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GRASSHOPPER project: grid assisting modular hydrogen PEM power plant

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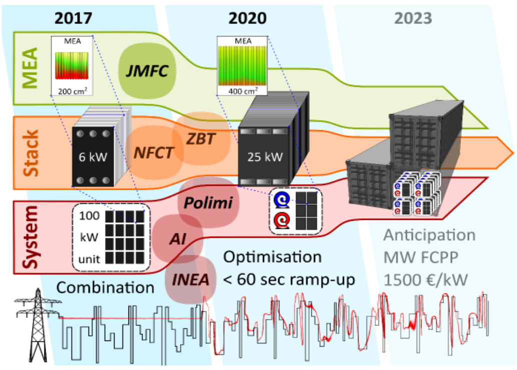
Abstract

The Fuel Cell Power Plant (FCPP) developed by the GRASSHOPPER consortium will represent a next-generation MW-size PEM FCPP, more cost-effective and flexible in power output (estimated CAPEX below 1500€/kW_e at a production rate of 25 MW_e / year), designed for grid support and participation to flexibility trading and renewable energy markets.
The power plant will be demonstrated through a 100 kW sub-module pilot plant, implementing newly developed improved stacks, MEAs and BoP components, combining benefits of coherent design integration. This unit will be operated continuously for 8 months in industrially-relevant environment in Delfzijl (NL), engaging grid support modulation as part of an established on-site Demand Side Management (DSM) program. The flexible demand-driven operation will be demonstrated in the range 20-100 kW with a ramp-up rate delivering 50 kW within 20 seconds and 100 kW within 60 seconds. Innovative DSM programmes will be completed to establish the best path forward for commercialization of the technology for a fast response FCPP. A prototype software interface to be used as a tool for aggregating and trading flexibility for offering services to the grid will be developed and will particularly enable integration of flexible FCPP into the DSM portfolio.



Concept and project delineation

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Introduction

Renewable energy is at the core of Energy Union's priorities. According to the Energy Directive 2009/28/EC, the member states of the European Union (EU) have to produce at least 20% of their total energy consumptions using Renewable Energy Resources (RES) by 2020 [1]. Even more ambitious targets are specified in the EU 2030 Energy Policy Framework for climate change (the Clean Energy for All Europeans package) and the Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources includes a binding renewable energy target for the EU for 2030 of 32% [2].

To reach these targets, a key contribution is given by increasing the share of electricity production from RES. Anyway, these higher share of RESs production that is uncertain, irregular and often distributed, causes demand-supply imbalances, more frequent occurrence of grid congestion, volatility and increase in the wholesale electricity price. Furthermore, due to the low power factor of RES, costly investments are necessary to have a sufficient capacity to support generation at few hours of peak.
To overcome these issues, the Clean Energy for All European package [3] has introduced new electricity market design rules in order to help the energy markets to include more renewables, empower consumers, and better manage energy flows across the EU. With these new energy market rules, consumers are put at the heart of the transition, giving them more choice and greater protection. With Demand Response (DR) schemes and infrastructures they are enabled to participate actively in the energy market, varying its consumptions and/or production in response to price changes in order to profit from the optimal price conditions. In this way, prosumers (i.e. who both produces and consumes) makes the grid more efficient and contribute to the integration of RES.

In this framework, GRASSHOPPER project focuses on FCPP (Fuel Cell Power Plant) technologies as flexibility enabler for prosumers through the use of hydrogen. The implementation of the FCPP technologies on the market will benefits for the new energy market rules. The introduction of scarcity pricing and the possibility to produce and sell electricity to the market on the base of price signals, allows FCPP technologies to take advantage of instantaneous market remuneration, thus creating the opportunity for longer-term investment in this technology.

The plant layout that has been considered so far is shown in *Figure 1*

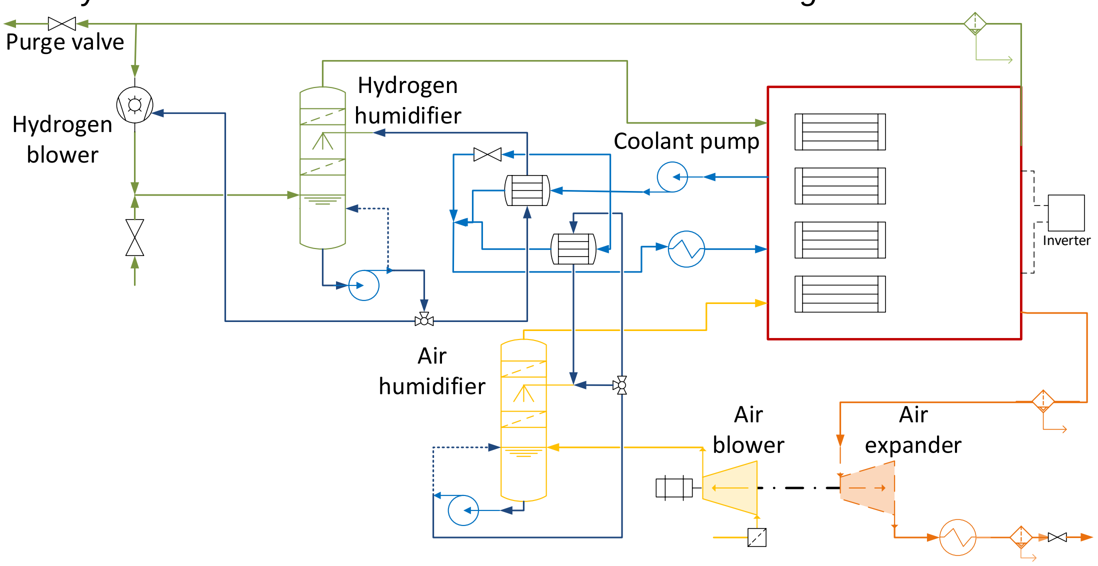

Figure 1 – 100 kW pilot plant Layout.

1. Grasshopper project concept and delineation

The technical feasibility of large MW-size PEM Fuel Cell Power Plant (FCPP) has been well demonstrated, for example in the DEMCOPEM-2MW project (FCH-JU 2015) [4,5]. However, the cost assessment of this 2-MW power plant shows a too high Capex level (4175 €/kW). Furthermore, this plant was operated without dynamic operation features for grid support. Therefore, a major step in the reduction of fuel cell stacks and system costs is still needed, together with the dynamic operation capability that is a new necessary feature to participate in renewable energy markets.

The GRASSHOPPER (GRid ASsiSting modular HydrOgen Pem PowER plant) project, that has started the 1st of January 2018 and will last 36 months, tackles these issues in order to enable a controlled, renewables-based energy infrastructure.
The goal of GRASSHOPPER is to realise a major step change in the cost structure of existing FCPP, realizing the next-generation modular Fuel Cell Power Plant unit targeting stationary application in the MW scale (such as > 2 MW) grid stabilization.
The FCPP will be more cost-effective and flexible in power output, accomplishing an estimated CAPEX below 1500 €/kW_e at a yearly production rate of 25 MW_e. This level is required to enter the markets as a competitive player.

Figure 2 shows the anticipated reduction of the CAPEX of multi-MW PEM FCPP, indicating the necessity of a major step change in cost reduction.

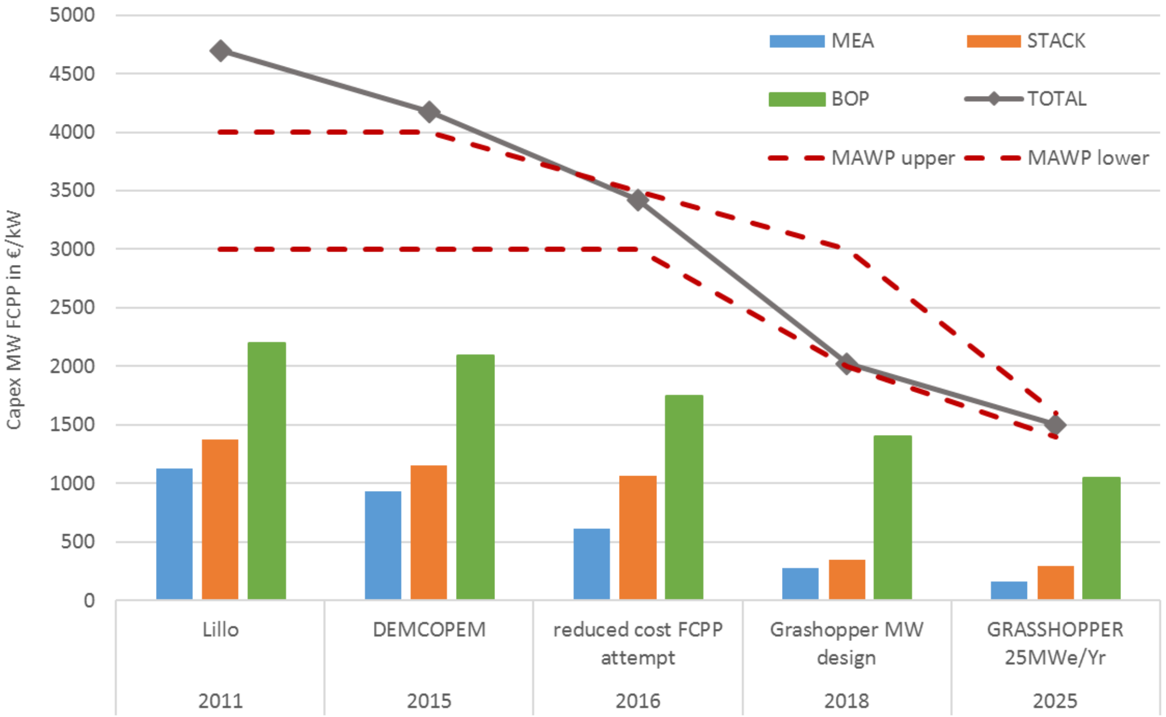

Figure 2 – Reduction of CAPEX in the multi-MW FCPP.

The consortium has the leading experience with building, operating and maintaining FCPP and hence a good understanding of what is needed to meet efficiency, performance and lifetime expectations. Scaling-up production volume alone is not sufficient to achieve 2023 target CAPEX costs of 1500 €/kW. First a design optimisation is proposed, coherently improving MEA, Stack and System together to realise a next-generation modular unit that does achieve the cost target when produced at scale. Thus, a first major step to approximate 2000 €/kWe will be made with the Grasshopper MW FCPP design and the target of 1500 €/kWe will be reached in the second stage via roll out to 25 MWe/year.

The MW-size FCPP unit will be based on the learnings from a 100 kW sub-module pilot plant, that will be demonstrated in the field. The 100 kW pilot plant will implement the design optimization; the power output will be increased from 6 to 25 kW_e to reduce system complexity and the operating pressures will be increased to improves the dynamic load range and flexibility. The 100 kW plant is large enough to implement cost savings and validate operation flexibility and grid stability capability via fast response.

The feature of flexibility and grid support functionality will be introduced by using a smart grid integration. The flexible demand driven operation will be demonstrated with a set point range between 20 kW and 100 kW and a ramp-up rate delivering 50 kW within 20 seconds and 100 kW within 60 seconds. This unit will be operated continuously for 8 months in industrially-relevant environment in Delfzijl, the Netherlands, for engaging grid support modulation as part of an established on-site Demand Side Management (DSM) programme. There is the intention of the consortium to keep the FCPP operating for 5 years after the project end. This will help to showcase the technology for interested parties, demonstrate the viability of the technology on medium term and serve as experimental validation of the operational costs for the system.

Project concept and delineation is summarized in *Figure 3.*

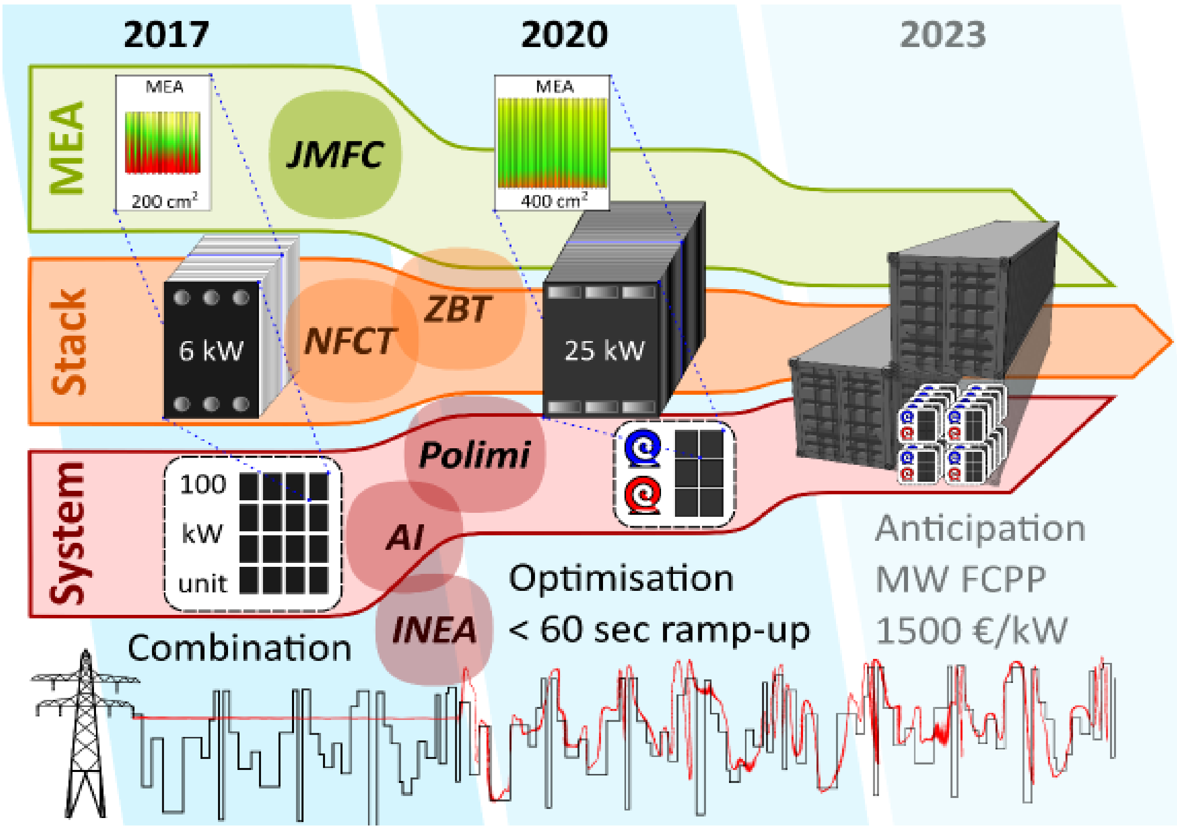

Figure 3 – Concept and project delineation

2. The project methodology and objective

Overall approach and methodology of the work plan consider a parallel approach, in which modelling activities and engineering activities for MEA, FC stack and FCPP are performed in parallel, with a continuous flow of information among the 6 members of the consortium.

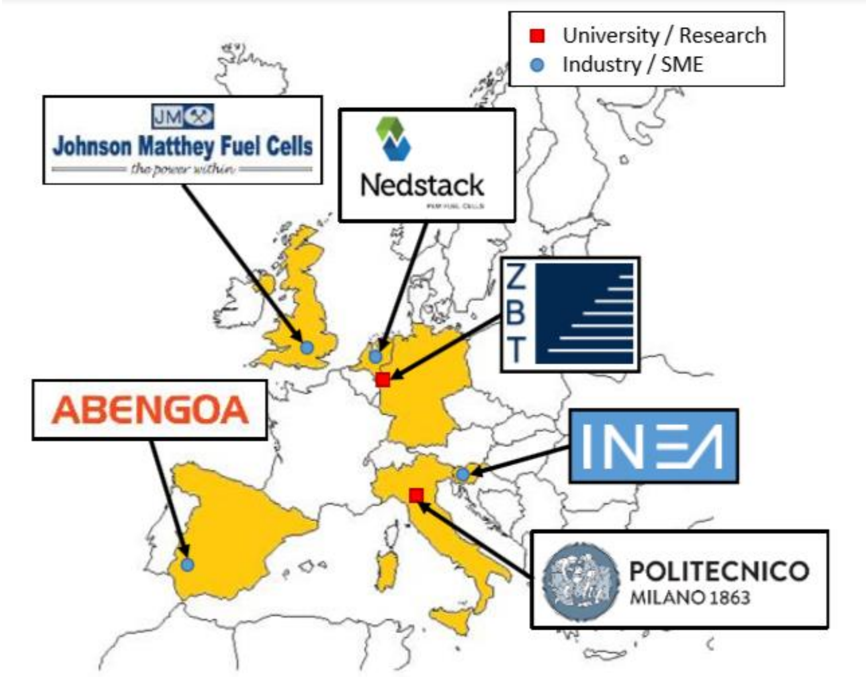

Figure 4 – Members of Grasshopper consortium

Taking DEMCOPEM-2MW in 2017 as the starting point, major cost reductions in MEA, stack and system need to be achieved by JMFC, NFCT and AI. This will be done for an important part by developing new stacks of larger sizes and higher power density, with improved MEAs and BoP system components. The step change in stack design is supported by modelling work from ZBT, which has extensive know-how on stack modelling and design. JMFC focuses on the MEA cost maintaining durability. POLIMI and AI focus on cost reduction of the FCPP BoP, using a wide knowledge of components of other industries such as AI manufacturing knowhow and POLIMI model of the overall system and component integration to reach optimal efficiency. In this way, the benefits of a coherent design integration will help to achieve cost and technical optimization. INEA will take care of the interface with the grid by bringing in the experience of the GOFLEX project; the feature of flexibility and grid support functionality will be introduced by using a smart grid integration.

The state of art and proposed improvements that will be realized in the project on MEA, stack and balance of plant are presented in the following paragraphs. Subsequently, the connection and integration with the local grid and local plant installation are described, as well as modelling, optimization and performance monitoring activities.

Targeted advances in PEM FC MEAs

Long lifetime PEMFC MEAs for large-scale stationary power generation applications require well over 20,000 hours of continuous operation, and thus have technical requirements which are very specific compared to automotive and small-scale stationary applications. The drive to reach higher power densities has not been the primary focus, whereas the requirement for stability and durability are of prime importance. The state of art MEA for large scale stationary application necessitate the use of a thicker membrane than automotive (up to 30 µm) to maintain durability, bonded catalysed substrate construction and high loaded cathode catalyst, which are incompatible with automotive type catalyst coated membrane (CCM) constructions.

Using a CCM MEA construction up to 75% lower Pt loading on a per unit power density basis than the current design is envisaged, thanks to thinner, higher quality printing, as well as reducing manufacturing costs by up to 65% on a cost per unit power basis, improving yield by 10% and providing the large scale stationary industry as a whole with a cost-effective MEA. The change to a CCM type process will also enable the use of cheaper gas diffusion substrate as the base-layer quality and porosity does not become the print quality limiting factor.

JMFC will mainly work on the realisation of improved MEAs with improved performance, no loss of durability and lower costs. The main activities are on the development of mechanically reinforced membranes, the integration of these membranes and catalyst layers to design and test CCMs, the scaling of CCM manufacturing to the volumes required for the stack validations and finally the integration of the CCMs within the new stack design.

Targeted advances in PEM FC stacks

Nedstack has shown long lifetimes and has successfully demonstrated its current stack technology for stationary MW-scale power plant applications (e.g. in the DEMCOPEM-2MW project). However, for successful future commercialization stack costs need to reduce drastically. This will be achieved mainly by step-increase in stack size and in power density.

Step-increase in stack size will be reached via a new cell plate design that will allow to increase the maximum cell count, reducing the stacks number and consequently the costs that are one-off per stack. The active area will be also increased and a new cell plate composition will allow for higher operating temperatures and lower cell plate thickness. Step-increase in power density will be achieved by running at higher current density, to fully utilize the stack power potential, and at different operating conditions, such as higher inlet pressures for hydrogen and air for stable operation at high current densities as well as fast dynamic responses. The stack housing design will be simplified and designed for mass production to reduce weight, volume and costs. Also a new gasket design will be required, as well as a different gasket material and gasket production process. This activity will be a joint development between NFCT and ZBT.

ZBT is responsible of the optimization of the fuel cell stacks flow field and of the operation point and operation strategy. A stepwise optimization of cell internal water management and cell operational uniformity linked to the external media conditioning and controls will lead to an optimized flow field and a streamlined operational strategy. Beside the most efficient working point, the operational stability of the new stack generation is in focus of numerical and experimental optimization both for the stack and the surrounding system and controls.

Targeted advances in the Balance of Plant

Stationary FCPP consists primarily of the fuel cell stack and the balance of plant (BOP) components. The BOP includes items such as humidifiers, valves, compressors, pumps, wiring, piping, meters, controls, instrumentation, manifolds etc. that are associated with the complete operation of the fuel cell system. As can be evidenced from previous work [6] the BOP can actually be the dominant cost driver in FCPP's.

To reduce these costs, design efforts towards easy fabrication and modularity are necessary. Improvements for both cost reduction and system efficiency increase have been identified by ABENGOA.

Improvements in the power electronics can reduce significantly the costs since part of the cost of BOP is covered by power subsystem, mainly the inverter and the converter. The traditional inverters used for FC system are expensive and have efficiency in the range of 95-96%. There are low cost inverters in the market used for solar PV plant, with efficiency above 98%, and FC systems may be designed to have a voltage that matches these commercially available solar inverters. In this project, companies making these inverters will be approached to purchase inverter for 100 kW pilot plant and to evaluate the available options for MW sizes. Further reductions in power electronics costs are going to be addressed in the current project after careful analysis of different levels of centralization (e.g number of inverters for a specific power) without compromising system availability and serviceability. In case the FCPP has to be operated off grid, the system should be hybridized with battery/supercapacitors [7]. The main challenge in designing a fuel cell system for off-grid operation is matching the stack variable voltage over the desired load range with the battery system while keeping it in an acceptable range for the DC/AC inverter. The most straightforward design is to have a DC/DC converter between the fuel cell and battery bus to keep the stack output voltage in a proper range for the battery and the DC/AC inverter. However, a DC/DC converter adds a significant cost to the system. Another option is to use a three-port hybrid converter, an emerging technology designed and marketed for PV applications, that is more economical than discrete components.

The power increase per stack will reduce the number of connections, valves and other components, decreasing the manufacturing costs. Efficient compressors will contribute to the efficiency of the complete system while the use of standard instead of customized containers will significantly contribute to cost reduction.

Integration with the local grid and local installations

Promising solutions to overcome the issues that comes from the pervasive emerging of distributing non programmable RES have been proposed in a number of technological areas. The challenges of modernizing the electricity grids in Europe lie in enabling an increased flexibility of the European power system, efficiently providing increased transfer capacity and enabling an active participation of users and new market actors. Demand Response schemes and infrastructures offer various incentive frameworks and solutions for making a prosumer active, so it varies its electricity consumption and/or production in response to direct commands or economic rewards, for: offering ancillary services, e.g. to aggregators, balance responsible parties (BRPs), distribution system operators (DSOs); creation of microgrids and virtual power plants (VPPs), to exploit flexibility in demand and supply. On the market, there are many technologies enabling to integrate prosumers in DSM programmes. EU Commission with "Clean Energy for All Europeans" package

(November, 2016) for clean energy transition is supporting new technologies and approaches to increase available prosumer's flexibility.

FCPP are to be competing with other available sources of flexibility. To showcase the benefits of FCPP for using its flexibility for grid support, for counter-balance peaks and drops in demand and supply, existing Demand Side Management (DSM) infrastructure will be adopted to integrate and validate FCPP as one of the key DSM enabling technologies on the side of prosumers. FCPP for grid support will target two groups of customers: a) Directly DSO or better aggregators with a goal to increase VPP (Virtual Power Plant) capacity and increased system stability, and b) Prosumers to enable them to participate in the market for flexibility and thus decrease their cost of electricity.

INEA will deal with power control and grid interaction, providing advanced solutions for gathering flexibilities on prosumer side. It will develop and validate prototype of FCPP to Grid interface as a tool to enable aggregators or Grid Operator to use FCPP flexibility for grid support services. Major roles will be to develop and validate a HW/SW tool that enables integration between FCPP and Distribution Grid Management System to be validated in an industrially relevant environment. On the other hand INEA will assess the business models and entrepreneurial strategies for integration of FCPP for grid support services and DSM programmes.

Modelling, optimization and performance monitoring

The modelling of mass and energy balances is an important step for identifying the reference theoretical performances of the system in terms of fuels consumption, electricity production, heat production and therefore of efficiency. This kind of analysis supports the improvement of system components and cost, identifying the most critical sections; on the other hand, also on-field measured values can be compared with results of simulations, identifying malfunctioning or unexpected operating conditions. The modelling activities are also relevant to investigate the behaviour of the system in off-design conditions (which are of large importance in the grid-support operation of the PEM plant), evaluating the technical viability in conditions that cannot be checked directly before real world application, supporting the exploitation process. A conceptual scheme of this approach is presented is Figure 5.

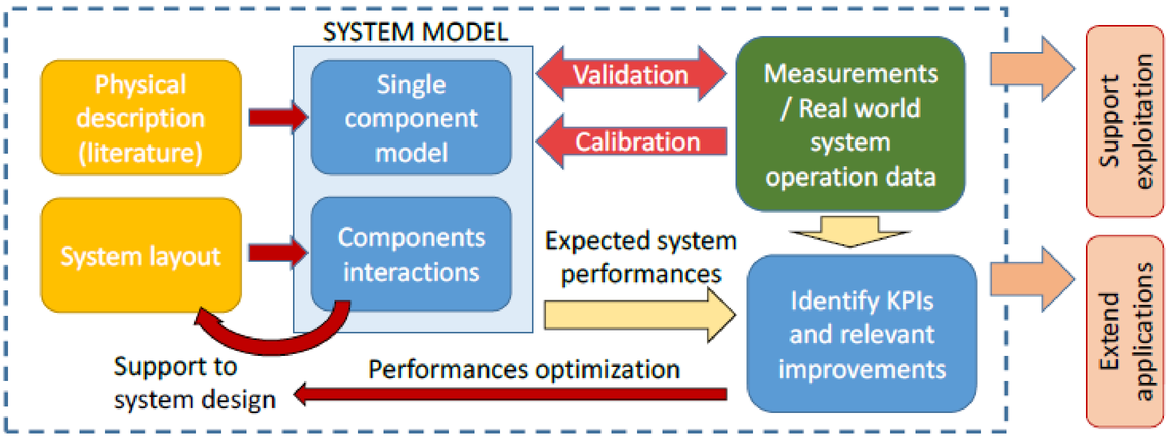

Figure 5 - Conceptual scheme of general modelling activities connected with field measurement and their impact on system performances optimization

POLIMI Energy Department has a long experience in the design, optimization and performance analysis of innovative energy system. In particular, in the field of hydrogen technologies several models have been designed related to both low and high temperature fuel cells and electrolysis systems, as well as for hydrogen production systems (steam reforming, membrane reforming, etc.). They make use of commercial (e.g. ASPEN), as well as in-house developed codes and are based on literature models for basic physics. Part-load operation of stacks at nominal temperatures can be simulated, as well as the influence of external conditions (e.g. environment temperature) and plant set-points (e.g. air excess).

An experimental section is also part of the experience of the group, focused on testing complete systems for cogeneration and fuel cell units at the POLIMI LMC (Micro-cogeneration Lab), laying also the basis for carrying out field tests on the systems once in operation, both during the FAT phase and during operation at the final installation site (e.g. specific measurements of reactant and cooling flows flow rate at inlet/outlet of groups of stacks), which are supporting the correct analysis of system performances. This activity, already performed in the previous project DEMCOPEM-2MW, allows to integrate the plant measurement system and to improve the accuracy in assessing the global performances of the system, where model results are compared with measurements for a mutual validation. Main challenges of the technical analysis of the PEM plant are related to the definition of a model sufficiently accurate to reproduce the different systems in order to support decisions in a) System layout optimization, b) Management of the plant in real world conditions; c) Identify possible improvements of operating strategies; d) Simulate the performance in conditions other with respect to the demonstration ones.

A sufficiently accurate and continuous flow of data will be guaranteed by the presence of the demonstration unit, operated in variable environmental conditions and subject to different loads. The identification by means of data analysis will be also a challenge of the project (i.e. optimal operation, possible presence of an electric energy storage).
The resulting tool will improve predictive capacities in terms of performance of the innovative system in different operating conditions and assist in the translation of pilot to MW FCPP. The models are expected to be improved both as benchmark for the current and future application, as well as to become a tool for estimating the impact of layout changes. The detail level in the description of part load and off-design conditions will be strongly improved and validated thanks to the large availability of data.

3. Conclusions

GRASSHOPPER project will develop a Fuel Cell Power Plant (FCPP) characterized by operation flexibility and grid stabilization capability. It will represent an example of the hydrogen-based electrical power generator with ability to participate in the automated flexibility trading market and to receive remuneration for providing ancillary services.

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