equation

$$h_{i} = \frac{AT}{1000} + \frac{B}{2}\left(\frac{T}{1000}\right)^{2} + \frac{C}{3}\left(\frac{T}{1000}\right)^{3} + \frac{D}{4}\left(\frac{T}{1000}\right)^{4} - \frac{1000E}{T} + F - H \qquad (5)$$

where $A,B,\ldots,H$ are polynomial coefficients. Since air, fuel and exhaust gas are mixtures of various gases, the above coefficients are calculated for the gas mixture using molar fraction weighted averages $\varepsilon_i$. The composition of the exhaust is considered stoichiometric. Assuming that the fuel fully reacts, i.e. there is no hydrogen or carbohydrates left in the exhaust gas, the expression for molar fraction weighted averages can be given as

$$\varepsilon_{avg} = \sum_{i}(\dot{n}_{i}\varepsilon_{i}) / \sum_{i}\dot{n}_{i} \quad (6)$$

where $\varepsilon$ = {A, B, C, D, E, F, H}.

The electrical demand of ancillaries is defined with separate polynomial equations. The net electrical output power of the SOFC plant can be defined as

$$P_{el} = P_{cell} - P_{af} - P_{fc} - P_{wp} - P_{anc} - P_{pc} \qquad (7)$$

where $P_{cell}$, $P_{af}$, $P_{fc}$, $P_{wp}$, $P_{anc}$, and $P_{pc}$ are the electrical powers of the SOFC power module, air blower, fuel compressor, water pump, ancillaries, and power conditioner, respectively. The utilizable heat flow $\Phi_{th}$ now depends on the capability of the heat recovery device to transfer heat from the exhaust gases to water circulation. In the present approach, the overall efficiency of the SOFC plant is

$$\eta_{tot} = \frac{P_{el} + \Phi_{th}}{\dot{H}_{LHV}} \qquad (8)$$

In the economic evaluation, savings are assumed to occur during operation, compared to gas heating without a fuel cell (reference). The condition of the financial viability presumes that the discounted savings are equal to the capital costs during a given period of time. This condition is satisfied when

$$C_{I,SOFC} - \frac{(1+r_e)^n - 1}{r_e (1+r_e)^n} \cdot \left[ c_{e,p} W_{e,ref} + c_{pr} Q_{pr,ref} - \left( c_{e,p} W_{e,p} - c_{e,s} W_{e,s} + c_{pr} Q_{pr,SOFC} \right) \right] = 0 \qquad (9)$$

where $C_{I,SOFC}$ is the capital (investment) cost of an SOFC plant, $r_e$ is the discount rate for energy costs, $n$ is the number of years on the time period, $W_{e,ref}$ and $Q_{pr,ref}$ are the annual electricity and input energy consumptions in the reference case, respectively, $c_{e,p}$ and $c_{pr}$ are the purchasing prices for electricity and input energy, respectively, $c_{e,s}$ is the buyback price of electricity, $W_{e,p}$ is the annual amount of electricity to be purchased in the case of SOFC operation, $W_{e,s}$ is the annual amount of electricity fed into the grid, and $Q_{pr,SOFC}$ is the input energy consumption of the SOFC plant (directly proportional to $H_{LHV}$).

## RESULTS

The computational study concerns a low-energy single-family house located in the Helsinki area. The habitable area is 131 m$^2$ and the U-values for envelope, roof, floor, windows and doors are 0.14 W m$^{-2}$K$^{-1}$, 0.1 W m$^{-2}$K$^{-1}$, 0.15 W m$^{-2}$K$^{-1}$, 1.0 W m$^{-2}$K$^{-1}$ and 0.5 W m$^{-2}$K$^{-1}$, respectively. The house is inhabited by four persons; the daily profiles for heat gains and domestic hot water (DHW) demand is illustrated in Figure 2.

The calculations were conducted for the reference case (water-based gas boiler heating) and the SOFC plant with two operational strategies: i) the SOFC plant was operated at a constant power throughout the year and ii) the operation was controlled by the electrical demand of the building. The energy prices were based on the rate schedules of local utilities in December 2006 for both natural gas and electricity. The efficiency of the gas boiler was assumed to be 0.93 [13]. The annual consumption of electricity and natural gas in the reference case were 6089 and 11186 kWh a$^{-1}$, and the corresponding annual costs were 583 and 771 EUR a$^{-1}$, respectively. The discount rate of 5 % was used. The annual energy profile of an SOFC system with an overall efficiency of 80 % is presented in Table 1.

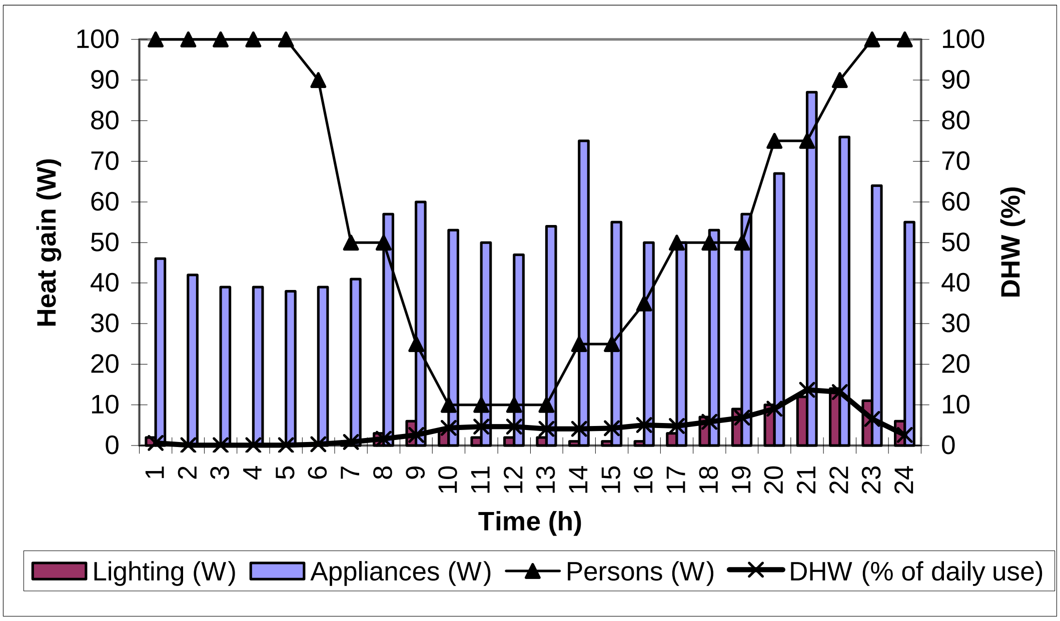

Figure 2. Daily profiles for heat gains and hot water usage [14].

Table 1. Annual energy profile for the SOFC heating system.

| **Constant operation** | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| eta = 80 % | Purchased electricity (kWh $a^{-1}$) | Delivered electricity (kWh $a^{-1}$) | Fuel to SOFC (kWh $a^{-1}$) | Fuel to boiler (kWh $a^{-1}$) | Fuel total (kWh $a^{-1}$) |
| 1 kWe | 47 | 2719 | 22464 | 4394 | 26858 |
| 2 kWe | 0 | 11382 | 39723 | 2274 | 41997 |
| 3 kWe | 0 | 20108 | 58204 | 861 | 59064 |
| | | | | | |
| **Adapted operation (electricity)** | | | | | |
| | | | | | |
| eta = 80 % | Purchased electricity (kWh $a^{-1}$) | Delivered electricity (kWh $a^{-1}$) | Fuel to SOFC (kWh $a^{-1}$) | Fuel to boiler (kWh $a^{-1}$) | Fuel total (kWh $a^{-1}$) |
| 1 kWe | 87 | 41 | 16418 | 5398 | 21816 |
| 2 kWe | 34 | 55 | 16565 | 5351 | 21916 |
| 3 kWe | 34 | 55 | 16565 | 5351 | 21916 |

As can be seen in Table 1, there is only a minor need to purchase electricity from the grid either when the SOFC plant is operated at constant power or following the electrical demand (adapted operation). The fuel consumption remains quite large in both cases. Instead, in constant operation, the amount of electricity fed to the grid is large. The match between the supply and demand of power in the case of adapted operation (SOFC plant follows the electricity demand) is illustrated in Figure 3.

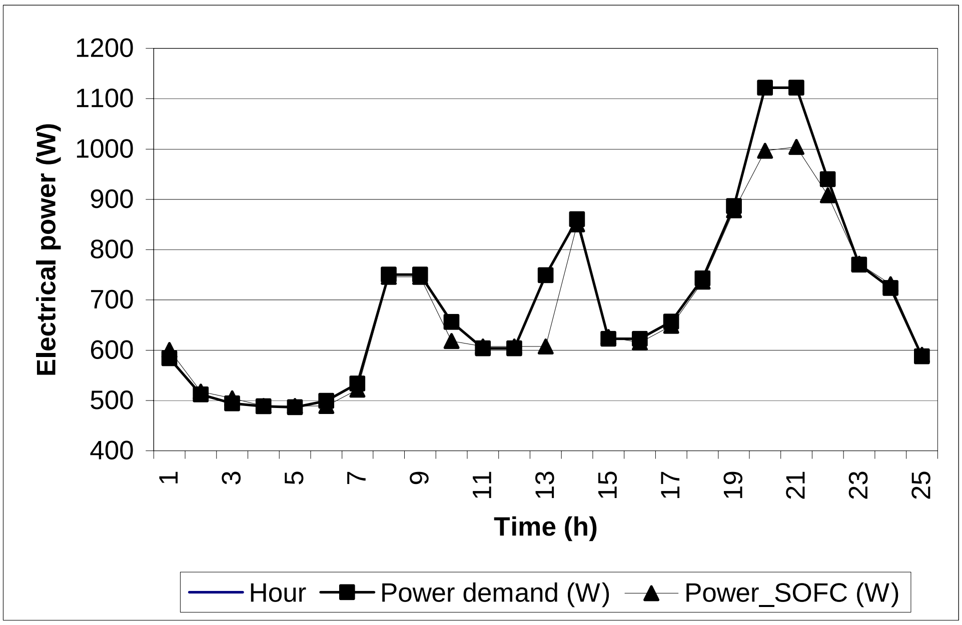

Figure 3. The match between power supply and demand.

The first condition enabling financial viability is that annual savings occur, which presumes here that a break-even buyback price must be first found for electricity (zero savings). Figure 4 illustrates the break-even buyback price of electricity when the SOFC plant is operated at constant power from 1 to 3 $kW_e$ and the overall efficiency, i.e. the ratio of heat that can be transferred from the exhaust gases to the water circulation, varies from 0.5 to 1.0. The result suggests that a significantly low buyback price of electricity is not achievable when the operating power is more than 1 $kW_e$. Based on the overall efficiency, an obvious reason for this is large, but unavoidable, heat loss in the constant operation, which cannot compensate the incomes from buyback electricity. Figure 4 shows also that annual savings are not possible if there is no compensation for the electricity fed into the grid. The lower the buyback price, however, the more eagerly it will probably be offered by the energy utilities to a private producer. For the above reasons, the further considerations focus on 1 $kW_e$ operation.

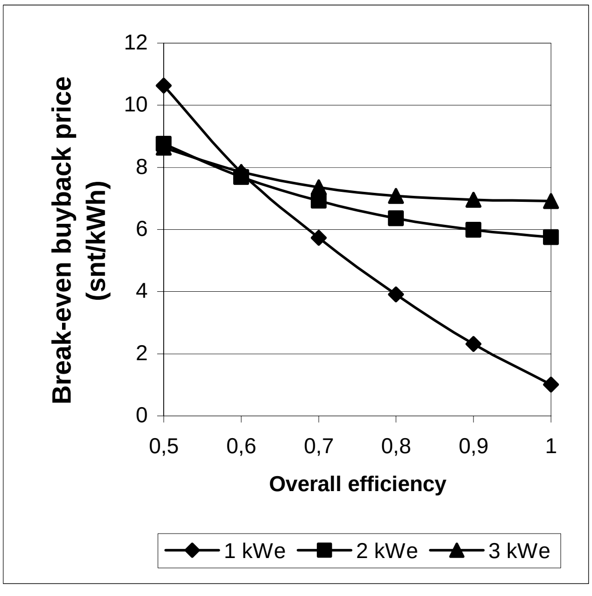

Figure 4. Break-even buyback price of electricity.

In Figure 4, the curve of break-even buyback prices represents zero savings. Considering a 1 $kW_e$ SOFC plant with an overall efficiency of 80 %, the buyback price should be more than 4 snt $kWh^{-1}$ to create annual savings. The relation between the overall efficiency, buyback price, payback period and the maximum allowable capital costs invested in an SOFC plant are presented in Figure 5.

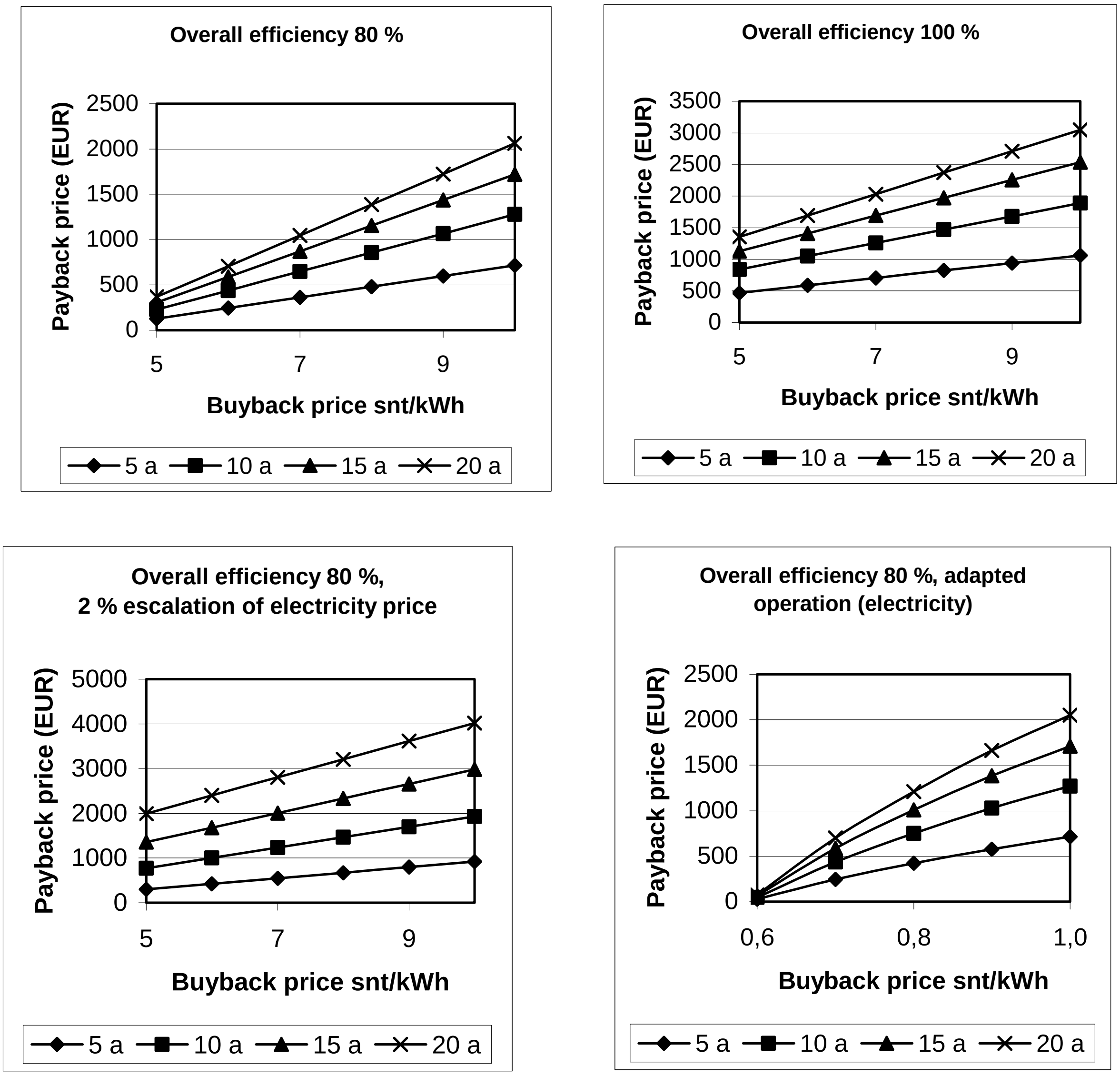

Figure 5. Payback price of SOFC technology.

Figure 5 implies that, in the ideal case (overall efficiency 100 % and payback period 20 years), the maximum allowable technology price would be 3000 EUR. In the sense of earlier studies (e.g. [3]), the life span of an SOFC stack may be less than 10 years, which suggests that an allowable payback period might be rather 5 than 10 years. In this case, the allowable capital costs would remain less than 1000 EUR. The situation from the viewpoint of short payback periods will not improve, even when one assumes that the escalation of electricity price with respect to that of natural gas is 2 % (see Figure 5). Without significant investment support, the investment in SOFC technology does not seem feasible in the case considered here.

## DISCUSSION

In this paper, we present the economic analysis of a solid-oxide fuel cell (SOFC) micro-cogeneration plant in a characteristic single-family low-energy house in Finland. Our results suggest that the optimal operation of an SOFC plant would encompass a constant run with electrical power no more than 1 $kW_e$. Here, the break-even buyback price would remain less than 0.04 EUR $kWh^{-1}$, provided that the overall efficiency exceeds 80 %. However, taking into account the requirements concerning the payback period and the price of technology, it seems that, without significant investment support, the investment would not be feasible in the case considered here. One should note, however, that this result is only valid for the present case building. Furthermore, our approach did not employ an actual demand profile of a building and the study was unable to analyze the real impact of peak demands. Therefore, more studies are needed to draw further general conclusions about the viability of SOFC cogeneration in Finnish households.

## REFERENCES

[1] Barreto, L, Makihira, A and Riahi, K. The hydrogen economy in the 21st century: a sustainable development scenario. International Journal of Hydrogen Energy, Vol. 28(3) pp 267-284.

[2] Alanne, K., Saari A. 2006. Distributed energy generation and sustainable development. Renewable & Sustainable Energy Reviews, Vol. 10 (6) pp 539-558.

[3] Onovwiona, H.I. and Ugursal, V.I. 2006. Residential cogeneration systems: review of the current technology. Renewable and Sustainable Energy Reviews, Vol. 10(5) pp 389-431.

[4] Hawkes, A. and Leach, M. 2005a. Solid oxide fuel cell systems for residential micro-combined heat and power in the UK: Key economic drivers. Journal of Power Sources, Vol. 149 pp 72-83.

[5] Alanne, K., Saari, A., Ugursal, V.I. and Good, J. 2006. The financial viability of SOFC cogeneration system in single-family dwellings. Journal of Power Sources, Vol. 158(1) pp 403-416.

[6] Björsell, N., Bring, A., Ericsson, L., Grozman, P., Lindgren, M., Sahlin, P., Shapovalov, A. and Vuolle, M. 1999. IDA indoor climate and energy. Proceedings of the IBPSA Building Simulation '99 conference, Kyoto, Japan.

[7] Shalin, P. 1996. Modeling and simulation methods for modular continuous system in buildings. Doctoral Thesis. KTH, Stockholm, Sweden.

[8] Achermann, M. and Zweifel, G., 2003, RADTEST - Radiant heating and cooling test cases. Subtask C. A report of IEA Task 22. Building Energy Analysis Tools.

[9] Travesi, J. et al., 2001, Empirical validation of Iowa energy resource station building energy analysis simulation models, IEA Task 22, Subtask A.

[10] Beausoleil-Morrison, I, Schatz, A and Maréchal, F, 2005, "A Proposed System-Level Model for Simulating the Thermal and Electrical Production of Solid-Oxide Fuel Cell Residential Cogeneration Devices within Whole-Building Simulation", Proc. Building Simulation 2005, Ninth International IBPSA Conference, Montreal, Canada, August 15-18, 2005

[11] Sahlin, P, Sowell, E. F., 1989, "A Neutral Model Format for Building Simulation Models", Conference Proc. Building Simulation '89, IBPSA, Vancouver, Canada

[12] Sahlin, P., 1996, "NMF Handbook: An Introduction to the Neutral Model Format, Nmf version 3.02", Nov 1996, Building Sciences, KTH, Stockholm, ASHRAE RP-839

[13] Ministry of the Environment. 2006. Section D5 of the National Building Code of Finland - Calculation of performance and energy requirement for the heating of buildings (Draft: December 19, 2006).

[14] Laitinen, A, Shemeikka, J, Klobut, K. 2005. RET-pientalon määrittely (in Finnish).VTT Rakennus- ja Yhdyskuntatekniikka. Espoo, 2005.