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Performance analysis of a micro CHP system based on high temperature PEM fuel cells subjected to degradation

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Abstract

Micro Combined Heat and Power (microCHP) systems based on High Temperature Polymer Electrolyte Membrane (HTPEM) fuel cells is a promising technology allowing to produce electricity and heat with very high efficiency and low emissions also for small power systems. Polybenzimidazole (PBI) based HTPEM fuel cells, thanks to their high CO tolerance, allow the use of fuels other than pure hydrogen by means of a simplified fuel processing unit. However, their relatively low performance and performance degradation rate are still issues to be overcome in order to allow commercialization. In this work, an energy simulation model developed by the authors in a previous research work, has been improved taking into account the degradation of the fuel cell stack in order to assess the performance of the system over long period of operation. The fuel cells performance degradation over time has been implemented on the basis of experimental data obtained by the authors and on data found in literature. The performance of the system has been studied in different configurations that include the introduction of a lithium battery storage in addition to the fuel cell stack.
System parameters, such as electrical and thermal energy production, import/export of electricity and primary energy savings have been calculated and compared for different system configurations. Results show that battery integration can improve system performance and that the effect of fuel cell degradation reduces the electricity production. The effect on overall efficiency can be mitigated if heat is recovered.

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Keywords: PEM fuel cell; hydrogen; lithium battery; storage systems

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1. Introduction

Fuel cells based CHP systems have the great advantage to maintain good electrical efficiencies for small size plants and during partial load operation.

Various types of fuel cells exist but, for CHP applications, the market is nowadays contended by three main technologies: SOFC (Solid Oxide Fuel Cells), LT-PEM FC (Low temperature Polymer Electrolyte Fuel Cell) and HT-PEM FC (High temperature Polymer Electrolyte Fuel Cell).

SOFC systems, have the potential of a very good electrical efficiency, good contaminants tolerance and they can easily be fuelled with methane but they still show problems in materials durability especially during variable load operation and start-up process [1].

LT-PEM fuel cells are nowadays the most used technology for CHP systems due to their good electrical efficiency (almost 40%) and a lifetime that can be longer than 20 000 h. This technology owes its success mainly to the Japanese Ene-Farm project that brought to the installation of more than 100 000 residential fuel cell micro CHP units [2].

However, in the last few years, a promising alternative to LT-PEM fuel cells seems to be represented by HT-PEM fuel cells systems, having the main advantage to bear CO contamination up to 3% [3] allowing an important simplification of the fuel processing. Another important system simplification is obtained thanks to the elimination of the humidification process that, for HT-PEM, is not required. Moreover, operating at high temperature, the heat recoverable for cogeneration is of better quality and the heat recover system is simplified [1].

The energy performance analysis of HT-PEM system considering typical domestic electric and thermal load profile can be done using energy simulation models. In literature there are many examples for these models. For example, in [4] a high temperature PEMFC-based micro-CHP system similar to the one studied in this paper is considered. The overall efficiency is higher than 83%, with 28% of net system electrical efficiency and 55% of net system thermal efficiency. Fuel cell stack efficiency is 38%. The same authors, in [5], implemented a genetic algorithm to optimize the system and they improved the electrical efficiency up to 41% while thermal efficiency and total system efficiency were respectively 50% and 91%. A major problem for this type of fuel cells is the degradation rate that is higher than LT-PEM FC. When analysing CHP systems, performance over long period is an important factor and, therefore, degradation should be considered. In [6] the authors implement a simulation model of a HT-PEM micro CHP system and validate it with experimental data and use the model in [7] to analyse the system performance over one year of operation. As for the system degradation modelling, in [8], both the stack and reformer long term performance have been considered. A multi-objective optimization approach has been introduced in order to find the optimal operating parameters within the first 15 000 hours of operation while considering the impact of the degradation. In this work, an energy simulation model developed by the authors in a previous research work [7], has been improved taking into account the degradation of the fuel cell stack in order to assess the performance of the system over long period of operation. System parameters, such as electrical and thermal energy production, import/export of electricity and primary energy savings have been calculated and compared for different system configurations.

2. Simulation model description

2.1. System layout

The system is composed of a 1 kW_{el} fuel cell system, which encompasses a fuel processor and a HTPEM fuel cell stack, and a 3 kWh lithium battery pack. An auxiliary boiler is used when heat from the fuel cell system is not sufficient for providing the heating demand. Fuel cell system, battery pack and grid are electrically connected by means of a power conditioning system. The fuel processor is composed of a steam reforming reactor based on nickel catalyst and a single CO purification stage. A catalytic burner is used to supply heat for the reforming reaction. Fuel sulphur compounds are removed by means of a dry desulphurization unit before fuel enters the system. The HTPEM fuel cell stack is based on a commercial PBI MEA fuel cell (BASF Celtec P1000). The battery pack is composed of 3.2 V, 40 Ah Li-FePO4 battery cells. Battery performances are experimentally investigated in [9]. Additional information on the system were presented by the authors in [10]. In order to connect the fuel cell to the battery pack and to the grid, a power conditioning system is required. In this work a multi converter connection has been considered as it allows the power output of each source to be properly controlled and to fully control battery charging and discharging operations, safeguarding battery life time. The DC bus is then connected to a DC/AC inverter. A Battery Management System (BMS) protects the battery from over charge/discharge current and balances cells during charging operations.

2.2. Domestic power demand curves

The domestic electrical and thermal load curves considered are shaped in order to satisfy a single-family dwelling of four people. Annual electric and thermal energy power demand are assumed to be 4,415 kWh/year and 12,412 kWh/year. The values of the energy demand are representative of a typical European 100 m^2 single family dwelling [11,12]. To simplify the computation, the year has been described by means of 12 typical days, which represent each month.

2.3. Fuel cell system electric efficiency

As defined in [7], the electric efficiency of the fuel cell system is expressed as:

$$\eta_{fcs} = \eta_{FP} \cdot \eta_{FC} \cdot \xi_{BOP} \cdot \xi_{REC} \tag{1}$$

Where η_{FP} is the fuel processor efficiency, η_{FC} is the efficiency of the fuel cell, ξ_{BOP} the balance of plant efficiency coefficient and ξ_{REC} is a coefficient that takes into account for the influence of anode off gas recirculation on efficiency. The coefficient ξ_{REC} was introduced in order to avoid considering a reformer efficiency value that is not dependent on the intrinsic quality of the reformer itself, but it is dependent on the anode off gas recirculation and therefore dependent on the operating characteristics of the fuel cell. BOP efficiency, ξ_{REC} evaluation and fuel processor efficiency have been calculated in the same way as in [7] by means of a simulation model and experimental data. In particular, the fuel processor efficiency has been assessed to be 78% at nominal load condition, when using natural gas. In order to take into account for fuel cell performance degradation, a reference polarization curve for a new CHP system (zero hour of operation) has been considered and a degradation rate has been taken into account that allows modelling the polarization curve considering stack performance variation over time. Two different degradation rates, named in the following DR1 and DR2, have been considered in order to analyse the effect of the degradation on the system performance. DR1 is an experimental value found by the authors [13,14] and found in literature [15,16] also. DR2 is a hypothetical higher value, that is two times DR1. This higher value has been considered to take into account for more detrimental operating conditions [17]. The values of the degradation used by the authors and those found in literature are presented in Table 1. The voltage degradation over time is modelled according to the following equation:

$$V_{cell}\ j,t\ = V_{0,cell}\ j\ - DR_{cell}(j) \times t \tag{2}$$

Where *j* is the current density (mA/cm^2), *DR* is the single cell degradation rate (µV/h), *t* is the operational time (h).

Table 1. Degradation rate considered in the degradation model and in literature: (*) MEA type: BASF Celtec P1000 obtained with constant load 0.2 A/cm^2 average for 6000h, T=160°C single cell test; (**) MEA type: BASF Celtec P1000 obtained with constant load 0.2 A/cm^2 average for 17000h, T=160°C single cell test; (***)BASF Celtec P1000 in a 24 cells stack operated with reformate and load cycle simulating household needs.

Current den. (mA/cm^2)	Degrad. rate DR 1 *Authors exper. Value* (µV/h)	Degrad. rate DR 2 (µV/h)	Degradation rate *Literature* [15]* (µV/h)	Degradation rate *Literature* [16]** (µV/h)	Degradation rate *Literature* [17]*** (µV/h)
200	7.77	15.54	5	< 6	-
400	14.79	29.58	-	-	30

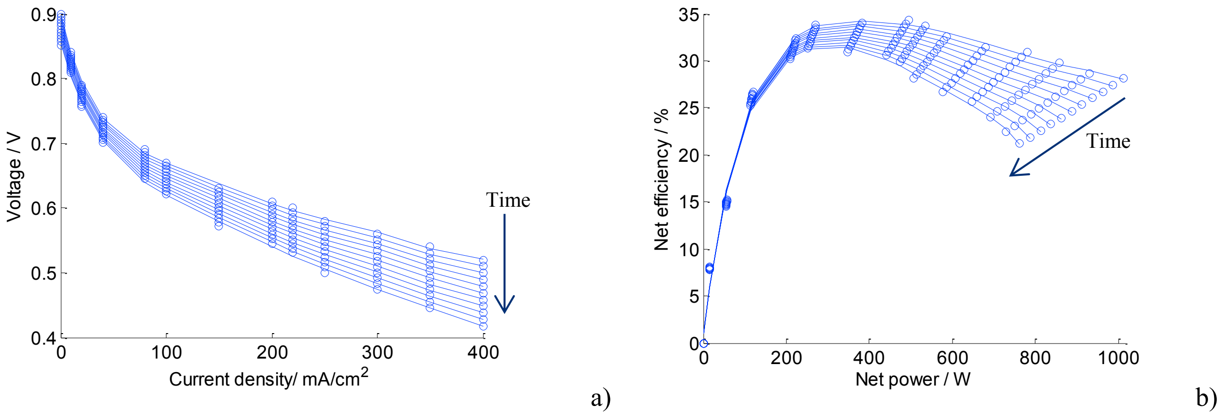

Fig. 1. (a) Cell polarization curves over one year of operation (DR1); (b) CHP system efficiency variation over one year of operation (DR1). Each curve represents fuel cell performance after 796 hours of operation.

In Fig. 1 (a) the polarization curves over time are shown. The obtained time-dependant polarization curves have been implemented in the previous described process model and the fuel cell system efficiency over time has been calculated. Fig. 1 (b) shows the CHP fuel cell system efficiency variation over time: it is possible to observe that higher performance losses occur at higher operating currents.

2.4. Thermal energy recovered

The heat generated by the fuel cell system is supposed to be stored in a water tank. In the simulation, it has been assumed that the water flowing from the tank can be heated by an auxiliary boiler to satisfy the heat demand [7].

2.5. Battery and power conditioning systems

For evaluating battery energy efficiencies, it has been chosen to refer to the experimental data presented in [9] where battery charging and discharging efficiencies are expressed as function of battery charging–discharging rates. Charging and discharging rates are defined as the ratio between charging or discharging current and battery capacity. The State of Charge (SOC) of the battery is defined as the amount of energy left in the battery compared to the energy it has when it is fully charge. For the power conditioning system constant efficiency values have been assumed.

2.6. System configuration, system operating strategy and test cases

The system performances have been calculated for 4 different system configurations:

- 1 kWel microCHP only;
- 1 kWel microCHP and battery storage;
- 1.2 kWel microCHP only;
- 1.2 kWel microCHP and battery storage;

and considering 2 different degradation rates DR1 and DR2. The 1 kWel fuel cell stack size configuration with no degradation, with or without the battery storage, is the reference case while the other cases are named "test cases" as described in Table 2. The configuration with a 1.2 kWel fuel cell stack has been taken into account in order to compensate the loss in electric energy production that is expected after one year of operation considering the DR1 degradation rate previously defined. In all cases, electricity led has been chosen as microCHP operating strategy. In particular, the following operating conditions are considered:

- electricity demand higher than the maximum fuel cell system electrical output: the fuel cell system works at the maximum capacity and battery is discharged. If battery SOC is below 20%, electric energy is imported from the grid;

- electricity demand between the lower and maximum fuel cell system electrical output: if battery is fully charged the fuel cell system follows the electrical demand;
- electricity demand lower than the minimum fuel cell system electrical output: if battery is fully charged the microCHP works at a minimum capacity and excess electricity is sold to the grid;
- battery charging operation: electricity demand is lower than 30% fuel cell system capacity. At this condition, the fuel cell system operates at 35% capacity (highest efficiency). Part of the electricity output is used to meet demand and part is used to charge the battery.

In the battery charging mode, the fuel cell load is maintained at the highest efficiency. Furthermore, it has been assumed that, in case of low energy requirements, the microCHP system runs at a minimum load (20%). For each considered configuration, the following system annual performances have been calculated and compared:

- AC electrical energy production;
- microCHP thermal energy production;
- exported electricity to the grid;
- imported electricity from the grid;
- auxiliary boiler energy production;
- primary energy saving index.

Table 2. System configuration and tested cases.

	Ref. Case [10] (Ref)	Test case 1 (TC1)	Test case 2 (TC2)	Test case 3 (TC3)	Test case 4 (TC4)	Test case 5 (TC5)
Degradation rate	-	DR1	-	DR1	DR2	DR2
Stack size (kW)	1	1	1.2	1.2	1	1.2

3. Results

3.1. Energy balance

Fig. 2, Fig. 3 and Fig. 4 show annual electrical and thermal energy production, annual exported and imported electrical energy and annual auxiliary boiler thermal energy production for the CHP system configurations previously defined.

Fig. 2 (a) shows system annual performance obtained for the reference case (Ref), while Fig. 2 (b) shows the test case 1 (TC1) where degradation rate 1 (DR1) is considered. In both systems with and without battery, fuel cell degradation causes a 10% annual electrical production reduction, and an increase of the thermal energy production of 4% and 6% respectively. Neglecting cost issues, in order to recover the annual electical energy loss due to the fuel cell performance degradation over time, it is necessary to consider a larger fuel cell stack. Fig. 3 (a) shows (TC2) where the stack power is 1.2 kWel and no degradation effect is considered, while Fig. 3 (b) shows (TC 3) where the same fuel cell stack power is considered and the degradation is taken into account. Comparing (TC2) and (TC3), the electrical production reduction due to degradation is about 8% while the increasing of thermal production is about 6%. However, when comparing (TC3) and (Ref) case the electrical producticon loss due to degradation is about 3%, as a bigger stack has been chosen.

Concerning thermal energy production, a 17% increase is obtained with respect to (Ref) case for both configurations with and without battery. In Fig. 4 the case with a higher degradation (DR2) is analysed.

Comparing Fig. 4 (a) (TC4) with the (Ref) case it can be noticed that the electrical power is reduced of about 18% and 20% due to degradation, while thermal power is increased of 4.5% and 9% in the cases with and without battery respectively. In Fig. 4 (b) (TC5), the case with 1.2 kW stack power output and (DR2) is shown. In this case, it can be noticed that, with respect to (Ref) case the electricity loss due to degradation is 9% and 7%, while the heat production is increased by 17% and 19% again in the cases with and without battery, respectively.

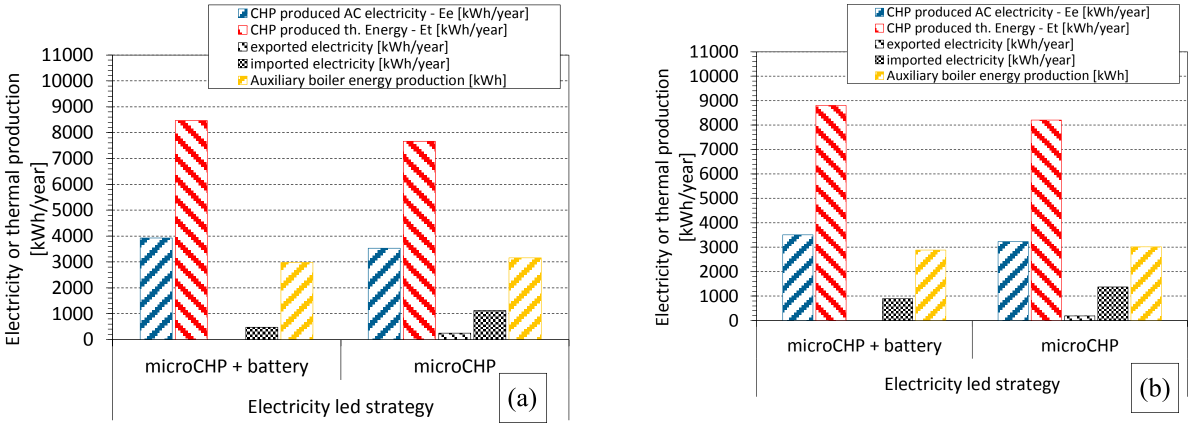

Fig. 2. Electrical (▨) and thermal (▨) energy annual production; annual exported (▨) or imported (▨) electrical energy; annual auxiliary boiler thermal energy production (▨); (a) Reference case (Ref) [10]; (b) degradation rate DR1 (TC1).

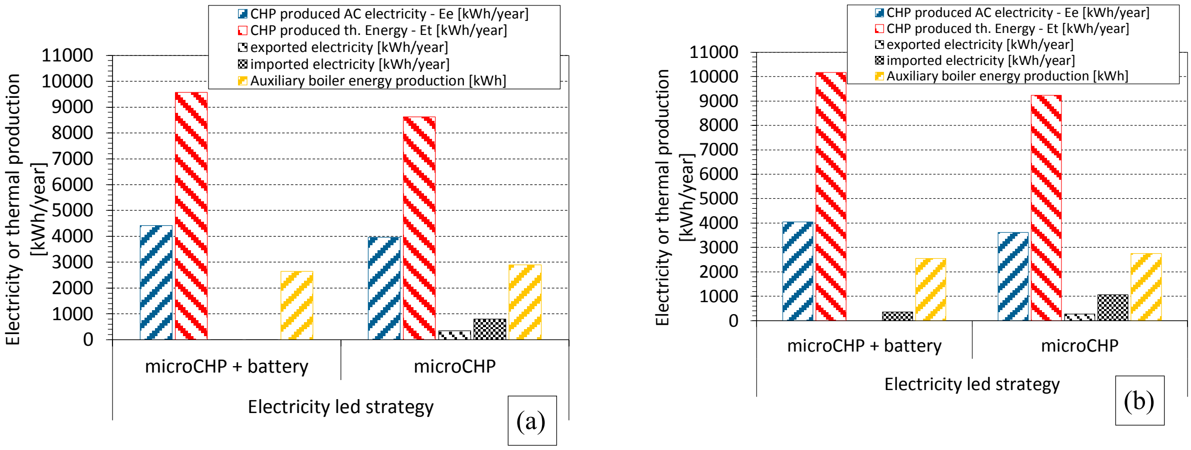

Fig. 3. Electrical (▨) and thermal (▨) energy annual production; annual exported (▨) or imported (▨) electrical energy; annual auxiliary boiler thermal energy production (▨). (a) 20% oversizing without stack degradation (TC2); (b) 20% oversizing, degradation rate DR1 (TC3).

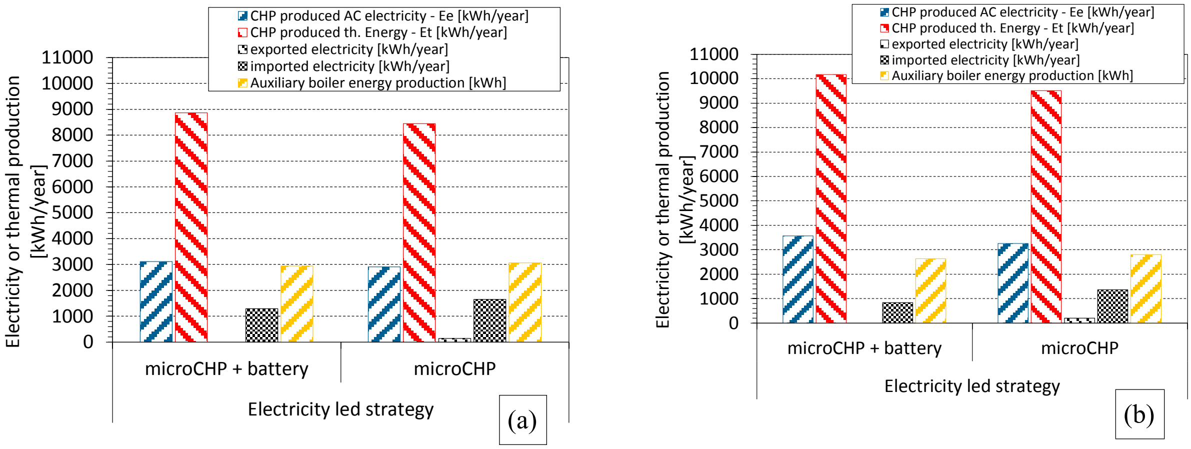

Fig. 4. Electrical (▨) and thermal (▨) energy annual production; annual exported (▨) or imported (▨) electrical energy; annual auxiliary boiler thermal energy production (▨). (a) degradation rate DR2 (TC4); (b) degradation rate DR2 and 20% oversizing (TC5).

3.2. Primary Energy Saving index (PES)

The test cases have than been analyzed in terms of a simplified Primary Energy Saving index (PES) defined as follows:

$$PES = 1 - \frac{E_f}{\frac{E_e}{\eta_{es}} + \frac{E_t}{\eta_{ts}}}$$

Where E_e and E_t are the produced electrical and thermal energy and E_f is the energy of the fuel feeding the fuel cell system in CHP configuration, while η_{es} and η_{ts} are efficiency reference values for the separate production of electricity (0.39) and heat (0.9), respectively. As the installed power is small, all the heat generated can be used and, therefore, the PES is always positive, reaching 0.22 in the (Ref) case with battery. In all the cases, the configuration with battery shows a higher PES. Values of PES for the different test cases are reported in Table 3.

Table 3. PES values for different test cases

Test case	PES	
	CHP + battery	*CHP only*
Ref. [10]	0.22	0.20
TC1	0.20	0.18
TC2	0.22	0.19
TC3	0.20	0.18
TC4	0.18	0.17
TC5	0.18	0.16

4. Conclusions

A battery integrated residential micro CHP system, based on HTPEM fuel cells technology, is analysed in terms of operational performance by means of an energy simulation model. The applied load profile consists of the electrical and heat demands for a single-family dwelling. In particular, the model allows assessing the impact of battery storage on system energy production, primary energy saving and on the import and export of energy from the electrical grid. Results indicate that, respect to a system without battery storage, micro CHP battery integration has the potential to satisfy the electricity demand and ensure higher primary energy savings. Stack degradation is still an issue that hampers the full exploitation of the technology. The effect of stack performance degradation over one year of operation is analysed. The detrimental effect can be mitigated choosing to increase the size of the stack, even if this condition affects system cost. Finally, the model can be a valuable tool for conducting sensitivity analysis, to provide insights in battery storage operations for determining battery expected life, find optimal size of system components taking into account the system performance degradation over time.

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