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Modelling and optimization of a flexible PEMFC power plant for grid balancing purposes

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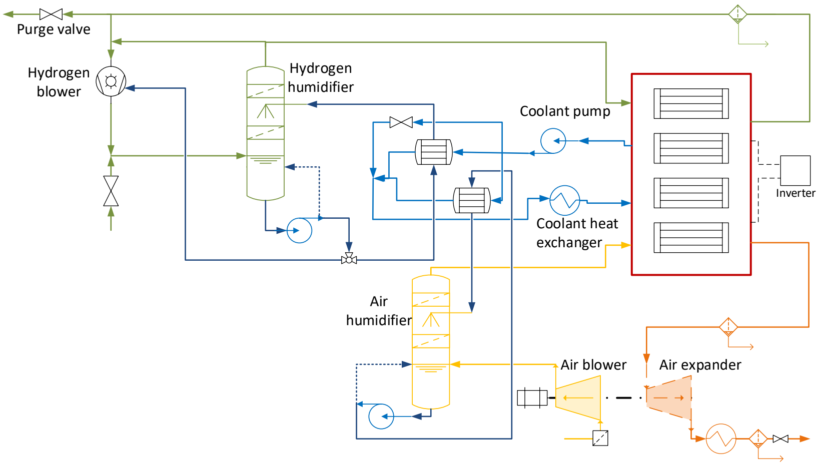
Abstract

Flexible power resources in the electric system, capable to rapidly ramp their electricity production or consumption, must compensate for the variability given by the increasing penetration of renewable energy sources. The EU project GRASSHOPPER[1] aims to setup and demonstrate a 100 kW_{el} PEM Fuel Cell Power Plant unit which is cost-effective, flexible in power output and scalable to MW-size, designed to provide grid support with a Demand Side Management program.
In this work, different layouts proposed for the pilot plant are simulated with Aspen Plus® for system performance evaluation, optimization of design and operating conditions. The system may operate at atmospheric or mild pressurised conditions (0.1-0.6 bar_g), using a compressor and optionally a turbine expander on the cathode exhaust side for energy recovery. The simulation includes a custom PEMFC model, reflecting the voltage dependence on pressure, relative humidity and gas composition. The main BoP components are also modelled in detail (see Figure). The increased voltage of the cell allows a slightly higher net system efficiency with pressurisation (taking into account increased BoP consumption) and the turbine adds nearly 2$\%_{pt}$ of net electrical efficiency, reaching 45$\%_{LHV}$.



Proposed layout for the 100 kW PEMFC pilot plant.

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Introduction

In Europe in the last years the share of renewable energy sources (RES) in the electricity production has grown according to the 20-20-20 targets [1] and is expected to grow even more to reach the ambitious targets specified in the EU 2030 Energy Policy Framework for climate change [2]. However, the increasing penetration of non-programmable RES may hinder the security and reliability of the transmission and the distribution grids, being their generation mainly uncertain and dispersed. To overcome these issues, it is necessary to evolve the system to more efficient networks. Many studies have investigated the effects that a high penetration of RES have in term of backup generation [3] and storage needs [4,5]; analysing options for grid improvement [6] and comparing introduction of storage systems as well as grid extension and repowering [7]. The concept of Smart Grid [8] is considered at international level, taking advantage of the increased intelligence and flexibility of the grid to facilitate the connection of DG units, increase the reliability and security of supply and allow the consumers to contribute in optimizing the operation of the system with Demand Response schemes.

Indeed, sufficient flexible resources [9], i.e. resources that can rapidly modify their electricity production or consumption to face an unbalance, must be present in the power system to cover the variability in net load. Within all the sources of flexibility, this work focuses on stationary Fuel Cells Power Plants (FCPP) based on low temperature Proton Exchange Membrane Fuel Cells (PEMFC). These plants, whose feasibility on a significantly large scale has been demonstrated in projects such as DEMCOMPEM-2MW [10,11], are seen as an essential technology for the future renewable based energy infrastructure [12] thanks to their very fast ramp rates and excellent load following capabilities that make them perfectly suited for grid balancing. It is therefore necessary to study how they can contribute to balancing the grid.

In this context, the EU project GRASSHOPPER [13] aims at analysing how distributed and fast-ramping fuel cell systems can be used to provide ancillary services and help balancing the grid. It will setup and demonstrate a 100 kW_{el} PEM FCPP unit which is cost-effective, flexible in power output and scalable to MW-size, designed to provide grid support with a Demand Side Management program.

1. Modelling Approach

In this work, two different layouts proposed for the GRASSHOPPER pilot plant (rated at 100 kW_{el} gross DC output) are simulated in order to support the decisional process for defining the plant layout, to support the plant design and engineering phase as well as to allow optimizing the plant expected operating conditions and evaluate its performance. The modelling activities are also relevant to investigate the behaviour of the system in off-design conditions, influencing the definition of an optimized plant control strategy.

A stationary model of the FCPP is developed in Aspen Plus®, building a network of components and calculating detailed mass and energy balances. The model includes the PEMFC and the main balance of plant components.

PEMFC model

A custom model is used for the PEMFC, considering a lumped-volume approach where the cell performances are dependent on the voltage-current polarisation curve. The polarisation behaviour is expressed through a semi-empirical equation, that simplifies the theoretical polarisation curve equation aiming at reproducing the real cell performances. The coefficients of this polarisation curve are regressed on the basis of experimental datasets. These data allow to evidence the influence on the performance of three operating parameters: stack backpressure, air ratio to stoichiometry and air relative humidity. The influence of the hydrogen stoichiometry is not included in the model since it is known from previous experiences that its influence on cells performances is low.

Equation *(1)* shows the polarisation curve formulation, whose coefficients are regressed with experimental data; the first two terms represent an apparent open circuit voltage and its change with pressure and air ratio to stoichiometry, the third term represents the ohmic losses and the last two terms represent the activation and the concentration losses respectively.

$$V_{cell} = OCV + K_{S_a,p}\, ln(x_{O_2} \cdot p) + i\,\left(R_{ohm,1} + R_{ohm,2}\left(1 - \frac{x_{H2O}}{x_{H2O,rif}}\right)^{G_{ohm}}\right) + K_{act}\, ln\left(1 + \frac{i}{i_0\left(\frac{p}{p_{ref}}\right)^{G_{act}}}\right) + K_{conc}\, ln\left(1 - \frac{i}{\left(i_{L,1} + i_{L,2}\frac{x_{O_2}}{x_{O_2,rif}}\right)\left(\frac{p}{p_{ref}}\right)^{G_{conc}}}\right) \quad (1)$$

In this formulation, the effect of the air ratio to stoichiometry is included considering the dependence of the open circuit voltage and of the limiting current density on the oxygen molar fraction. On the contrary the dependence of the exchange current density on the oxygen molar fraction is not expressed because it resulted negligible. The effect of the backpressure is included in the open circuit voltage and in the activation and concentration overvoltage, since it influences both the exchange current density and the limiting current density. The voltage dependence on the air relative humidity is introduced in the ohmic resistance term, since the membrane conductivity is dependent on the number of water molecules that are present.

Figure 1 shows how the regressed polarisation curves fit the experimental data at different pressures. Relative errors are always below 8% and they remain below 3% in the common operating conditions, i.e. for currents below 1500 mA/cm^2. Regressions are made for a single cell.

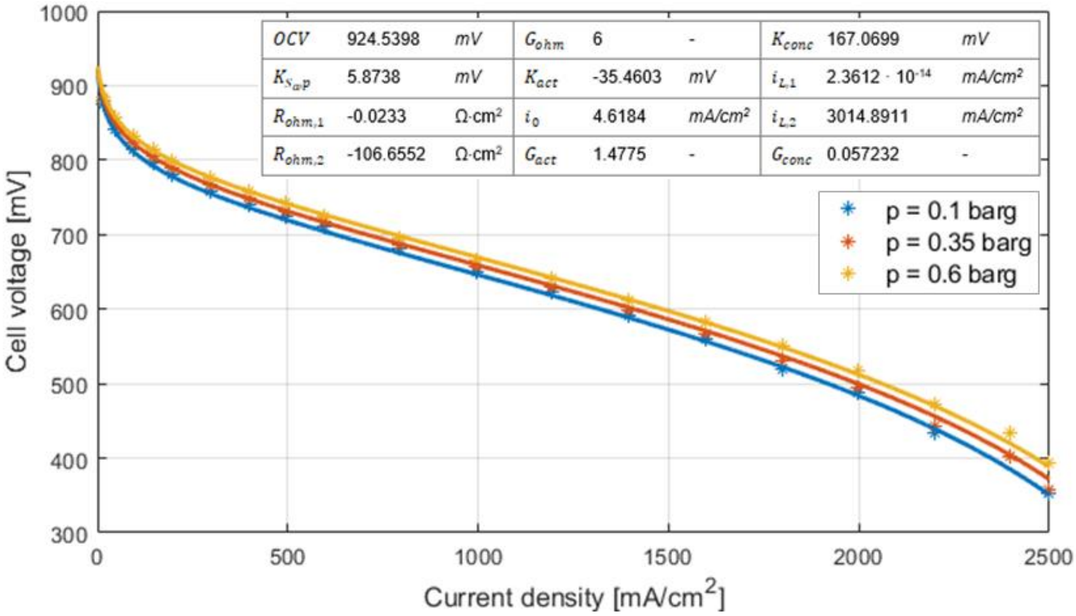

Figure 1 – Comparison between experimental and regressed curves.

The model assumes that cells are electrically connected in series to form a stack and stacks are in turn connected in series to form a module (details are omitted here for confidentiality). The total number of cells is determined in order to be able to generate 100 kW of gross DC power at nominal operating conditions for the cells (see *Table 1*). The model computes then energy and mass balances to determine outlet gas conditions. Pressure drops in the channels are considered dependent on the volumetric gas flow rates.

Table 1 – Stack nominal operating conditions

Nominal operating conditions	
Nominal current density	1 A/cm^2
Air ratio to stoichiometry	2
Hydrogen ratio to stoichiometry	1.5
Air / H2 average RH over the stack	100 %
Stack backpressure	0.1 bar$_g$
Stack temperature	70 °C
Coolant temperature gain over the stack	10 °C

Main Balance of Plant (BoP) components

The main BoP components that are included in the model are shown in *Figure 2.*

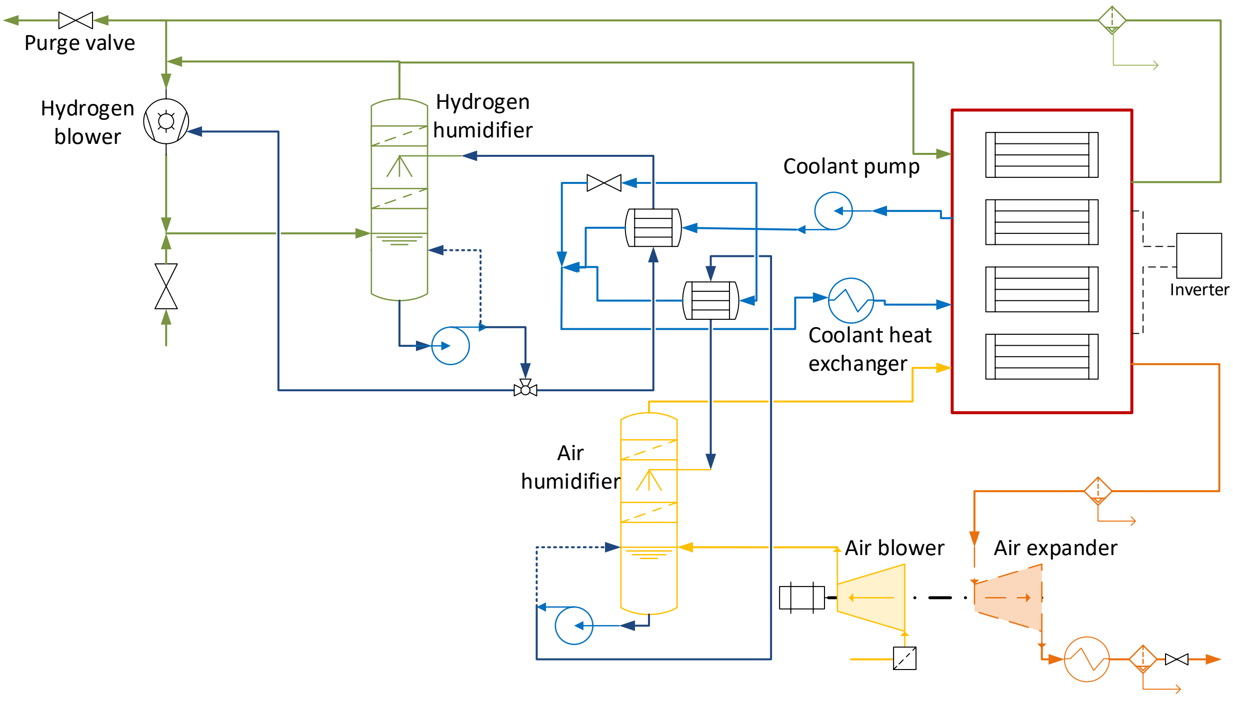

Figure 2 – Proposed layout for the 100 kW PEMFC pilot plant.

Fresh air is compressed, humidified and sent into the FC. A backpressure valve is then installed to keep the system pressurised and investigate the plant behaviour under mildly pressurized conditions. Two different options are considered:

- Option A: air exiting the cathode is cooled in order to condensate the water vapour. Air is then expelled into the atmosphere;
- Option B: air that exits from the cathode is sent into an expander in order to recover energy. Air is then cooled to condensate and separate the demineralized water and finally expelled.

Exhaust hydrogen is compressed to overcome the pressure drops, recirculated and mixed with pure hydrogen which is assumed to be available at the plant inlet at a minimum pressure of 2 bar. Hydrogen is then humidified with a dedicated loop. A small amount of water is continuously recirculated internally to the humidifier to be filtered. A purge valve on the hydrogen line is required to avoid inert gases build-up.

Both for air and hydrogen humidification, shower-type humidifiers are adopted. These humidifiers are water scrubbing units, that have also the function of removing possible pollutants from the inlet flows. These components are simulated by discretizing the columns along the direction of the flows in 4 sections and solving mass and energy balances assuming water-liquid equilibrium conditions in each discretization section. The reactants temperature at the humidifier outlet is controlled to obtain the relative humidity that is required in each operating condition. The heat necessary to control the humidifiers temperature is obtained from the hot side of the cooling circuit; the coolant fluid temperature is then further decreased to the desired stack inlet value in a heat exchanger dedicated to heat rejection. Heat exchangers are modelled considering the respective heat transfer areas and empirical correlations reproducing the dependence of global heat transfer coefficients and pressure drops on the flow rates (Table 2).

Table 2 – Heat exchanger characteristics

Heat exchanger	A [m^2]	$U_{nominal}$ [W/m^{2}K]	U dependence on flow rate
Coolant – air humidifier loop	1.530	3170	$U = U_{nominal}\left(\frac{\dot{m}}{\dot{m}_{nominal}}\right)^{\frac{4}{5}}$
Coolant – H_2 humidifier loop	0.105	6200	
Coolant heat exchanger	6.630	2960	

For hydrogen compression a liquid ring compressor is considered while for the incoming air a volumetric blower is adopted. For Option B, it is assumed that the expander is a volumetric machine coupled with the compressor on a single shaft. In this way, the expander directly provides part of the mechanical power requested by the compressor. The values of the efficiencies assumed in the simulations for compressors, the expander and pumps are reported in *Table 3*. The inverter efficiency is assumed equal to 95%.

Table 3 – Efficiencies of the BoP components

Auxiliary component	Isentropic efficiency	Mechanical efficiency
Pumps	70 %	90 %
Liquid ring compressor	9 %	85 %
Air blower	Functions of flow rate and pressure gain (*Figure 3*)	
Expander	80 %	90 %

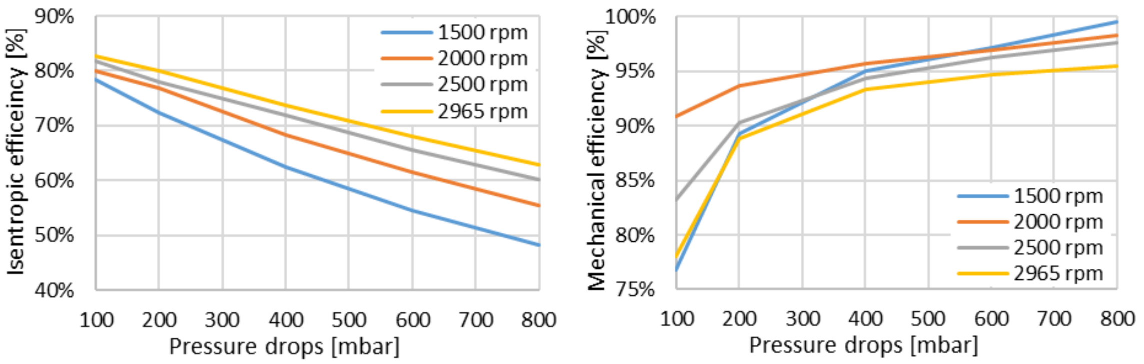

Figure 3 – Air blower efficiency curves

2. Simulations

The FCPP model described in the previous chapter is used to compare the performances of the 100 kW plant in different operating conditions. Performances are express in term of gross and net electric efficiencies – Eq. (2) and (3) - where the first one represents the efficiency of the PEM fuel cell only and the second one, depurated from the DC/AC inverter losses and auxiliary power consumptions, represents the overall efficiency of the plant. The energy input to the system is computed according to the Lower Heating Value (LHV) of the hydrogen feed stream.

$$\eta_{GROSS} = \frac{P_{FC}}{m_{H_2} \cdot LHV} \tag{2}$$

$$\eta_{NET} = \frac{P_{FC} \cdot \eta_{inverter} - P_{auxiliaries}}{m_{H_2} \cdot LHV} = \frac{P_{NET}}{m_{H_2} \cdot LHV} \tag{3}$$

In the project perspective, coherently with the scope of offering ancillary services, the plant is expected to work most of the time at partial load conditions. Simulations should therefore analyse the plant performances not only at the nominal operating point but also in off-design conditions. For this purpose, simulations are run in correspondence of a range of currents between 20% and 150% of the nominal current value (i.e.1 A/cm^2).
The possibility of increasing the efficiency by working in mild pressurised conditions is also explored in the simulations. Simulations are performed both at ambient pressure and at slightly pressurised conditions (below 1 bar$_g$) to analyse how pressure influences the gross efficiency and the consumptions of the auxiliaries and how these effects are reflected on the plant net efficiency. For each chosen operating condition, plant simulations are performed with both layouts options A and B, allowing to understand under which operating conditions the introduction of the air expander may bring significant advantages.

Table 4 summarizes the simulation cases; air and fuel ratio to stoichiometry are always kept constant at the nominal values (2 and 1.5 respectively) by varying the reactants flow rates while changing the electric load. The coolant flow rate that passes through the cells is also varied: it is decreased with the load to avoid excessive low temperatures at FC outlet, and increased at high loads to limit the maximum temperature gain. This is possible by regulating the rotational speed of the dedicated pump. Ambient temperature is always assumed equal to 15°C.

Table 4: Summary of the simulation cases

Case 1	Case 2	Case 3	Case 4
Ambient pressure	Ambient pressure	Pressurised (0.6 bar$_g$)	Pressurised (0.6 bar$_g$)
Option A (no expander)	Option B (with expander)	Option A (no expander)	Option B (with expander)

3. Results

Simulation results show that the designed plant is fully controllable in term of temperature, flow rates and air relative humidity, able to reach the desired values for any current density and for both low and higher FC backpressure. Indeed, full controllability of these parameters

is given by the inclusion of two separate circuits for air humidification and stacks cooling and by the arrangement of the coolant heat exchangers in parallel configuration with a bypass system. The possibility of using an ethylene glycol/water mixture to cool the stacks, allowed by the use of a separated coolant circuit, is also interesting for possible fully independent applications in cold climates.
On the contrary, in some cases it is not possible to fully control the hydrogen relative humidity, which - as a consequence of the hydrogen recirculation through a liquid ring compressor - can be higher than required. In such cases it would be therefore necessary to cool down the hydrogen humidifier.

Figure 3 shows the net power output and the corresponding gross and net efficiencies, obtained in each case by varying the current density from 20% to 150% of the nominal value. The higher gross efficiencies are reached at higher backpressures (Case 3 and Case 4) for any given net power output. On the net efficiency point of view, it can be highlighted that maximum net efficiency at full power is reached with Case 4, i.e. at max pressure with expander. The introduction of the air expander is instead obviously not attractive at low pressures (Case 2). At partial loads, the maximum net efficiency is reached at nearly 30kW at low pressure (Case 1 and 2), approaching 50% net; while it is reached at ~60 kW at higher pressure (Case 3 and 4), with Case 4 close to 48.5%.

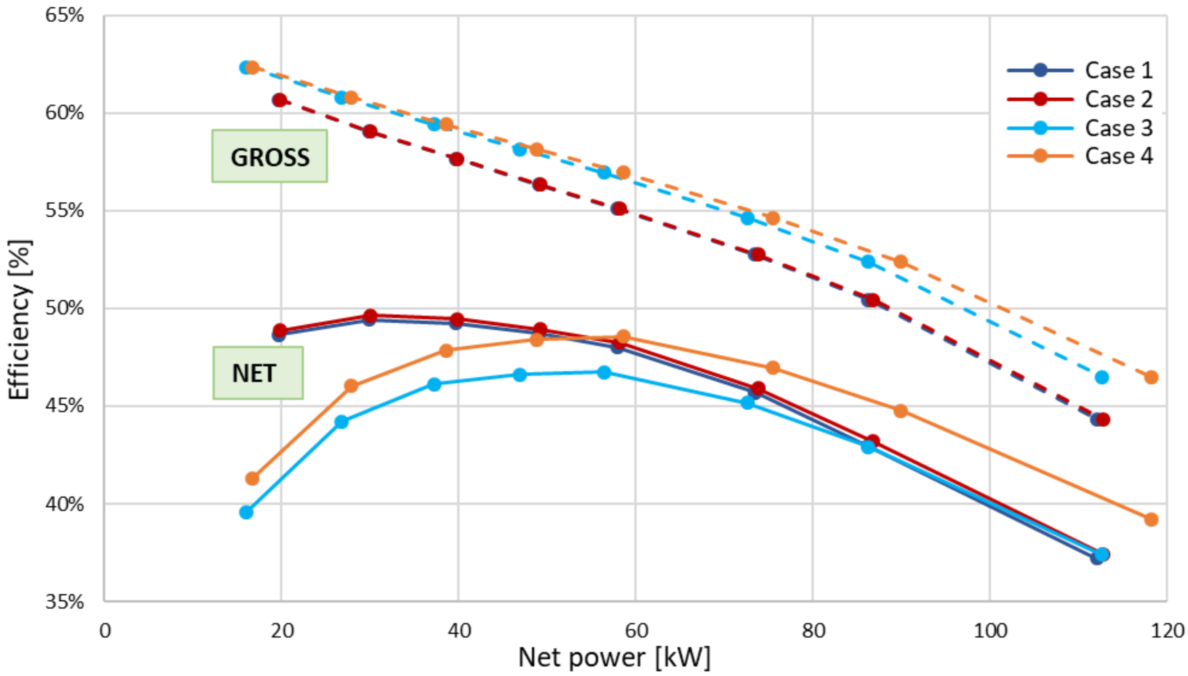

Figure 3 – Gross & net efficiency Vs net power

Figure 4 shows the total power consumed by the plant auxiliaries as a function of the net power. Auxiliaries consumptions always increase by increasing the net power except in Case 4, where in the range 20-60 kW they remain almost constant; in this range the additional power required by the auxiliaries when the load increases is perfectly counterbalanced by the additional power that the expander is able to provide by expanding air from 0.6 bar_g to ambient pressure.
Figure 5 shows the percentage gain in the net power output obtained with respect to the case at low pressure without expander (Case 1), at constant current density, i.e. at constant hydrogen consumption. It is clear that it is not effective to pressurize the stacks at low loads, where pressurisation leads to a net power loss higher than 15% with respect to the base

case. Pressurisation becomes attractive at higher loads if an expander is also installed, giving the possibility of a 5% gain in net power output.

A further gain in the net power output can be reached saving energy during compression by substituting the blower (assumed here to operate with the efficiency curves of Fig.3) with a more efficient machine, like a radial compressor. For such a system it is also more customary to have the compressor and turbine running on the same shaft, like in conventional turbochargers for the automotive industry, thus decreasing the electrical losses. The system envisaged would be in this case similar to units which are currently designed for mobility applications of PEM fuel cells.

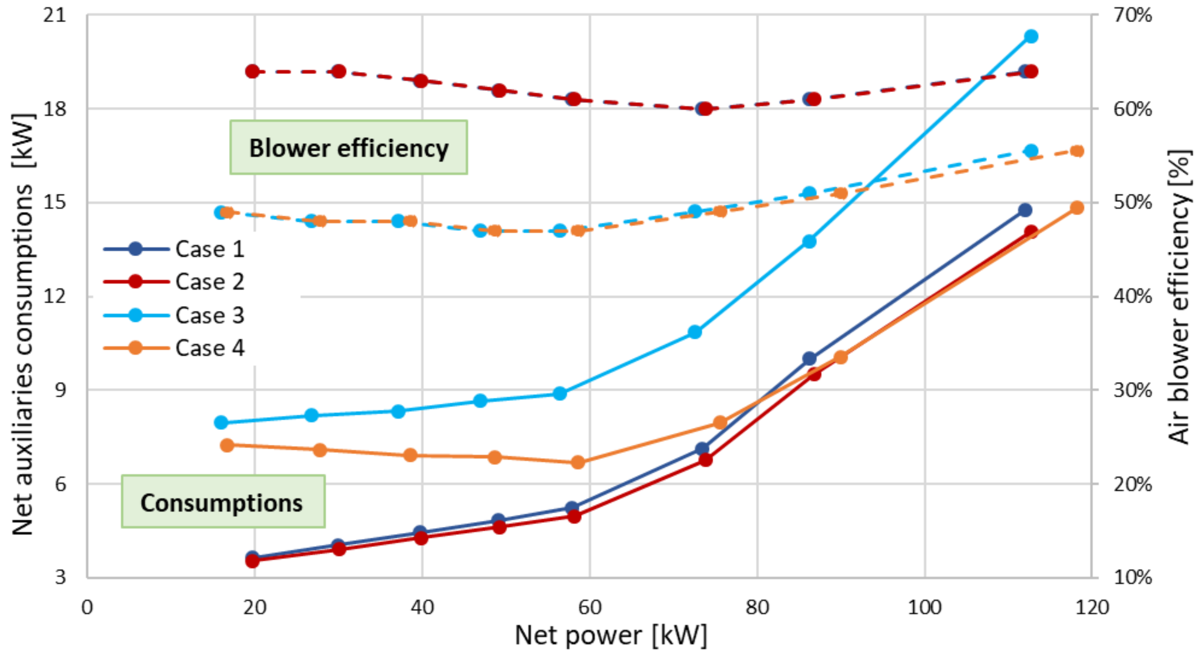

Figure 4 – Total auxiliaries consumptions and air blower efficiency Vs net power

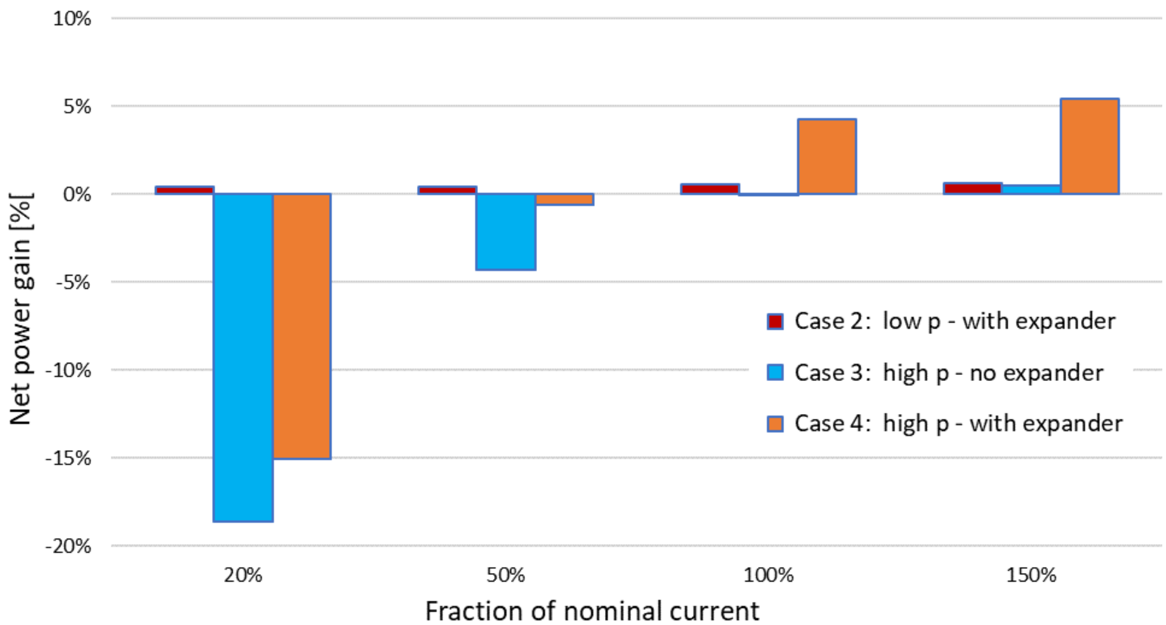

Figure 5 – Efficiency gain with respect to low pressure case without expander (Case 1).

References

[1] European Commission, Directorate–General for Energy, “Energy 2020: A strategy for competitive, sustainable and secure energy”. COM(2010) 639 final, 2010.

[2] Council of the European Union, European Parliament, Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources. Official Journal of the European Union. December 2018

[3] H.C. Gils, Y. Scholz, T. Pregger, D.L. de Tena, D. Heide, “Integrated modelling of variable renewable energy-based power supply in Europe”. Energy, 2017.

[4] J.R. Doyle, H. Johlas, “Energy Storage Considerations for High Renewable Power Penetration: A Case Study”, in: S. SenGupta, A.F. Zobaa, K.S. Sherpa, A.K. Bhoi (Eds.), “Advances in Smart Grid and Renewable Energy”. Springer, Singapore, 2018.

[5] X. Luo, J. Wang, M. Dooner, J. Clarke, “Overview of current development in electrical energy storage technologies and the application potential in power system operation”. Applied Energy, 2015.

[6] GridTech, “Deliverable D4.2: Analysis and discussion of the results of the four pan-European scenarios on the implementation of new innovative technologies fostering RES-Electricity and storage integration”.

[7] F. Steinke, P. Wolfrum, C. Hoffmann, “Grid vs. storage in a 100% renewable Europe”. Renewable Energy, 2013.

[8] Ilhami Colakabe, Gianluca Fullia, Seref Sagirogluc, Mehmet Yesilbudakd, Catalin-Felix Covriga, “Smart grid projects in Europe: Current status, maturity and future scenarios”. Applied Energy, 2015.

[9] IEA (International Energy Agency), “Harnessing Variable Renewables”. 2011.

[10] EU project “DEMCOPEM-2MW”. [Online]. Available: http://www.demcopem-2mw.eu/project/. [Accessed: 10/05/2019].

[11] S. Campanari, G. Guandalini, J. Coolegem, J. ten Have, P. Hayes, A. H. Pichel “Modeling, development and testing of a 2 MW PEM fuel cell plant fueled with hydrogen from a chlor-alkali industry”, Journal of Electrochemical Energy Conversion and Storage (JEECS), doi 10.1115/1.4042923, 2019.

[12] Fuel Cells and Hydrogen Joint Undertaking (FCH JU), “Multi-Annual work plan 2014-2020”. 2014.

[13] EU project “GRASSHOPPER”. [Online]. Available: http://www.grasshopperproject.eu/ [Accessed: 10/05/2019].