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GRASSHOPPER

Grid Assisting Modular Hydrogen PEM Power Plant

D8.6: Final summary project results

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Fuel Cells and Hydrogen Joint Undertaking (FCH JU),
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Executive Summary

The deliverable D8.6, prepared by Abengoa Innovación with the partners of Consortium, is a public document of the GRASSHOPPER project, produced in the context of WP8 (Task 8.1 Dissemination activities).

The scope of this deliverable is to collect the main final publishable results generated by each partner of the GRASSHOPPER project, protecting the confidential information and the intellectual property of commercial value for the consortium. Likewise, besides the summary of the work performed from the beginning to the end of the project, the deliverable includes the results obtained at the end of the project, as well as the potential impacts.

The final results will be also published in the project's public website:

www.grasshopperproject.eu

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 779430. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

Document History

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List of Acronyms and Abbreviations

Abbreviation	Definition
BOP	Balance of Plant
CCM	Catalyst coated membrane
DSM	Demand Side Management
FAT	Factory Acceptance Test
FC	Fuel Cell
FCPP	Fuel Cell Power Plant
FCPP2G	Automatic Trading Interface of Fuel Cell Power Plant
GH	Grasshopper
INEA	Informatizacija Energetika Avtomatizacija
IPR	Intellectual property
JMFC	Johnson Matthey Fuel Cells Limited
MEA	Membrane Electrode Assembly
NFCT	Nedstack Fuel Cell Technology B.V.
Polimi	Politecnico di Milano
S2TF	Stack to The Future
SAT	Site Acceptance Test
ZBT	Zentrum für Brennstoffzellen Technik Gmbh

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1. Introduction

The objective of the GRASSHOPPER project is to create a cost-effective, flexible, MW-size FCPP unit based on the learnings from a 100 kW pilot plant design, implementing newly developed stacks and MEA's. This pilot plant is large enough to implement cost savings as well as to validate operation flexibility and grid stabilization capability via fast response. This unit will be validated under a real industrial environment using by-product hydrogen from chlorine production and will be operated continuously for several months for engaging grid support modulation as part of an established on-site Demand Side Management (DSM) programme.

This deliverable D8.6 collects the main publishable results generated by each partner of the project, protecting the confidential information and the intellectual property of commercial value for the consortium. It includes a brief description of the scope of each partner, the expected objectives and the main achievements and results obtained, including graphic information. At the end of the document it has been included a general conclusion about the results obtained in the project.

2. Description of the project

2.1 Abengoa

Abengoa was in charge of the WP6 - Development and Validation of Modular low-cost Power Plant. This WP was dedicated to the design and development of a modular, flexible, and low-cost power plant design. First a 100 kW pilot plant was designed and constructed. After several months of operation, it was evaluated, and the learnings were included in the design of a modular MW scale low-cost FCPP with grid supporting capability

- T6.1 Design of a flexible, modular, low cost 100 kW pilot plant
- T6.2 Procurement & Construction of Pilot Plant
- T6.3 Pilot plant testing
- T6.4 Validation
- T6.5 Design of MW scale plant and cost assessment

Abengoa was also in charge of WP8 - Dissemination and Exploitation. This WP included activities related to the dissemination of the project results in order to create awareness of the GRASSHOPPER project, its objectives and results. Further, it included activities related to the development of an exploitation plan for the project results and a business plan for the technology developed.

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- T8.1 Dissemination activities. The main tool for dissemination and coordination of the project has been the project website
- T8.2 Exploitation plan. It included an exploitation plan for the project results
- T8.3 Business plan (with the leadership of INEA).
- T8.4 Advisory Board activities (with the leadership of INEA).

2.2 INEA

INEA was in charge of the WP1 - Coordination of the GRASSHOPPER project. It includes:

- T1.1. Overall Project Management & Technical Coordination. INEA has been the responsible for the overall management and coordination of the project and the Consortium and was the unique project interface with the FCH JU.
- T1.2. Planning and Scheduling: This task provided for management and planning of different actions during the projects' lifetime.
- T1.3. Reporting and Internal Communication: This task included the activities related to periodic and final reporting to the FCH JU.
- T1.4. Monitoring, Control and Quality Management: This task ensured that all project objectives were achieved within the work plan time and resource constraints. It guaranteed the effective and efficient progress of work.
- T1.5. IPR Management. This task was based in the management of project knowledge.

INEA also was in charge of the WP7 - Power control and grid integration. This WP was responsible for the development of prototype software interface to be used as a tool for aggregating and trading flexibility for offering services to the grid and will particularly enable integration of flexible FCPP into the Demand Side Management portfolio.

- T7.1 Requirement analysis and specifications of FCPP2G system
- T7.2 Development of FCPP2G interface.
- T7.3 Simulation and validation of FCPP2G interface.

2.3 Johnson Matthey Fuel Cells Limited

JMFC was in charge of the WP3 - Realisation of improved MEAs with long lifetime and lower costs. It includes:

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- T3.1 Develop highly durable MEA. Harnessing the knowledge acquired from DEMCOPEM as well as the membrane and manufacturing development from VOLUMETRIQ this task aimed at providing a highly durable MEA compatible with 20000hrs of continuous operation utilizing 60% less Pt than the previous DEMCOPEM MEA.
- T3.2 scale-up MEA manufacture and delivery of MEAs for inclusion in new NFCT stacks. Exploiting the learning from DEMCOPEM, VOLUMETRIQ and INSPIRE, the manufacturing processes utilized the large-scale roll to roll coating and converting processes developed for the automotive industry with the aim to increase yield significantly and reduce manufacturing cost by up to 65% on a cost per unit power basis.
- T3.3 Boundary condition and long term testing analysis. Short stacks and full stacks testing were kept on long term testing with stability and durability assessed at various part of the project by JMFC and NFCT.

2.4 Nedstack

Nedstack was in charge of the WP4 - Improved stack design and pilot production. With the DEMCOPEM-2MW as a reference, a substantially increased stack output should lead to drastically reduced stack costs per kW as well as reduced power plant costs due to the reduced number of stacks. Such a significant increase in stack power were realized via a number of design changes:

- T4.1 Definition of stack operating conditions and design of new flow fields for anode, cathode, and coolant.
- T4.2 New cell plate design for larger stacks
- T4.3 New stack design with an increase in nominal output of > 4 x to 25 kWe
- T4.4 Development of production process and pilot production (100 kW) of the new stack design
- T4.5 Improved stack design and performance

2.5 Politecnico di Milano

Polimi was in charge of the WP5 - System modelling and performance optimization. This WP was dedicated to advanced modelling of the system aiming at assessing the general mass and

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energy balances of the system as well as the global efficiency. The work is developed with an increasing level of detail.

- T5.1 Review of plant key features and definition of performance optimization criteria.
- T5.2 Modelling of the 100 kW and multi-MW plant for preliminary design and performance optimization
- T5.3 Plant dynamic modelling: model setup and definition of operating strategies
- T5.4 Refinement of the 100 kW and multi-MW plant design
- T5.5 Assessment of beyond project plant improvement (long-term roadmap) through modelling.

2.6 ZBT

ZBT was in charge of the WP2 - Flow field modeling and experimental validation. It includes:

- T2.1: Experimental flow field development and verification. Within this task ZBT concentrated on experimental investigations both to derive direct outcomes and results as well as parameter input for simulation studies in T2.2 and T2.3.
- T2.2: Model based development of principle flow field design. To quantify the physical dependencies between used components and structures of the cells an inside view is essential during cell flow field development.
- T2.3. Experimental and model based flow field optimization. The results of T2.2 regarding small scale flow field parts was transformed to large scale cell models within this work package for verification and operational optimization of both flow field and system parameters.
- T2.4. Model based analysis of test system data and field testing data.

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3. Objectives

3.1 Abengoa

The objectives of Abengoa in WP6 - Development and Validation of Modular low-cost Power Plant were:

1. Design, construction and validation of a modular, low cost 100 kW pilot plant.
2. Include operational flexibility and grid stabilization capability via fast (within seconds) response times and load following capacity in the range of 20-100%. 50% load in < 20 seconds and 100% load in < 60 seconds.
3. High electrical efficiency (> 50 %) and high availability (> 95%).
4. Optimization of power plant capital costs to < 1.5 k€ per kW for MW sizes.
5. Design of a modular highly flexible MW size based on pilot plant learnings.

Regarding WP8 - Dissemination and Exploitation, it is essential to manage appropriate dissemination of the obtained project results and new knowledge acquired with the Project to the scientific community, such as researchers, stakeholders, educators, etc. and the interested general public. This work package disseminated the project philosophy, objectives, challenges, progress and results widely outside the consortium through communication activities in addition to the general public. Main objectives were:

- To assess the business models and entrepreneurial strategies for integration of FCPP for grid support services.
- To influence European policy makers of new electricity market business models and entrepreneurial strategies to provide a better understanding and opportunities for integration of FCPP as prosumers in emerging Demand Response programmes
- To safeguard the process of exploitation of results
- To communicate clearly how GRASSHOPPER Project has contribute to European competitiveness and has solved societal challenges relating to the sustainability, affordability and security of supply H_2 production technologies.

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3.2 INEA

INEA acted as Project Coordinator and was responsible for the overall management of the GRASSHOPPER project. WP 1 ensured scientific and non-scientific dialogue across the Consortium, efficient administration in accordance with FCH JU guidelines and requirements, as well as timely reporting. According to that, the following objectives was defined:

1. Managing the project according to approved plans, guidelines and agreements as set in the Grant Agreement, Consortium Agreement and the relevant annexes.

2. Monitoring, tracking and controlling deviations due to progress, cost, financial and scheduling changes

3. Ensuring that the required reporting is prepared and delivered in a timely and consistent manner and according to quality assurance standards

4. Implementation and administration and communication infrastructure establishing a basis for efficient and easy communication within the project and to relevant external stakeholders.

As a responsible of power control and grid integration, INEA had the following objectives:

• To develop and validate a tool (an interface FCPP2G) that enables integration between FCPP and Virtual Power Plant platform (KIBERnet) for flexibility trading with Distribution Grid Management System to be validated in an industrially relevant environment.

• To support FCPP users integration actions by designing a prototype ICT trading interface solution for integration.

• To assess the business models and entrepreneurial strategies for integration of FCPP for grid support services.

3.3 Johnson Matthey Fuel Cells Limited

The objectives of JMFC were:

1. Develop highly durable stationary MEAs utilizing automotive industry CCM construction and processes leading to substantial MEA cost reductions

• Modify MEA to new NFCT stack platform

• 65% manufacturing cost reduction compared to the current DEMCOPEM MEA on a cost per unit power basis, by operating at higher power density and increasing active area.

• Reduce Pt content of MEA by >76 % compare to DEMCOPEM MEA on a power per unit mass of Pt basis.

• Alter operating point to 0.68 V at 1 A/cm² to deliver higher power density and maintain durability of current state of the art MEA as used in DEMCOPEM, at 20,000hrs.

2. Demonstrate scale-up MEA manufacture and associated quality control

3. Delivery of MEAs for inclusion in 100 kW prototype via roll to roll large scale manufacturing process

4. Determination of the boundary operating conditions of the new generation high durability MEAs

3.4 Nedstack

The objectives of Nedstack were:

1. Development of new stack platform with increase in nominal stack power under power plant conditions > 4 x to 25 kWe

2. Reduce stack costs (incl MEA) to < 450 €/kW (for series production > 25 MW/yr)

3. Maintain FC efficiency > 55% and lifetime expectation > 20,000 hrs

4. Development of stack production process and pilot production of new stack (> 100 kW)

3.5 Politecnico di Milano

The objectives of Polimi were:

1. To collect all the useful information from previous experience on FC plant layouts and operating conditions.

2. To propose alternatives plant layouts and operating conditions for the demonstration plant, comparing their performance through preliminary simulations.

3. To develop, calibrate and validate specific models of the FC system at different level of complexity. The models aim at investigating and optimize the plant performance and flexibility.

4. To extend the modeling activities to the MW-scale system, to define the best configuration, process variables and integration options.

3.6 ZBT

The objectives of ZBT were:

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1. Develop a large area (from the current 200 cm^2 up to 400 cm^2) flow field for stationary applications capable of high-power densities with high uniformity of current distribution in constant and load following operation

2. Flow field model development, setup and demonstration of test cells (25 cm^2) for validation and stack performance forecast

3. Derive specific flow field designs in conjunction with precise operation strategy for dynamic high power density operation

4. Main achievements and results

4.1 Abengoa

WP6:

Concerning WP6, the design and the construction of the GRASSHOPPER 100 kW Pilot Plant were completed. Once the construction phase was finished, the 100 kW FCPP was moved to Abengoa's testing facilities (port of Seville, Spain).

In order to install and operate properly the GRASSHOPPER 100 kw pilot plant, an operating manual, an installation and maintenance manual were generated. Regarding safety concerns, the pilot plant safety implementation is also produced.

Factory Acceptance Tests (FAT) have been carried out in Abengoa's testing facilities, during more than a year, with the purpose of testing the plant performance and checking that the pilot plant operates according to the design specifications. The testing period has been split in two phases: before installation of stacks, and after installation of stacks. During the first phase the focus is to ensure the safe operation of the plant as well as advance on the definition of control loops and strategies. Since there are no fuel cells to produce power, external equipment and simulations have been used to mimic the stacks behaviour. At the second phase, after the stacks have been installed, power generation tests began. The main focus on this phase is to optimize the plant and stack performance. Due to delays in the "GRASSHOPPER" (GH) stacks manufacturing, the pilot plant was commissioned with the "Stack to the Future" (S2TF) stacks. Regarding FAT results, it is remarkable that the plant is fully capable of operating from 20% to 100%, FCPP provides a fast response within the limitations of mFRR markets, efficiency of the pilot plant is within the expected results since pressurized operation is not possible at the current time, the pilot plant is capable of operating remotely.

A preliminary guide for performing the Site Acceptance Test (SAT) of the 100-kW pilot plant with S2tF was generated. Once the 100 kW pilot plant will be located in its final site in Delfzijl (The Netherlands), the SAT will be carried out updating the SAT protocol and check list.

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Due to the delays in legal issues regarding the adequacy of the final site, mainly because of the adaption of the hydrogen pipeline infrastructure by it's owner Groningen Seaports, the construction of the connection to the Grasshopper site is also delayed. Because of these delays, the SAT and the validation testing will not be executed during the requested extension period of GRASSHOPPER project.

Abengoa and NFCT have decided to validate the GRASSHOPPER FCPP after the project end in order to install GH type stacks and complete testing scope. The operation of the pilot plant will be during 5 years after the project end, to demonstrate the viability of the technology in the medium term and serve as experimental validation of the operational costs for the system.

Regarding the MW size PEM FCPP, a preliminary design with its corresponding costs assessment, have been made based on learnings from a 100 kW pilot plant design, which was tested in Seville. After studying several unit sizes, a 2 MW was selected as the base unit rated power. With which the following achievements are reached

- CAPEX has been reduced to 1500€/kWe for a 2MW unit designed for providing grid balancing services. Considering a value of 450 €/kWe for stack manufacturing
- AI has also started the development of other units both in size and application to accelerate the go-to-market time of the technology.
- Electrical efficiency of the MW plant will reach 50% at any load if the 55% efficiency of the stacks is also reached.
- Redundancy of equipment is also present in the design to reach 95% availability.

With the continuous validation of the pilot plant during the following 5 years, AI will continue developing strategies to further reduce cost and study maintenance and availability. In order to offer the most competitive product for grid balancing services but also other markets.

<u>WP8:</u>

During the first period of the project, the webpage (www.grasshopperproject.eu) was launched and the first project leaflet was produced.

During the second period of the project:

- The GRASSHOPPER website was continuously updated, including new sections as “results”, and was improved using the Wordpress tools. Additional news was published in the GRASSHOPPER Linkedin Group (https://www.linkedin.com/groups/12204671/).

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- There were generated two type of leaflets: one first edition and a second one once the pilot plant was constructed. The leaflets were distributed to the different partners to use them in different events, congress. The leaflets were very useful in the visits to the 100 kW pilot plant.
- It was installed a decor for the GRASSHOPPER container for marketing purposes.
- There were created 6 different videos for using it as a dissemination material in the social networks and at different events (https://www.youtube.com/c/grasshopperproject).
- Roll-ups with commercial and technical content were generated.
- The GRASSHOPPER pilot plant was visited by different key energy players and also, by local and regional authorities in Seville. The visits were previously organized, and a formal presentation was prepared. These dissemination activities were successfully developed, and they had a strong impact in the audience and in the social networks. It is expected that the visits in the final location will be also a powerful tool of dissemination.
- A webinar/ virtual conference was organized on 29th March to disseminate the main results and knowledge from the Grasshopper project, including a virtual visit to the pilot plant. It was prepared a suitable presentation for this specific event. The event was announced by email and social networks to the target audience.
- The obtained results from the second period were presented by Abengoa in the European Hydrogen Energy Conference, EHEC2022, in May 2022 where an oral presentation and a poster were accepted.
- All the dissemination activities from Abengoa and from the Consortia were collected in the deliverable “Final report on dissemination actions and updated dissemination plan”.
- The Final Exploitation plan was produced in order to identify the exploitable project results (automatic trading interface of FCPP to grid, new fuel cell stack and MW scale FCPP) with their corresponding exploitation roadmap, establish the model and strategies for post-project commercialization.

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4.2 INEA

The FCPP2G interface was designed, implemented and tested. The FCPP2G is capable to connect several distributed FCPPs into one virtual power plant and offer the communication interface for grid system services and other smart grid features.

The FCPP2G interface supports the following modes:

- Power flexibility, FCPP2G controls the FCPP based on the power-set point received by the VPP/DSM services.

- Energy flexibility, FCPP2G controls the FCPP based on the energy setpoints received by the VPP/DSM services.

- Combination of power and energy flexibility.

- Disabled VPP/DSM services (local schedule, as defined by FCPP operator).

4.3 Johnson Matthey Fuel Cells Limited

Johnson Matthey Fuel Cells developed a catalyst coated membrane (CCM) to fulfil the aims of the GRASSHOPPER project. The CCM was optimized for flexible, grid supporting stationary fuel cell power. The needs of the 100kW grid assisting power plant called for a CCM that was low cost and durable but capable of operating at high power density with rapid response to changes in power demand.

JMFC built on advances in automotive-type CCM production technology, which is now in high volume manufacture at JMFC. The CCM was made more durable with measures to extend the expected lifetime of the membrane and cathode against the likeliest corrosion mechanisms.

The EU funded VOLUMETRIQ project[1] partners devised a drive cycle partly based on the New European Drive Cycle to evaluate performance over CCM lifetime. JMFC tested the GRASSHOPPER-design CCM in this drive cycle. The profile of current vs time, as implemented at JMFC, is shown in section 5, in Figure 30.

The CCM contained a 20 µm membrane electrolyte with a physical reinforcement, and chemical stabilisers against expected corrosion mechanisms. The resulting MEA showed very high stability in the drive cycle testing compared to the pre-project CCM.

After a period of initial performance gain during early CCM conditioning, the MEA showed minimal loss of performance over its lifetime, which combined to give near-zero measurable degradation over 10 000 hours, as show in **Error! Reference source not found.Error! Reference source not found.**, below, and in Figure 31, in section 5:

[1] FCH-JU (grant no. 671465),

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Table 1. MEA voltage decay at three selected testpoints from drive cycle testing.

Test point current density/A cm^{-2}	0.21 (Low)	0.63 (Mid)	1.16 (High)
CCM:	Decay rate/µV hr^{-1}:		
GRASSHOPPER	-0.66	+0.04	+0.31
Pre-project CCM	-17	-34	-56

JMFC built 2000 MEAs from this CCM, in 200cm² and 300cm² formats. The MEAs were built into stacks by GRASSHOPPER project partners Nedstack FCT, and will power a 100 kW pilot-scale plant, assembled by Abengoa Innovacion. Operating data from the pilot-scale power plant over its lifetime will allow JMFC and partners to assess this MEA design and its components in real-world grid-assisting power operation.

4.4 Nedstack

Nedstack designed a new fuel cell stack with an output power of over 25 kW for long lifetime powerplant applications. A new flowfield has been designed in close cooperation with the activities on simulation of cells at ZBT in Duisburg and the development of new CCM materials at JMFC. This flowfield was modeled and simulated in WP2, where key characteristics of this flowfield are targeted at a pressure ranging from ambient pressure up to 2 Bar(a), making it a versatile design for various conditions. Based on this design a cell plate design has been made, which was optimized by support of WP2 on distribution a media. The tooling and process were designed to manufacture these plates and samples have successfully been validated on initial performance.

A production manufacturing process concept has been developed for pilot production of the grasshopper fuel cell short- and full stacks, using the new sealing technology as well as the new CCM materials developed in this project.

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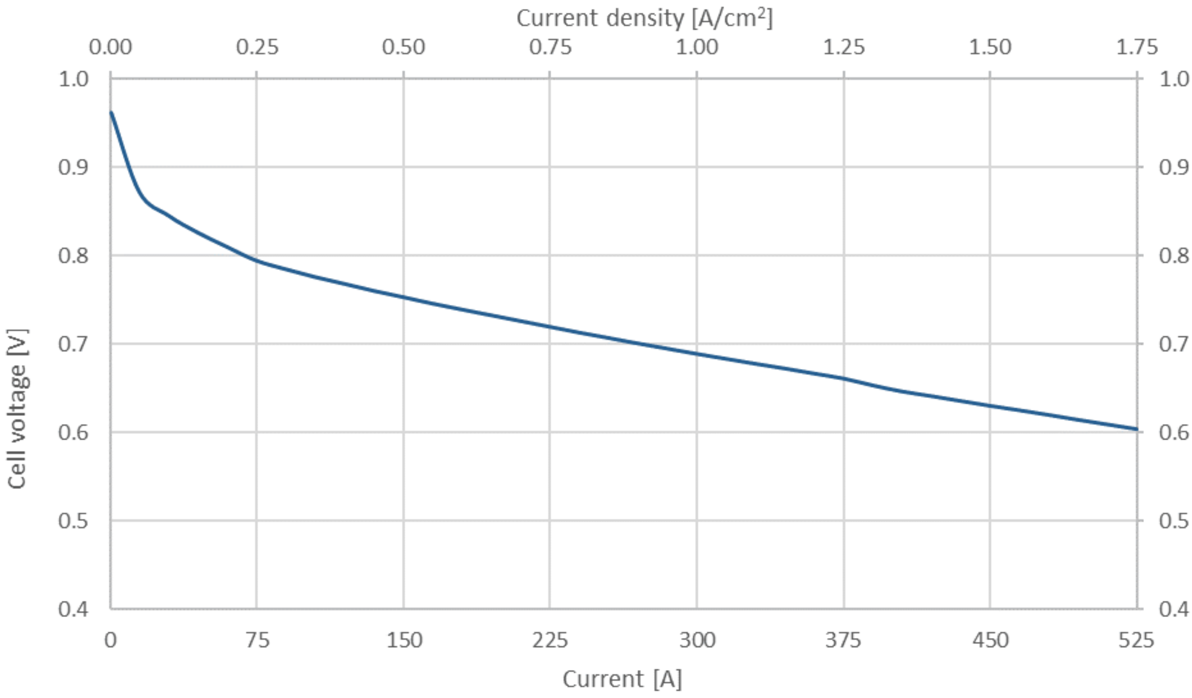

Figure 1: Performance curve Grasshopper short stack

Short stacks have been assembled using the newly developed GH3 CCM material. The short stack performance at pressurized conditions (1 barg) are exceeding the initial project targets of 0.68V at 1 A/cm^2 by approximately 10 mV.

Based on the short stack results and the cell design, a 132 cell stack has been developed with a power output of more than 25 kW. The stack contains media interfaces both for media and electrical connections for easy connection/disconnection in the field.

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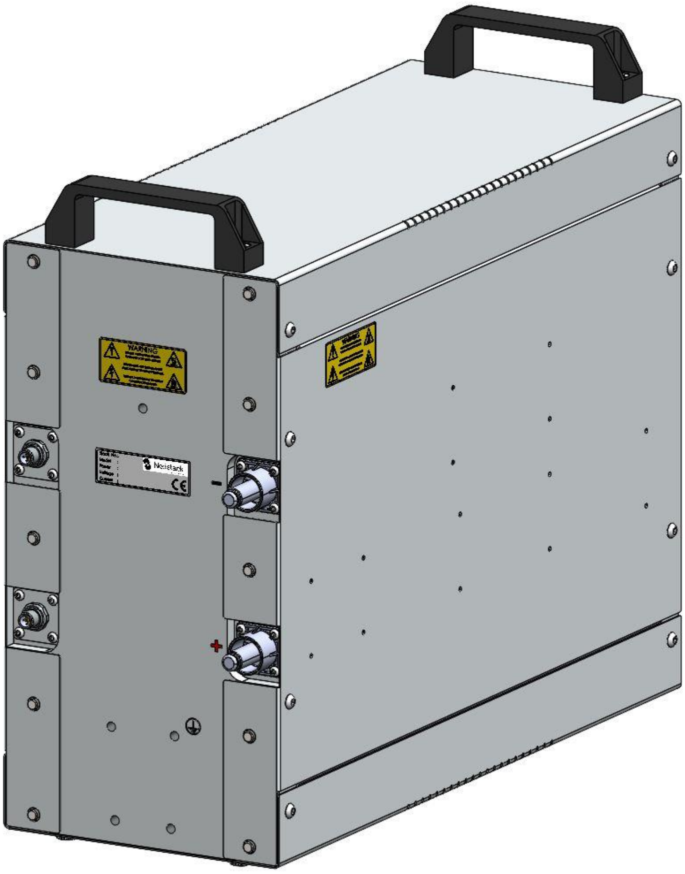

Figure 2: 132 Cell Grasshopper stack

In parallel the lessons learned during the design process of the fuel cell stack were applied to the DEMCOPEM-2MW stack and resulted in the S2TF stack. The power output per stack is increased by 30% under nominal conditions. 100 kW of S2TF stacks were manufactured and delivered for installation in the pilot plant. These stacks contain the newly developed CCMs as developed by JMFC.

4.5 Politecnico di Milano

Polimi's main achievements are related to the development of a stationary and a dynamic simulation tool to assess and optimize the performance of flexible Fuel Cell power plants.

The stationary simulation tool has been developed with the simulation software Aspen Plus. The model includes the PEM FC stack through a customized model, realized with Aspen Custom Modeler, and all the main Balance of Plant (BoP) components through Aspen Plus standard libraries.

First, the model has been applied to compare several possible layouts for the 100 kW pilot plant, simulating the plant behavior in different operating conditions, for currents ranging from 20% to 150% of the nominal value. The activity allowed the consortium to identify the optimal plant design, considering also the limitations given by the market availability of the required components. This activity is detailed in Deliverable D5.2 and D5.3.

Then, the model has been applied to optimize the design and operation of a MW-scale system, in the perspective of scaling up the pilot plant for commercialization (see Deliverable D5.3). The simulation results have shown that the installation of two air compressors in parallel configuration guarantees a perfect control of the air stoichiometry at any load, without impacting on the power consumption. Additionally, an increase in the cathode backpressure (from atmospheric to 1.6 bar) always leads to a gain in the FC stack gross efficiency, while the pressure that maximizes the net efficiency increases with the load. The installation of an air expander unit, recovering energy from the FC cathode exhaust air in order to drive the compressor units, allows to higher net efficiency, especially in pressurized conditions. The installation of air expanders also allows operating at the highest tested pressure in the entire operating range, without a negative impact on the net efficiency.

The dynamic simulation tool has been developed with the simulation software Matlab Simulink. As for the stationary model, the dynamic model includes the FC stack and the BoP components (see Deliverable D5.4).

Preliminary simulations of the cold start-up of the 100 kW system helped in the definition of the control system of the pilot plant, where smooth predictors were needed.

The 100 kW pilot plant model has been calibrated and validated through experimental data from the pilot plant Factory Acceptance Tests (FAT), collected by AI in September 2021 (see deliverable D5.5). The calibrated model showed its ability to reproduce with a good accuracy both the stationary behaviour of the components in different operating conditions and the system dynamics (e.g., thermal transients, effects related to delays in mass transfer, etc.).

The validated model has been applied to the optimization of the system scale-up to 1 MW (see D5.5). Simulations have compared the flexible performance during warm-up and variable load operation of the 100 kW unit to the one expected from the 1 MW unit. The comparison has allowed pointing out the main criticalities and proposing solutions to improve the MW plant design and operation strategy. Among others, the importance of the choice of the warm-up strategy has been stressed, since it affects the warm-up time (with higher current the warm-up time decreases substantially). Additionally, simulation results highlight the importance of designing a compact system, since the warm-up time are strongly dependent on the distance between the system components. Regarding load following operation, simulations have shown that, once the nominal operating point has been reached, the system is able to follow an imposed load profile, regardless the system size, and the time required to reach the new setpoint depends only on the limits on the current rate of change imposed to limit the stack degradation.

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 779430. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

4.6 ZBT

The simulation-based flow-field development at ZBT was very successful in the context of several themes. In Figure 3 can be seen, that the target operation point has been achieved even with operation conditions at a lower pressure. This flow-field structure has been adapted for the 300 cm^2 GRASSHOPPER design and ZBT has assisted with fluid dynamic simulations to design the subdividing manifold regions (Figure 5). The design process was completely successful and NFCT was able to achieve the target performance also in the 300 cm^2 GRASSHOPPER design.

Next to the design of the 300 cm^2 GRASSHOPPER flow-field itself the methodology of the design process was part of the ZBT development. The goal has been the reduction of hardware cost and computational times. In the case of the hardware, it was shown that many tests can be performed with a 25 cm^2 test platform to minimize the work in the expensive 300 cm^2 design. Also based on accompanying simulations it was possible to predict the performance in the 300 cm^2 design. For this purpose, strategic simplifications were also made in the simulation. A development path could be established which, in addition to the multiphysics simulation in the 300 cm^2 cell, includes electrochemical simulations in a single and straight channel and pure fluid dynamic simulations in the 300 cm^2 design. Thus the multiphysic simulation in the 300 cm2 design, that require a lot of resources, could be reduced significantly.

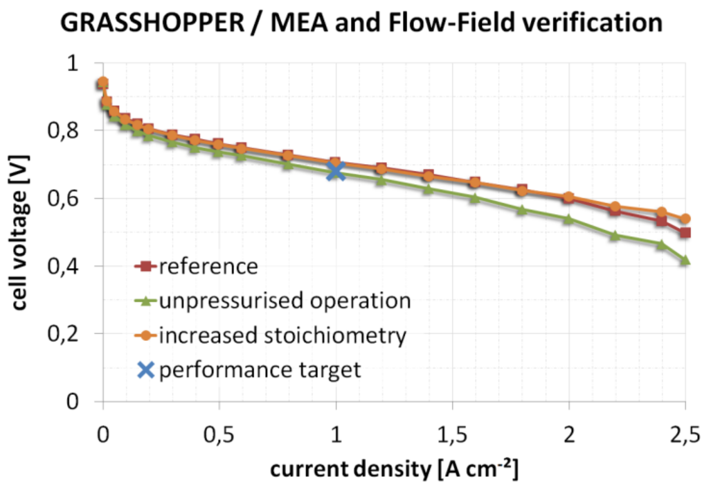

Figure 3 Performance of the basic flow-field structure, measured in a 25cm² test cell, and target performance. The new flow-field is entirely successful.

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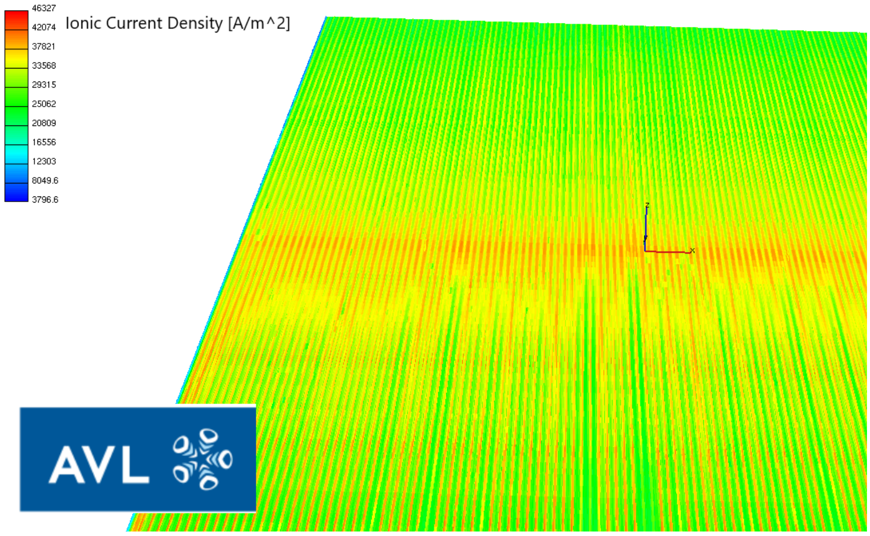

Figure 4 Simulation of 300 cm2 cell. The flow distribution is on a very good level. The visible differences along the channels do not result from unsufficiently distributed flows, but from the operating point itself.

In the project, it was also possible to work out where the accuracy of the simulations is not yet sufficient. The interaction between the channel and landing level with the GDL and the subsequent MEA is not yet implemented to the extent that a prediction regarding different flow-fields is possible. Even if these model problems could not be solved, the knowledge itself is of great importance to derive necessary measurements from it. In Figure 5,it is shown that there are still two parameter set necessary for the MEA ("Simulation" and "Simulations2"), to reproduce different flow-field designs ("ZBT-FF" and "FFF").

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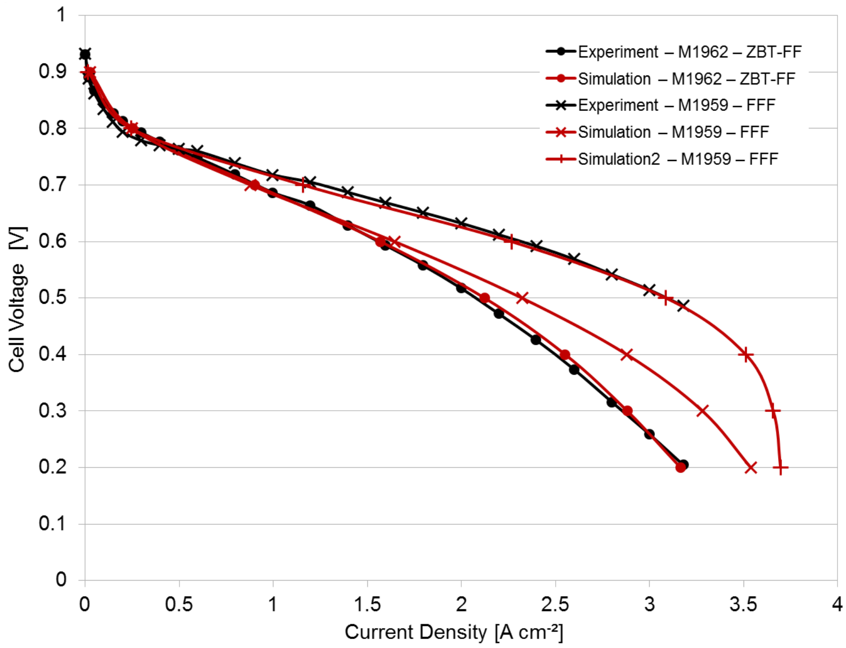

Figure 5: Basic analysis of various processes in the interplay flow-field, GDL and CCL. The models do not yet sufficiently represent the processes today, but the weaknesses could be clearly identified and named.

Finally it was possible to calculate the degradation of the cell and its distribution within the active area. The degradation takes place in the region with the highest activities due to the highest oxygen partial pressure; at the cathode inlet. These degradations are based on the operation point and can not be affected by the flow-field design. The flow-field, on the other hand, has almost no influence on the distribution of degradation, which is a further positive result for the flow-field design.

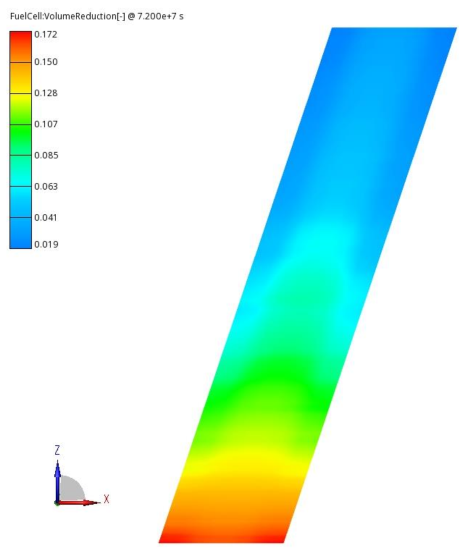

Figure 6: CCL volume reduction

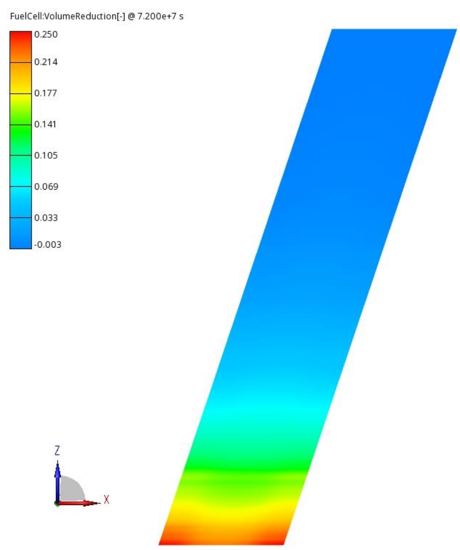

Figure 7: Membrane volume reduction

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5. Graphic documentation

Graphic documentation of GRASSHOPPER project is included in this section. The images and figures are a proof of the project development.

5.1 Abengoa

In WP6, the GRASSHOPPER 100 kW pilot plant was designed, constructed and tested as it can be observed from Figure 8 to Figure 15.

Figure 8– Finalisation of the construction phase for GRASSHOPPER pilot plant

Figure 9–GRASSHOPPER pilot plant is moved to the Abengoa´s testing facilities (port of Seville)

Figure 10–Installation of the GRASSHOPPER pilot plant in the Abengoa´s testing facilities (port of Seville)

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Figure 11–GRASSHOPPER pilot plant in the Abengoa´s testing facilities (port of Seville)

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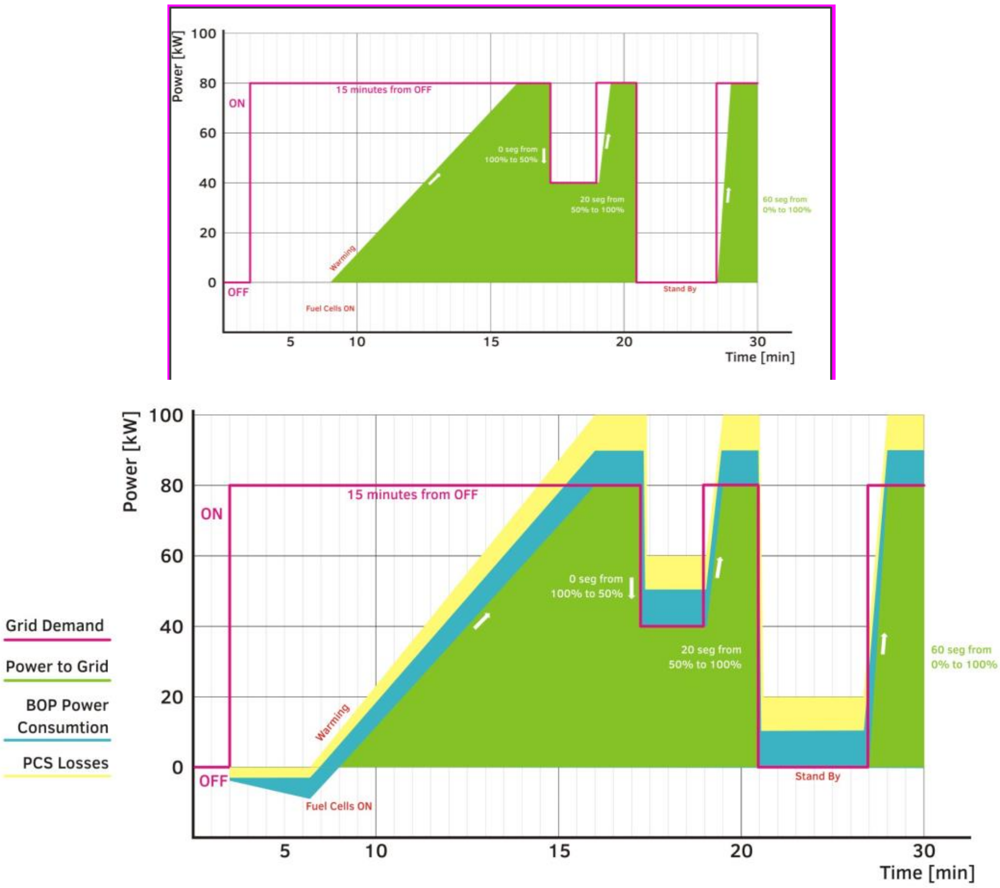

Figure 12–GRASSHOPPER testing results of the pilot plant (FAT testing)

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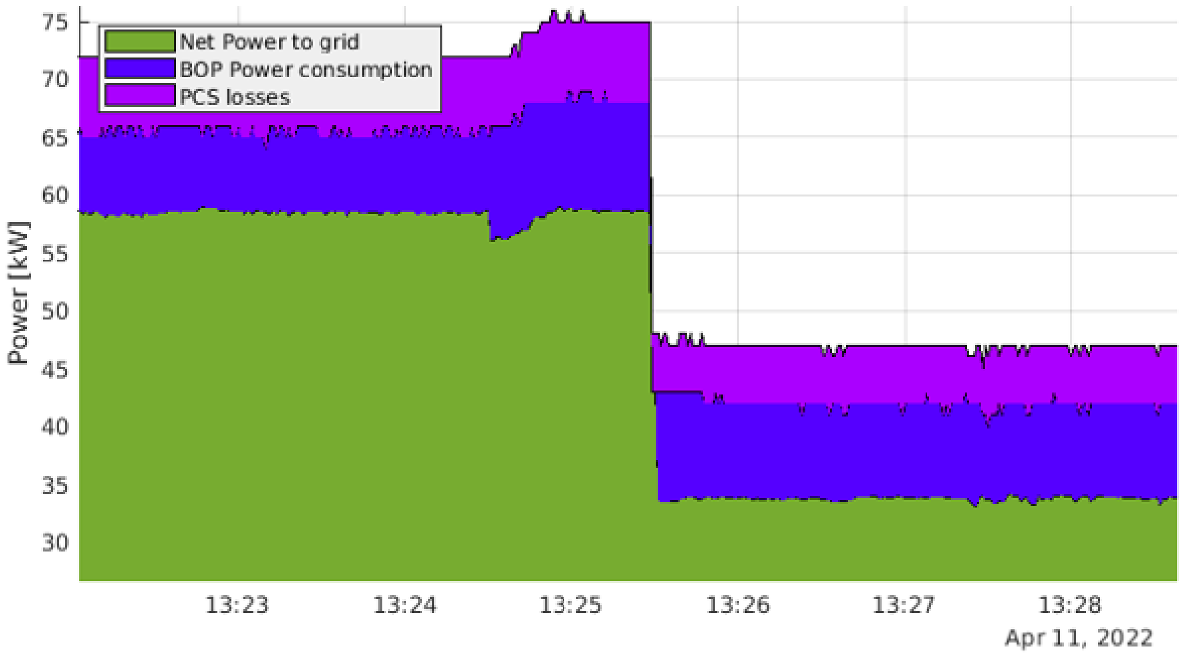

Figure 13–GRASSHOPPER dynamic operation. Load change from 100% to 50% (FAT testing)

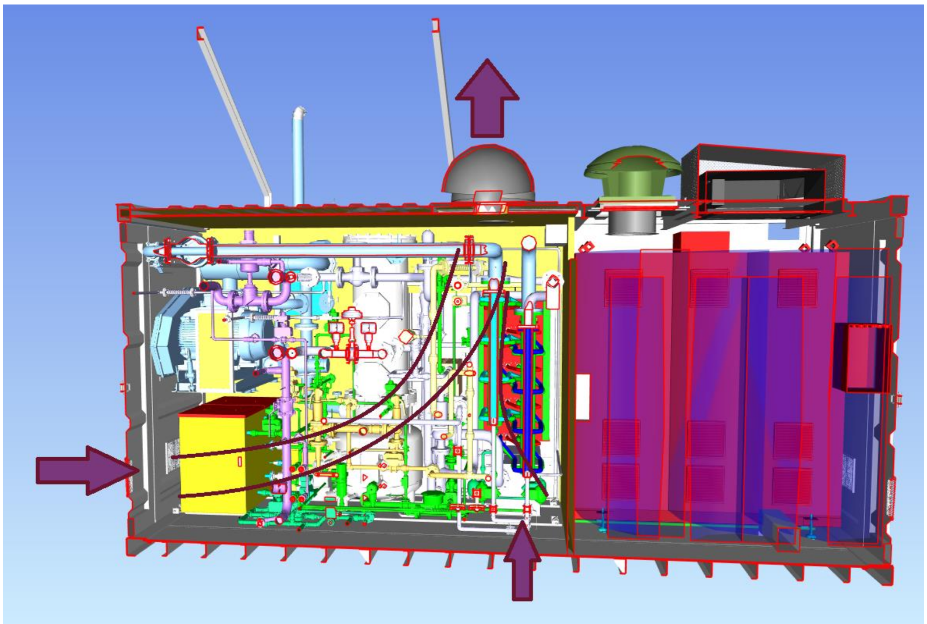

Figure 14–GRASSHOPPER pilot plant safety studies

In Figure 15, a render of the modular and low cost GRASSHOPPER MW- scale FCPP is shown:

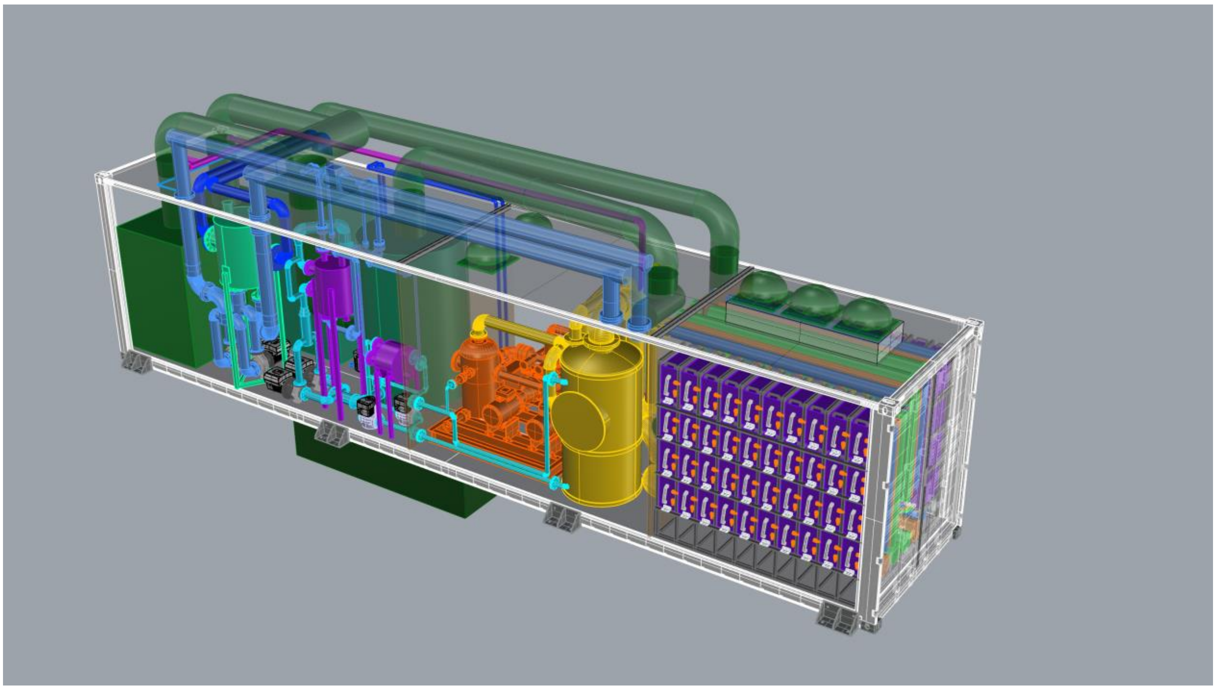

Figure 15–GRASSHOPPER MW scale FCPP

Regarding WP8, a visual summary of the activities carried out are shown from Figure 16 to Figure 27:

Figure 16– Screenshot of Grasshopper website (https://www.grasshopperproject.eu/)

Figure 17–Grasshopper leaflets

Figure 18–Grasshopper decor

Figure 19– Extracts from Grasshopper videos (https://www.youtube.com/watch?v=CvFyVZUOJJ4)

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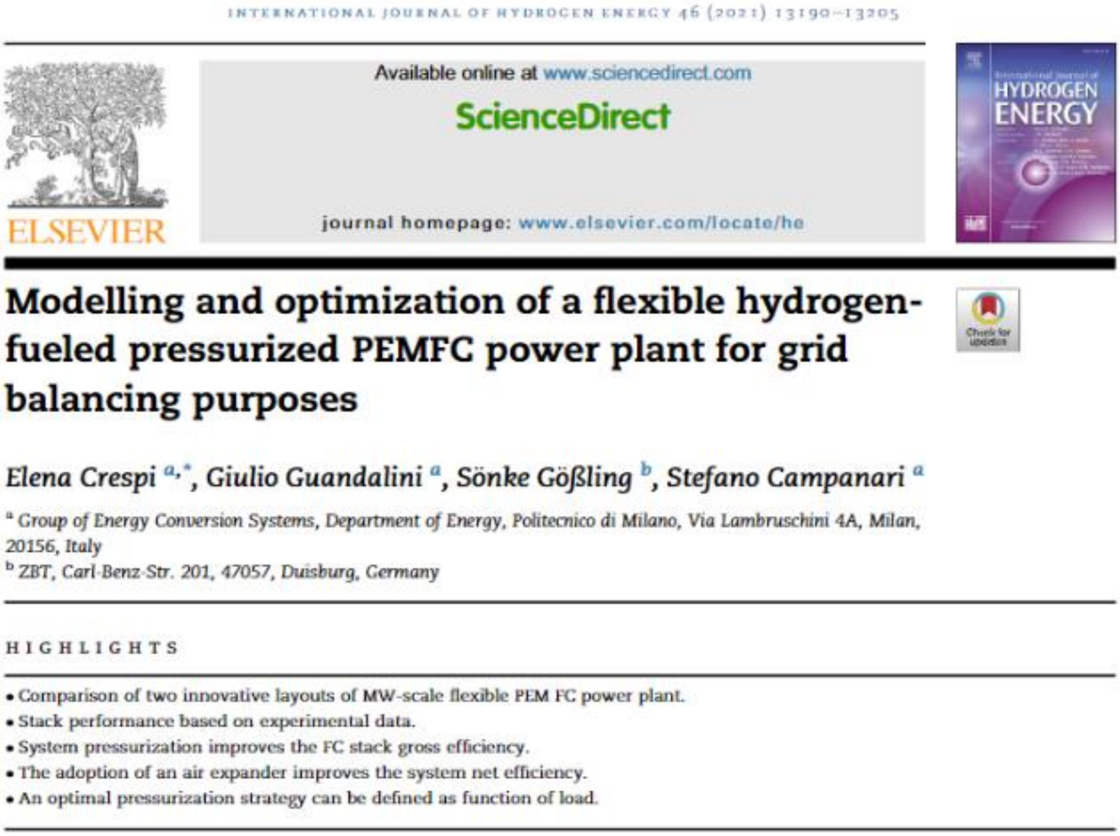
Figure 20– Grasshopper roll-up

Figure 21– Photo of one of the visits to the GRASSHOPPER pilot plant: Major of Seville city and Special Delegate Free Trade Zone Seville (Spanish Government). 01/12/2021

Figure 22–GRASSHOPPER Webinar diffusion



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Modelling and optimization of a flexible hydrogen-fueled pressurized PEMFC power plant for grid balancing purposes

Elena Crespi [a,*], *Giulio Guandalini* [a], *Sönke Gößling* [b], *Stefano Campanari* [a]

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[b] *ZBT, Carl-Benz-Str. 201, 47057, Duisburg, Germany*

HIGHLIGHTS

- Comparison of two innovative layouts of MW-scale flexible PEM FC power plant.
- Stack performance based on experimental data.
- System pressurization improves the FC stack gross efficiency.
- The adoption of an air expander improves the system net efficiency.
- An optimal pressurization strategy can be defined as function of load.

Figure 23–Article from Polimi and ZBT published in April 2021 in the International Journal of Hydrogen Energy as "Gold" open-access publication

European Hydrogen Energy Conference 2021. Madrid, Spain

Grasshopper: A Modular and Flexible Hydrogen PEM Power Plant for Grid Balancing Services

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[1]Abengoa Innovación, 41014 Sevilla/España

(*) maria.tejada.v@abengoa.com

Large and dynamic MWe Fuel Cell power plants are one of the key enabling technologies for the new renewable-based energy infrastructure to reach the decarbonisation and contribute to a sustainable and efficient framework to combat climate change. The technical feasibility of PEM MW Fuel Cell Power Plants (FCPP) has been well demonstrated, but a significant step in dynamic operating and system costs is still needed. In the current scenario, the continuous growth of non-programmable renewable energy resources penetration leads to unpredictable oscillations of the net load faced by power plants, hindering reliability and stability. In that sense, the need for fast-ramping grid-balancing power plants with a dynamic operating capability is a necessary feature to participate in renewable energy markets. In this framework, the Grasshopper (GRid ASsiSting modular HydrOgen Pem PowER plant) FCH-JU2 European Project [1] aims to realise a next-generation MW-size PEM FCPP, which is cost-effective and flexible in power output, specifically designed for the provision of ancillary services to the power grid, accomplishing an estimated CAPEX < 1500 €/kWe at a yearly production of 25 MWe.

Grasshopper Project and the current pilot plant present several technological advances made at many different levels, from individual components to the whole system. The MW-size FCPP unit is based on learnings from a 100 kW pilot plant design, implementing newly developed stacks and MEAs; which is already validated and running satisfactory.

Main characteristic

The power plant is mainly characterised in the following points:

Figure 1. Grasshopper Pilot Plant in Abengoa's facilities

- Flexible and dynamic operation: Flexibility in a Hydrogen fuel cell power plant means two different things. First of all, the ability to dynamically change the power output on demand. This allows the use of the technology both as a baseload or peak power plant. On the other hand, flexibility also means a wide range of applications.
- Contenerised solution: The plant could be easily fabricated in a different location, transported and installed in a remote location where workforce and/or resources are scarce. This gives the plant a valuable "plug and play" philosophy. This method also makes scalability easier. More power means increasing the number of stacks installed in the container, and besides all stacks share the same design, it is a simple "copy-and-paste" process.
- Smart grid philosophy: It includes a bidirectional communication interface with the grid, allowing real-time participation in the electrical market. It is completely autonomous and therefore needs no operators on-site to generate power apart from the occasional maintenance.
- Self-supply: the plant can power self-supply, and during operation, the plant consumes part of its power to keep electronics, pumps, and other equipment running. This allows it to operate in a warm standby mode for a quicker response time.
- Robust control system: precise control of flow, pressure, temperature, and humidity allows to dynamically change operation setpoint maintaining efficiency, without neglecting that these changes must be made in a swift time.

Figure 24–GRASSHOPPER abstract accepted for the EHEC2022

Figure 25–GRASSHOPPER news in the Abengoa corporate website

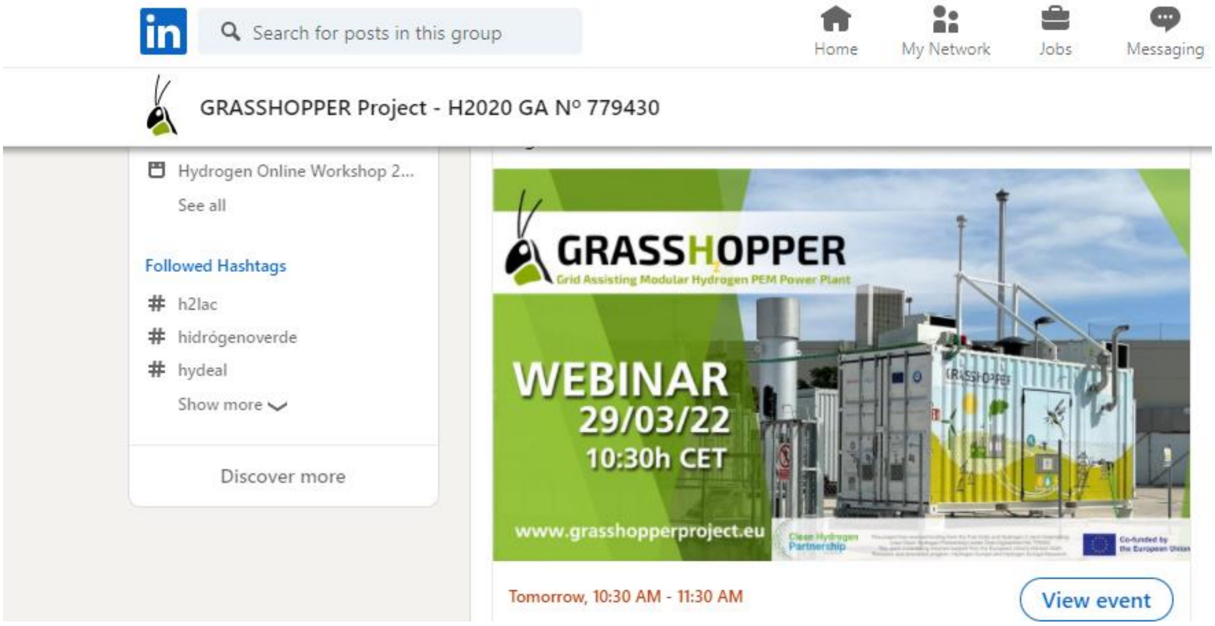

Figure 26–GRASSHOPPER webinar announcement in the LinkedIn group of GRASSHOPPER project

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 779430. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

Figure 27–GRASSHOPPER news in the Abengoa corporate twitter

5.2 INEA

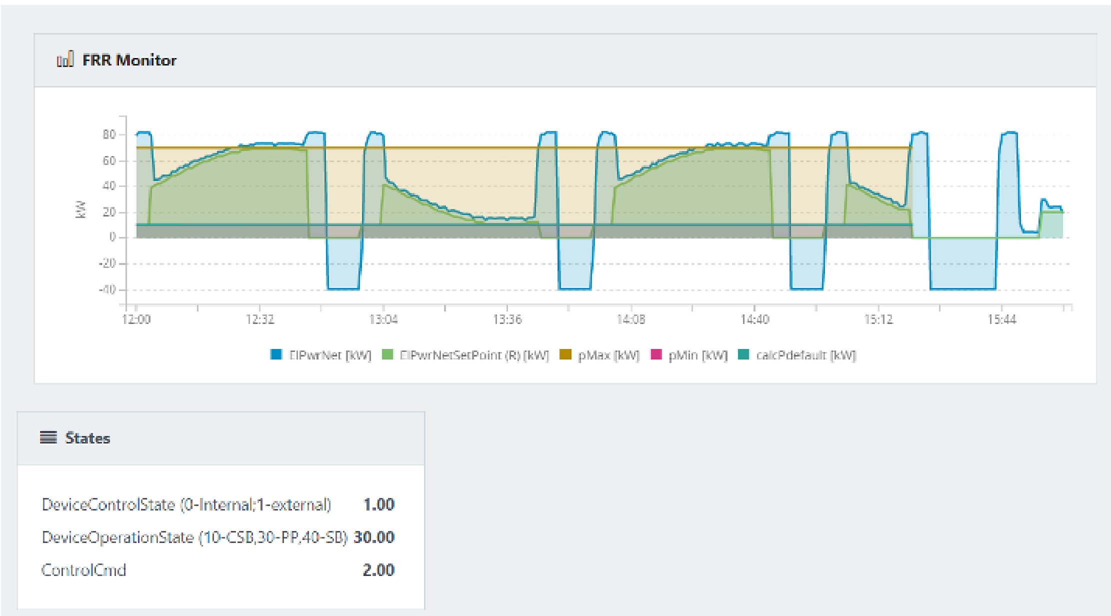

Figure 28–FCPP operation state when command for power set point executed

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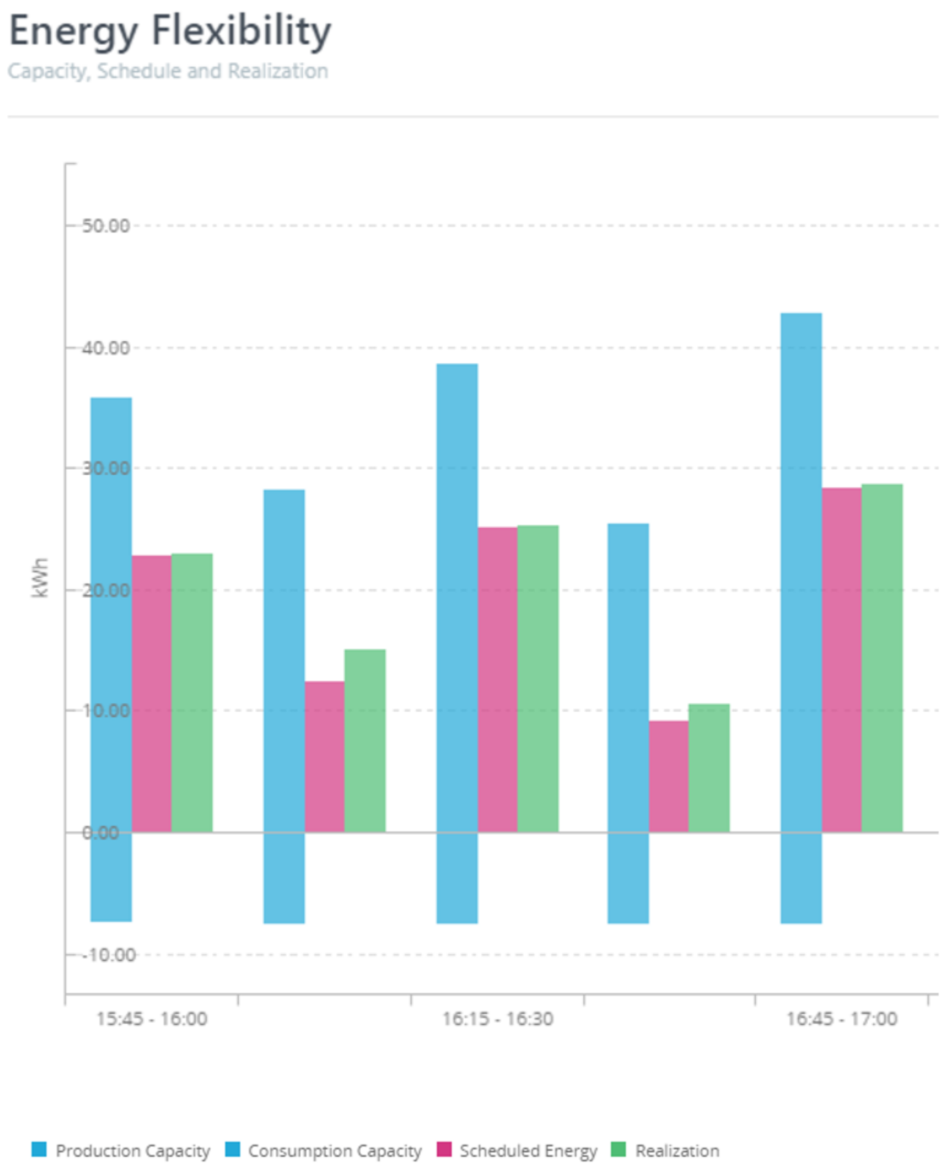

Figure 29–Energy flexibility, offered to the market, requested from the energy market and realised by FCPP

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5.3Johnson Matthey Fuel Cells Limited

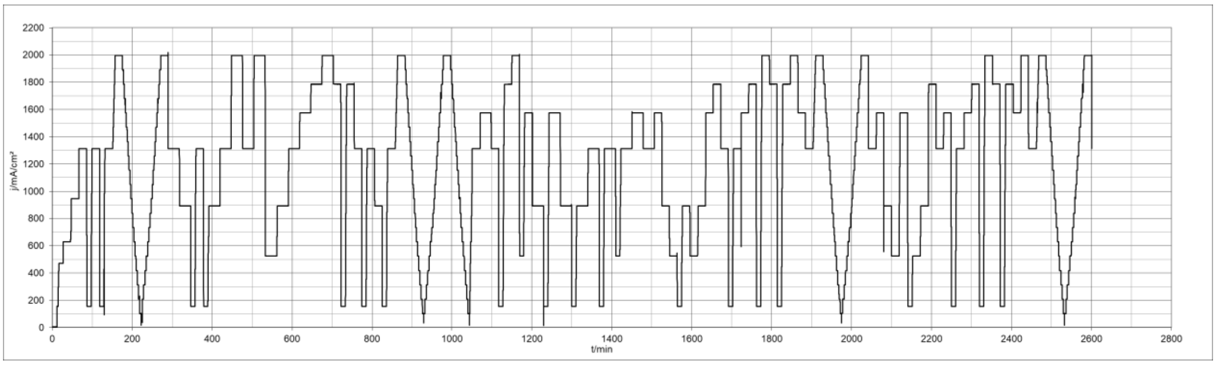

Figure 30–Current density vs time profile of JMFC's implementation of the VOLUMETRIQ drive cycle.

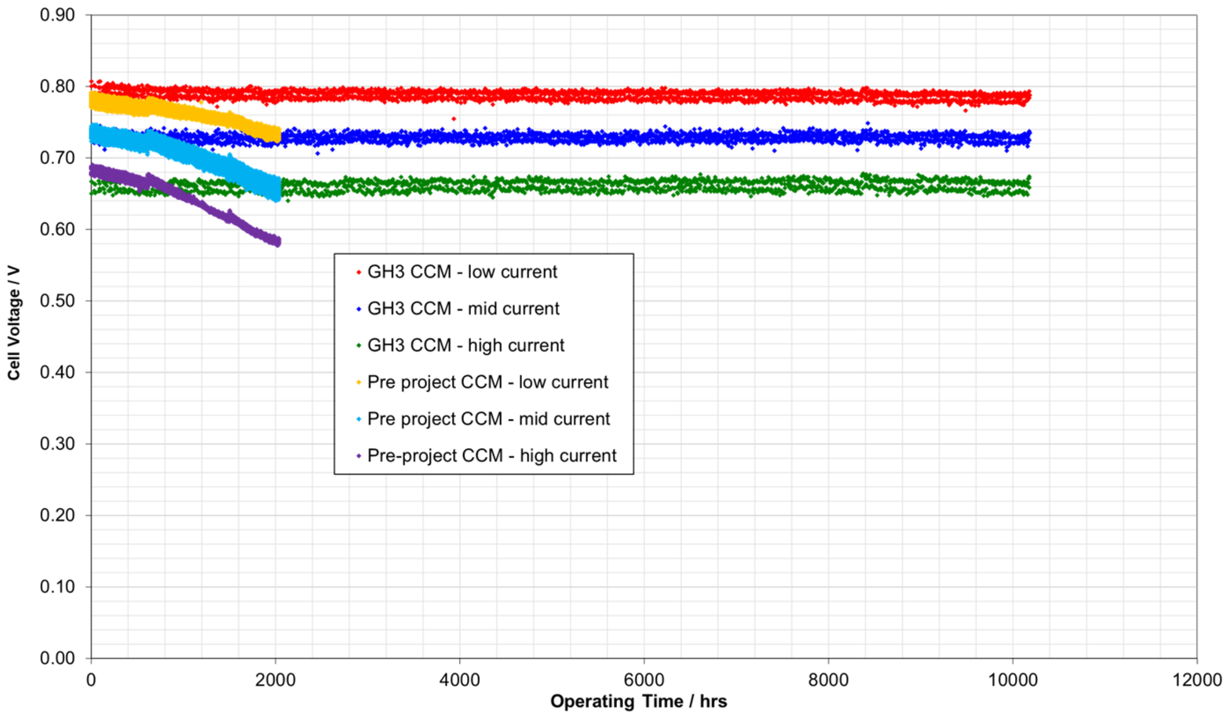

Figure 31–GTest points from drive cycle for the pre-project and GRASSHOPPER CCM vs total test time

5.4 Nedstack

The graphic documentation from Nedstack are included in the section 4.4.

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5.5 Politecnico di Milano

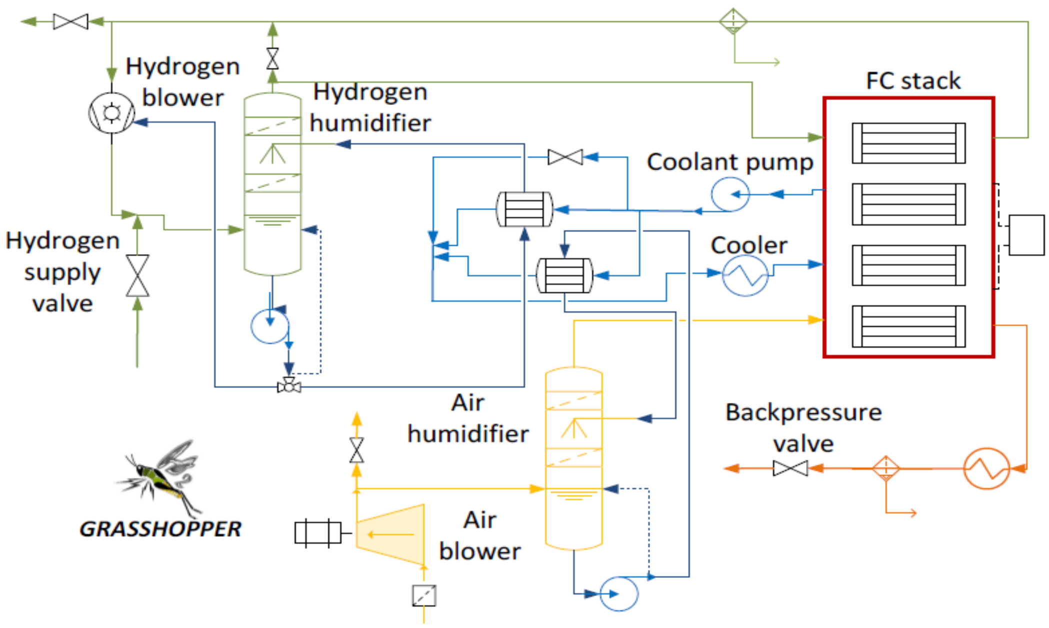

Figure 32– Layout of the pilot plant on which the stationary and the dynamic model of the 100 kW PEM FC power plant are based.

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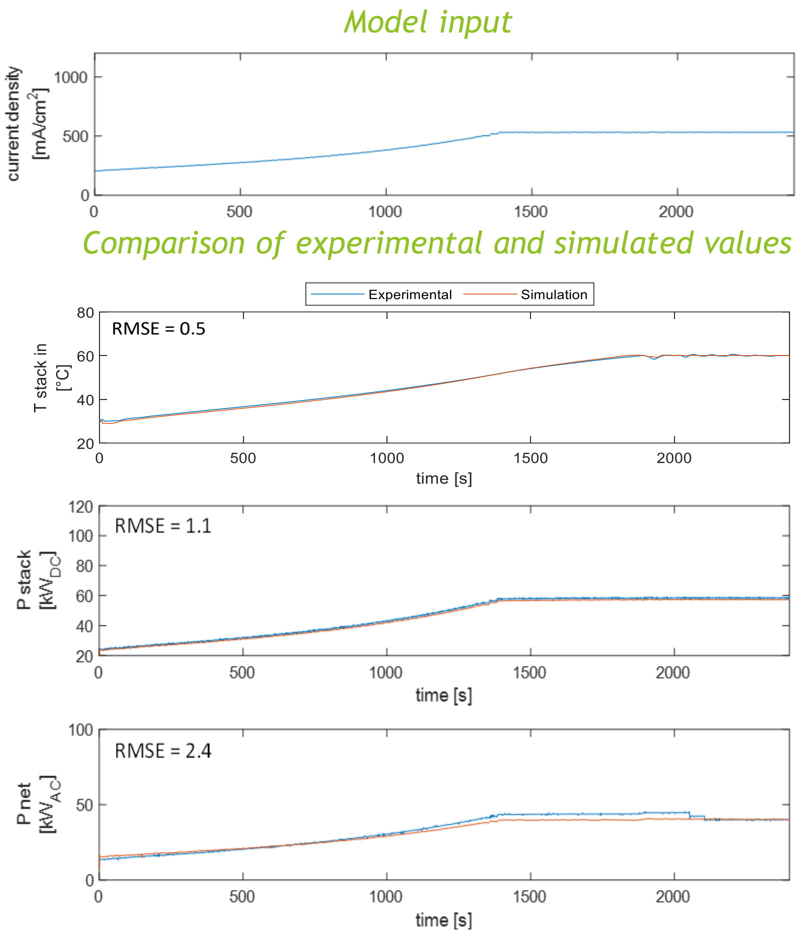

Figure 33– Validation of the 100 kW unit dynamic model - example of the comparison between experimental data from plant FAT and simulation results.

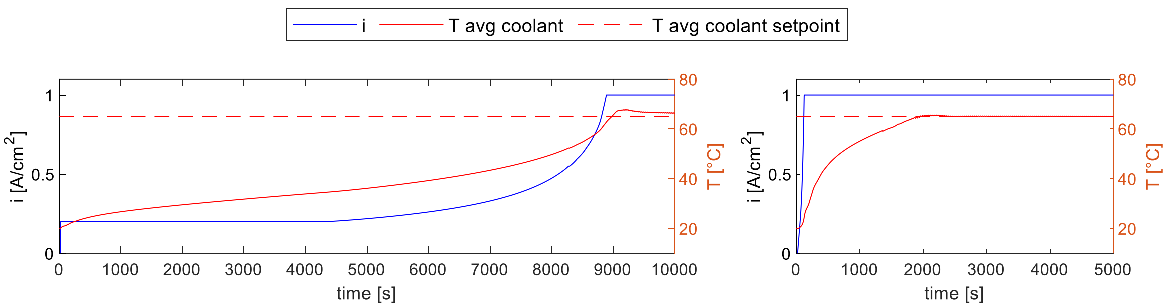

Figure 34- Dynamic simulations of the 1 MW unit - example of temperature variation following cold start-up with two different current density profiles. The warm-up time decreases substantially when the stack operates with a higher current density.

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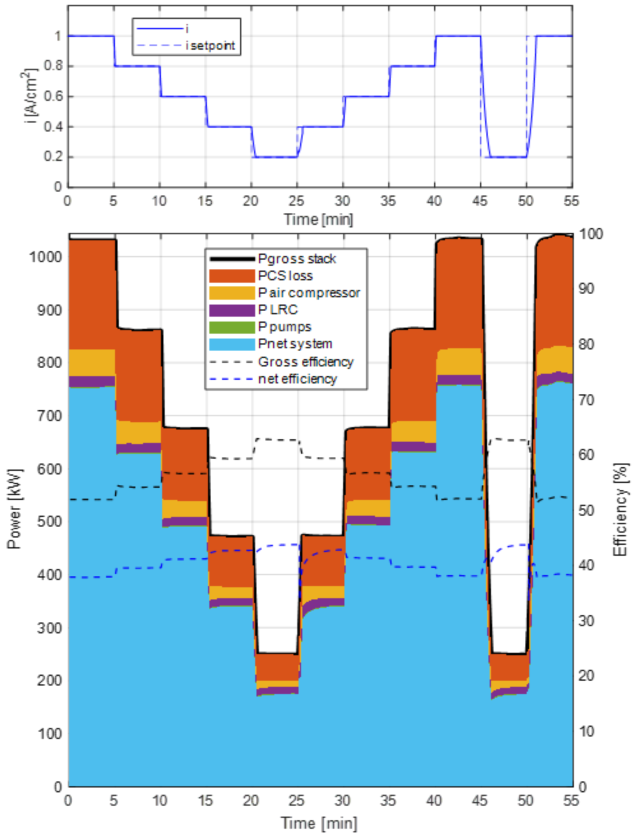

Figure 35- Dynamic simulations of the 1 MW unit - example of load-following simulations: stack power generation, auxiliary power consumptions, gross and net efficiency over time for stepwise changes of the current setpoint.

5.6 ZBT

The graphic documentation from ZBT are included in the section 4.6.

6. Conclusions

As a conclusion of this deliverable, the project has demonstrated its technical viability and efficiency. The key performance indicators have shown a very successful results as it is indicated in the Figure 36:

Key Performance Indicator	Description
KPI 1	Percentage of deviation from target CAPEX of 1500 €/kW system of MW size with total capacity of 25 MW/year.
KPI 2	Fuel cell power density [W/cm2] @ 55% FC efficiency. This KPI will be monitored right from the start for single cells and stacks at test bench, up to stacks in the FCPP towards the end.
KPI 3	Extrapolated lifetime based on FCPP field tests.
KPI 4	Percentage of deviation from target CAPEX FC of 450 €/kW stack.
KPI 5	Deviation from target time of 20 seconds up to 50% power and 60 seconds up to 100% power during FAT and SAT.
KPI 6	Percentage of deviation from target electrical efficiency of 50% during FAT and 8 months validation.
KPI 7	Percentage of deviation from availability expectation of 95% based on the availability verified after 8 months of validation.

Figure 36- KPI description for GRASSHOPPER project

The project has created a satisfactory 100 kW FCPP for testing, validation and dissemination of Power Plants based on PEM fuel cell technology for grid assisting services and, a next generation design for a MW- scale plant, achieving the CAPEX objectives.

The dissemination activities have helped to the diffusion of the results of the projects and to stablish contact with several industries and possible investors in the energy and hydrogen sector.

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7. Annexes

7.1 Annex A: Consortium

Table 2 – Consortium.

Participant organization name	Short name	Country
INEA INFORMATIZACIJA ENERGETIKA AVTOMATIZACIJA DOO	INEA	Slovenia
NEDSTACK FUEL CELL TECHNOLOGY BV	NedStack	Netherlands
JOHNSON MATTHEY FUEL CELLS LIMITED	JMFC	United Kingdom
ABENGOA INNOVACIÓN SOCIEDAD ANÓNIMA	Abengoa, AI	Spain
ZENTRUM FUR BRENNSTOFFZELLEN-TECHNIK GMBH	ZBT	Germany
POLITECNICO DI MILANO	Polimi	Italy

7.2 Annex B: Dissemination contact points

Table 3 – Dissemination contact points.

Partner identification and basic Information		
Project Partner	Responsible for Dissemination Activities	E-mail
INEA	Pia Kuralt	pia.kuralt@inea.si
NedStack	Jos Lenssen	Jos.Lenssen@nedstack.com
JMFC	Paddy Hayes	paddy.hayes@matthey.com
Abengoa, AI	María Tejada Valderrama	maria.tejada.v@abengoa.com
ZBT	Peter Beckhaus	p.beckhaus@zbt-duisburg.de
Polimi	Giulio Guandalini	giulio.guandalini@polimi.it

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