Field-test economic and ecological performance of Proton Exchange Membrane Fuel Cells (PEMFC) used in micro-combined heat and power residential applications (micro-CHP)

Nicolas Paulus[a], Camila Dávila[b] and Vincent Lemort[c]

[a] *University of Liège, Thermodynamics Laboratory, Liège, Belgium, nicolas.paulus@uliege.be, CA*

[b] *University of Liège, Thermodynamics Laboratory, Liège, Belgium, cdavila@uliege.be*

[c] *University of Liège, Thermodynamics Laboratory, Liège, Belgium, vincent.lemort@uliege.be*

Abstract:

Energy transition currently brings focus on fuel cell micro-CHP systems for residential uses. One of the latter systems is a PEMFC-gas boiler hybrid system, fed by natural gas, designed to provide all the heat demands of residential houses and to participate locally in the electrical production. Thanks to high integration levels, it combines a PEMFC of nominal constant power of $0.75kW_{el}$ and $1.1kW_{th}$, a 220L DHW (Domestic Hot Water) tank and a boiler, mainly used for peak heat demands (up to $30.8kW_{th}$). The machine is not electrically driven. This study is monitoring two of those installations in residential houses in Belgium for two whole years (2020 and 2021). It focuses on the comparison of the actual field test performance with the targets expected for this technology. Since the financial incentive represents a major factor in the investor's decision towards such a technological change, focus is brought on an economical indicator based on an average Belgian household energy bill (including 2021 energy price significant increase). Through an analysis of emission factors of energy uses used by recognized organizations, utilization ecological indicators (CO_2 or CO_{2eq} balances) are established in an attempt to foresee the place of this micro-CHP technology in the energy transition challenge of today facing global warming. Although only the utilization phase is considered for ecological balances of this CHP system, some of the emission factors used in this work are considering the whole LCA (Life-Cycle Assessment) of the reference energy uses. This study demonstrates quite poor ecological and economic balances for this particular system and it states as its main outcome that this technology could be improved if it were electrically driven and therefore flexible.

Keywords:

Balance of emissions; Field test; Fuel cell; Micro-CHP; Monitoring; Technico-economical assessment.

1. Introduction

In Belgium, at the end of 2020, the Walloon Region has legally acted that the reduction of its territorial greenhouse gas emissions should reach at least 95% by the year 2050 compared to the 1990 levels [1]. However, such a long-term objective is not sufficient to ensure that one does not overcome the IPCC carbon budget recommendations way before that date [1]. Regarding that matter, CHP systems and/or hydrogen systems hold much hope, even at the domestic scale (micro-CHP). Indeed, commercial applications, such as fuel cells, already exist for residential purposes [2]. This paper treats one particular PEMFC hybrid system, fed by natural gas, designed to cover all the heat demands (including DHW) of residential houses and to participate locally in the electrical production. This particular system exists in several versions all based upon the same PEMFC module of nominal constant power of $0.75kW_{el}$ (and $1.1kW_{th}$) and all based upon the same 220L DHW tank. The only module that may vary is the gas boiler that is supposed to ensure peak heat demands. Indeed, it exists in four rated power versions from 11.4 to $30.8kW_{th}$, depending on thermal needs [3]. System's architecture is presented in Fig. 1 and main datasheet characteristics are presented in Table 1.

The complete system behaviour is heat driven. Its PEMFC has not been designed to be driven by the electrical demand and it is preferable that it runs as long as possible. One explanation is that the electrical efficiency of fuel cell technologies lowers as operating conditions differ from the design ones [4], but it is mostly because of durability reasons (the goal is to reduce start-up/shut-down cycles [5] and ensure easier thermal management, critical issue for both performance and lifetime of PEMFC [6]). In fact, literature reports that PEMFC could be stopped for unproper thermal conditions (to ensure its integrity [7]) and this is probably why the manufacturer states that the maximum internal return temperature to the fuel cell is 50°C [3]. It includes a methane reforming apparatus for clean hydrogen feed to the stack and requires a fuel cell shutdown recovery procedure of 2.5 hours at least every two days to handle some reversible ageing processes [8].

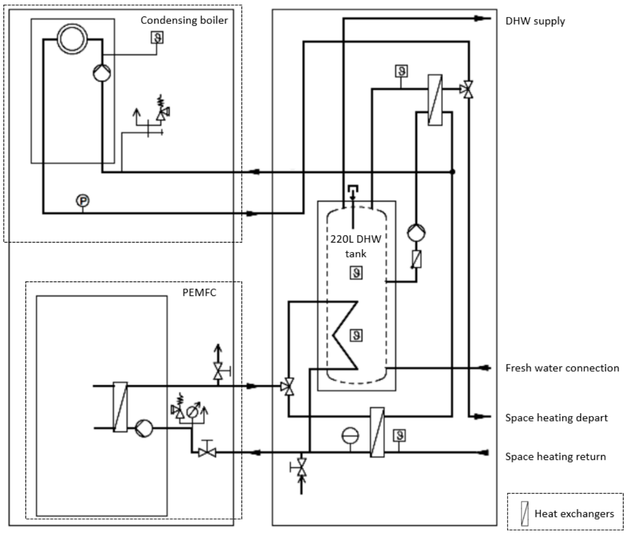

Fig. 1. System's architecture – High level of integration (through two heat exchangers, several 3-way valves and several pumps) of the PEMFC with the gas condensing boiler and the DHW tank.

Thanks to Wireless M-bus communications, this study has monitored quite exhaustively two of those systems in residential houses scattered in Belgium for the years 2020 and 2021. First, it brings special focus on the comparison of the actual field test performances with the expected targets for this technology.

Secondly, since the financial incentive will always represent a major factor in the investor's decision towards such a technological change, in addition to efficiency analyses, focus is brought on a specific economical indicator representing utilization cost savings of an average Belgian household. To build this indicator, utilization costs are reproduced with the monitoring data for the whole years 2020 and 2021. They are subsequently compared to those of a common condensing gas boiler with electricity drawn from the grid.

The pricing assumptions used here are relevant to the Belgian market but, as it will be seen, they have a certain level of validity in neighbouring countries and regions.

At last, this study analyses CO_2 (equivalent) emissions potential savings according to several assumptions based on widely recognized emission factors, which are discussed and sensitively studied. Those ecological indicators also take as reference the classical condensing boiler for heat production.

Table 1. PEMFC gas boiler hybrid expected targets (data published by manufacturer) [3].

Datasheet figures	Values
Maximum electrical production a year	$6200kWh_{el}$
Fuel cell rated electrical and thermal power as defined by EN 50465 [9]	$0.75kW_{el}$ & $1.1kW_{th}$
Electrical fuel cell efficiency	37% (LHV)
Max global Fuel cell efficiency	92% (LHV)
Max boiler efficiency (at rated power)♣	108.6% (LHV)

♣ Considering HHV to LHV ratio of 1.1085 [10]

2. Field-test configuration and key figures

2.1. Brief description of the monitored houses and of the space heating architecture

The first house is located in Huy (South-East Belgium) whereas the other one is located in Oostmalle (North of Belgium). One can state that the two houses are located in the same climatical region. Gas boiler rated thermal power within the machine is $11.4kW_{th}$ in Oostmalle whereas it is $24.5kW_{th}$ in Huy.

The first monitored building (Huy) is a semi-detached house of the early 20th century but significant insulation work of walls and roofs has been conducted. Single-glazing windows have been replaced by double-glazing windows and a balanced ventilation has been installed. However, terminal units still consist of high temperature radiators. The family that lives there consists of two active adults and three children under the age of ten.

The second monitored building (Oostmalle) is a fully detached house from the 70^s but deep renovation just took place before the study. Insulation of course, but the whole space heating architecture has also been revisited with the implementation of floor heating for the ground floor. On the first floor, terminal units consist of high temperature radiators. The family consists of a young active couple with one child of small age.

Occupants' behaviour and building heat demand are quite different and that results in unalike fuel cell electrical behaviours and production [11]. Both houses are equally monitored. Sensors are identical and are placed at the same spots [11]. Sensor reference, precision and resolution are presented in Table 2. Last very important parameter not shown in Table 2 is the sampling rate, the frequency of the acquisition. With this data logger and its “T2” communication mode [12], it is impossible to set a time step smaller than 2 minutes due to the fact that it must establish a successful Wireless M-bus (Meter-bus) connection with every sensor, one after the other, and that takes time (a few seconds for each connection) [12].

Table 2. Reference of the monitoring sensors.

Sensors	Reference	Resolution *(data logger included)*	Accuracy
External temperature and humidity	Weptech Munia	0,1 K | 0,1 %	± 0,3 K | ± 2 %
Internal temperature and humidity	Weptech Munia	0,1 K | 0,1 %	± 0,3 K | ± 2 %
DHW and space heating heat counters	Qalcosonic E1 Qn2,5 qi=0.025m^3/h | L=130mm	1 kWh | 1 L | 0,1 K	Accuracy Class 2 [13]
Machine 2-ways electrical energy counter	Iskraemeco MT174-D2A42-V12G22-M3K0	10 Wh	Accuracy Class 1 [14]
House 2-ways electrical energy counter	Iskraemeco MT174-D2A42-V12G22-M3K0	10 Wh	Accuracy Class 1 [14]
Gas volume counter	BK-G4T DN25 Qmax 6 m^3/h	10 L	<0.5%
Data logger (cloud connection)	Viltrus MX-9	NA	NA

Except for temperatures and humidity, all of those meters are computing energy index values (always increasing). Only the heat meters are also able to provide the instantaneous power but the quite large monitoring sampling time is not sufficient for drawing relevant information from those power measurement.

The heat meters base their energy index on the integration of their flow rate measurement, combined to (in-pipes) temperature probes on both depart and return lines of the machine (separate PT-500 temperature measures). They simply follow the first thermodynamics principle based on pre-programmed enthalpy laws (internal correlation with temperature is implemented). Sensor pre-programming thus depends on the heat transfer fluid (which is simple water in both houses). It also depends on the flow meter position (supply or return circuit) as this will impact the flow meter operating temperature, along with the properties of the fluid being measured. Heat meters are preferably placed on the pipe returning to the machine, as the temperature is lower and more stable. The life of the components is thus extended [15] and both sites considered in this study indeed follow this best practice.

Each electrical energy meter measures the net electrical flow and continuously computes its integration into two indexes of energy: one for the electrical production/rejection, one for the electrical consumption. This means that the consumption of the system’s auxiliaries cannot be observed while the PEMFC is producing electricity. Similarly, only the net electrical production (minus the power consumption of the auxiliaries) can be measured.

At last, the hourly values of the High Heating Value (HHV) of the natural gas mix of both sites have been provided for each field-test site for the whole years by the gas provider. This information, whose process is described in another paper [16], allows for achieving a better accuracy of the analyses, since no assumption of “gross average” calorific values of the gas mix had to be made.

2.2. Key field-test figures

Before considering economical and ecological aspects, one can observe in Table 3 and Table 4 the energy performance and key figures of both sites. HHV to LHV ratio has been once again assumed to be 1.1085 (according to the assumption of the Walloon energy regulator) [10]. Maximum propagated uncertainty (from sensors described in Table 2) can be considered to be about ±5% without considering the potential unoptimized placement of sensors (especially for thermal probes). Uncertainty propagation has been conducted according to the National Institute of Standards and Technology method similar to what is described in a parallel study conducted on another fuel cell system [17].

Table 3. 2020 field-test figures for both PEMFC (1866 degree-days in 2020 [18], base 16.5°C [19]).

Monitored data	Huy	Oostmalle	Monitored data	Huy	Oostmalle
HHV equivalent energy consumed (kWh)	19515	32391	LHV Electrical efficiency (%)	12,4	11,0
Electrical production (kWh)	2175	3213	LHV Thermal efficiency (%)	70,3	80,3
Electrical consumption (kWh)	270	255	LHV Total efficiency (%)	82,7	91,3
DHW (kWh)	1599	1998	Space heating (kWh)	10779	21481

The share of equivalent energy consumed by the fuel cell only can be estimated by dividing the electrical production by the announced 37% LHV efficiency of Table 1. It is however not trivial to estimate the share of thermal energy provided by the fuel cell only.

Electrical consumption of the system (quite low and only occurring when the PEMFC is not producing) has not been considered in the efficiency calculations of Table 3 and Table 4.

Only the total yearly efficiency in Oostmalle comes close to the declared optimal efficiencies of Table 1, mainly thanks to the higher thermal efficiency allowed by terminal units of lower temperature (floor heating).

Lower electrical efficiency in Oostmalle, due to higher heat demand, is balanced thanks this higher thermal efficiency. Electrical production in Oostmalle is greater, thanks to the higher heat demand and fuel cell increased capability of dissipating its heat in the space heating [11], but it is still about two times lower than the full PEMFC capacity (see Table 1). Actual PEMFC load factor [16] is therefore below 50%.

Table 4. 2021 field-test figures for both PEMFC (2286 degree-days in 2021 [18], base 16.5°C [19]).

Monitored data	Huy	Oostmalle	Monitored data	Huy	Oostmalle
HHV equivalent energy consumed (kWh)	20083	38243	LHV Electrical efficiency (%)	11,1	9,3
Electrical production (kWh)	2011	3222	LHV Thermal efficiency (%)	69,4	84,5
Electrical consumption (kWh)	298	258	LHV Total efficiency (%)	80,5	93,8
DHW (kWh)	1627	2095	Space heating (kWh)	10941	27061

Key figures are similar for 2021 except that Oostmalle space heating demand has increased by 50%, which allowed for a prevalent use of the boiler within the system (at its nominal output) resulting in a better thermal (and total) efficiency. It is worth mentioning that the 16.5°C degree-days were increased by about 25% in 2021 compared to 2020. The reason for the lower 2021 efficiencies in Huy (compared to 2020) is not yet established.

3. Economic and ecological performance indicators' definitions

The chosen methodology for establishing performance indicators is similar to what the European Parliament recommends for calculation of primary energy savings of CHPs [20]. It recommends to study the performance of a cogeneration by comparison to state-of-the-art separate heat and electrical energy productions. Based on this, the Walloon energy regulator has stated that the reference state-of-the-art system for heat production is a gas condensing boiler of 90% LHV efficiency [21] (close to the total yearly efficiency in Oostmalle in 2020 and 2021). As a first approach, this 90% constant efficiency assumption for heat production will be considered. Later on, a more accurate gas condensing boiler model (depending on heat demand) will be used to simulate the performance again. This boiler model will be based on real field-test empirical results [22].

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 [21] following European directives [20], the combined cycle gas turbine (CCGT) plant of 55% LHV efficiency [21]. 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 CHPs, 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). System performance is indeed established by considering the monitored gas consumption multiplied by the gas price assumption or by the gas consumption emission factors. On the other hand, reference state-of-the-art performance is established by considering the monitored energy productions (thermal and electrical).

Positive indicators imply better performance than reference machines.

All performance indicators only focus on the utilization balances of the CHP system so its manufacturing and its disposal are not considered.

3.1 Economic

In this study, one has neither taken into account the investment costs for the machine nor the one for its installation (or its removal). The economical indicator does not include any CO_2 pricing and only consists of utilization cost savings (€ saved/year) compared to a reference machine, which is, as stated, a classical gas condensing boiler.

In order to compute those utilization cost savings, one has considered the following assumptions for the year 2020: 0.2425€/kWh_{el} for electrical energy and 0.041€/kWh_{HHV} for natural gas [23]. Those prices are considered constant, which might be an assumption that is relevant for the whole year 2020 (the year of this performance study) but that could be criticised for further projections (as demonstrated by the energy crisis of 2021 [24]). For the year 2021, only the second semester average prices have been considered and applied to the whole year monitoring data, in order to partially consider the impact of the energy crisis on the economic performance of the machine. Indeed, energy crisis is likely to last due to recent geopolitical issues [25]. For 2021, the energy prices are thus 0.333€/kWh_{el} for electrical energy and 0.093€/kWh_{HHV} for natural gas [23]. It must be pointed out that European natural gas prices even rose by almost 70% after Russia invaded Ukraine in February 2022 [26] but that is not yet considered in this work.

Those prices are provided by the Belgian energy federal regulator, named CREG (Commission de Régulation de l'Électricité et du Gaz), that oversees the whole energy market and parties. They correspond to annual average residential prices (coming from total energy invoice, including taxes) for a Belgian average household of 3500kWh_{el} of electrical consumption a year and 23260kWh_{HHV} of natural gas consumption a year, which is quite close to the consumption of the field-test sites (Table 3 and Table 4). As stated by the Belgian regulator, they are close to the effective mean prices for the Belgium neighbouring countries for the same base consumptions (France, Germany, the Netherlands, the United Kingdom) [23].

One limitation of these pricing assumptions is that they are less relevant as one's actual consumptions deviate from of those average figures, which can particularly be the case with micro-CHP technologies.

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 distribution and 0.05€/kWh$_{el}$ for transport) as considered by the Walloon regulator (named CWaPE) in its tariffication plans [27]. 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.

3.2 Ecological

The ecological indicators computed in this work consist of absolute CO_2 or CO_{2eq} (equivalent) savings, depending whether all Greenhouse Gases (GHG) are considered or not. The system is once again compared to reference energy production appliances (for heat and power).

In order for those indicators to be computed, one must establish emission factors for natural gas combustion (heat production) or consumption as well as for the electrical production. It is not in the scope of this study to build an emission factor accurately for each field-test site so several set of assumptions, from several widely known organizations, have been reported and simulated. Another purpose of having computed several sets of assumptions is to bring sensitive studies on the ecological balances of those systems in case one particular emission factor is disputed. The emission factors used in this work are provided in Table 5.

Even if natural gas combustion (or consumption in a fuel cell) emission factor is quite stable in time, it is not the case for the electrical mix (mainly thanks to increased yearly penetration of renewables). Therefore, one should look for the date considered for the establishment of the emission factors (and preferably consider the most recent ones).

One must also pay attention that the electricity mix considered for Belgium can either be relevant for the territorial production or for the territorial consumption. The difference relies on the exportation/importation of electricity with neighboring countries. Consumption mix might be more relevant as it is the one that is really used by our monitored houses but its variation is way greater with time. From one day to the other, Belgium could import low-carboned electricity from France and the day after, it could import quite high-carboned electricity originated from Poland. The only emission factor that would account for that is the consumption one.

In addition to CO_2 only or CO_{2eq} specification, one must pay attention if the emission factor provides non-LCA or LCA values for the energy uses, which implies that emissions of the whole cycle of energy or fuel production are included. However, as stated earlier, even the utilization ecological balances that consider LCA emission factors for energy uses do not include the whole LCA of the PEMFC system, i.e. neither its manufacturing or its disposal is accounted for.

At last, to the understanding of the authors, grid transportation and distribution electrical losses (which can reach about 6-7% in EU [28]) have not been considered in any of the electrical emission factors.

To sum up:

- Dataset “A” represents the CO_{2eq} LCA savings considered by the Walloon regulator for CHP systems. This latter wants to promote CHP based on European Parliament directives [29] and they especially consider an overestimated emission factor for the electricity mix of 456gCO_{2eq}/kWh (LCA) [10]. It assumes that all the electricity produced by the CHP system replaces electricity generation from a CCGT plant of 55% LHV efficiency [21]. The regulator indeed divides its natural gas combustion emission factor by 0.55. Since the PEMFC is not electrically driven and is supposed to run as long as possible, this cannot be considered as accurate compared to set of assumptions considering the actual electrical mix (actually represented by a great fraction of nuclear energy that is often assumed to be “low-carboned” [30]). However, it would still be relevant if this PEMFC technology became electrically driven and if it was only producing just before or when CCGT plants are turned on. Actually, the electrical market and electrical prices (at least in the EU) relies on the System Marginal Price system [31] and it means that they are defined by the last power plants that have to be launched to meet the demand. Those are generally the CCGT plants for flexibility, ecological and economic reasons. Therefore, if one day flexible, it could be considered that decentralized PEMFC systems could have a higher priority than CCGT plants in the System Marginal Price hierarchy, bringing true meaning to ecological indicator “A”.

  The emission factors (and the efficiencies of the reference machines) of this dataset have been established in 2005 but they are still currently used. This is mainly because there has neither been any game changer regarding the efficiency of the reference systems for energy production nor regarding natural gas production and importation.

- Dataset “B” considers savings only for CO_2 emissions (not all GHG) but the main issue is that the complete LCA is not considered (only combustion is considered). Combustion only emission factors (especially expressed in CO_2 only) do not evolve in time as they are mainly related to the carbon content of the fuels and to the intrinsic efficiency of the power plant technologies. However, the electrical mix evolves (mainly due to renewable penetration). This is therefore probably the most accurate dataset due to the recent information on the Belgian electrical mix and the constant carbon content of natural gas through time. However, this might not be the most relevant one as it considers the electrical production mix (whereas the consumption one is preferred) but mainly because it does neither consider all GHG nor the full LCA.

- Dataset “C” considers CO$_{2eq}$ LCA savings. This could be considered as relevant but the consumption mix considered is the one of 2013 and is therefore quite obsolete. In fact, according to the International Energy Agency [32], the Belgian production mix emissions per kWh (CO$_2$ only) have been reduced by 15.2% between the year 2013 and the year 2020. Therefore, if one was to consider the same reduction in the LCA CO2$_{eq}$ emissions, one would be at about 203gCO2$_{eq}$/kWh instead of the 239gCO2$_{eq}$/kWh of the dataset. Nevertheless, this LCA consumption of 203gCO2$_{eq}$/kWh does not account for an officially recognized value and has not been computed.

Table 5. Reference and values found in literature for emission factors (LHV based figures).

Organization	Emission factor of natural gas combustion and consumption	Emission factor for electricity production from natural gas power plant	Emission factor for Belgian electricity consumption	Emission factor for Belgian electricity production
Internal Energy Agency (combustion only) [33] [32]	202 gCO$_2$/kWh (2013 but relevant) B	400 gCO$_2$/kWh$_{el}$ (2013)	Not established	160 gCO$_2$/kWh$_{el}$ (2020) B
IPCC 2014 (combustion only) [34]	202 gCO$_{2eq}$/kWh	370 gCO$_{2eq}$/kWh$_{el}$	Not established	Not established
IPCC 2014 (LCA) [34]	Not established♣	490 gCO$_{2eq}$/kWh$_{el}$		
European Commission CoM [35]	240 gCO$_{2eq}$/kWh (LCA) – (2008-2015) C	543 gCO$_{2eq}$/kWh$_{el}$	239 gCO$_{2eq}$/kWh$_{el}$ (LCA) – (2013) C	Not established
Walloon energy regulator – CWaPE [21] (2005 but still used)	251 gCO$_{2eq}$/kWh (LCA)	456 gCO$_{2eq}$/kWh$_{el}$ (LCA) A	Not established	Not established
Electricitymap.org (yearly average) They consider the IPCC 2014 (LCA) emission factors [34]	Not established♣	490 gCO$_{2eq}$/kWh$_{el}$ (LCA)	162 gCO$_{2eq}$/kWh$_{el}$ (LCA) - (2020) 167 gCO$_{2eq}$/kWh$_{el}$ (LCA) - (2021) D1	148 gCO$_{2eq}$/kWh$_{el}$ (LCA) - (2020) 145 gCO$_{2eq}$/kWh (LCA) - (2021) D2
Electricitymap.org (hourly computation mainly from IPCC 2014 (LCA) emission factors [34]	Not established♣	490 gCO$_{2eq}$/kWh$_{el}$ (LCA)	Hourly computation from the LCA data provided by Electricitymap.org E1	Hourly computation from the LCA data provided by Electricitymap.org E2

♣Can be estimated between 241 gCO$_{2eq}$/kWh and 254 gCO$_{2eq}$/kWh. Those figures have been established from the 202 gCO$_{2eq}$/kWh base value [34] considering an additional 0.52 gCH$_4$/MJ$_{LHV}$ [34] of methane leakage in fuel supply (main contributor of indirect emissions [34]). Global Warming Potential over 100 years (GWP100) of methane has been considered as recommended [34], which can be assumed equal to 21 according to 1996 IPCC assumptions [36], 28 according to IPCC 2014 assumptions [37] and 27.9 according to IPCC 2021 assumptions [38]. It is worth observing that the resulting values come close to previous LCA set of assumptions A and C. 254 gCO$_{2eq}$/kWh will be considered in this study as it involves the most recent consideration of methane GWP100.

- Dataset “D” and “E” considers CO$_{2eq}$ LCA savings similarly but the emission factors are built thanks to Electricitymap.org database that has been granted for Belgium for this academic work. This database collects real-time data from electricity generation and imports/exports around the world [39]. It calculates the resulting (hourly) emission factor according to the real-time mix. It is mainly based according to IPCC 2014 (LCA) emission factors for electricity generation power plants [34]. It provides both the emission factors for the production and for the consumption. Dataset “D” considers the statistical average emission factors for the whole given year (between the population of unweighted hourly emission factors) whereas dataset “E” has discretised the study down to the hour. This allows for individually considering and computing each provided real-time emission factors. Dataset “E1” (consumption electrical mix) is very likely to be the most relevant set of assumptions. In fact, the IPCC 2014 based emission factors for electricity production means are still valid as they have not been updated in IPCC Sixth Assessment Report published in April 2022.

4. Empirical gas condensing boiler model

One limitation of the based indicators described in the previous section is that the system is all season long compared to a gas condensing boiler of constant LHV efficiency. Indeed, the reference 90% LHV efficiency is a yearly average: it is expected to be higher in cold season and lower in warm season. This seasonal effect can be explained because there is almost no space heating in summer whereas prevalent use of DHW occurs, usually at high temperatures for comfort or legionella prevention [40] and usually through a DHW tank, subjected to stand-by losses [41], which can be significant with this system [42]. This can be seen in Fig. 3 reproduced from literature on similar field-test studies [22]. Thus, a more accurate but still simple model could be thought of, which would at least depend on the amount of heat to be delivered by the gas condensing boiler, as Fig. 3 shows it has a key influence on performance. The goal is to establish a regression law to account for the empirical results of Fig. 3 and that would serve as an improved gas condensing boiler model. It has been found that the exponential relation with an additional linear term defined Eq. (1) could fit those empirical results quite well and provide an estimated HHV thermal efficiency $\eta_{th,HHV}$ (%) according to the heat demands:

$$\eta_{th,HHV}\ (\%) = K_1 + K_2\left(1 - e^{-\frac{(Q_{DHW}+Q_{SPH}+K_4)}{K_3}}\right) + \frac{Q_{DHW} + Q_{SPH}}{K_5} \tag{1}$$

K_1 to K_5 are constants to be optimized to enhance the fit whereas $Q_{DHW} + Q_{SPH}$ represents the total heat demand (kWh), i.e. the addition of the DHW production and the space heating demand.

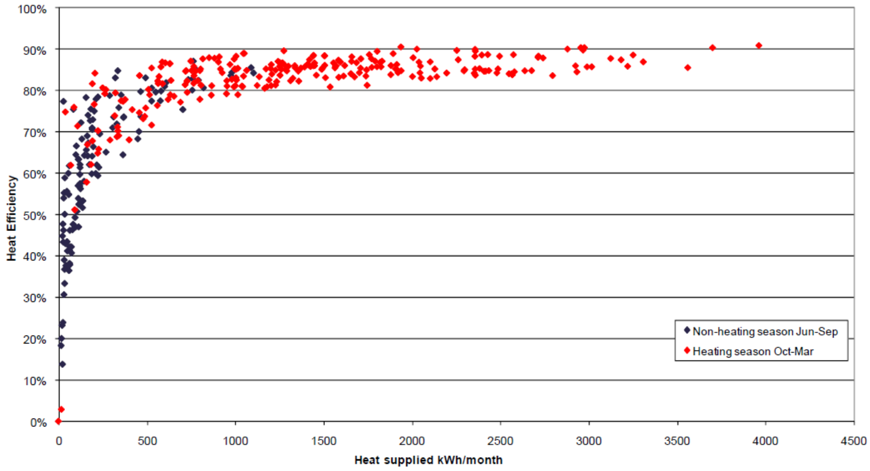

Fig. 3. Reproduction of monthly HHV efficiency (%) against heat supplied for combination boilers (gas condensing boiler combined with storage DHW tanks). The study [22] monitored 31 of those systems for 12 consecutive months in 2007-2008 (each dot corresponds to one monthly performance of one system).

It is worth mentioning that the most advanced performance balances (Datasets "E) are computed hourly whereas the empirical boiler results of Fig. 3 are provided monthly. It is therefore assumed that such an exponential relation also exists on a rescaled timeframe. It has been chosen to rescale the gas condensing boiler model on a daily timeframe. Eq. (1) is thus used to provide the daily thermal efficiency (based on the corresponding daily heat demands) and is applied to the 24-hours discretised performance assessment (economic and ecological, as explained in the previous section). The monthly empirical results of Fig. 3 had also to be rescaled to a "daily timeframe", as it can be seen in Fig. 2. This has been performed linearly compared to the daily total heat demand monitored, i.e. by attributing the highest gas-boiler empirical efficiency given in Fig. 3 (about 90%) to the daily data for which the monitoring total heat demand was at its maximum (about 100 kWh). This constitutes one of the main limitations of this work as the resulting model of the reference gas boiler is "case-dependent". It indeed depends on the monitoring data and one improvement could be implemented simply by dividing the monthly heat supplied of Fig. 3 by 30 (which would provide a very similar rescaled model).

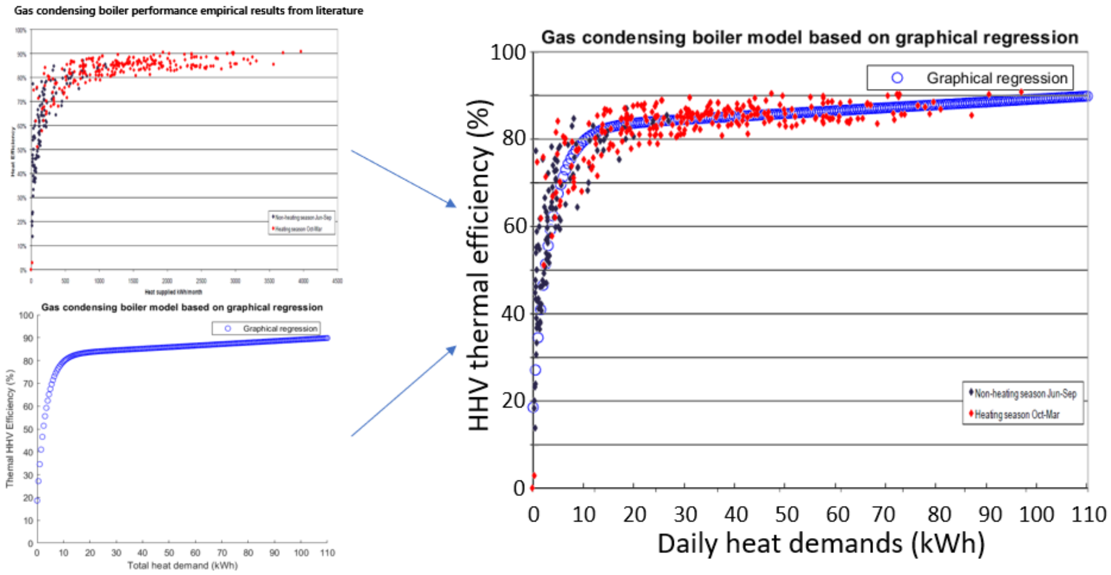

Fig. 2. Graphical regression of the gas condensing boiler model to optimize constants K_1 to K_5 of Eq. (1).

Fig. 2 also shows how the K_1 to K_5 constants have been graphically and manually identified (simply through graphs superposition) and Table 6 provides their resulting values.

The resulting graphical optimization provides the desired enhanced heat-dependent-gas condensing boiler model and it can therefore replace the 90% constant LHV efficiency in the performance balances.

It is worth mentioning that HHV to LHV ratio is once again assumed to 1.1085 [10] for computation with LHV emission factors of Table 5.

Table 6. Optimized constants of the heat-dependant gas-boiler model defined by Eq. (1)

K_1	K_2	K_3	K_4	K_5
-2.5	85	3.5	1	15

5. Results

This time, the electrical consumption of the system has been considered in each of the following indicators (whereas it was not the case in the yearly efficiency assessments of Table 3 and Table 4).

5.1 Economic

Daily utilization cost savings have been cumulated and presented in Fig. 4 for the year 2020 and in Fig. 5 for the year 2021. Firstly, it is worth mentioning that the November 2020 inflection point in Oostmalle is due to a PEMFC breakdown within the system that was only fixed in 2021 (so only the boiler worked within the system). The quite horizontal curve for November and December 2020 in Oostmalle (for the 90% LHV efficiency gas condensing boiler reference machine) indicates that the boiler within the system performs expectedly.

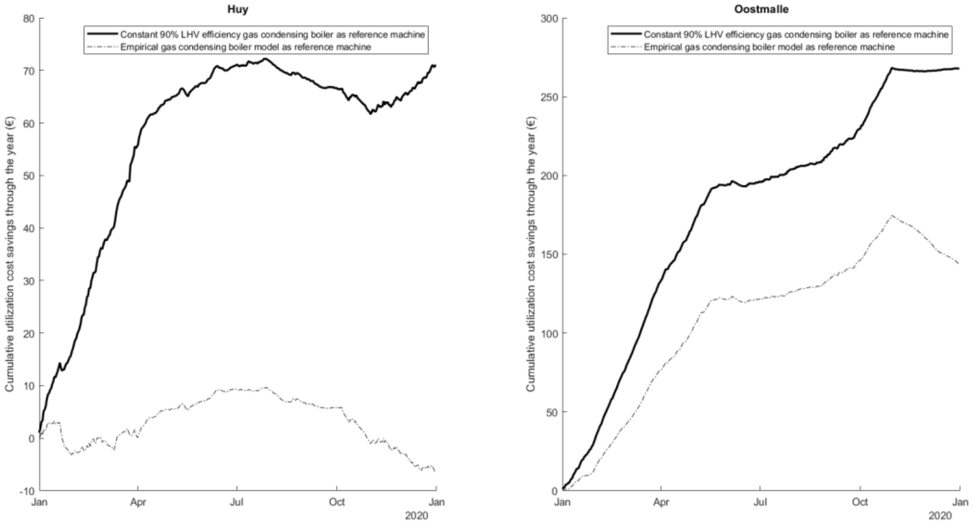

Fig. 4. Cumulative utilization cost savings in 2020 compared to reference machines for both field-test sites (gas condensing boiler of 90% constant LHV efficiency or heat-demand-dependent gas condensing boiler). Electrical price: 0.2425€/kWh$_{el}$. Gas price 0.041€/kWh$_{HHV}$ [23].

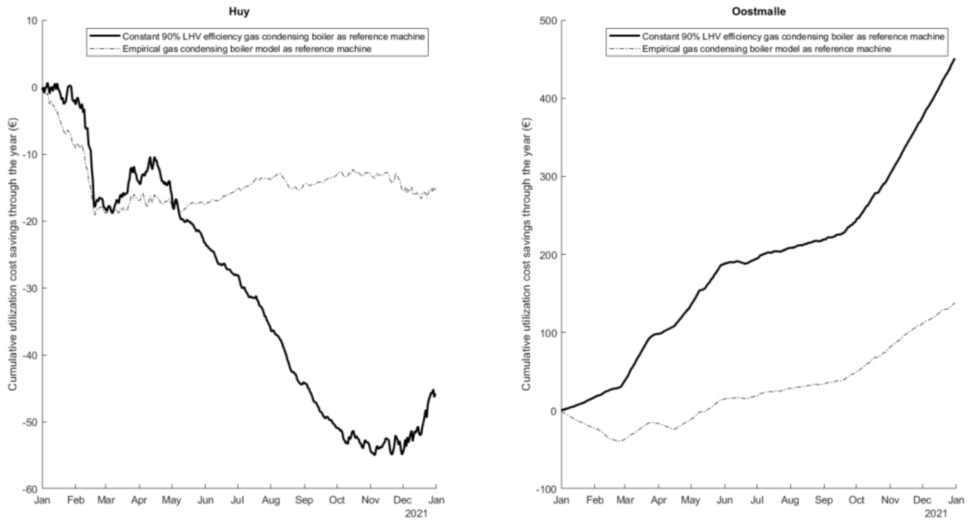

Fig. 5. Cumulative utilization cost savings in 2021 compared to reference machines for both field-test sites (gas condensing boiler of 90% constant LHV efficiency or heat-demand-dependent gas condensing boiler). Electrical price: 0.333 €/kWh$_{el}$. Gas price 0.093 €/kWh$_{HHV}$ [23].

Although, it could perform even better since that, for the same period, the curve for the enhanced heat-demand-dependent gas condensing boiler reference machine is slightly dropping (meaning that the winter heat demand is normally sufficiently high to obtain thermal efficiencies higher than 90% LHV).

Secondly, it can be observed that thanks to its higher total efficiency, the system in Oostmalle is more profitable. The consideration of the heat-demand-dependent gas condensing boiler reference machine generally seems to decrease economical indicators. Also, seasonal trends and summer decrease are generally quite noticeable. However, these last two observations are not always applicable to the house in Huy compared to the heat-demand-dependent gas condensing boiler reference machine. Indeed, the heat demands are so low in summer for that house that the electrical production leads to better economic performance than the modelled gas condensing boiler. This is no longer the case as soon as heat demand increases (in winter) for which the system in Huy shows similar or worsen performance than the heat-demand-dependent boiler model.

Even if the system in Oostmalle is always profitable (even with the enhanced heat-demand-dependent boiler model), the yearly savings are quite insufficient (between 100€ and 450€ of utilization costs savings a year). For instance, in order to achieve return on investments times under 10 years, the system's capital costs shall not be higher than 1k€ to 4.5k€ compared to classical gas condensing boiler, which seems unrealistic for the moment. Based on the results in Huy, if any, the system utilization costs savings are unsignificant compared to a gas condensing boiler. The 2021 indicators for Huy even show slightly negative profits probably because of the higher gas price (compared to the electrical price) and the lower total efficiency of the system.

5.2 Ecological

Only the 2020 ecological performance will be reported in this paper. Main resulting yearly indicators are reproduced in Table 7 whereas Fig. 6 provides graphical seasonal behaviour of some of the most relevant and advanced indicators.

Table 7. Ecological savings of the field-test systems compared to reference machines for the year 2020 and according to the established emission factors of Table 5. The only potential saving occurs for Oostmalle with Dataset A, considering that the PEMFC electrical production always replaces production from CCGT power plants (criticisable since the PEMFC is not electrically driven).

Reference machine for heat production (and electrical emission factor)	Datasets	Gas consumption emission factor	Electrical emission factor	Huy	Oostmalle
90% LHV efficiency gas condensing boiler (and CCGT power plant emission factor)	Dataset A (LCA)	251 gCO$_{2eq}$/kWh	456 gCO$_{2eq}$/kWh	-97 kgCO$_{2eq}$	566 kgCO$_{2eq}$
90% LHV efficiency gas condensing boiler (and Belgian electrical production mix)	Dataset B	202 gCO$_2$/kWh	160 gCO$_2$/kWh	-473 kgCO$_2$	-159 kgCO$_2$
90% LHV efficiency gas condensing boiler (and Belgian electrical consumption mix)	Dataset C (LCA)	240 gCO$_{2eq}$/kWh	239 gCO$_{2eq}$/kWh	-469 kgCO$_{2eq}$	-45 kgCO$_{2eq}$
90% LHV efficiency gas condensing boiler (and Belgian electrical consumption mix)	Dataset D1 (LCA)	254 gCO$_{2eq}$/kWh	162 gCO$_{2eq}$/kWh	-670 kgCO$_{2eq}$	-316 kgCO$_{2eq}$
90% LHV efficiency gas condensing boiler (and Belgian electrical production mix)	Dataset D2 (LCA)	254 gCO$_{2eq}$/kWh	148 gCO$_{2eq}$/kWh	-696 kgCO$_{2eq}$	-358 kgCO$_{2eq}$
90% LHV efficiency gas condensing boiler (and Belgian electrical consumption mix)	Dataset E1 (LCA)	254 gCO$_{2eq}$/kWh	Hourly data from Electrictymap.org	-746 kgCO$_{2eq}$	-273 kgCO$_{2eq}$
90% LHV efficiency gas condensing boiler (and Belgian electrical production mix)	Dataset E2 (LCA)	254 gCO$_{2eq}$/kWh	Hourly data from Electrictymap.org	-752 kgCO$_{2eq}$	-279 kgCO$_{2eq}$
Heat-demand-dependent condensing boiler (and Belgian consumption electrical mix)	Dataset E1bis (LCA)	254 gCO$_{2eq}$/kWh	Hourly data from Electrictymap.org	-916 kgCO$_{2eq}$	-802 kgCO$_{2eq}$

With actual electrical mix emission factor and its 2020 performance, the system never indicates CO$_2$ or CO$_{2eq}$ savings. The ecological balances are trivially worsened as the ratio between electrical emission factor and gas consumption emission factor decreases.

Hourly emission factor computation (from Datasets D to E) can improve (Oostmalle) or degrade (Huy) the ecological balances. The minimum impact of the hourly consideration in the ecological balance is 8% (Huy, Dataset E2) whereas the maximum impact is 22% (Oostmalle, Dataset E2). These quite significant impacts emphasize the relevance of hourly consideration because of the variability of the electrical grid emission factor. This can be observed both in Table 7 and Fig. 6.

At last, considering the heat-demand-dependent gas condensing boiler model of this work as the reference machine for heat production significantly worsen the ecological balances. The house in Huy is less impacted as it has been stated in the previous section that its heat demands are often in the lower range of the boiler model, which accounts for lower efficiencies of the reference machine (observable in Fig. 2).

Fig. 6 indicates the cumulative ecological balance through the year 2020. The difference between the hourly computation of the electrical consumption and production emission factor is not significant, meaning that the ecological balances of the system are not influenced by Belgium's electrical importations and exportations with neighbouring countries. Indeed, the emission factor of the electrical mix from neighbouring countries can be assumed to follow quite similar daily trends as the one of Belgium (mainly depending on the renewables availability).

For the ecological indicators studied in Fig. 6, the system in Huy never seems to show better performance than the reference machines. This is not always the case in Oostmalle. In the end of the year 2020, when the PEMFC has been known to have broken down, when the system was relying only on its gas condensing boiler, some of the ecological indicators are increasing (at least compared to a 90% LHV efficient gas condensing boiler reference machine but not with the heat-demand-dependent gas condensing boiler reference machine).

It is worth mentioning that decentralized local electrical production avoids transportation and distribution losses (which can reach about 6-7% in EU [28]). This could be considered in the ecological balances and they would actually be slightly improved. However, it is assumed to be compensated by the fact that it could also be considered that the extra gas consumption for the decentralized PEMFC electrical production is subjected to fugitive methane emissions (with high GWP) on longer gas network distances. For information, fugitive losses can be estimated to 5.4×10^{-6}kg for the transport of 1kg of natural gas for a distance of 1km [43].

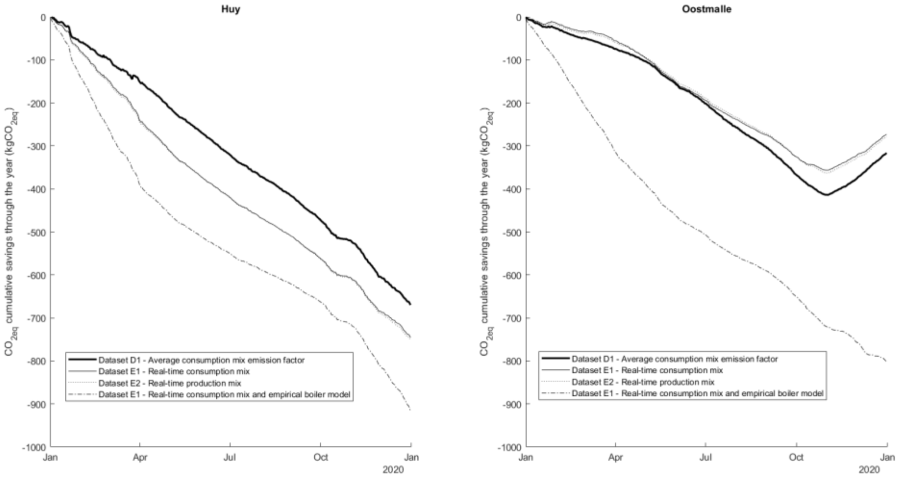

Fig. 6. Cumulative CO_{2eq} in 2020 compared to reference machines for both field-test sites for some of the most relevant emission factors assumption given in Table 5 (reference machine for heat production is either a gas condensing boiler of 90% constant LHV efficiency or a heat-demand-dependent gas condensing boiler).

5. Limitations and conclusions

This paper has conducted an extensive review of emission factors from widely known organizations for energy uses and has summed it up in Table 5. They serve has bases for ecological balance calculations of the two field-test PEFMC micro-CHP systems, that are compared to reference machines (which mainly consist in gas condensing boilers). Unfortunately, those ecological indicators mainly lead to negative GHG impacts, even without considering the whole LCA of the PEMFC system (especially the manufacturing and disposal processes, which could even be performed in future works).

Parallelly, it has been established that it is preferable to compute ecological balances with hourly emission factor data (if available). However, considering the emission factor of the production electrical mix has not shown any significant difference compared to the emission factor of the consumption electrical mix.

This paper has also studied the 2020 and 2021 economic performance of the field-test systems again compared to gas condensing boilers. It has shown that if any, the utilization cost savings of the system are not significant (especially if they shall compensate the higher capital costs of the system).

The main limitation of this study is that its results are in principle limited to the two field-test houses and occupants. Extension to other houses, occupants, countries or PEMFC systems shall be conducted with caution. However, since it shows such unsignificant yearly savings and such poor ecological balances, it can be stated that tremendous improvements are required for this system to play a role in the energy transition.

The main reason is that it seems difficult for this system to show positive environmental balances with actual (and future even greener) electrical mixes. Therefore, the PEMFC production could be made electrically driven and coincides with CCGT production. It could thus be considered that the PEMFC electrical production could replace the highly GHG emitting CCGTs. With potential dynamic electrical production contracts, for example based on day-ahead hourly prices [44], this additional flexibility service seems also necessary for economic reasons (in addition of lowering as much as possible the capital costs of the system).

Although the gas condensing boiler model developed in this paper to serve as a reference machine for heat production is both quite innovative and more relevant than considering a constant 90% LHV efficient appliance, it has been scaled on the field-test daily heat demands data population. The maximum efficiency of the model is indeed assumed to occur the day of the maximum observed daily heat demand of both field-test sites. For instance, if the observed maximum daily heat demand was 50% higher than it was, the model would be rescaled and the resulting indicators would be different. Further work could reduce this sensitivity by non-dimensioning the heat demand (according to the power output of the system, for example, or more simply by dividing the initial empirical monthly data of Fig. 3 by 30 to obtain daily values).

Last main limitation is that both energy prices and electrical emissions factors evolve greatly in time, which limits the relevance of the results to the studied timeframes. For example, further work could study the economic performance of the system according to spark spread (defined as the difference between the price of electricity and the cost of gas used for the generation of electricity [45]). Similarly, ecological balances could be performed considering the difference between electrical mix and the gas consumption emissions factors.

Nomenclature

CHP Combined Heat and Power

CoM Covenant of Mayors

CWaPE Commission wallonne pour l’Energie

DHW Domestic Hot Water

GHG GreenHouse Gases

GWP Global Warming Potential

HHV High Heating Value

LCA Life-Cycle Assessment

LHV Low Heating Value

PEMFC Proton Exchange Membrane Fuel Cell

Greek (and other) symbols

$\eta_{th,HHV}$	daily HHV thermal efficiency of the gas condensing boiler model used as reference machine, %
K_1 to K_5	constants that have been optimised to offer a good fit of the heat-demand-dependent gas boiler thermal efficiency model compared to the results of an empirical field-test study of gas condensing boilers [22], units are to be set accordingly to the other inputs used in Eq. (1)
Q_{DHW}	monitored calorific energy produced by the machine for domestic hot water, kWh
Q_{SPH}	monitored calorific energy produced by the machine for space heating, kWh

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