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# Model of electricity and heat generators based on a high temperature fuel cell for residential applications

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**Abstract**

Increasing electricity requirements in the residential sector open up a possible market for small cogeneration systems. A system of this type can be based on new, highly efficient technology such as high temperature fuel cells. Mathematical modeling is a low cost and effective method for analyzing possible operation strategies and commercial results for the system. The objective of this paper was to present the simulation results of operation of a micro CHP system based on an SOFC in Polish circumstances. The model of an SOFC-based micro-CHP system was developed. Based on this model a technical and commercial analysis was performed. The results of sensitivity analysis established SOFC performance variation with changes in the prices of utilities. The optimum micro-CHP system was found to be 1 kW.

*Keywords:* Fuel cells, Economics, Electricity generator, Heat generator

## 1. Introduction

Modeling is a key stage in new technology development. Micro combined heat and power systems based on a solid oxide fuel cell appears very promising technology. Krist in his work [1] shows the possible advantages of a fuel cell system as a combined heat and power installation as well as the requirements such systems have to withstand. Krist highlights the high power generation efficiency, low emissions and low noise characteristics as the main advantages of fuel cells systems. In the work of Slowe a possible market for micro-CHP systems was presented. It also underlined that to date fuel cell projects have stayed at the developmental phase while the growth market in micro-CHP units is mainly based on internal combustion engines [2]. The results of SOFC-based micro-CHP systems present in the work of Hawkes et al. [3], Wakui et al. [4] and Braun [5, 6] vary according to the assumptions made of heat and electric requirements, prices of gas and electricity as well as configuration of system [7] and [8] show the problem of control strategy for fuel cells, an issue which is not discussed in this paper. The main objective of this work was to examine the work of an SOFC-based micro combined heat and power system in Poland. This work includes: a sensitivity analysis on fuel and electricity prices, the impact of investment cost on the commercial result and analysis of tank size on system operation.

The mathematical model of a CHP system was developed and solved using EES software. This software was used for solving mathematical equations

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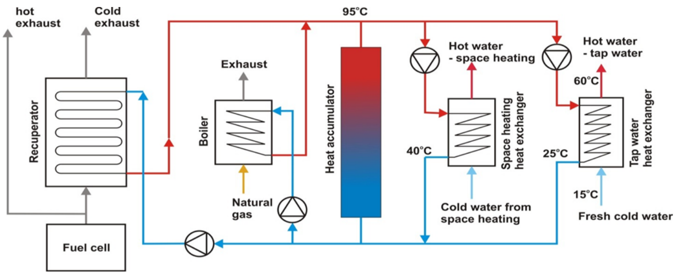


Figure 1: Schematic of the heat recovery system of an SOFC-based micro-CHP

and description of system work. The EES results show the performance of an SOFC-based micro-CHP system. The model gives the amount of electricity and heat produced in every hour of the year and addresses other factors concerning the CHP such as $CO_2$ emissions and efficiency. Commercial and technical system evaluations were made based on the results.

## 2. Modeling

The model was divided into two subsystems: a SOFC power module and a waste heat recovery system. The model of the SOFC power module was based on previous work [5, 6]. This work was concentrated on the SOFC-based micro-CHP technology development of the heat recovery system model depicted in Fig. 1 and on analyzing system performance.

The heat recovery system was a closed loop system supplied with demineralized water. The use of demineralized water was essential to avoid silica, calcium chloride and magnesium salt deposition at temperatures above 60°C [9].

The recovered heat was stored in a heat accumulator or used by households. In the design the water is heated to 95°C by hot exhaust from the SOFC and cooled to around 30°C in two heat exchangers. Additional heat requirements were covered through a gas boiler. The gas boiler was connected to the enclosed loop of demineralized hot water and was used only to supply households with heat in the case of a deficiency in heat production from the CHP system. The considered model was a steady state model based on a 1-hour average step. In addition, for better understanding of the SOFC-based CHP system, the time step was changed to 15 minutes. The purpose of this

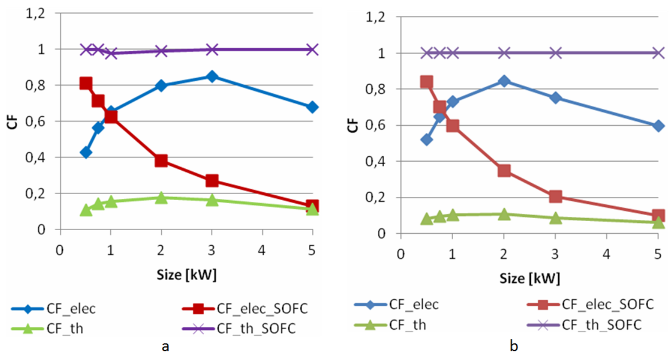


Figure 3: Capacity factors for different sizes of system: (a) literature data [10, 11] (b) experimental data

change is explained later in this paper. The mathematic model assumed constant temperature before and after the heat exchangers and the amount of heat provided by system depends on mass flow of water in the heat exchangers.

Key factors are presented in Table 1 below. These coefficients were used to rate the micro-CHP system with SOFC.

The SOFC micro-CHP model results were based on two different load requirements. One of the models of requirements was made based on the literature [10, 11]. The other model of requirements derived from observed energy usage in a standalone family house, as described later in the paper as experimental requirements. Load requirements consist of electricity requirements, heat demand and cooling demand for a single family household in Poland.

## 3. Results

Examples of seasonal change in electricity requirement and electricity generation of 0.5 and 3 kW systems are shown in Fig. 2. The presented examples of systems performance are based on two days in the year, one during the heating season and one in summer. This example helps to describe the work of the SOFC-based micro-CHP unit on the experimental requirements.

The problem of selecting the FC size appropriate for a household is evident in Fig. 2. Electrical requirements change during the day, making it almost impossible for a single-size FC to fulfill all requirements. A small fuel cell works well more often, but it is unable to meet all the needs of a residence. To se-

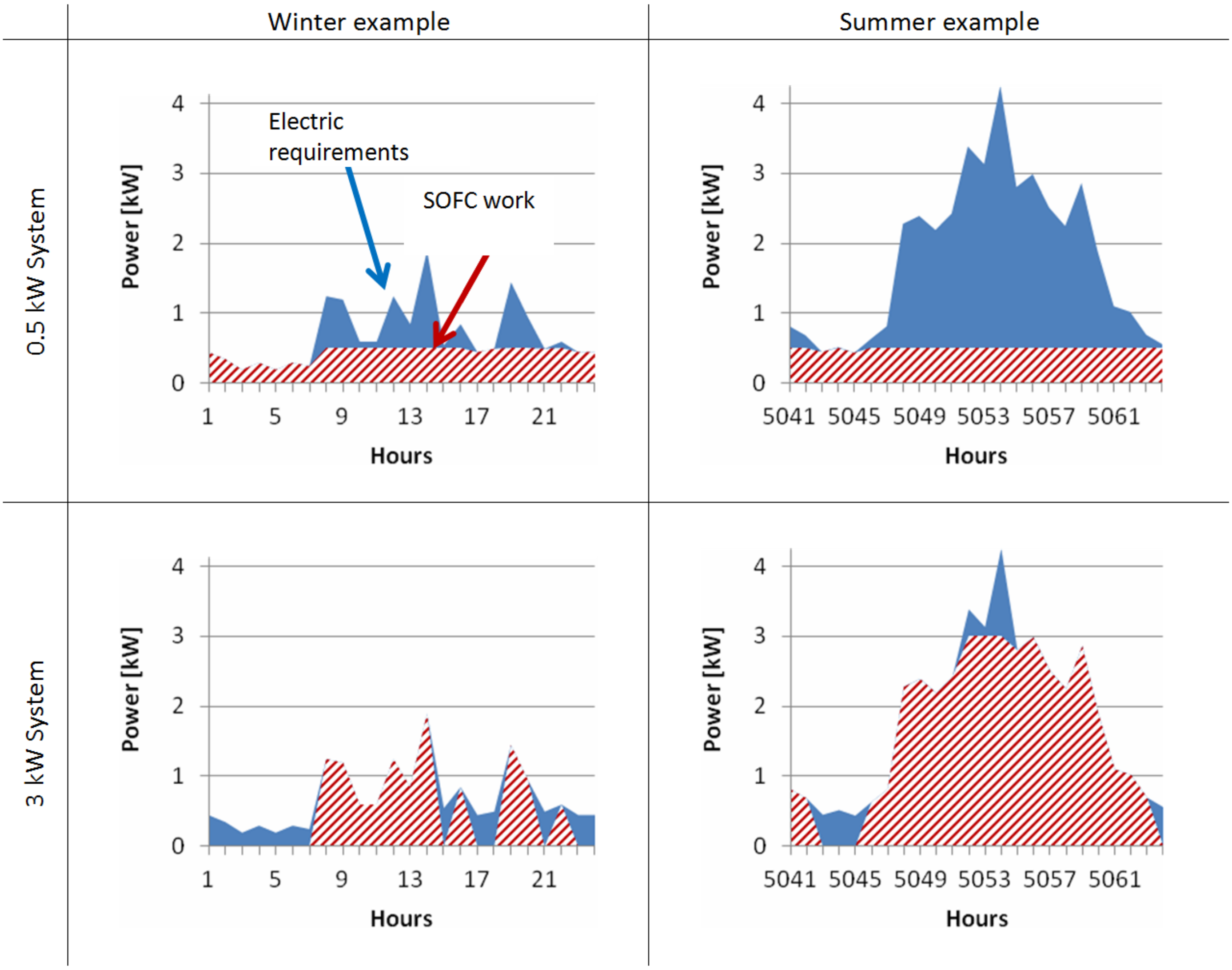


Figure 2: SOFC work patterns for 0.5 and 3 kW systems

Table 1: Factors used in the paper and their equations

| Factor | contraction | Equation |
|---|---|---|
| Electric capacity factor of the SOFC | $CF_{elec,SOFC}$ | $CF_{elec,SOFC} = \frac{total\, electricity\, generation}{total\, theoretic\, electricity\, generation}$ |
| Electric capacity factor of the household | $CF_{elec}$ | $CF_{elec} = \frac{total\, electricity\, provided}{total\, electricity\, requirement}$ |
| Heat capacity factor of the SOFC | $CF_{th,SOFC}$ | $CF_{th,SOFC} = \frac{total\, heat\, recovered}{total\, theoretic\, heat\, recover}$ |
| Heat capacity factor of the household | $CF_{th}$ | $CF_{th} = \frac{total\, heat\, recovered}{total\, heat\, requirement}$ |
| Thermal-to-electric ratio | $TER$ | $TER = \frac{total\, heat\, generation}{total\, electricity\, generation}$ |
| Electric efficiency | $\eta_{elec}$ | $\eta_{elec} = \frac{electricity}{energy\, in\, fuel\, (LHV)}$ |
| System efficiency | $\eta_{system}$ | $\eta_{system} = \frac{electricity+heat}{energy\, in\, fuel\, (LHV)}$ |
| Cash flow in "i" year | $CF_i$ | $CF_i = \sum cost\, of\, based\, installation - \sum cost\, of\, consider\, installation + O\&M$ |
| Net present value | $NPV$ | $NPV = \sum_{i=1}^{n} \frac{CF_i}{(1+r)^i}$ |

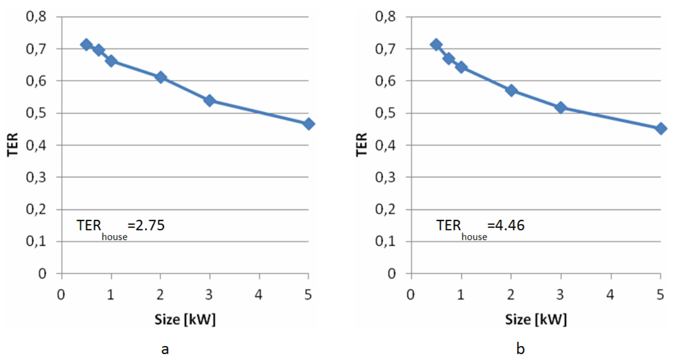


Figure 4: TER of an SOFC-based micro-CHP for: (a) literature data [10, 11] (b) experimental data

lect the best size of a SOFC system the author used CFelec and CFth. The results of CFelec and CFth can identify what the possible optimum fuel cell size is. Moreover, the fuel cell capacity factors are shown in Fig. 3. A comparison of these factors for two different load assumptions is shown in Fig. 3.

A comparison of all values of capacity factors for the house show that the optimum size of a CHP unit is around 2 and 3 kW. Systems of comparable size have the highest electric and thermal capacity factors. In closer analysis the maximum thermal capacity factor for the house is between a 1 and 2 kW system, which is still close to the optimum established earlier. Analysis of Fig. 3 shows that bigger changes are apparent between electric capacity factors than thermal capacity factors. This fact makes CFelec (Table 1) more important in the search for the optimum since the effect on system performance is greater. The reason for that is the higher exergy of electric power compared to heat power. Moreover, the ratio of used electric power to potential generation is at its highest for the smallest units. The task of determining the optimum size of the SOFC-based micro-CHP is very complex. Other factors are very helpful in adjusting the installed power. The result of the thermal-to-electrical ratio (TER) is a key tool in determining the right size SOFC-based micro-CHP system. The TER is shown in Fig. 4.

Analysis of the thermal-to-electric ratio of the micro-CHP system shows that, in general, the system generates more electricity than heat power. However, the household requires more heat than electric power. The TER varies according to the size of the analyzed fuel cell system. This is an effect of SOFC electrical efficiency. The big difference between the TER of a system and the TER required by a household causes problems in determining the right size fuel cell. Moreover, the comparison of TER for system and household explains the low CFth (Table 1). It shows that the thermal energy produced is lower than the electrical energy and, since the system follows the electrical requirement, the total amount of heat generated is small.

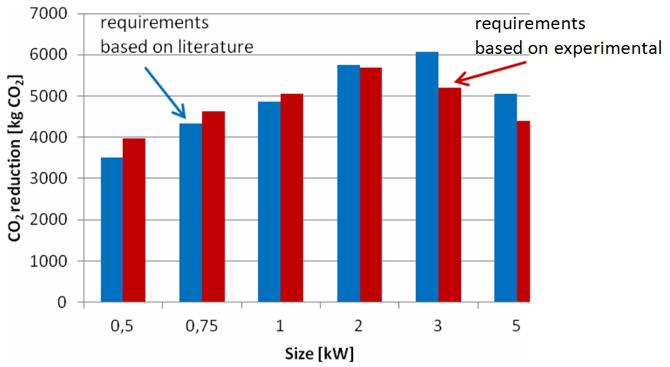


Figure 5: $CO_2$ emissions reduction through an SOFC-based micro-CHP unit

In conclusion the SOFC-based CHP system produces more electricity than heat. The total electricity covers up to 85% of household requirements in the best case scenario. Moreover, all the generated heat is used by a family house. Less than 20% of the heat requirement is covered. Results of this kind are satisfactory since electric power is a more valuable source of energy.

Other parameters were checked in the process of system analysis and search for an optimum, to wit: reduction of $CO_2$ emissions, achieved electrical efficiency and system efficiency based on LHV. Another very important factor for a commercial system is its economic rating. Fig. 5 illustrates the $CO_2$ emissions results. The $CO_2$ reduction depicted is the difference between: (i) emissions generated through an SOFC-based CHP system, (ii) $CO_2$ production from average grid electricity emissions, and (iii) $CO_2$ originated from family house heating.

The $CO_2$ reduction is greater for a 2–3 kW fuel cell system micro-CHP due to its high efficiency electricity generation, which is at its peak for 2–3 kW units. The $CO_2$ reduction results show that combined heat and power generation is environmental friendly, since all of the examined units achieved $CO_2$ reduction. Since the larger units produce more energy, they also have bigger $CO_2$ reduction. The lower $CO_2$ reduction achieved by the 5 kW and 3 kW systems based on experimental data is caused by lower system usage due to the turndown ratio: the more efficient the system, the greater the $CO_2$ reduction. This causes a shift in the optimum size of the CHP system to slightly bigger systems than would be assumed in

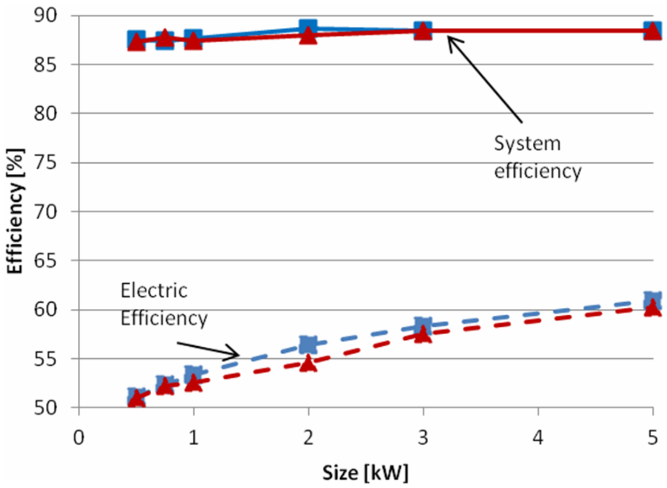


Figure 6: System efficiency and electric efficiency of (square) literature data [6, 9] (triangular) experimental data

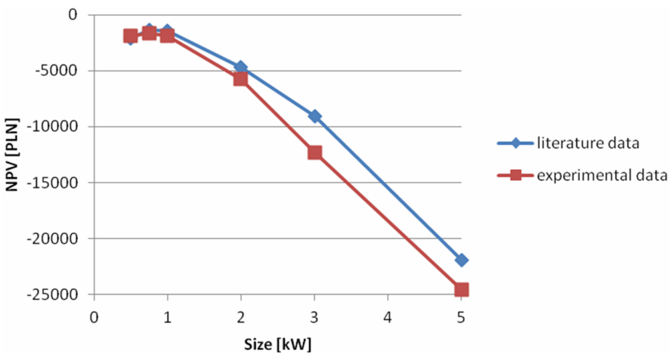


Figure 7: Comparison of NPV results

the case of an optimum based on CF values. The electric efficiency of the SOFC micro-CHP system increases with system size. Electrical efficiency and overall system efficiency are shown in Fig. 6.

High system efficiency is aided by high heat demand. High heat demand makes it possible to use most of the energy in the fuel. The electrical efficiency increases, because fuel cells enjoy higher efficiency at partial load. System efficiency results of about 87% are high and are in agreement with the theory. Moreover, achieving such high results makes SOFCs very interesting and a better prospect than natural gas technology. The range of system efficiency of 87.3–88.7 enables one to choose between various sizes of fuel cell.

The NPV results for two sets of data are presented in Fig. 7.

The results in Fig. 7 show that the SOFC-based micro combined heat and power system considered

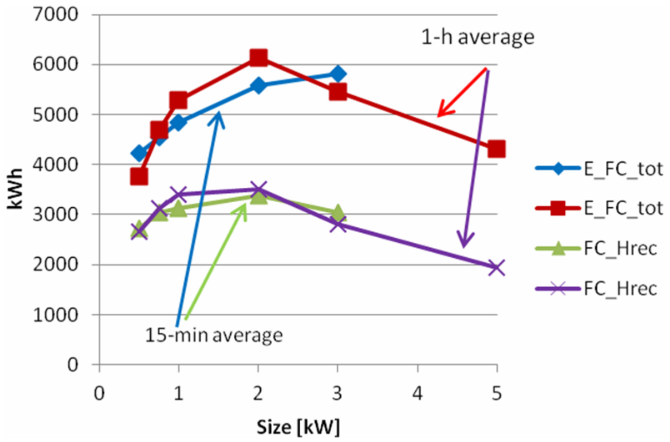


Figure 10: Total heat and electricity generation through the SOFC-based micro-CHP system

literally falls off the scale from the commercial point of view. The decreasing NPV with fuel cell size above 1 kW is caused through the low capacity factor of the system. The lower NPV for the 0.5 kW unit than for 0.75 and 1 kW is caused by the much higher investment cost per kW.

After considering all factors, it was decided that 1 kW was the optimum SOFC-based micro-CHP system, since it is very effective, has a good TER factor and satisfactory CF values. Moreover, these systems are the closest to being commercially viable.

The SOFC-based micro-CHP system model was also based on 15-minute average load requirements. Rapid changes in real-life household electricity usage and heat consumption drove this analysis. To make the simulation more realistic the 15-minute average time step was selected. The comparison of these two different averages was made based on requirements from the experiment. The difference in work of an SOFC micro-CHP system is shown in Fig. 8.

Fig. 8 clearly shows that the 15-minute average requirements are more dispersed. This gives slightly different results for total power generation through the year. The exact difference in performance can be seen in the comparison of technical factors, such as CFth and CFelec. Fig. 10 presents a comparison of heat and electricity total generation.

Fig. 9 shows requirements and electricity production from the SOFC for both 15-minute and 1-hour averages. These figures help explain the difference in heat and electricity generation between 15-minute and 1-hour averages.

Differences arise due to the two approaches of averaging requirements. Fig. 8 shows why the generation of electricity varies between different average bases. Fig. 9 shows the difference between work based on 15-minute and 1-hour averages. Nevertheless, it is hard to determine in which case electricity and heat production is smaller or greater. The difference between 15-minute and 1-hour averages is shown in Fig. 10, through the total electrical generation and heat production of an SOFC-based micro-CHP system.

In Fig. 10 it is shown that electricity generation differs between the chosen average requirements. This is caused by the match of possible system electricity generation to the assumed household demand. Moreover, maximum electricity generation varies between considered requirements. In Fig. 10 also shows a comparison of heat generation based on 1-hour and 15-minute averages. Heat power generation is similar in both options. The comparable heat generation is due to maximum heat recovery by the household. The differences are driven by electricity generation, since the fuel cell system follows the electrical load. This result was expected since, in the considered household, the use all of provided heat from the fuel cell system and heat generation is directly proportional to the electricity production.

The heat generation results based on the 15-minute average show that in the case of big changes in electrical load a heat accumulator is needed. This is confirmed through the comparison of heat generation and electricity generation curve in Fig. 10. Electricity generation increases with system size while heat generation achieves a maximum with the 2 kW SOFC.

## 4. Sensitive analysis

A sensitivity analysis of the system was made based on the variation of fuel cell stack price, presented in Table 2. The price of the heat storage tank was assumed to be 685 PLN [13].

The sensitivity analysis was also based on the changing cost of electricity and fuel, presented in Table 3.

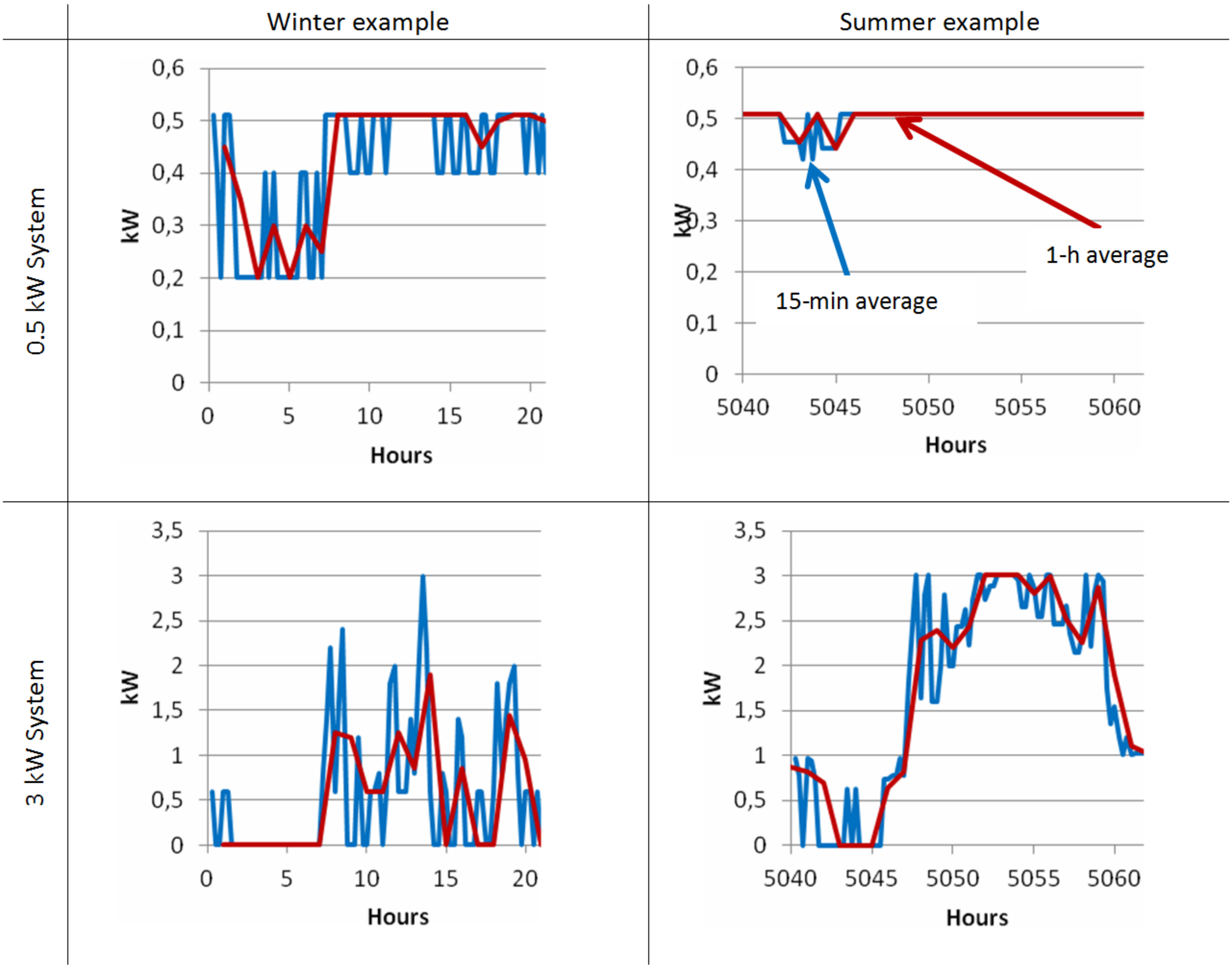


Figure 8: Work of an SOFC system based on 15-minute and 1-hour averages

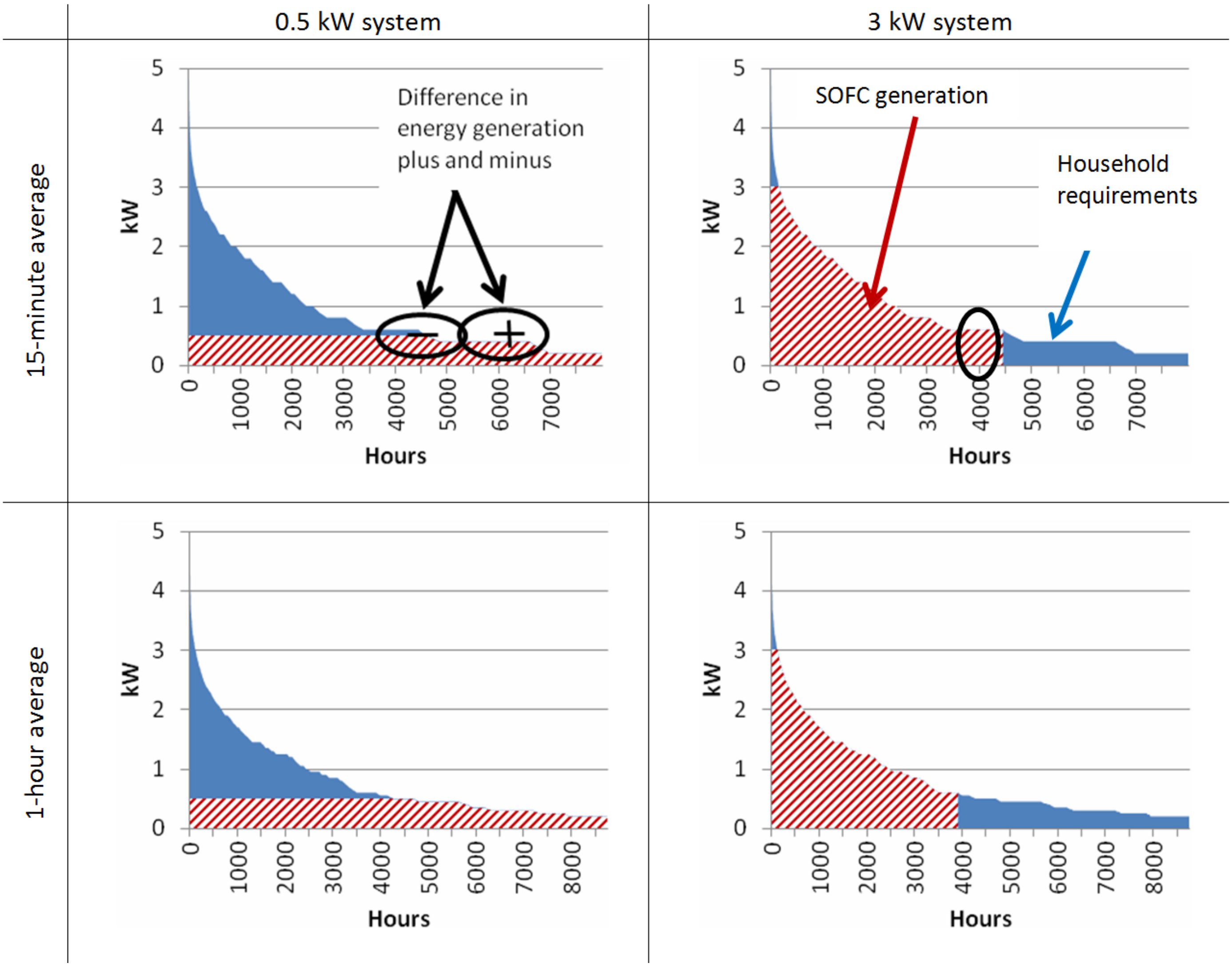


Figure 9: The monotone figure of an SOFC-based micro-CHP unit, with example difference in electricity generation

Table 2: Cost of fuel cell [12]

| Fuel cell power, $kW_e$ | Based cost of fuel cell, $PLN/kW_e$ |
|---|---|
| 0.5 | 8275 |
| 0.75 | 6484 |
| 1 | 5578 |
| 2 | 4184 |
| 3 | 3678 |
| 5 | 3227 |

Table 3: Fuel and electricity prices [14–18]

| Gas price | |
|---|---|
| Fuel price, PLN/$m^3$ | 1.2741 |
| Constant price, PLN/month | 56.50 |
| **Electricity price** | |
| Electricity price, PLN/kWh | 0.6099 |
| Constant price, PLN/month | 61.22 |

A discount rate of 8% was assumed for this commercial analysis. The NPV (Table 1) indicator was counted for 15 years of operation. The results of this analysis determine whether the considered system can deliver a positive commercial result. Moreover, system performance was checked for variation according to different size heat accumulators. A sensitivity analysis was performed for the experimental data with the 1-hour average. Fig. 11 presents the results of change of investment cost.

Fig. 11 shows the impact on the NPV of a system for different size micro-CHP units based on percentage changes in the investment cost of the SOFC.

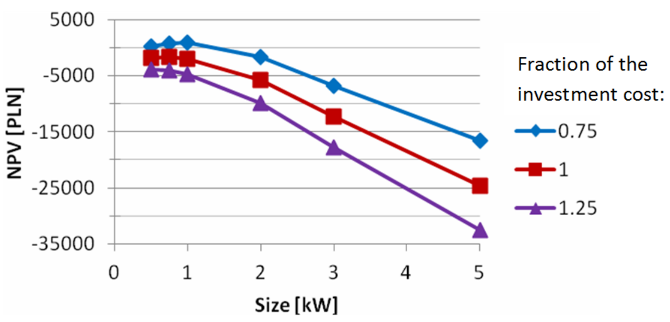


Figure 11: Results of a sensitivity analysis on the change in investment cost

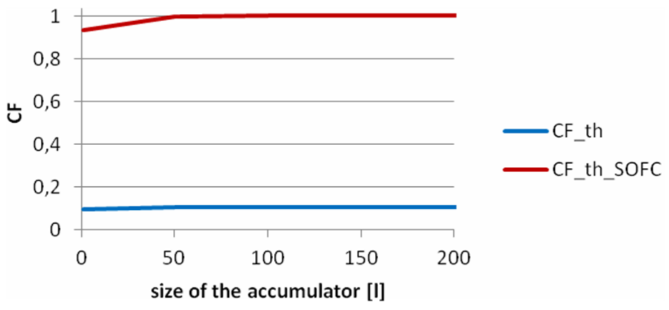


Figure 13: Sensitivity analysis of changed size of heat accumulator

It is shown that the differences are greater for 3–5 kW systems. This is caused by the lower impact of the investment cost on the NPV indicator for bigger SOFC-based CHP systems. Furthermore, greater possible savings on electricity and heat create a bigger difference in the NPV indicator. Moreover, 3–5 kW systems have higher electrical efficiency, as is presented in Fig. 6. The NPV results across a range of investment cost show that a small system has positive commercial results if the investment cost is reduced by 25%.

Fig. 12 shows the impact of price change. The analysis was made for two different options. In the first option the prices of electricity and natural gas change by the same percentage. The second shows the change in electricity price according to the expectations of the Polish Economy Ministry [19].

The presented results are very optimistic since they show that higher gas and electricity prices make the system more commercially viable. Moreover, they show that based on the official forecast prices of electricity [19] 0.75–1 kW systems already have positive commercial results (see Fig. 12b).

Fig. 13 shows the effect of a size change of the heat accumulator on the technical performance of the SOFC-based micro-CHP unit.

Analysis of the results presented in Fig. 13 shows that the size of the heat accumulator has almost no bearing on the heat recovery results. The negligible effect of accumulator size on the system's technical performance is caused by the large heat requirements. This means that all of the heat generated by the SOFC is immediately used in the household. Moreover, a system without a heat accumulator is cheaper and hence has a shorter payback time. On

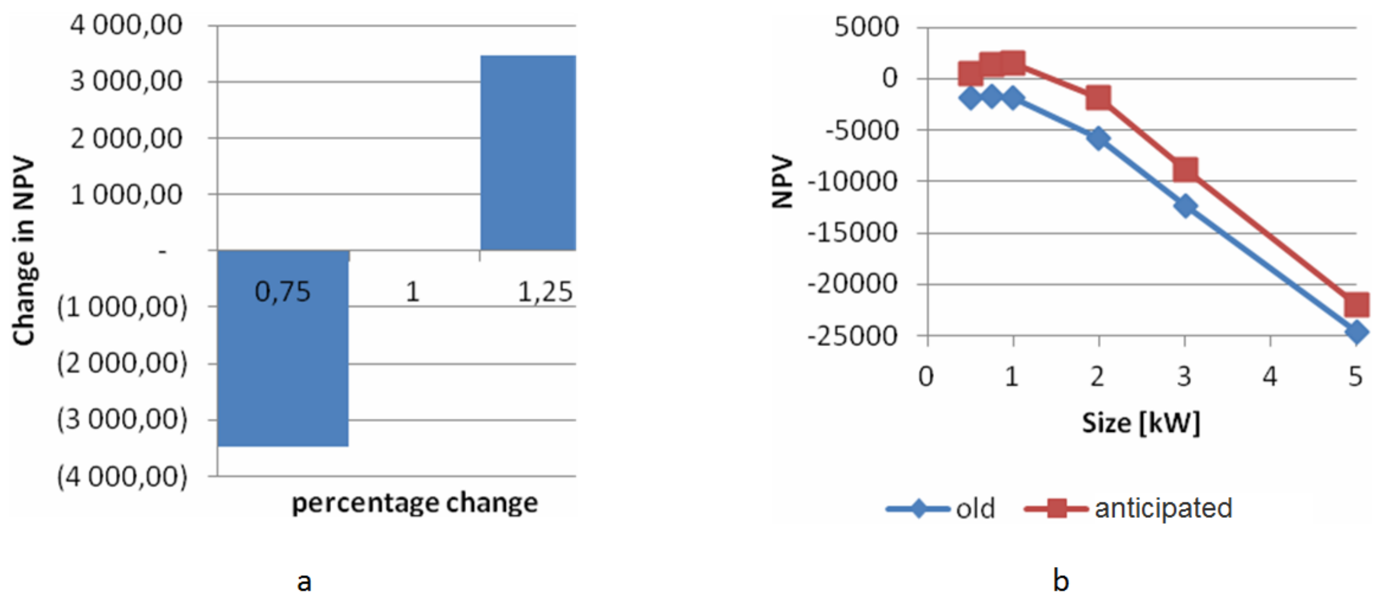


Figure 12: Results of a sensitivity analysis on the change of (a) electricity and heat cost and (b) just electricity cost

the other hand, the results of the 15-minute average work suggest greater use for a heat storage unit. The greater heat accumulator use in the 15-minute average simulation suggests that this device is actually necessary in a real-life scenario, where the requirement for heat and electricity is more unstable.

## 5. Conclusion

The model presents the expected results of SOFC-based micro-CHP system work in residential application in Poland. It was found that in the assumed conditions the system does not break even. It was also found that a positive commercial result is possible if the price of electricity goes up. The simulation based on 1-hour and 15-minute load averages shows that the real results of the system might differ slightly. The results of work are consistent with those found in the technical literature.

Analysis of the presented results shows that 1 kW units are the optimal size of micro-CHPs for Polish households.

## References

[1] K. Krist, K. Gleason, Sofc-based residential cogeneration systems, in: Electrochemical Society Proceedings, Vol. 99-19, Chicago, 1999.

[2] J. Slowe, Micro-chp: Coming to a home near you?, Platts Research & Consulting.

[3] A. Hawkes, P. Aguiar, B. Ceoxford, M. Leach, C. Adjiman, N. Brandon, Solid oxide fuel cell micro combined heat and power system operating strategy: Options for provision of residential space and water heating, Journal of Power Sources 164 (2007) 260–271.

[4] T. Wakui, R. Yokoyama, K. Shimizu, Suitable operational strategy for power interchange using multiple residential sofc cogeneration systems, Energy 35 (2010) 740–750.

[5] R. Braun, Optimal Design and Operation of Solid Oxide Fuel Cell Systems for Small-scale Stationary Applications, University of Wisconsin-Madison, 2002.

[6] R. Braun, S. Klein, D. Reindl, Evaluation of system configuration for solid oxide fuel cell-based micro-combined heat and power generators in residential applications, Journal of Power Sources 158 (2006) 1290–1305.

[7] J. Milewski, T. Świercz, K. Badyda, A. Miller, A. Dmowski, P. Biczel, The control strategy for a molten carbonate fuel cell hybrid system, International Journal of Hydrogen Energy 35 (7) (2010) 2997–3000.

[8] J. Milewski, A. Miller, A. Dmowski, P. Biczel, Methodology for the control strategy for a solid oxide fuel cell hybrid system, Archives of Thermodynamics 30 (4) (2009) 25–44.

[9] http://www.chemorganiczna.com/content/view/19/6/, Chemia organiczna (December 2010).

[10] S. Mańkowski, Projektowanie instalacji ciepłej wody użytkowej, Arkady, Warsaw, 1981.

[11] A. Hawkes, M. Leach, Cost-effective operating strategy for residential micro-combined heat and power, Energy 32 (2007) 711–723.

[12] B. Brown, Techno-Economic Optimal Design of Solid Oxide Fuel Cell Systems for Micro-Combined Heat and Power Applications in the U.S., Colorado School of Mines, 2010.

[13] W. Skowroński, Simulation of sofc-based micro-combined heat and power system in residential applications, Master's thesis, RES The School for Renewable Energy Science in affiliation with University of Iceland & University of Akureyri, Iceland (February 2011).
[14] Vattenfall poland, cennik produktu klasyczny e1 (23 May 2011).
[15] Vattenfall poland, cennik prodiktu klasyczny e2 (23 May 2011).
[16] Taryfa dla dystrybucji energii elektrycznej rwe stoen operator sp. z o.o.; valid form 1st january 2011 r. (23 May 2011).
[17] PGNiG, Taryfa w zakresie dostrarczania paliw gazowych nr 3/2010 (23 May 2011).
[18] PGNiG, Zmiana taryfy dla paliw gazowych pgnig s.a. (23 May 2011).
[19] Ministerstwo Gospodarki, Warsaw, Prognoza zapotrzebowania na paliwa i energię do roku 2030, 2009 (November).