International High Performance Buildings Conference

School of Mechanical Engineering

2022

Field-test performance of Solid Oxide Fuel Cells (SOFC) for residential cogeneration applications

Nicolas Paulus

Paulus, Nicolas, "Field-test performance of Solid Oxide Fuel Cells (SOFC) for residential cogeneration applications" (2022). *International High Performance Buildings Conference.* Paper 405.
https://docs.lib.purdue.edu/ihpbc/405

Field-test performance of Solid Oxide Fuel Cells (SOFC) for residential cogeneration applications

Nicolas PAULUS[1]*, Vincent LEMORT[1]

[1]University of Liège, Thermodynamics Laboratory,
Liège, Belgium
nicolas.paulus@uliege.be,

* Corresponding Author : nicolas.paulus@uliege.be

ABSTRACT

Much needed energy transition brings special focus on fuel cell micro-combined Heat and Power (mCHP) systems for residential uses, one of which is a SOFC, fed by natural gas, designed to provide continuously 1.5 kW_{el} (up to about 13 000 kWh yearly). However, this constant power output can be modulated as desired down to 500 W_{el}. With this machine, heat can also be recovered to partially contribute to the heat demand of the household. One main advantage of this appliance is that the heat recovery system is designed to be purely optional and it can be shut down, removed or added as desired, even if the machine is running. The machine is driven and completely monitored by the manufacturer remotely. This study is monitoring two of those installations in residential houses in Belgium for the whole year 2021. It focuses on the comparison of the actual field test performance with the targets expected for this technology, electrical efficiency of 60% at nominal power output being the main selling argument that has been verified in the real onsite applications studied in this work.

Since the financial incentive represents a major factor in the investor's decision towards such a technological investment, focus is brought on an economic indicator based on an average Belgian household energy bill, with promising results of about 1,3-1,4 k€ of utilization cost savings per year. At last, ecological indicators are established in an attempt to foresee the place this mCHP technology in the energy transition challenge of today towards the carbon neutral future everyone should aim for. The ecological balances can either be considered as positive, if the system is supposed to replace Combined-Cycle Gas Turbine (CCGT) power plant electrical production, or negative, compared to the actual Belgian electrical mix.

1. INTRODUCTION

Although its high operating temperature could be seen as a drawback (Ellamla, et al., 2015), SOFC technology has nevertheless a lot of advantages in comparison to other fuel cells, as summarized in the following lines :

- Higher electrical efficiency (Ellamla, et al., 2015).
- Fuel flexibility (Hauch, et al., 2014) because practically all hydrocarbons can be used with SOFC thanks to internal reforming allowed by the tremendously high temperatures.
- Low sensitivity to impurities. Carbon deposition is indeed less an issue in this system thanks to internal high reforming temperature whereas it is one of the main contaminants of Proton-exchange membrane fuel cells (Paulus & Lemort, 2022a). However, sulphur compounds are still absolute poison for SOFC's and fuel desulphurization is often required when the system is not fed with pure hydrogen (Fernandes, et al., 2018).
- No necessary use of platinum, rhodium and other precious metals as catalysts (Peng, et al., 2021).

The studied system is a commercialized SOFC for residential applications. Its expected specifications are presented in Table 1. It is not supposed to be turned OFF and ON and it is supposed be ran at a constant power output that can be chosen between 0.5 and 1.5 kW_{el} (nominal output power). The machine is remotely controlled by the manufacturer over an Ethernet port and, to adapt its system power output, the owner must send an email or give a phone call.

Internal schematics and working principle are unknown for intellectual property protection. However, base principle is quite common. Such as any fuel cell, this system provides electricity through redox reactions between a hydrocarbon fuel (here, natural gas) and an oxidizing agent (here, as often, oxygen). Since those redox reactions have combustion-like resulting equations (Shao, et al., 2005), there are thus exothermic by nature (Schmidt-Rohr, 2015) and release heat in addition of the produced electricity. Cogeneration is thus possible.

Specific literature review on mCHP SOFC's combined with little reverse engineering performed by observing the system with its protective cover unmounted has nevertheless allowed for assuming the most probable internal scheme of the system, which is presented in Figure 1. This scheme's lay-out is strongly inspired from literature (Braun, et al., 2006) cross-check against a specific study conducted along with this particular SOFC's manufacturer (Wagner, 2019). Adjustments to the literature scheme have been performed for relevance with the physical observations of the system without its covers (indeed, for example, the system involves two water outlets periodically actioned).

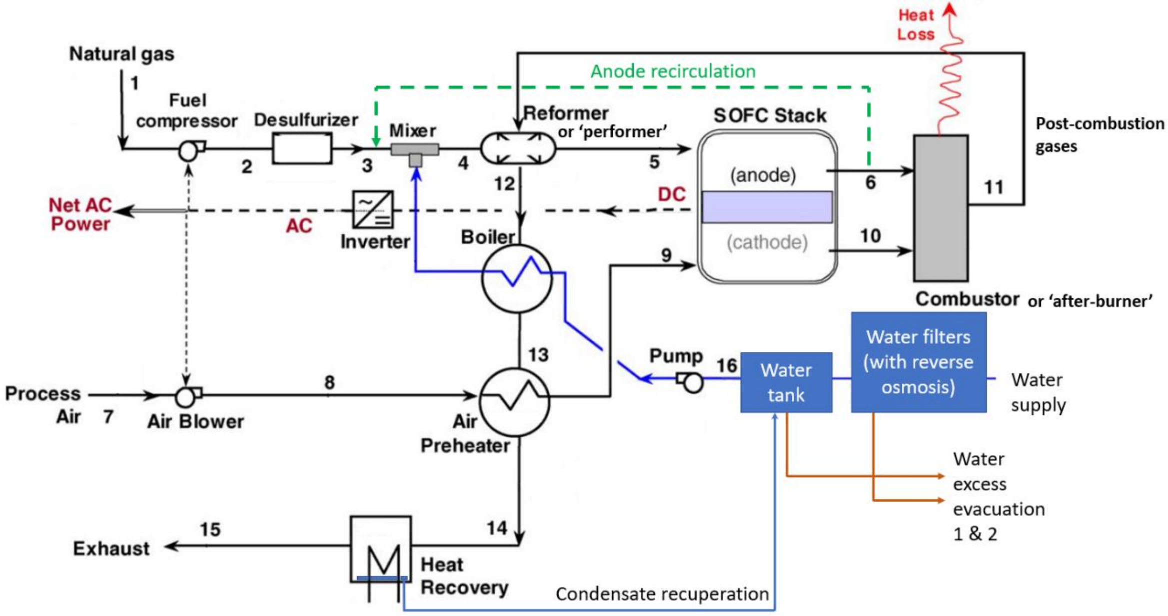

Figure 1: Most probable internal scheme. Lay-out strongly inspired from literature (Braun, et al., 2006)

Important elements are presented in the assumed configuration of Figure 1:

- Natural gas fuel supply is desulfurized as it is an absolute poison for SOFC's (Fernandes, et al., 2018).
- Natural gas is mixed with water vapor in order for steam reforming to take place (a reformer is implemented before the stack, also called "preformer" for this reason). Therefore, the reforming process in not only internal (directly onto the stack).
- Some of the fuel (mainly methane) is not directly consumed by the stack. It is rather consumed in an "after-burner" in order to generate the heat required for steam generation (for the reformer).
- The post-combustion gases are then used to provide heat to the preformer, to the boiler (as explained) and at last, before the exhaust, to the external heat recovery auxiliary circuit (offering the CHP capability of the system).
- Figure 1 does not show that the exhaust gases are providing their remaining heat to the inlet air thanks to a "double walled chimney" (Lichtenegger, et al., 2015), in addition to the probable "air preheater".
- Anode recirculation is most likely implemented to increase fuel utilization (Chen, et al., 2021). Indeed, the gases at the outlet of the anode still contain H_2, CO and CH_4 that can still react and provide power, but they also contain H_2O usable for the required steam reforming upstream of the stack. Maybe cathode recirculation has also been implemented but this is not the strongest assumption one could make because it complexifies

the system. It is unknown to the authors if cathode recirculation already exists in commercialized units whereas it is known that this SOFC involves anode recirculation (Wagner, 2019).

- The system requires a connection to water mains for steam reforming purposes. The system periodically draws water from the main, processes it and stores it in a tank. However, if heat recovery is implemented (which is actually optional with this system, that can function as an electrical generator only), water can be recuperated from the condensation of the flue gases. This reduces the grid water consumption. Potential excess of water in the tank can be evacuated through one specific water outlet.
- Water impurities are processed through several filters involving reverse osmosis (Fritzmann, et al., 2007). It is believed that, at a certain point, the water impurities concentration in the periodical inlet water volume becomes too high compared to the pressure used for the reverse osmosis. Thus, the remaining inlet water (with high levels of impurities) has to be thrown away for another periodical grid fresh water inlet to take place (and to be submitted to the reverse osmosis filter).

Table 1: Studied SOFC expected targets (data provided by manufacturer)

Type	**Technical specifications**
Operation mode	Power-led, continuous (approx. 8,700 h per year)
Fuel type	Natural gas, bio-methane
Fuel consumption[1]	2.51 kW
Electrical efficiency[1,2] (output)	Up to 60 % (1.5 kW)
Thermal efficiency[1,2] (output)	Up to 25 % (0.6 kW)
Electrical and thermal energy generated per year	~ 13,000 kWh_{el} | ~ 5,220 kWh_{th}
Weight, Dimensions (H x W x D)	195 kg, 1010 x 600 x 660 mm
Service interval[3]	12 months

[1] - Low Heating Value (LHV) based figures
[2] - At maximum electrical efficiency, nominal output of 1.5 kW
[3] - Replacement of filters depending on local water, air and gas quality

As explained, two systems have been monitored in Belgian households for the whole year 2021 (one in Riemst, East of Belgium and the other one in Duffel, North of Belgium). The monitoring architecture is presented in Figure 2. Contrary to other commercialized fuel cells in Belgium (Davila, et al., 2022), there is no internal DHW tank in the system so the standby losses, which can be significant with such systems (Paulus & Lemort, 2022b), do not affect the thermal output measure. Sensor reference, precision and resolution of the acquired data are presented in Table 2.

Table 2: Reference of the monitoring sensors. The data logger (cloud connection) is a Viltrus MX-9

Sensors	**Reference**	**Resolution**	**Accuracy**
Indoor & Outdoor temperature and humidity	Weptech Munia	0,1 K 0,1 %	± 0,3 K ± 2 %
Heat recovery counter	Qalcosonic E1 Qn2,5 qi=0.025 m³/h L=130mm	1 kWh 1 L | 0,1 K	Accuracy Class 2 (OIML R 75-, 2002)
Machine 2-ways electrical energy counter	Iskraemeco MT174-D2A42-V12G22-M3K0	10 Wh	Accuracy Class 1 (IEC 62053-21, 2003)
House 2-ways electrical energy counter	Iskraemeco MT174-D2A42-V12G22-M3K0	10 Wh	Accuracy Class 1 (IEC 62053-21, 2003)
Gas volume counter	BK-G4T DN25 Qmax 6 m³/h	10 L	<0.5%

Last very important parameter not shown in Table 2 is the sampling rate, the frequency of the acquisition, of the measurements. It could not be smaller than 5 minutes to prevent the battery inside the sensors to empty. Except for temperatures and humidity, all of those meters are computing energy index values (always increasing). The heat counter is preferably placed on the return line (Paulus, et al., 2022a).

It is worth mentioning that the equivalent energy of the consumed gas is established thanks to hourly heating values given by the gas provider. The method used for this energy computation has been described in a parallel study (Paulus & Lemort, 2022c).

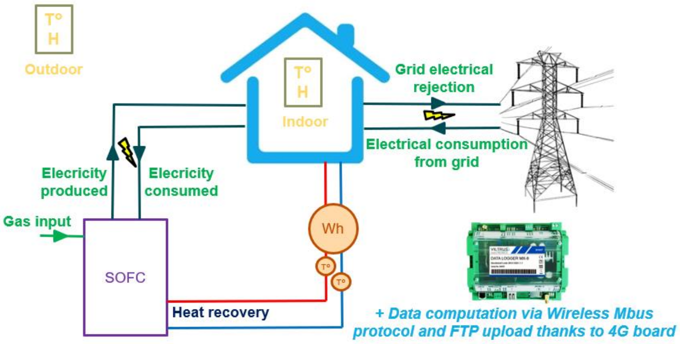

Figure 2: Monitoring architecture of both field-test households

2. METHODOLOGY

2.1 Energetical performance

Electrical efficiencies have been computed without considering the monitored electrical consumption of the system. Only the equivalent energy of the consumed gas has been considered at the denominator of the efficiency calculations. It is worth mentioning that a consumption signal at the system's output can only be seen if the machine is not producing electricity. Indeed, the system provides electricity to its own auxiliaries in running mode and only the net electrical production is measured. Since the system is supposed to be ran constantly, its remaining measured electrical consumption is not relevant in the efficiency calculations.

2.2 Economical and ecological performance

The chosen methodology for establishing performance indicators is similar to what the European Parliament recommends for calculation of primary energy savings of CHP (European Parliament, 2012). Their directive recommends to study the performance of a cogeneration by comparison to state-of-the-art separate heat and electrical energy productions. Based on this European directive, the Walloon energy regulator (in Belgium) has stated that the reference state-of-the-art system for heat production is a gas condensing boiler of constant 90% LHV efficiency (CWaPE, 2005).

Reference electrical state-of-the-art production system will consider the actual electrical Belgian mix in most cases or, as considered by the Walloon energy regulator (CWaPE, 2005), following European directives (European Parliament, 2012), a CCGT plant of constant 55% LHV efficiency (CWaPE, 2005). This assumption is only considered once, for one single ecological indicator. The CCGT plants considered in this work as reference electrical production systems are never assumed to be used as CHP, as it is still not that common.

Each indicator of this paper has been established by considering the actual pricing or ecological performance in the field-test (computed with given assumptions) subtracted to the assumed performance that would be achieved by reference machines based on the same field-test heat demands (and local electrical production). Positive indicators imply better performance than reference machines.

Economical indicator subsequently consists in utilization cost savings (€ saved/year) compared to the reference machine, which is, as stated, a classical gas condensing boiler. In this work, one has neither taken into account the investment costs of the machine nor the one of its installation (or its removal). The pricing assumptions for this economical indicator have been provided by the Belgian energy regulator, named CREG (*Commission de Régulation de l'Électricité et du Gaz*), that oversees the whole energy market and parties. The federal regulator is providing those energy pricing based on the average Belgian household energy bills (Paulus, et al., 2022b). For 2021, only the second semester average prices have been considered and applied to the whole monitoring data of the year, in order to partially consider the impact of the energy crisis (Statistisches Bundesamt - Destatis, 2021) on the economical performance of the machine. The energy prices, considered constant for the whole year, are thus 0.333€/kWh$_{el}$ for electrical energy and 0.093€/kWh$_{HHV}$ for natural gas (CREG, 2021). It must be pointed out that European natural gas prices even rose by almost 70% after Russia invaded Ukraine in February 2022 (Emerald Expert Briefings, 2022) but that is not yet considered in this work.

Other important pricing assumption is that the electrical energy transport and distribution costs are rounded to 0.15€/kWh$_{el}$ (0.1€/kWh$_{el}$ for distributions and 0.05€/kWh$_{el}$ for transport) as considered by the Walloon regulator (named CWaPE) in its tariffication plans (CWaPE, 2020). This means that rejected energy on the grid will not be bought back to the residential customer at the same kWh price mentioned earlier. This is because the customer uses the grid to sell its extra energy and it must pay for it. The selling price of the rejected electrical energy is thus equal to the electrical price mentioned earlier minus the 0.15€/kWh$_{el}$ to account for transport and distribution costs.

As stated, the environmental indicators are based on the same method of comparison with reference systems. The pricing assumptions are simply replaced by emission factors set through Life Cycle Assessment studies (Paulus, et al., 2022b). Two sets of assumptions are considered in this work. The first one is used by the Walloon energy regulator (CWaPE, 2005) to promote CHP. It overestimates on purpose the reference electrical emission factor by considering that the local electrical production allowed by the system replaces CCGT power plants (of 55% LHV efficiency) whereas actual Belgian mix is far more decarbonated, as it involves renewables and significant part of nuclear energy considered as "low carbon" (Sovacool, 2008). Indeed, Belgian CHP investors can beneficiate from public grants depending on those CO_2 savings. The second ecological indicator considers the hourly emission factor for the Belgian consumption electrical mix (data provided for the whole year 2021 by www.Electricitymap.org for academic purposes). Therefore, the first indicator implies an electrical emission factor of 456 gCO_{2eq}/kWh_{el} whereas the second evolves hourly. For information, the statistical electrical emission factor for the whole 8760 hours of 2021 is 167 gCO_{2eq}/kWh_{el} (Paulus, et al., 2022b), well below the assumption of the first indicator.

Regarding the emission factor for natural gas consumption/combustion, it is quite close between the two sets of assumptions : 251 gCO_{2eq}/kWh for the first indicator as used again by the Walloon regulator (CWaPE, 2005) and, for the second one, relevant with the www.Electricitymap.org data, 254 gCO_{2eq}/kWh, (Paulus, et al., 2022b).

Further explanations on the method used to establish economical and ecological indicators have been presented in a parallel study for a different system (Paulus, et al., 2022b). That study also involves further explanations on emission factors. It is worth mentioning that the ecological indicator used in this work accounts for all greenhouse gases (expressed in CO_{2eq} and not in CO_2 only). Also, even if the first dataset has been established in 2005, it is still valid and used as there has neither been any game changer regarding the efficiency of the reference systems for energy production (nor regarding natural gas production and importation). Actually, the only emission factor that is likely to become obsolete in the few years to come is the electrical one considered in the second set of assumption (from the www.Electricitymap.org data). This is because electrical mix evolves constantly, especially with increased penetration of renewables.

At last, to the understanding of the authors, grid transportation and distribution electrical losses, which can reach about 6-7% in EU (Psomopoulos, et al., 2010), have not been considered in any of the electrical emission factors. However, this is assumed to be compensated by the fact that it could also be considered that the extra gas consumption for the decentralized SOFC electrical production is subjected to fugitive methane emissions, which implies a high 100-year GWP of about 28 (Paulus, 2022), on longer gas network distances. For information, fugitive losses can be estimated to $5.4\times10{-}6$kg for the transport of 1kg of natural gas for a distance of 1km (NETL, 2010).

3. RESULTS

Performance results are presented in Table 3. Overall, performance of both field-test machines are quite similar.

The first observation is that the Duffel system is really close to the expected electrical efficiency whereas the Riemst system is a little below. The main reason is that the Riemst system's power output has been modulated down for some significant amounts of time through the year (for the vacation of the occupants) whereas the system in Duffel was running at nominal power the whole year. This can be perceived by the lower yearly electrical production (Table 3). Indeed, partial electrical load induces a reduction in electrical efficiency, as it can be seen in Figure 3. Second possible explanation is the probable intrinsic statistical efficiency difference between produced units. Indeed, the difference between percentile 0.9 and percentile 0.1 can account for a 2.5 percentage points efficiency difference for this system at nominal output power (Föger, 2011).

Second observation is that thermal efficiency (and heat recovered) is higher for Riemst. This is mainly again because of the fact that the SOFC electrical output power in Riemst was modulated down to the minimal value (500 W_{el})

during the vacation time of the owner. Indeed, the lower the electrical output, the higher the thermal recuperation, as it can be seen in Figure 3. In both cases, by looking only at the absolute yearly amount of heat recovered (and not the daily profiles nor the working temperature), the heat recovered with this system is greater than the amount required by the "M" DHW profile from European Standard EN 16147:2011 (Fuentes, et al., 2018). It is also greater than the average household's DHW consumption for a lot countries, such as the USA, the UK, Finland or Spain (Fuentes, et al., 2018). The fact that this system might be able to provide all the DHW demand of the household might allow significant capital savings as it simplifies the DHW production system. For example, there would be no need for a dedicated heat pump water heater or extra investments for the gas condensing boiler or the heat pump to be able to provide DHW in addition to its space heating function. It seems however preferable to at least include a backup heating resistance in the upper part of the DHW tank in order to ensure minimum DHW delivery temperature. Especially if the household DHW demand occasionally peaks, the system's DHW capability might not suffice.

Table 3: 2021 monitoring performance of the field-tested SOFC's. Utilization savings indicators consider a gas condensing boiler of 90% constant LHV efficiency as reference for heat production

Monitoring performance	Riemst	Duffel	Monitoring performance	Riemst	Duffel
HHV energy consumed (kWh)	25031	24273	LHV Electrical efficiency (%)	52,4	59,0
Electrical production (kWh)	11843	12922	LHV Thermal efficiency (%)	15,8	11,6
Electrical consumption (kWh)	11	2	LHV Total efficiency (%)	68,2	70,6
Heat recovered (kWh)	3569	2549	Utilization CO_{2eq} savings – 1st dataset ($kgCO_{2eq}$)[2]	723	1107
Utilization cost savings (€)[1]	1429	1308	Utilization CO_{2eq} savings – 2nd dataset ($kgCO_{2eq}$)[3]	-3013	-2969

[1] - Electrical price: 0.333€/kWh$_{el}$. Gas price 0.093€/kWh$_{HHV}$.

[2] - 1st dataset emission factors : 251 gCO_{2eq}/kWh for gas and 456 gCO_{2eq}/kWh$_{el}$ for electricity.

[3] - 2nd dataset emission factors : 254 gCO_{2eq}/kWh for gas and hourly data from Belgian electrical consumption mix from www.Electricitymap.org for electricity.

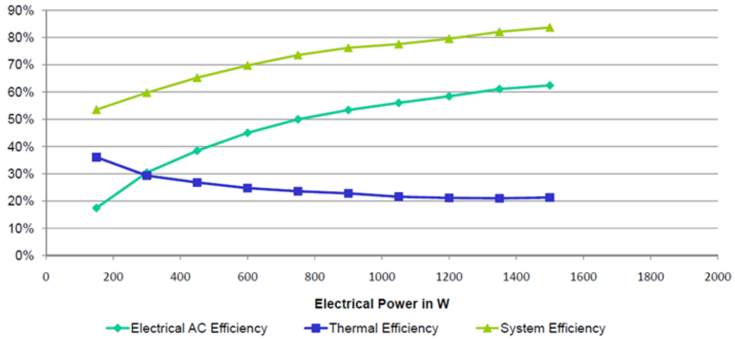

Figure 3: LHV efficiencies of the BlueGen (for 30°C return temperature) reproduced from literature (Föger, 2011)

It is worth mentioning that utilization cost savings depend greatly on the ability of the household to consume the electricity the system is producing while it is producing (as it is financially not that interesting to reject electricity on the grid with such fixed electrical tariffication assumptions). Therefore, cost savings of Table 3 are strongly case-dependent: both households involve an electric car that truly helps increasing the "self-consumption" of the electricity produced, also called "supply cover factor" (Paulus, et al., 2022a), to about 60%. This improves the economical indicator. In addition to local spark spread (Näsäkkälä & Fleten, 2005) and household supply cover factor, utilization cost savings should be looked at considering the capital costs of the system, as they will define the Return On Investment (ROI). For instance, with those results, if an investor wanted to ensure reaching ROI before 10 years, the maximum capital costs of the system should not reach more than about 13-14 k€ (this is considering that the owner already has a gas condensing boiler as main space heating appliance and this is not considering the additional capital savings of the already stated simplified DHW production). This example is also valid for households that do not need space heating at all (passive houses). If one particular household needed to invest in a space heating appliance such as a gas condensing boiler and was also considering this SOFC, that example shall not directly be considered as valid. Indeed, that household's choice would therefore lie between a single gas condensing boiler (also able to provide DHW) against the combination of the SOFC system and a gas condensing boiler (or another space heating appliance). For the 10-years ROI to be reached, the addition of both appliances shall not exceed the stated 13-14 k€, which is more restrictive than the previous cases. Potential maintenance costs have not been considered in those economical analyses. Although this SOFC's capital costs are unknown to the authors, it is interesting to point out that back in 2015, residential SOFC technology cost (with auxiliaries) was estimated to about 10 k€/kW (Napoli, et al., 2015). This would mean that this 1,5 kW_{el} system would cost about 15 k€, slightly above the 10 years utilization savings stated earlier. It is possible that current and future SOFC technology costs have been reduced and will continue to reduce (with higher technology penetration and prices learning curve).

At last, from an environmental point of view, the emission factors have significant influences. The ecological balances can either be considered as positive or negative. On one hand, the fact that the first dataset gives positive CO_{2eq} savings means that these decentralized electrical production systems are more environmentally friendly than centralized CCGT plants. On the other hand, fact that the second dataset gives negative CO_{2eq} savings means these systems are ecologically worse than the average local electrical mix (with its renewables and its nuclear energy). As these systems are currently used with constant output power, the second emission factor dataset with the resulting negative CO_{2eq} balances is more relevant. However, since remote control is already possible, these SOFC systems have the ability to only be powered up to replace CCGT electrical production, which mainly occurs for grid peak load (thanks to the high flexibility allowed by CCGT). In addition, with potential dynamic electrical production contracts, for example based on day-ahead hourly prices (Huisman, et al., 2019), this SOFC potential flexibility service could lead to higher rejection prices for the household and subsequent quicker ROI.

4. UNCERTAINTY ANALYSES

The method used for uncertainty propagations in this report is the one advised by the National Institute of Standards and Technology (Taylor & Kuyatt, 1927) and to do so, the EES (Equation Engineering Solver) software has been used.

In order to compute the propagation of uncertainties, one must establish it for every variable. For each monitored sensor, it comes directly from Table 2 and its referenced standards. However, the uncertainty has not been established for the hourly HHV figures given by the gas provider for each field-test site. Therefore, it is assumed that it is directly linked to the variance of all the given HHV figures: the uncertainty has been set to thrice the standard deviation of the given HHV figures for the whole monitored year (actually, the standard deviation has been calculated from the population of the hourly HHV figures provided for 2020 and 2021). According to statistics theory, fictively assuming that the actual HHV is constant all year long and that the values given by the gas provider follow a normal distribution around it, this would mean that the obtained uncertainty window accounts for 99.7% of the given HHV figures, which is, as often considered in statistics, sufficient. In reality, the actual HHV is not constant and slightly varies all year long but one can assume that the uncertainty window established here remains valid around the evolving actual value.

This gives an uncertainty on HHV figures of approximately ±234 Wh/m^3 for Riemst and ±105 Wh/m^3 for Duffel. There is a need for separate uncertainty analyses between the sites because the gas type provided to the machine by the grid is different: according to the gas provider, Duffel has still been provided with lean gas (called "type L" in Belgium) whereas Riemst already has a rich gas supply (called "type H" in Belgium). There is about a 10% difference in the given HHV figures between the two types of gas. Such a difference in the chemistry of the gas could indeed have a significant impact on the accuracy of the method used by the gas provider to establish HHV figures.

Thanks to the uncertainty on the HVV figures and the accuracy of the gas meter (about ±0.5% according to Table 2), one can propagate the uncertainties to the daily HHV energy consumed and then to the total yearly HHV energy consumed presented in Table 3 (which corresponds to 8760 observations of hourly HHV equivalent energy consumption). Thanks to the accuracy of the energy meters deduced from Table 2 (±5% for heat meters and ±1% for electrical energy meters), one obtains, for the site of Riemst, uncertainties of about ±0.5 percentage points for the electrical efficiency, ±0.8 percentage points for the thermal efficiency and ±1 percentage points for the total efficiency. For the site of Duffel, one obtains respectively ±0.6, ±0.6 and ±0.8 percentage points for the electrical, thermal and total efficiency.

One limitation of those uncertainty calculations is that they have not considered the accuracy of the correction factor that must be applied to the metered volume to convert it in the reference conditions used by the gas provider in its

HHV definition (Paulus & Lemort, 2022c). According to this study, the metered volume has to be multiplied by a correction factor established from the real gases equation of state. This correction factor, close to one, involves thus pressure ratio, temperature ratio and compression ratio between standard conditions and delivery conditions. Only the delivery conditions account for uncertainties. Delivery temperature uncertainty can be neglected as the gas meter used in the field-test (BK-G4T, as stated in Table 2) implements temperature compensation. According to the values given in ISO 13443:1996, it is unlikely that the compression factor ratio would have an uncertainty greater than ±0.0002 (absolute). At last, delivery pressure depends on the setting of the pressure regulator upstream of the system and on the atmospheric pressure at the field-test site. The pressure regulator setting is either 21 or 25 mbar depending on the gas type in Belgium (Paulus & Lemort, 2022c), so a relevant maximum uncertainty can realistically be assumed to about ±2 mbar. Regarding the atmospheric pressure, it comes from hourly measurement from Royal Meteorological Institute (in Belgium). The real uncertainty of those pressure measurements is unknown, especially since the pressure measurement are not performed at the field-test sites but at a meteorologic station nearby. Therefore, it has been assumed that the uncertainty of each pressure measurement is again equal to thrice the standard deviation of all the hourly pressure measurements that have been provided (again for two years: 2020 and 2021). This leads to an uncertainty of about ±3000 Pa. The propagated uncertainty on the correction factor is thus equal to ±0.028. This is actually too small to have an influence on the propagated uncertainties on the efficiencies stated before.

The emission factor and pricing assumptions are not assumed to be subjected to any uncertainty (uncertainty only propagated on monitored measures and HVV figures). Since the economical and ecological balances are resulting mainly from the efficiencies of the system, it can be assumed that the maximum relative efficiency stated earlier can be considered for all the economical and ecological balances of this work. Actually, the relative uncertainty on thermal efficiencies is of about ±5% for both field-test system.

In conclusion, it is safe to consider that the propagated uncertainties for all the results of this work are at about ±5%. Of course, this is only based on the measured values and the intrinsic accuracy of the sensors. There is no estimation of the uncertainty induced by potential unoptimized installations of the sensors or unoptimized fluidic conditions, especially for the temperature probes of the heat flow meter. Indeed, literature usually finds it is better to mount the probe within the pipe in an elbow to allow it to be parallel to the incoming flow (ASME, 2010). However, that is not the case for the monitored sites, where probes are mounted perpendicularly to the pipe-wall (easier installation as they are commercialized monitoring sensors and not quite laboratory equipment). This probe configuration is still accepted in literature. Indeed, those two possibilities of mounting temperature probes on a hydraulic pipe (along with a third angular one) are shown in Figure 4 (a) (Klason, et al., 2014). Also, as the temperature probes are singularly placed in the pipe, the assumption is made that the single in-pipe temperature point accounts for all the fluid on the measured section of the pipe. As shown in Figure 4 (b) (Klason, et al., 2014), this might not be the case as wall effects as well as temperature gradients may happen. Therefore, there might be a temperature distribution along the section of the pipe that one single temperature measurement might not reliably represent. This is another example of a source of uncertainty due to the quality of the installation and of the monitoring equipment that is neglected in this report uncertainty studies. At last, literature has established the need for the depth of the probe in the pipe to be set precisely, down to 45 to 50% of the pipe diameter (Kolpatzik, et al., 1998). This time, this is likely to be ensured for the monitored sites, as the probes are sold with the corresponding portion of pipe that they are supposed to be screwed in. A mechanical stop is also involved within this probe-pipe assembly, for which a picture is shown on Figure 4 (c). So, an unoptimized depth could only come from the unlikely unproper mounting of the technician that may not have screwed the probe all the way to its mechanical stop. Unfortunately, this could still happen and there is no way of knowing for sure remotely without visiting the installations. Still, as best practices and sensor mounting manufacturer recommendations have been followed, these kinds of eventual misplacements can be neglected.

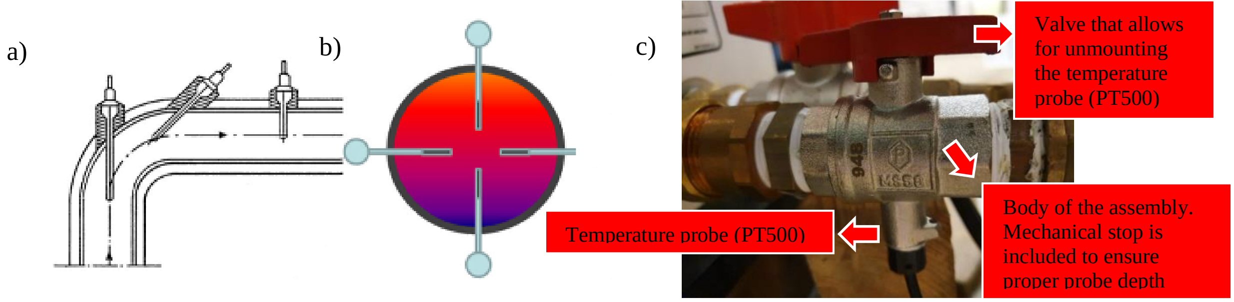

Figure 4: a) The three recommended options to mount a temperature sensor in a pipe (Klason, et al., 2014) b) Example of the distribution of the temperature of the fluid within a pipe along with an example of multiple probes installation in order to study it (Klason, et al., 2014) c) Example of in-pipe temperature probe assembly used in this study

5. LIMITATIONS AND CONCLUSIONS

The strongest limitation of this work is that the resulting economical indicators are strongly case dependent and that considering only two systems does not allow for drawing statistical conclusions on the system's performance (especially the economical ones). The results developed here shall thus be considered as case studies. However, the ecological balances are unlikely to change much from one household to the other as it does not depend on supply cover factors and as the system is mainly used with a constant and nominal power output.

This 2021 field-test monitoring study has demonstrated in real applications the 60% LHV electrical efficiency of this residential SOFC mCHP system (at least for one of the two SOFC's, the other being close to that figure probably because of intrinsic variance between manufactured products, because it has been functioning at partial load on the studied timeframe and because of aging, as it was commissioned one year before the other unit). Demonstrated LHV thermal efficiency is not higher than 12-15%, mainly because the heat recovery is mostly used for DHW production (at high delivery temperature). However, the amount of heat still recovered has been proven to be quite significant and sufficient, for example, to cover DHW demand of the average USA household (backup heating appliance is still advised to ensure sufficient temperature delivery at all times). Resulting yearly utilization costs savings (not considering the impact of the conflict in Ukraine on the energy prices) are significant and at about 1.3 - 1.4 k€/year (for 2021 Belgian energy prices assumptions). This figure has been achieved thanks to a quite high supply cover factor of about 60% for each household (mainly allowed thanks to one electric car). Potential dynamic day-ahead tariffication could even improve those utilization cost savings. From an environmental point of view, two considerations could be made: compared to the actual Belgian consumption mix, the CO_{2eq} balance are way negative because of the intrinsic use of natural gas (that remains a carbonated fossil fuel). However, the system has better efficiencies than CCGT power plants and its power output can be modulated from distance. Therefore, it can partially be considered that this system allows for decreasing the electrical demand on centralized CCGT power plants. This consideration changes totally the CO_{2eq} balances that become quite positive.

NOMENCLATURE

CCGT	Combined Cycle Gas Turbine
CREG	Commission de Régulation de l'Électricité et du Gaz
DHW	Domestic Hot Water
HHV	High Heating Value, [J/kg]
LHV	Low Heating Value, [J/kg]
mCHP	micro-combined Heat and Power
ROI	Return On Investment, [years]
SOFC	Solid Oxide Fuel Cells

REFERENCES

ASME, 2010. *Thermowells - Performance test codes.* s.l.:American Society of Mechanical Engineers.

Braun, R., Klein, S. & Reindl, D., 2006. Evaluation of system configurations for solid oxide fuel cell-based micro-combined heat and power generators in residential applications. *Journal of Power Sources,* 158(2).

Chen, K. K. et al., 2021. Membrane processes for CO2 removal and fuel utilization enhancement for solid oxide fuel cells. *Journal of Membrane Science,* Volume 620.

CREG, 2021. *Analyse semestrielle de l'évolution des prix de l'énergie – 2e semestre 2021,* s.l.: CREG.

CWaPE, 2005. *Décision CD-5j18-CWaPE relative à "la définition des rendements annuels d'exploitation des installations modernes de référence, ...",* s.l.: CWaPE.

CWaPE, 2020. *Communication - FAQ – Tarif Prosumer,* s.l.: CWaPE.

Davila, C., Paulus, N. & Lemort, V., 2022. *Experimental Investigation of a Micro-CHP Unit Driven by Natural Gas for Residential Buildings.* Purdue, s.n.

Ellamla, H. R. et al., 2015. Current status of fuel cell based combined heat and power systems for residential sector. *Journal of Power Sources,* Volume 293.

Emerald Expert Briefings, 2022. *Ukraine crisis will bring heavy costs for Europe,* s.l.: Oxford Analytica.

European Parliament, 2012. *DIRECTIVE 2012/27/EU on on energy efficiency,* s.l.: s.n.

Fernandes, M. et al., 2018. SOFC-APU systems for aircraft: A review. *International Journal of Hydrogen Energy,* 43(33).
Föger, K., 2011. *Ceramic Fuel Cells Residential Generator BlueGen - Ultra-efficient distributed power generation in Smart Grid Environment.* Seoul, s.n.
Fritzmann, C., Löwenberg, J., Wintgens, T. & Melin, T., 2007. State-of-the-art of reverse osmosis desalination. *Desalination*, 216(1-3).
Fuentes, E., Arce, L. & Salom, J., 2018. A review of domestic hot water consumption profiles for application in systems and buildings energy performance analysis. *Renewable and Sustainable Energy Reviews,* 81(1).
Hauch, A., Hagen, A., Hjelm, J. & Ramos, T., 2014. Sulfur Poisoning of SOFC Anodes: Effect of Overpotential on Long-Term Degradation. *Journal of The Electrochemical Society,* 161(6).
Huisman, R., Huurman, C. & Mahieu, R., 2019. Hourly electricity prices in day-ahead markets. *Energy Economics,* 29(2).
IEC 62053-21, 2003. *Electricity metering equipment (a.c.) – Static meters for active energy (classes 1 and 2)*.
Klason, P. et al., 2014. Measuring temperature in pipe flow with non-homogeneous temperature distribution. *International Journal of Thermophysics*, Volume 35.
Kolpatzik, S., Hilgenstock, A., Dietrich, H. & B., N., 1998. The location of temperature sensors in pipe flows for determining the mean gas temperature in flow metering applications. *Flow Measurement and Instrumentation,* 9(1).
Lichtenegger, K. et al., 2015. The role of leak air in a double-wall chimney. *Heat Mass Transfer*, 51(6).
Napoli, R., Gandiglio, M. L. A. & Santarelli, M., 2015. Techno-economic analysis of PEMFC and SOFC micro-CHP fuel cell systems for the residential sector. *Energy and Buildings,* Volume 103.
Näsäkkälä, E. & Fleten, S.-E., 2005. Flexibility and technology choice in gas fired power plant investments. *Review of Financial Economics*, 14(3-4).
NETL, 2010. *Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant,* s.l.: US Dpt. of Energy.
OIML R 75-, 2002. *Heat meters. Part 1: General requirements.* s.l.:International Organization of Legal Metrology.
Paulus, N., 2022. Will Greenhouse Gas emission commitments in France and Wallonia respect IPCC's carbon budget ?. *Energy Policy,* Under review.
Paulus, N., Davila, C. & Lemort, V., 2022a. *Grid-impact factors of field-tested residential Proton Exchange Membrane Fuel Cell systems.* Rotterdam, doi: 10.34641/clima.2022.176
Paulus, N., Davila, C. & Lemort, V., 2022b. *Field-test economic and ecological performance of Proton Exchange Membrane Fuel Cells (PEMFC) used in residential micro-combined heat and power applications (micro-CHP).* Copenhagen, s.n.
Paulus, N. & Lemort, V., 2022a. Review of probable degradation mechanisms and recovery procedures for reversible performance losses in a residential cogeneration polymer electrolyte membrane fuel cell. *To be submitted.*
Paulus, N. & Lemort, V., 2022b. *Correlation between field-test and laboratory results for a Proton Exchange Membrane Fuel Cell (PEMFC) used as a residential cogeneration system.* Valenciennes, doi: 10.25855/SFT2022-119
Paulus, N. & Lemort, V., 2022c. Field-test performance models of a residential mi-cro-cogeneration system based on a proton exchange membrane fuel cell and a gas condensing boiler. *To be submitted.*
Peng, J. et al., 2021. Solid oxide fuel cell (SOFC) performance evaluation, fault diagnosis and health control: A review. *Journal of Power Sources,* Volume 505.
Psomopoulos, C. et al., 2010. Electricity savings and CO2 emissions reduction in buildings sector: How important the network losses are in the calculation?. *Energy*, 35(1).
Schmidt-Rohr, K., 2015. Why Combustions Are Always Exothermic, Yielding About 418 kJ per Mole of O2. *Journal of Chemical Education*, 92(12).
Shao, Z. et al., 2005. A thermally self-sustained micro solid-oxide fuel-cell stack with high power density. *Nature,* 435(7043).
Sovacool, B.-K., 2008. Valuing the greenhouse gas emissions from nuclear power: A critical survey. *Energy Policy,* 36(8).
Statistisches Bundesamt - Destatis, 2021. *Prices - Data on energy price trends*, s.l.: s.n.
Taylor, B.-N. & Kuyatt, C.-E., 1927. *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, s.l.: s.n.
Wagner, P. H., 2019. *Integrated Design, Optimization, and Experimental Realization of a Steam-Driven Micro Recirculation Fan for Solid Oxide Fuel Cell Systems (PhD Thesis),* s.l.: Ecole Polytechnique de Lausanne.