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Hendrik Langnickel [a], Markus Rautanen [b,*], Marta Gandiglio [c], Massimo Santarelli [c], Tuomas Hakala [d], Marco Acri [e], Jari Kiviaho [b]

[a] *Danmarks Tekniske Universitet, Denmark*
[b] *VTT Technical Research Centre of Finland, Finland*
[c] *Politecnico di Torino, Italy*
[d] *Convion Ltd, Finland*
[e] *Societa Metropolitana Acque Torino S.p.a, Italy*

A B S T R A C T

Solid oxide fuel cell systems (SOFCs) are able to convert biogas from e.g. waste water plants highly efficiently into electricity and heat. An efficiency study of industrial sized solid oxide fuel cell systems installed at a waste water treatment plant is presented. The site consist of a biogas cleaning unit, two Convion C50 SOFC systems and a heat recovery section. The electric and total efficiencies of the systems are analyzed as a function of the electric net power output. The two systems achieved consistently high electric (50–55%) and total (80–90%) efficiencies in an electric net power output range between 25 kW and 55 kW. The study also shows that the high system efficiencies are independent of the CH_4 content in the biogas. The results indicate that fuel cell systems are able to perform power modulation according to the power demand, while achieving constant high efficiencies. This is a clear benefit in comparison to micro turbines and combustion engines which are normally used for converting biogas into electricity and heat.

1. Introduction

Efficient utilization of waste is an important step towards circular economy and reduction of greenhouse gas emissions. Biogas is generated in e.g. waste water treatment and municipal waste management plants. Anaerobic digestion of biomass results in biogas consisting of mainly CH_4 and CO_2. Biogas often also includes contaminants like sulfur compounds and siloxanes depending on feedstock [1]. In 2016 the total biogas energy production was 190 TWh in Europe. The electricity production from biogas in Europe was in 2016 approximately 63 TWh. Around 17% of the used biogas was produced from landfill and 9% from waste water. The other 74% was produced by different industrial plants like decentralized agricultural plants and methanation plants [2]. Anaerobic digestors are mostly connected to conventional gas-fired engines for heat and power generation [3]. One way to reduce the emissions and increase the efficiency of waste management systems is to utilize the produced biogas for electricity and heat production on-site, thus reducing the required external energy input of the plant. Conventional approach to convert

biogas into electricity and heat has been to utilize internal combustion engines or micro-turbines. This has the disadvantage of low electric efficiencies and air pollution with nitrogen oxides and small particles [4]. An alternative option is the use of fuel cell systems. A fuel cell is a chemical converter which converts hydrogen based fuels highly efficiently into electricity and heat. The use of fuel cells for converting biogas into electric energy has been discussed and demonstrated on different levels. Technical- or techno-economic studies have been presented in e.g. Ref. [5–7] and experimental research as well as early demonstrations in e.g. Ref. [8–16]. The advantages of fuel cells for emission reduction and increasing the efficiency of waste management systems has been investigated for example by Lombardi et al. [7] and Gandiglio et al. [17]. Successful operations and analysis at cell level for a solid oxide fuel cell (SOFC) fueled with real biogas from landfill was reported by Hagen et al. [18,19]. Successful 500 h operation of a SOFC short stack fueled with pre-mixed dry biogas and including the use of a cleaning unit and a pre-reformer was presented by Papurello et al. [8]. A review about dealing with fuel contaminants in the biogas for operation of biogas
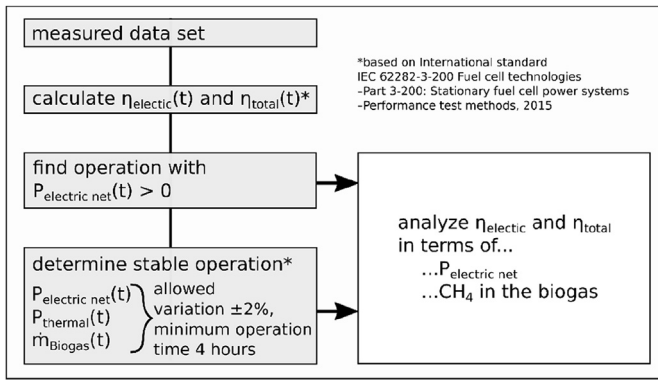
Fig. 1. Illustration of the data analysis procedure which is based on the International standard IEC 62282-3-200 Fuel cell technologies – Part 3–200: Stationary fuel cell power systems – Performance test methods, 2015 [24].

fueled SOFC's and molten carbonate fuel cells (MCFC) is provided by Lanzini et al. [9]. In comparison to other fuel cell types SOFCs have the advantage of fuel flexibility and can be operated directly with hydrocarbon fuels such as biogas [19]. Furthermore this type of fuel cell is more robust to impurities in the fuel because of the high operation temperature.

One of the first field tests of a commercial fuel cell system at a landfill gas site using a phosphoric acid fuel cell (PAFC) is reported by Spiegel et al. [10]. The first installation of a fuel cell system in Europe for converting biogas from a waste water plant into electricity and heat was demonstrated in Germany [11]. The system was based on a 200 kW PAFC system. The biogas was pre-cleaned by a two-phase purification phase and an adsorption step using an activated carbon filter. Furthermore, a reformer unit was used for converting the biogas into a H_2 rich gas. The first use of a MCFC system for converting biogas from a waste water plant in Europe is reported by Krumbeck et al. [12] The first 20 kW SOFC based system fueled with biogas from landfill was demonstrated by Wärtsilä in Finland [13,14].

The DEMOSOFC project is the first industrial sized SOFC site operated at a waste water plant [20]. The project aims to install and operate a biogas fed 174 kW electric SOFC site at the SMAT Collegno waste water plant close to Turin in Italy. The project should illustrate the technical and economical practicability of SOFC systems operated at a waste water plant. Furthermore, the increase of the overall waste water plant efficiency and reduction of the environmental plant emissions is demonstrated in the project. A detailed description and first results of the SOFC site at the Turin waste water plant have been reported by Gandiglio et al. [21] and M. Santarelli et al. [22].

The aim of this article is to analyze the performance of the biogas fed SOFC systems from October 2017 until the end of 2019. It is expected that the SOFC systems will be operated at least until the end of 2020 to gain further experience of the installation and operation.

2. Experimental

The data was recorded at the biogas fed SOFC site located at the SMAT Collegno waste water plant close to Turin in Italy. The site can be

Fig. 2. Electric and total efficiencies of the first Convion C50 SOFC system as function of the electrical net power output and corresponding normalized distributions. a) Electric (red squares) and total (black crosses) efficiency mean values for electrical net power output segments during stable operation. Segments are represented by the vertical dashed lines. Black dashed and dotted lines represent second order polynomial fits of the electric and total efficiencies for electric net power output values greater zero. b) Normalized distribution of the electric net power output. c) Normalized distribution of the electric and total efficiencies. Combined standard uncertainties were around 3% for the electric and around 6% for the total efficiency. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
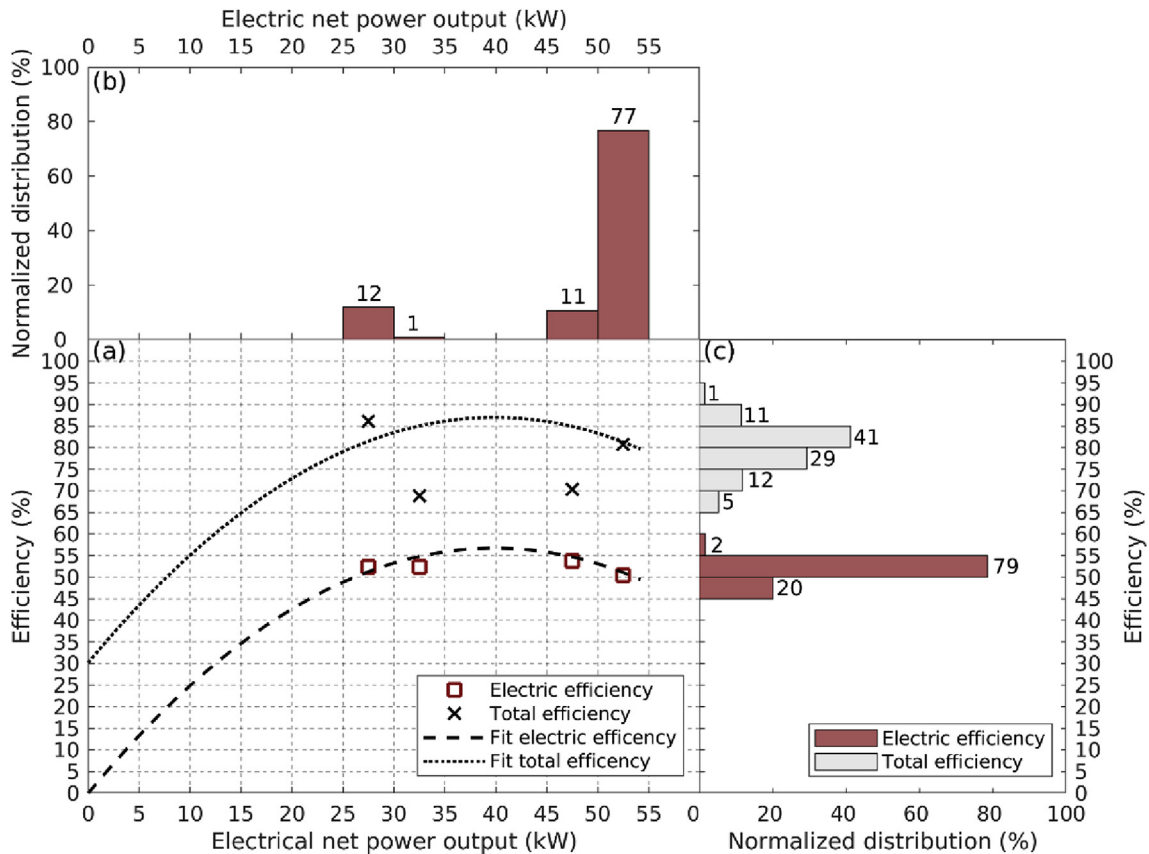
Fig. 3. Electric and total efficiencies of the second Convion C50 SOFC system as function of the electrical net power output and corresponding normalized distributions. a) Electric (red squares) and total (black crosses) efficiency mean values for electrical net power output segments during stable operation. Segments are represented by the vertical dashed lines. Black dashed and dotted lines represent second order polynomial fits of the electric and total efficiencies for electric net power output values greater zero. b) Normalized distribution of the electric net power output. c) Normalized distribution of the electric and total efficiencies. Combined standard uncertainties were around 3% for the electric and around 6% for the total efficiency. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
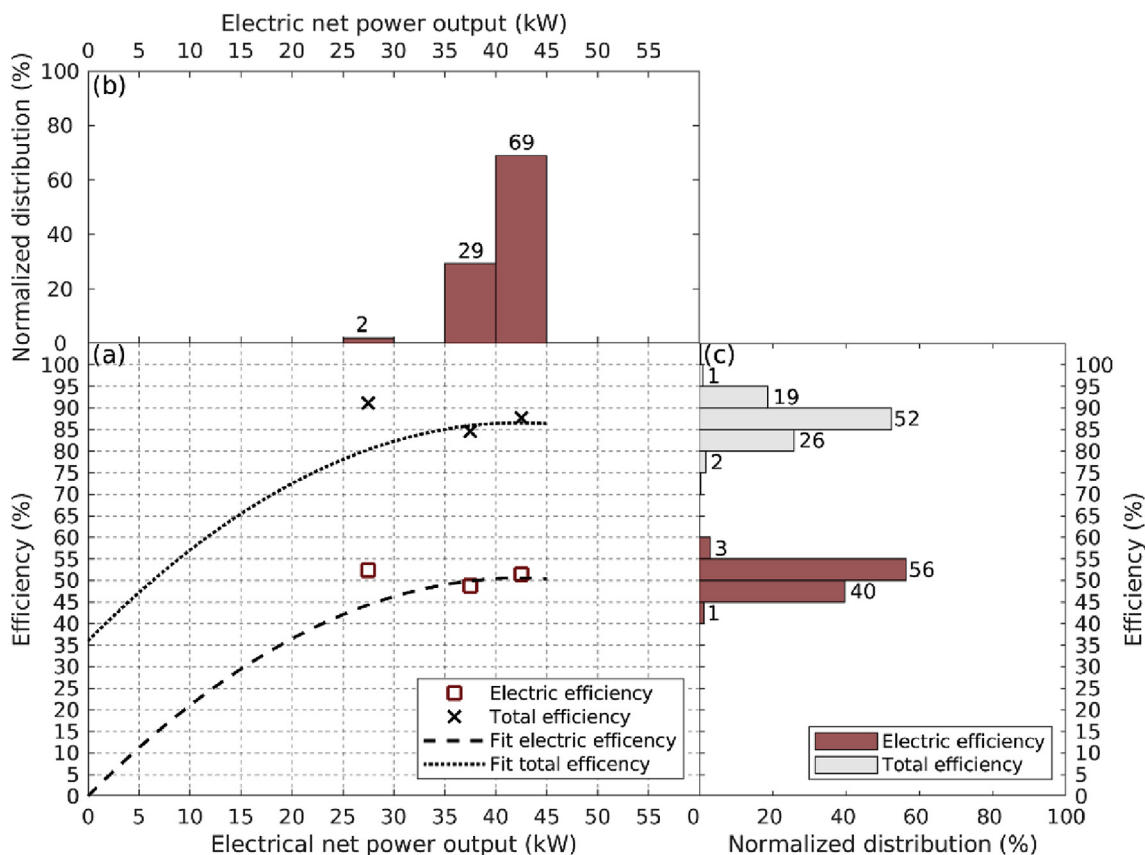
divided into three sections: biogas cleaning and compression, SOFC framework and heat recovery. Commercial impregnated activated carbon filters are used for the biogas cleaning. The SOFC section consists of two C50 SOFC power systems and one C60 SOFC power system from the company Convion [23]. The systems have an electric net power output of 40–60 kW each. A heat recovery unit is included in the systems. At the end of 2019, the two C50 systems have been installed, while the C60 system is planned to be installed in 2020. Except of the implemented SOFC stack technology the two C50 systems are identical. In the heat recovery section the heat provided by the SOFC systems is transferred to the waste water plant. The operation of the biogas fed SOFC site is monitored by different sensors. The sensors are located at various positions on the site.

Data for the analysis is coming both from the plant site sensors, installed by the end user, and SOFC system specific sensors, installed within the system control volume. Some measurements are done both by the end user and the SOFC producer, for example the power production, the heat recovery rate, the biogas flow rate consumed. All the values are logged at a 10-min interval by the PLC and stored in the onsite operator panel. The data is exported from the operator panel by POLITO and/or SMAT personnel and is shared through a dedicated cloud with VTT personnel responsible for the analysis. More detailed descriptions concerning the set-up of the SOFC site are given in Ref. [21,22].

The data has been recorded from beginning of October 2017 until the end of 2019. For the analysis the data were interpolated to 1 h time steps. Results like the electric and total efficiencies of the C50 systems were calculated according to the international standard IEC 62282-3-200 for stationary fuel cell power systems. In addition stable operation

conditions for the C50 systems were defined based on the guideline as well [24]. An overview about the data analysis is given in Fig. 1.

3. Results and discussion

The first system and the second system have been operating in total for 9113 h providing electricity and heat to the plant. In Fig. 2 the data analysis results of the first system are shown. In Fig. 2a) the total electric efficiency and the total efficiency as a function of the electric net power output from 0 to 55 kW are illustrated. The red squares in Fig. 2a) represent the mean values of the electric efficiencies of the corresponding electric net power output segment during stable operation. The SOFC system was operated stable in an electric net power output range between 25 kW and 55 kW. In this range the electric efficiency stayed stable between 50% and 55%. The black crosses show the total efficiency mean values which were between 67% and 87% during stable operation. The larger deviation of the total efficiency in comparison to the electric efficiency was caused by heat recovery flow rates not being optimized in the beginning of the operation. The stable and high electric efficiencies over the operating net power output range (25–55 kW) illustrate an advantage of fuel cell technology in comparison to micro turbines and internal combustion engines. The results show that power modulation according to the site demand is possible with high efficiencies using SOFC systems.

In Fig. 2b) the normalized distribution of the electric net power output is shown. Two main electric net power output operation regions can be identified. The first one between 45 and 55 kW with 88% of the stable operation time which corresponds to 442 h. And the second one
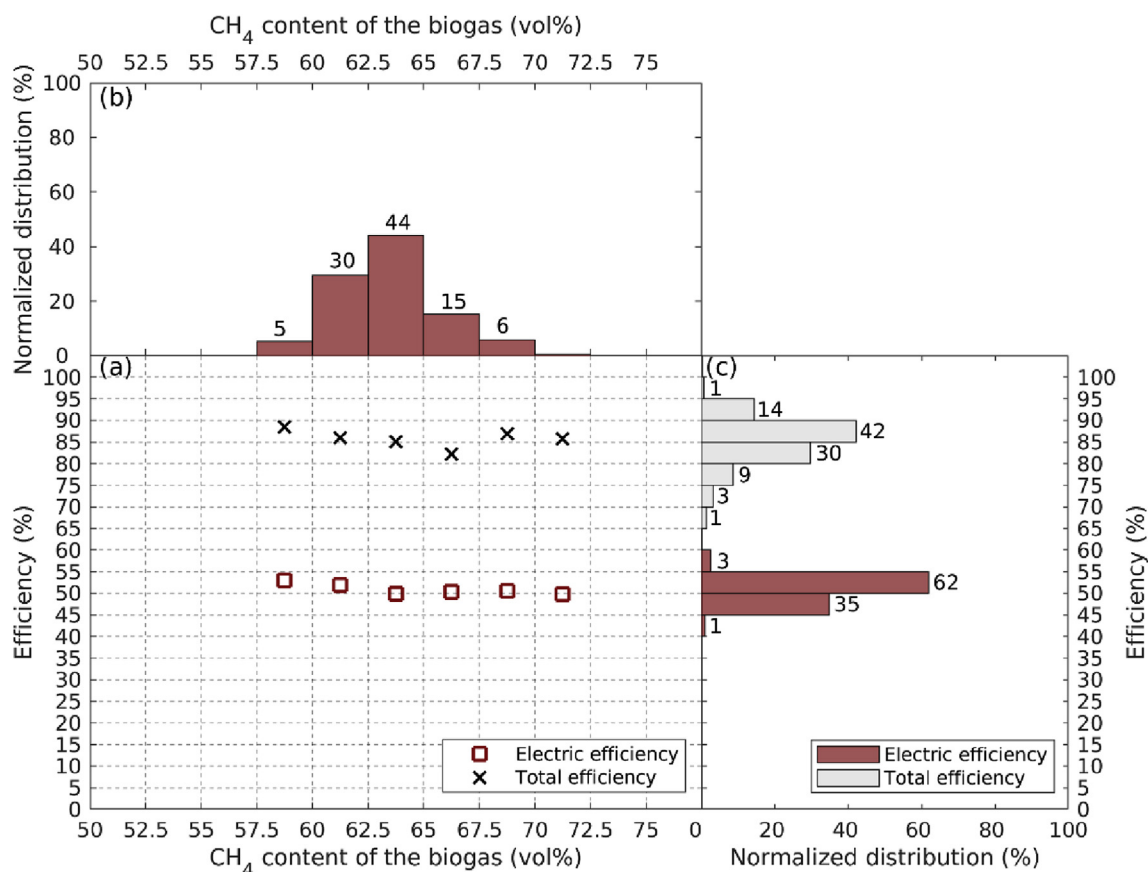
Fig. 4. Electric and total efficiencies of both Convion C50 systems as function of the CH_4 content of the biogas and corresponding normalized distributions. a) Electric (red squares) and total (black crosses) efficiency mean values for CH_4 content of the biogas segments during stable operation. Segments are represented by the vertical dashed lines. b) Normalized distribution of the CH_4 content of the biogas. c) Normalized distribution of the electric and total efficiencies. Combined standard uncertainties were around 3% for the electric and around 6% for the total efficiency. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

between 25 and 30 kW at which system one was operating for around 12% of the stable operation time. The rest of the time the system was operating in the range 45–50 kW and 30–35 kW.

During stable operation the electric efficiency was between 45% and 60%. (see Fig. 2c)). For the majority of the time (79%) the electric efficiency was between 50% and 55%. Around 2% of the time the electric efficiency was even higher with values between 55% and 60%. The total efficiency variation was with values from 65% up to 95% broader than the variation of the electric efficiency. Three main areas can be identified in terms of the total efficiency of the first system. Firstly, the total efficiency was between 75% and 85% for 70% of the stable operation time. Secondly, 17% of the stable operation time the total efficiency was between 65% and 75%. Finally for 12% of the stable operation time the first system reached a total efficiency between 85% and 95%.

In Fig. 3 the data analysis of the second system is illustrated. Similar to the first system, the electric efficiency stayed stable with values in the range of 48%–53% (red squares Fig. 3a)). The total efficiency stayed steady between 82% and 92% (black crosses, Fig. 3a)). The maximum achieved electrical net power output during stable operation was 45 kW. The lower electric net power output was caused by the fact that the systems were not identical in terms of the stack implementation. The stacks were from different manufacturers and the number of stacks implemented in the hot box were different. The similar achieved efficiencies of the systems are an indication for similar stack performances. The lower net power output of the second system was due to a lower number of stacks implemented in the hot box in comparison to the first system. The dashed and dotted black lines which represent the electric efficiency and total efficiency as a function of the electrical net power

output have a similar shape as the corresponding lines of the first system (compare Fig. 2a)).

The normalized distribution of the electric net power output shown in Fig. 3b) illustrates that the second system was operated for around 69% (~1040 h) of the stable operation time between 40 kW and 45 kW. The rest of the time the unit was operated in the ranges 35–40 kW and 25–30 kW. This shows that the second system was operating more at one specific electric net power output than the first system which was operating in a larger range. Around 59% of the stable operation time the electric efficiency of the second system was between 50% and 60% (see Fig. 3c)). This is similar with the observed electric efficiency distribution of system one. The rest of the operation time the electric efficiency was mainly between 45% and 50%. A similar behavior can be observed for the total efficiency of system one: for 52% of the stable operation time the total efficiency was between 85% and 90%. The rest of the time the total efficiency was mainly between 80-85% and 90–95%. Therefore it can be stated that the second system was operating steadier at a higher total efficiency as the first system.

In general the second system was operating more stable at one specific operation point than the first system. In terms of the electric efficiency similar values could be achieved. Concerning the total efficiencies the values of the second system were around 5–10% higher compared to the first system. This shows that the system maturity in terms of operation monitoring and controlling was improved from the first system to the second system. Additionally the site operation was improved with less interruptions caused by the auxiliary equipment and more optimized heat recovery loop control, which resulted in a more stable total efficiency of the second system in comparison to the first system. These are

good indications for future installations.

System efficiency at steady-state as a function of CH$_4$ content of the fuel gas was analyzed for both systems (Fig. 4). During the total operating time at positive net power output (4501 h including both systems), the CH$_4$ content in the biogas was varying from 58% up to 71%. The mean values of the electric efficiency (red squares in Fig. 4a)) and total efficiency (black crosses in Fig. 4a)) stayed constant with values around 50–52% and 82%–88% respectively. This indicates that high electric and total efficiencies can be achieved by the SOFC systems with varying CH$_4$ content in biogas. This is supported by the normalized distribution plots of the system efficiencies shown in Fig. 4c). The electric efficiency was for 97% of the stable operation time between 45% and 55%. Furthermore the total efficiency was for 72% of the stable operation time between 80% and 90%. Additionally the normalized CH$_4$ content distribution in Fig. 4b) shows that the CH$_4$ content was mainly between 60% and 65% in the biogas during the stable operation time.

The abovementioned efficiencies, measured in real operation with real biogas on-site, can be considered very promising for the SOFC technology as conventional combustion engines operating with biogas typically only reach electrical efficiencies of 34 … 40%. [25].

4. Conclusion

Electric and total efficiency data of two industrial sized Convion C50 SOFC systems installed at the same waste water plant were presented. During stable operation the SOFC systems were operating in an electric net power output range between 25 kW and 55 kW. The two SOFC systems fed with biogas were constantly achieving high electric efficiencies in the range of 50%–55% and total system efficiencies in the range of 80%–90%. Moreover it was shown that the high electric and high total efficiencies were independent of the CH$_4$ content in the biogas.

This study points out that high electric and total efficiencies can be achieved with biogas fed SOFC systems. The high efficiencies are stable at varying electric net power output and changing CH$_4$ content of the biogas. This is a clear advantage of the SOFC technology in comparison to micro turbines and combustion engines. The results underline the fact that fuel cell systems are able to perform power modulation according to the power demand, while achieving constant high efficiencies. In addition the improvement of the site and system maturity which was achieved during this investigation are promising indications for further installations.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Author number five (Tuomas Hakala) is working at Convion (fuel cell system provider) and also owns a small share in the company with other Convion employees. As the results presented in the manuscript are referring to fuel cell systems manufactured by Convion, someone could argue that this could affect the "neutrality" of the manuscript so the authors wanted to make it clear in this statement. However, Tuomas Hakala or any other employee from Convion has not participated in the analysis of the data or influenced in any way how the results have been calculated. In fact, the calculation of results follows the relevant standard procedure (IEC 62282-3-200) as far as applicable. Convion responsibility has been the day-to-day operation and maintenance of the fuel cell systems and the research partners are carrying out the analysis of the results.

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