Grid-impact factors of field-tested residential Proton Exchange Membrane Fuel Cell systems

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Abstract. Much needed energy transition currently brings focus on micro-combined heat and power (mCHP) systems for residential uses, especially on low-capacity fuel cells (about 1 kW_{el}) because it has been reported that they allow for increased CO_2 savings per kW_{el} compared to engine-based mCHP's [1]. One of those (already commercialized), is a Proton Exchange Membrane Fuel Cell (PEMFC) system hybridized with a conventional gas condensing boiler. It is fed by natural gas; it is designed to cover all the heat demands of residential houses as well as 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 condensing gas boiler, mainly used for peak heat demands, that designed to provide up to $30.8kW_{th}$.

The financial incentive representing a major factor in the investor's decision towards such a technological change, focus will indeed be brought on supply and demand cover factors since they are directly linked to how much the citizens are individually billed and since they constitute actual and future unavoidable keys in the energy transition, as more and more intermittent renewable energies will be integrated to the energetic mix.

This study is monitoring two of those installations in residential houses in Belgium, arbitrary chosen, for the whole year 2020. Sampling time of the monitoring hardware is between 2 and 5 minutes but it has been chosen to analyse the grid impacts factors according to average daily values (along with their seasonal trend and yearly figures).

This paper has established yearly supply cover factors between 34 and 36%, which are believed to be higher (based upon literature) that what typical photovoltaics (PV) power plants would have allowed. It unfortunately remains lower than the 37.46% "prosumer" limit considered in the tariffication of Wallonia PV installations [2]. On the other hand, this paper has established yearly demand cover factors of 25 and 33%.

Keywords. Grid-impact factors, PEMFC, CHP, cogeneration, Fuel Cell, supply cover factor, demand cover factor.
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1. Introduction

Nowadays, the higher share of intermittent renewables in the electricity mix, especially with PV installations, the more the electrical network is stressed. Around noon, the electrical demand on the centralized power plants drops and the electrical peak consumption of the evening (when most people are coming home from work, are cooking, heating, and globally consuming electrical energy) is not significantly diminished by the PV energy [3]. This means a very steep electrical demand slope is imposed to the electrical network and this effect is commonly represented by a "Duck curve", as shown in **Fig. 1** [4]. It is worsened by the electrification planned for the energy transition (space heat systems, mobility, etc.) that is currently increasing the daily peak demands on the grid. For information, in the future, it would be preferable for the electrical space heating with heat pump to be modulated down while maximum load is requested on the grid, i.e. in the evening, but it is mostly not currently the case.

This "Duck curve" raises tremendous challenges on the infrastructure. The first one is quite trivial as this highly transient electrical demand requires flexibility (of the centralized production) and this is both expensive and difficult to manage. The second one comes from the fact that the electrical network

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infrastructures (cables, converters, transformers, centralized power plants) are sized based upon peak power demand. Therefore, if electrification of the society is increasing peak demands and if it is not mitigated by renewables (or by energy consumption mitigation measures such as degrowth, building insulation, teleworking, which are not in this paper's scope), it is likely that the electrical network will have to be refurbished (and that cost must not be forgotten in the energy transition).

Currently, total transmission distribution, and administration costs represent already a significant part of the household electrical bill. For example, those costs have typically been between 0.025 – 0.035 $/kWh since 1980 in the US [5], which represented in 2009 about 20 to 30% of the final customer electrical price [5]). In Wallonia (in South of Belgium), it is even more as they can be established to be equal to about 0.15 €/kWh [2] and that represented in 2020 about 60 % of the end price to the customer (based on the Belgian regulator prices [6]). The main difference is that, in Belgium, the 0.15 €/kWh stated here for transport and distribution include (significant) federal taxes that are imputed by the network company and not directly by the state. In 2020, without considering the taxes, the share of the distribution and transport cost in Belgium in the average household electrical bill drops to 33% (close to the US figure) whereas the electricity generation represented only 23 % of the final customer electrical bill [7].

Thus, in the energy transition that is coming, the shares of the distribution and transport prices (electrical network infrastructure) are likely to account for an even bigger share of the end customer price (at least in a stable geopolitical context).

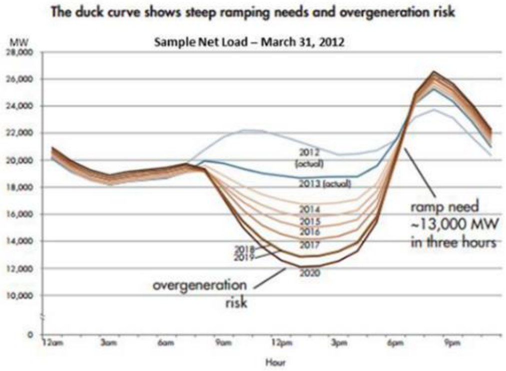

Fig. 1 - "Duck curve" is worsen with higher renewable share (in California) [4]. Figure reproduced from reference with permission.

Therefore, to limit the "stresses" on the electrical network that both the electrification and the renewables are causing, focus is brought on grid impact factors. This is also the case for residential electrical production systems, especially again with high PV penetration, even in developed countries such as Japan where capital investments for distribution lines reinforcement have already been requested [8]. This is why the concept of "prosumer" has been recently established (as agents that both consume and produce energy [9]), which requires some specific regulation framework in electrical markets [10]. In Belgium, these current prosumer regulations are called "the prosumer tariffication" and are designed to bill the energy rejected on the grid [2]. It is therefore critical to mention that economical performance of residential PEMFC systems depend directly on the supply cover factor (and not only on the demand cover factor). This is mainly because the grid energy consumption avoided is far more expensive than the one rejected ("sold") and bought back later on.

2. Research method

Maximizing building load matching factors (demand and supply cover factors, as defined in equation (1) and equation (2) [11]) is thus crucial in order to reduce the impact on the electrical grid. In the energy transition context, this will prevent some additional investments to ensure grid peak power demand or to prevent overvoltage (too much decentralized electrical production at the same time not consumed locally and rejected on the distribution lines).

Supply cover factor γ_s is most critical in a grid configuration as it is the one which maximization would prevent overvoltage (by limiting the power rejected on the grid). Demand cover factor γ_d is also important for obvious economic reasons (while investing in a local electrical production, you would want it to match your power demand as much as possible) and its maximization is critical for off-grid applications. But it is also important for grid configuration as it will mitigate the increasing power demand due to the increasing electrification (less demand from the building on the grid). Actually, both shall be maximized but it is likely that a compromise has to be found between the two factors. It is worth mentioning that whereas those factors should always be considered, there are not the only key design drivers while sizing a local electrical production system. ROI, capital costs, dimensions, load factor, life expectancy, LCA environmental impacts, *etc…* shall be considered as well.

Of course, maximizing cover factors will also have an environmental beneficial aspect as refurbishing the distribution lines might be avoided but also because electrical consumption of the electricity produced locally prevents technical network losses (which can reach about 6-7% in EU [12]).

1.1 Grid-impact factors definition

Both factors are defined as follows [11]:

$$\gamma_s = \frac{\int \min\{P_D, P_S\}dt}{\int P_S dt}$$

$$= \frac{\text{Onsite consumption (of production)}}{\text{Total onsite production}} \quad (1)$$

$$\gamma_d = \frac{\int \min\{P_D, P_S\}dt}{\int P_D dt} \tag{2}$$

$$= \frac{\text{Onsite consumption (of production)}}{\text{Total demand of the building}}$$

Where P_S is the local power supply and P_D the local power demand. Both numerators are identical for the two factors, the term $\min\{P_D, P_S\}$ represents the part of the power demand instantaneously covered by the local electrical power supply or the part of the power supply matched by the power demand.

Both cover factors, by definition of equation (1) and equation (2), are defined over a certain period of time. One can consider instantaneous factors (which would be difficult to obtain in this study as it will be stated in ***Section 1.4 Measurement devices*** that sample time of the monitoring hardware is between 2 and 5 minutes) but one can also consider them daily, weekly, monthly, yearly, *etc*. In this case, they have been established daily, and yearly. Also, for both houses, the daily figures have been regressed in order to evaluate seasonal trends.

1.2 The system

The machine is the same in both studied houses and its internal schematics is presented in **Fig. 3**. Its main performance targets, declared by the OEM (Original Equipment Manufacturer) and expressed in Low Heating Value (LHV) are shown in **Tab. 1** and **Fig. 2**.

Tab. 1 - PEMFC gas boiler hybrid expected targets.

Datasheet figures	Values
Maximum electrical production a day	17 kWh_{el}
Fuel cell rated electrical & thermal power	0.75 kW_{el} & 1.1 kW_{th}
Electrical LHV efficiency of the PEMFC	37 %
Max global Fuel cell LHV efficiency	92 %
Max boiler efficiency (at rated power)[a]	108.6 %

[a] Considering HHV to LHV ratio of 1.1085 [13]

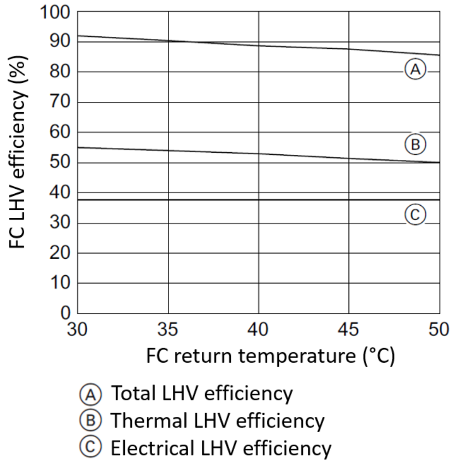

Fig. 2 - OEM's declared LHV efficiency for the PEMFC system only.

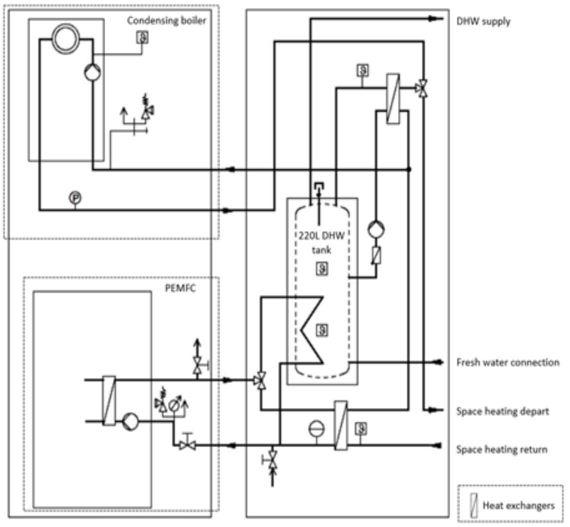

Fig. 3 - System's architecture: high level of integration (through two heat exchangers, several 3-way valves and several pumps) of the PEMFC with the gas condensing boiler and the DHW tank.

As mentioned, the system is fed by natural gas (high methane proportion). It involves an upstream "external" reformer before the PEMFC as temperature within the stack is not sufficiently high for direct "internal" reforming at the electrode [14], only possible with other kinds of technologies, such as solid oxide fuel cells [15]. The hydrogen production is instantaneous so the system is not subjected to the highly constraining safety issues regarding hydrogen storage such as the ICPE (Installation Classée pour la Protection de l'Environnement) authorization in France or similar other legal barriers on EU markets [16].

1.3 The houses

The first house is located in Huy (South-East Belgium) whereas the other one is located in Oostmalle (North of Belgium). From a climatic point of view, one can state that the two houses are located in the same climatic region. The location of the monitoring sites has been presented in **Fig. 4**.

Fig. 4 - Location of the monitoring sites.

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 cast-iron radiators. The family that lives there consists of 2 active adults and 3 children under the age of 10.

The second monitored building (Oostmalle) is a fully detached house from the 70s but tremendous renovation just took place before the study. Insulation has been increased 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 such as in the former house. The family consists of a young active couple with one child of a small age.

1.4 Measurement devices

Both houses are equally monitored. Sensors are identical and are placed at the same spots, according to the scheme of **Fig. 5**. Sensor reference, precision and resolution of the acquired data are presented in **Tab. 2**.

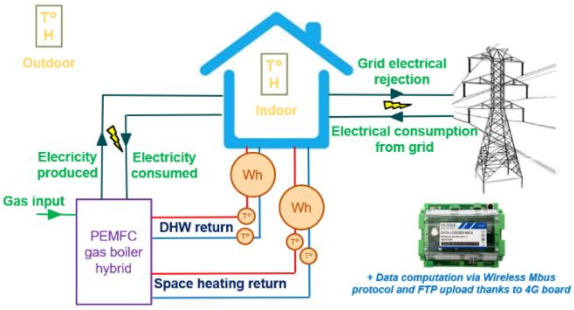

Fig. 5 - Monitored sensors configuration

Last very important parameter not shown in **Tab. 2** is the sampling rate, the frequency of the acquisition, of the measurements. It has been set to a 2-minute time step for the house in Huy and a 5-minute one in Oostmalle. With this data logger, 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). The reason not to have the same sampling rate for all houses is that the faster the rate is, the quicker the battery inside the sensors will be empty. Therefore, reducing the time step to 2 minutes required extra power supply, which was not possible to provide for the second house. Furthermore, for such thermal monitoring applications, a time step of 5 minutes is sufficient for the analyses that have been conducted.

Except for temperatures and humidity, all of those meters are computing energy index values (always increasing).

Tab. 2 - Reference of the monitoring sensors

Sensors	Reference	Resolution	Accuracy
Indoor & Outdoor 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=0.025 m^3/h L=130mm	1 kWh 1 L | 0,1 K	Accuracy Class 2 [17]
Machine 2-ways electrical energy counter	Iskraemeco MT174-D2A42-V12G22-M3K0	10 Wh	Accuracy Class 1 [18]
House 2-ways electrical energy counter	Iskraemeco MT174-D2A42-V12G22-M3K0	10 Wh	Accuracy Class 1 [18]
Gas volume counter	BK-G4T DN25 Qmax 6 m^3/h	10 L	<0.5%
Data logger (cloud connection)	Viltrus MX-9	NA	NA

The heat meters are basing 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 measures thanks to PT-500 probes). They are simply following 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 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 [19] and both sites considered in this study indeed follow this best practice.

Both electrical energy meters are measuring flows both ways: they are able to provide 2 indexes of energy, one for each flow. However, at one particular moment, the net flow is seen and only one of the two indexes can be increasing, following the current direction at that moment. Actually, the machine cannot at the same time consume and produce electrical energy. Since the current always uses the shortest path, in electrical production mode, the machine provides the electricity for its own auxiliaries so no consumption on the meter can be measured. Thus, only the lowered net electrical production is measured, because the power requested by the auxiliaries is taken directly from the gross production of the PEMFC. Same goes for the “grid electrical meter” that measures the net flows exchanged between the house and the grid. To compute the total electrical demand of the house $\int P_D dt$, one must use equation (3):

$$\int P_D dt = \int P_S dt - W_{el,house,out} + W_{el,house,in} \quad (3)$$

Where $\int P_S dt$ is the monitored electrical energy produced by the machine, $W_{el,house,out}$ is the monitored electrical energy rejected by the house on the grid and $W_{el,house,in}$ is the monitored electrical energy consumed by the house from the grid. Those electrical flows correspond to what is indicated in **Fig. 5**. As explained, there will always be one or several of these flows that will be constant.

3. Results

As shown in **Fig. 6** and **Fig. 8**, the system of Huy has a yearly supply cover factor of 33.84 % whereas it increases to 36.27% in Oostmalle (for the focus year of 2020). For the yearly demand cover factor, it drops to 24.52 % in Huy and 33.48 % in Oostmalle (for the focus year of 2020).

Demand cover factor is lower for Huy mainly because of smaller PEMFC production. It has indeed been observed (and confirmed by the owner) that the heat demand is not smooth enough for the PEMFC to be able to keep dissipating its heat over a long period of time, so the internal regulation of the fuel cell shuts it down. Indeed, the occupants in Huy are manually opening and closing their radiator valves fort a short period of time in the morning and in the evening. On the other hand, smoother heat demand is obtained in Oostmalle simply thanks to floor heating.

Monthly heat and power production are presented for both machines on **Fig. 7**. It can be seen that the heat demand in Oostmalle is higher even though it is believed to have better insulation, and non negligible summer heat demand tends to indicate higher temperature setpoint (for comfort reasons).

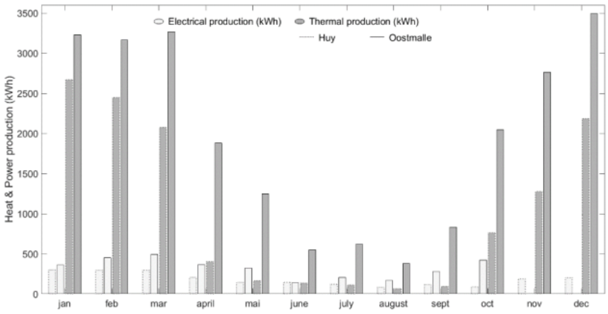

Fig. 7 - Monthly heat and power production for both machines on the year 2020.

The supply cover factor trend increases in the summer mainly because less electrical production occurs (see **Fig. 7**) and this intrinsically leads to less rejection on the grid. On the other hand, lower electrical production in the summer also comes with a lower demand cover factor. The trend curves in Oostmalle are greatly affected by the fact that the PEMFC was shut down (for unknown reasons) at the end of the focus year (also seen in **Fig. 7**). However, one can see that the seasonal trends (summer against winter) are similar for both houses.

In early 2020, Oostmalle demand cover factor reaches almost 70%, which is quite a good performance (compared to yearly performance of PV installations which will be discussed in the following section). Unfortunately, this supply cover factor value could not be maintained the whole year.

Both cover factor trends are nevertheless quite constant over the whole year, which is absolutely not the case with PV installations.

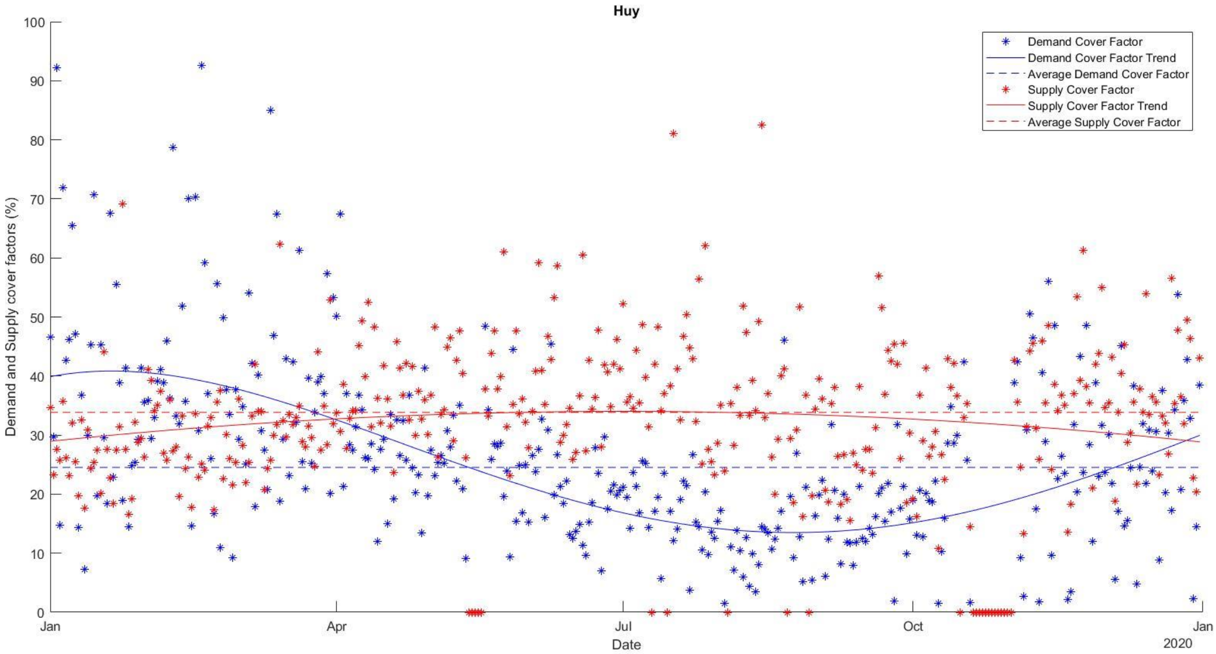

Fig. 6 - Supply and demand cover factors for the year 2020 in Huy.

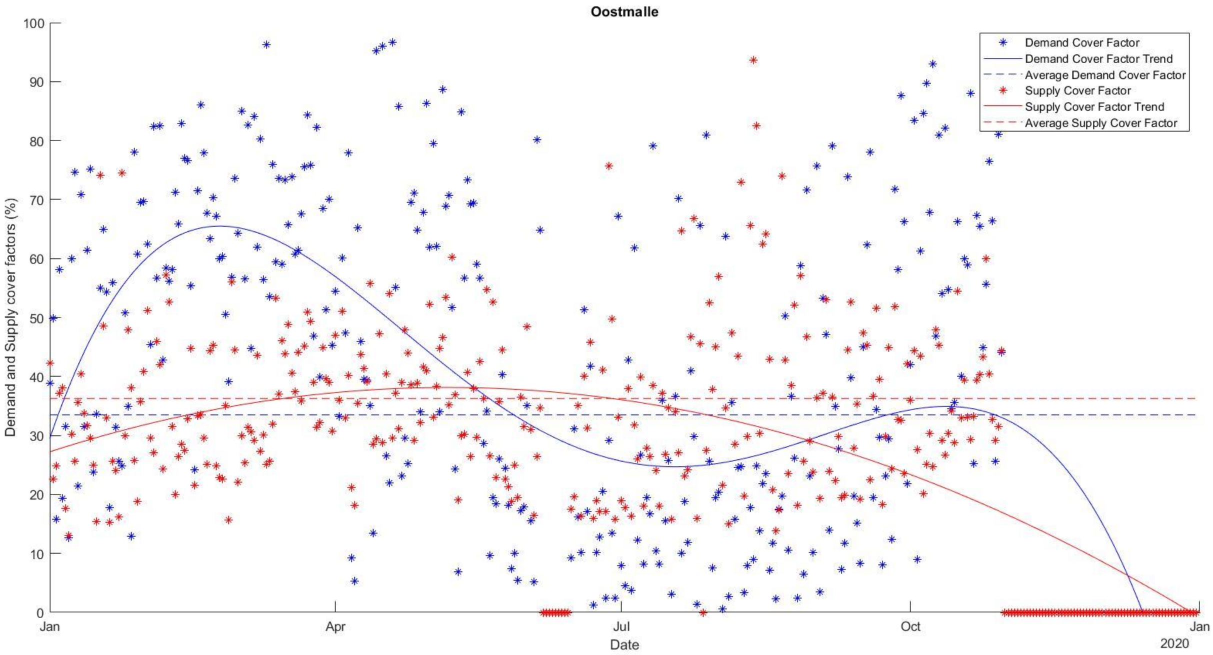

Fig. 8 - Supply and demand cover factors for the year 2020 in Oostmalle.

4. Discussion

It is interesting to point out that this system does not allow the seasonal supply cover factor trend to go higher than 40% (even in the summer) whereas, in its “prosumer tariffication” for PV panels, the Wallonia regulator has assumed a referenced yearly supply cover factor of 37.76% [2]. As established, the yearly values are even below this limit (but close to it). Even if the “prosumer tariffication” assumption for the supply cover factor is not realistic (in order to keep encouraging people to invest in PV installations), it means that this PEMFC system will not be that favorized in Wallonia in terms of electrical rejection compared to PV installations. However, it is worth mentioning that prosumer households with “smart” energy meters (which are mandatory for new electrical installations) are not subjected to this “prosumer tariffication” with the 37.46% assumption of supply cover factor, but they are billed based upon the exact electrical energy rejected on the grid. A “smart” energy meter is an electrical meter that measures both the building consumption and rejection on the grid and that is communicating its energy indexes in real-time to the electrical distribution administrator thanks to wireless communications.

Therefore, the 34 to 36% of supply cover factor obtained with the two houses can still be compared with realistic supply cover factor of PV installations. Of course, PV installations (and household electrical demands) always differ and the resulting supply cover factor can also greatly vary. However, literature can be helpful to obtain examples for those figures. Usually, one must consider the latitude (less PV production at the poles) and also the main electrical appliances of the house (typically, if the house is heated with a heat pump). In Belgium, for residential net zero-energy buildings (ZEBs, which represent a current standard as recommended by EU regulations [20]), supply cover factors have been simulated to reach 26±4% for different building types [11]. All systems have been assumed to be oriented South with an inclination of 34° resulting in the highest annual electricity production [21] and the building’s PV plant has been sized to match the yearly electrical demand. The paper mentions heating with heat pumps, which does not account for much energy demand as insulation levels in those kinds of buildings are tremendous. It does not mention any electric vehicle. A similar study conducted on Northern Latitude (Denmark and Sweden ZEBs, also with heat pumps), provides similar supply cover factors of 22 to 24% with simulation and monitoring data [22].

Another study conducted statistical simulations of several building profiles (not only ZEBs) with PV installations (sized based upon total yearly demand) and it stated that, for average European households, the supply cover in the absence of battery varies between 30% and 37% (the value tends to be slightly higher in southern countries) [23]. This study however states that the standard deviation of supply cover factors in the same country with different household profiles is much greater than the difference of the average between countries. For example, for France, it varies from about 18% to about 47% [23].

Therefore, it can be stated that the supply cover factor really depends on the building, on its location, on its occupants. Establishing precisely the supply cover factors that the two monitored houses of this work would have obtained with a PV installation sized on their yearly demand (or sized on the same yearly electrical production that their PEMFC system has allowed, or sized on a PV installation of similar investment costs) could therefore be performed in further work by simulation with the field-test data. However, based on the existing studies stated here above, it can be assumed that the supply cover factors for those buildings with PV installations would be lower than the ones obtained here with the PEMFC system and probably would be between 20% to 30%. It is worth mentioning that the occupants of the house in Huy have stated that they have been taking some measures in order to increase their supply cover factor (they "are waiting to hear the PEMFC running to launch some appliances such as dishwashers and washing machines"). Therefore, it is likely that they would have done the same with a PV installation so their monitored electrical demand profile shall not be considered directly as is in a PV system supply cover factor simulation.

Unfortunately, the cover factors obtained this paper for these PEMFC are trivially quite case-dependent. Further generalization work might be performed by modelling the PEMFC onsite performance and simulate it according to fictive standardized building demands (established statistically). It is worth mentioning that this system has been modelled in a parallel study [24].

5. Other limitations of this mCHP

As stated, one cannot only look at grid impact factors while considering such a mCHP system. Unfortunately, this particular system has some other limitations.

Firstly, it has been observed that yearly total LHV efficiencies can be at least 10 percentage points behind the reference gas condensing boiler efficiency of 90% (as it is the common assumption of nationally and internationally recognized organizations [25]). For sufficient daily local electrical production (consumed onsite), this relatively low efficiency can be economically compensated but, as it has indeed been stated in a parallel conference, it not exactly the case considering yearly economic performance [26] as expected return on investment is likely to exceed 10 years (based upon the monitoring results and the 2020 Belgian energy prices).

This also results in very questionable CO_2 savings, especially with Belgian electricity mix assumed emissions factors. Calculations are even showing worsen CO_2 emissions compared to reference machines (gas condensing boiler and Belgian electrical mix) no matter the relevant emissions factors that are taken in this study [26].

At last, since the system is not electrically driven (no modulation possible) and since it is designed to provide electricity constantly (as long as possible), the system cannot thus be considered versatile enough to provide flexibility services to the grid.

It is worth mentioning that another limitation of this system is that its PEMFC production has to be periodically stopped for a 2.5-hours regeneration procedure to take place [27].

6. Conclusions

Daily supply and demand cover factors have been established for the two residentials field-test PEMFC-gas condensing boiler mCHP systems for the whole monitored year 2020. Both machines are considered identical and the building they are placed in are similar to the exception that one has floor heating, which demonstrated smoother heat demand and therefore allowed the PEMFC (to keep dissipating its heat and) to run for a longer period of time.

Seasonal trends have also been showed, demonstrating a summer decrease of the demand cover factor while the supply cover factor increases. This is coming from the smaller electrical production that results from lower summer heat demands. Indeed, with few or no heat demand, the PEMFC can no longer release its heat and it shuts down.

On the one hand, yearly demand cover factors of 25 and 33% have been obtained. On the other hand, yearly supply cover factor is about 35% for both houses which is believed to be, based upon literature, 0 to 15 percentage points higher than what would have been obtained for a typical residential PV installation. Unfortunately for this PEMFC technology in Wallonia (South of Belgium), the local electrical regulator is assuming for billing purposes that unmetered residential PV installations are theoretically demonstrating 37,46 % of supply cover factors (even if it is most likely to be lower in reality). Therefore, the current billing framework is rather promoting usual PV installations that such mCHP systems.

However, an advantage of this mCHP system that is currently not considered in the billing framework is that supply and demand cover factors are quite constant over the whole year, which is absolutely not the case with PV installations.

7. Acknowledgement

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Data Statement

The datasets generated during and/or analysed during the current study are not publicly available because of GDPR (General Data Protection Regulation) but could be available under NDA (Non-Disclosure Agreement) with the data owners, i.e. the *Gas.be* (www.gas.be) company.