GRASSHOPPER

Grid Assisting Modular Hydrogen PEM Power Plant

D7.3: Report on validation of FCPP2G interface

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Executive Summary

To validate the FCPP2G interface design and technology for overall operation flexibility, it is tested in a selected simulated environment and real FCPP. Validation of the FCPP2G interface is according to the provided approach in D7.2, including the interfaces with FCPP internal control system and Virtual power plant system (upgraded KIBERnet) on the grid side. The interface has been tested for energy trading, power regulation, synchronous operation of both – energy and power – modes. The validation is done via few steps through validation of FCPP2G functionalities as: communication with VPP/DSM services, controlling the FCPP with integrated EMS module and collecting of electricity energy data from the device.

The integration test performed on real FCPP proved the expected technical operation with responsiveness and its readiness for to perform the evaluation of the whole system.

Document History

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List of Acronyms and Abbreviations

Abbrevi-ation	Definition
CA	Consortium Agreement
FCPP2G	Component for integration of FCPP into smart grid
FCPP	Fuel Cell Power Plant
FRR	Frequency Restoration Reserve
VPP	Virtual Power Plant
GUI	Graphical User Interface
DSM	Demand Side Management
FAT	Factory Acceptance Test
SAT	Site Acceptance Test

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1 Introduction

1.1 Purpose

The FCPP2G needs to be validated according to the specifications of FCPP2G interface, including correct interactions (interfaces), overall behaviour, roles and processes. Evaluation of the technical correctness of the FCPP2G interface, as a tool that enables integration between FCPP and Distribution Grid Management System, as well as performing a final performance evaluation of the whole system.

In the first part of the document, some basic functionalities were tested (communication, data availability etc.). In the second part the usage of FCPP2G for grid support services was successfully validated.

1.2 Related Documents

The D7.3 is closely related to the D7.1 “Conceptual architecture and requirements and D7.2 “Prototype of FCPP2G integration interface”, D6.1 “Design of modular, low cost 100kW pilot plant”, D5.1 “Report on workshop results on review of plant key features and definition of performance optimization criteria”, D5.2 “Simulations of layouts and report on operating conditions as support for 100 kW unit engineering”, D5.3 “Final report on stationary simulations and optimization of the 100 kW prototype and MW scale plant”, D5.4 “Final report on dynamic simulations and optimization of operation strategies for flexibility”, D5.5 “Report on prototype data analysis, validation and refinement of the optimal layout and operation, multi-MW plant expected performances”, D6.2 “Construction of modular, low cost 100 kW pilot plant” and D6.3 “FAT reports of 100 kW pilot plant”.

1.3 Document Structure

The deliverable covers validation of the FCPP2G interface, according to the technical specifications requested.

The FCPP2G tests executed covers various levels of the product operation and integration:

- Validation of the communications with the grid entity and FCPP devices, described in chapter 2.
- Validation test of the control command, described in chapter 3.
- Validation of the FCPP2G automatic operation. The tests include are covering the supported features of power and energy control, described in Chapter 4.
- FAT tests results of the FCPP2G interface, described in Chapter 5.

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2 Validation of the communications

To enable proper operation of integrated components, communications between them are validated in alignment with the specifications provided in D7.2, considering the data exchange table provided in appendix. Communications refer to the interfaces among following components, as shown on Figure 3:

- FCPP2G – FCPP,
- FCPP2G – VPP/DSM services.

The Figure 1 and Figure 2 presents the generic FCPP2G HW - cabinet with PLC, communication and auxiliary equipment.

Figure 1: A generic FEMS – external view.

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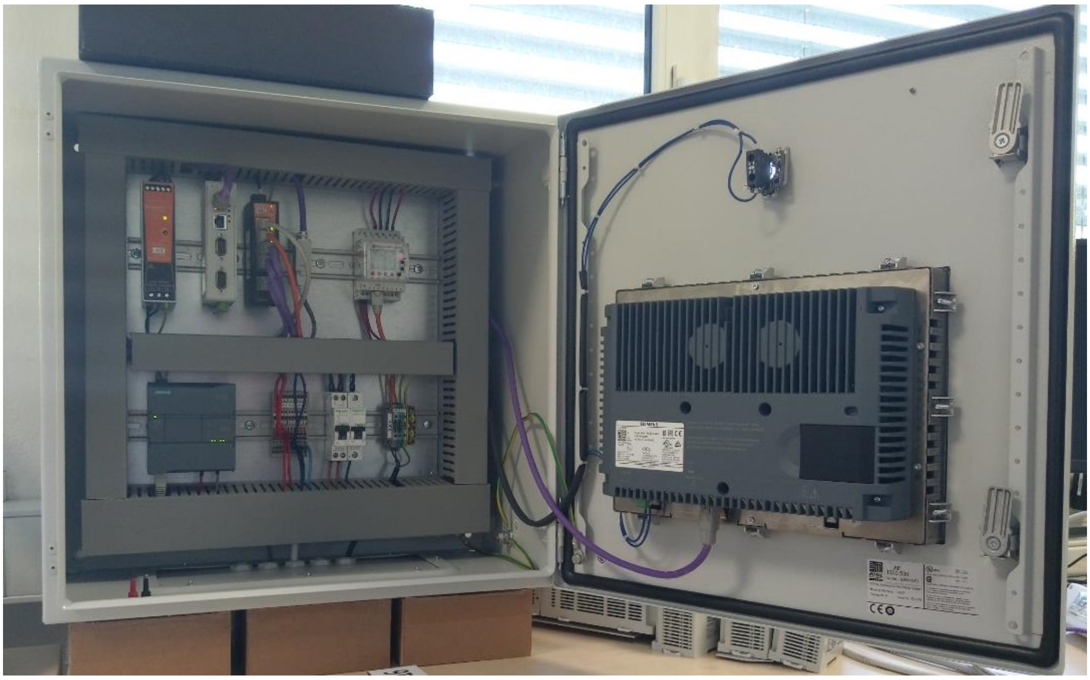

Figure 2: A generic FEMS – inside configuration.

The D7.2 foresees modbus TCP as primary communication between FCPP2G- FCPP, and modbus RTU as a backup. Since lack of resources and communication handover was actually not a research goal of the WP7, only first option was implemented and tested.

2.1 FCPP2G – FCPP data exchange

The communication with real FCPP device has been established and successfully tested and the results are provided in this chapter. The test was performed by FCPP2G manual operation, according to the data-exchange table.

The provided data-exchange table in D7.2 has been updated and the new version is provided in appendix of this deliverable, chapter 8. All signals defined in the data-exchange table were tested in two steps:

- Check the correctness of the read information on FCPP2G as provided in the table. The correctness of the values was performed with comparation of the values on FCPP, with the values on FCPP2G.
- Check the correctness of the write information from the table below – check the values defined in the table as write (by checking the read information of the items 27, 28, 29). The values were written directly inFCPP2G and were compared to the values on FCPP.

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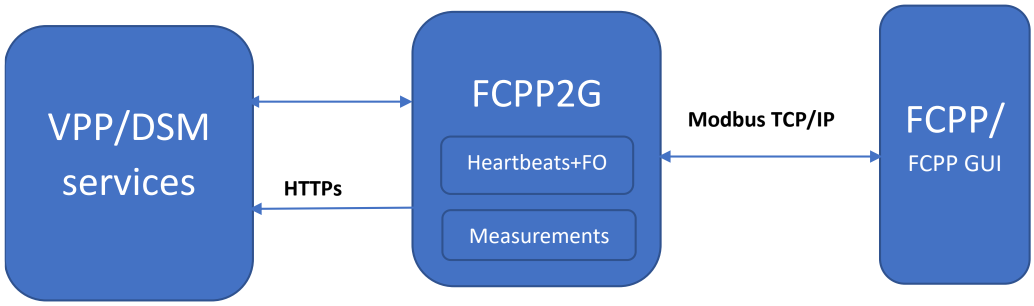

Figure 3: FCPP2G data exchange

Scenario executed:

- Change to "power production" (val = 2) and setpoint 50 kW.
- After some delay change setpoint to 20 kW.
- After some delay change to "stand by – zero power" (val = 1).
- After some delay change the setpoint to 40 kW.
- After some delay "shutdown command" (val = 0).

With that pre-test most of the control commands defined within the data-exchange table were covered.

FCPP2G GUI is accessible via web browser or via in-build touch panel. GUI is divided into two categories Dashboards and Settings. Dashboards menus are intended to provide a complete overview of the system components, monitoring purposes and some basic controls. Different useful menus are also available.

On FCPP the commands were correctly written and changing of the states was in accordance with the requests from FCPP2G. The data received on FCPP2G, including changing of the power and the states, was monitored via FCPP2G GUI, as shown on Figure 4. Visualisation of FCPP power, a short history and near future are presented.

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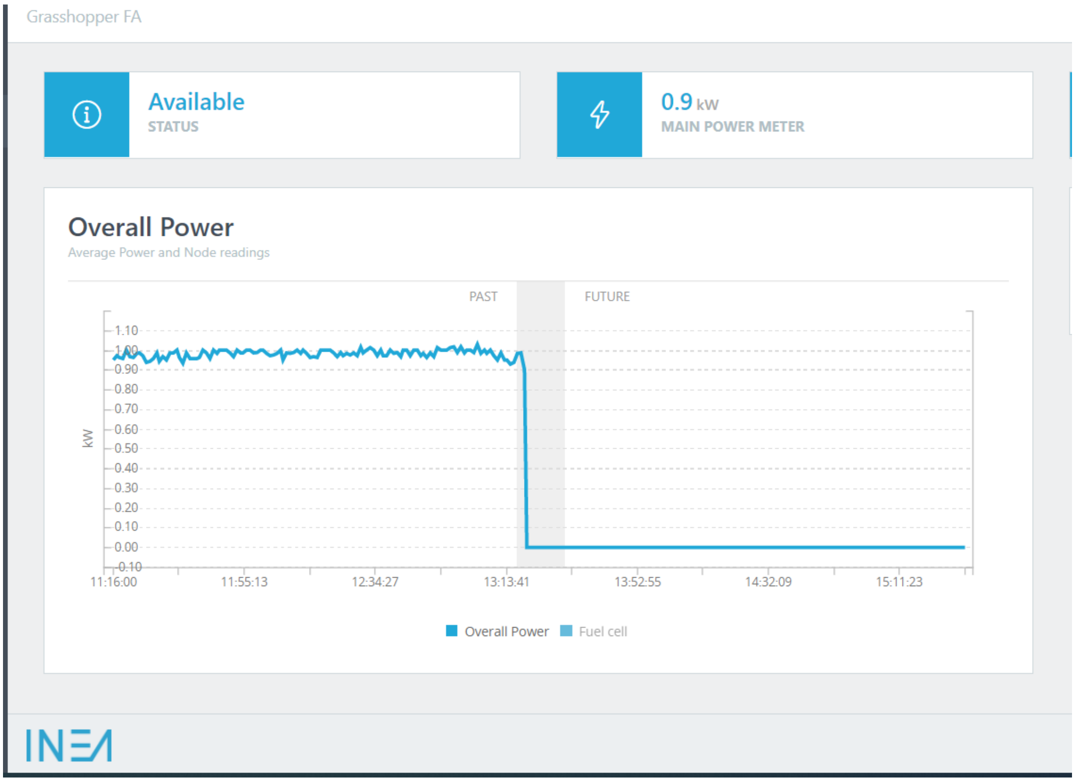

Figure 4: FCPP Power visualization

To proof successful communication between FCPP and FCPP2G, data exchanged was also monitored on FCPP GUI by Abengoa Innovacion, as shown on Figure 5 and Figure 6. The light green line FCPP2G-FCPP communication is representing successfully established communication.

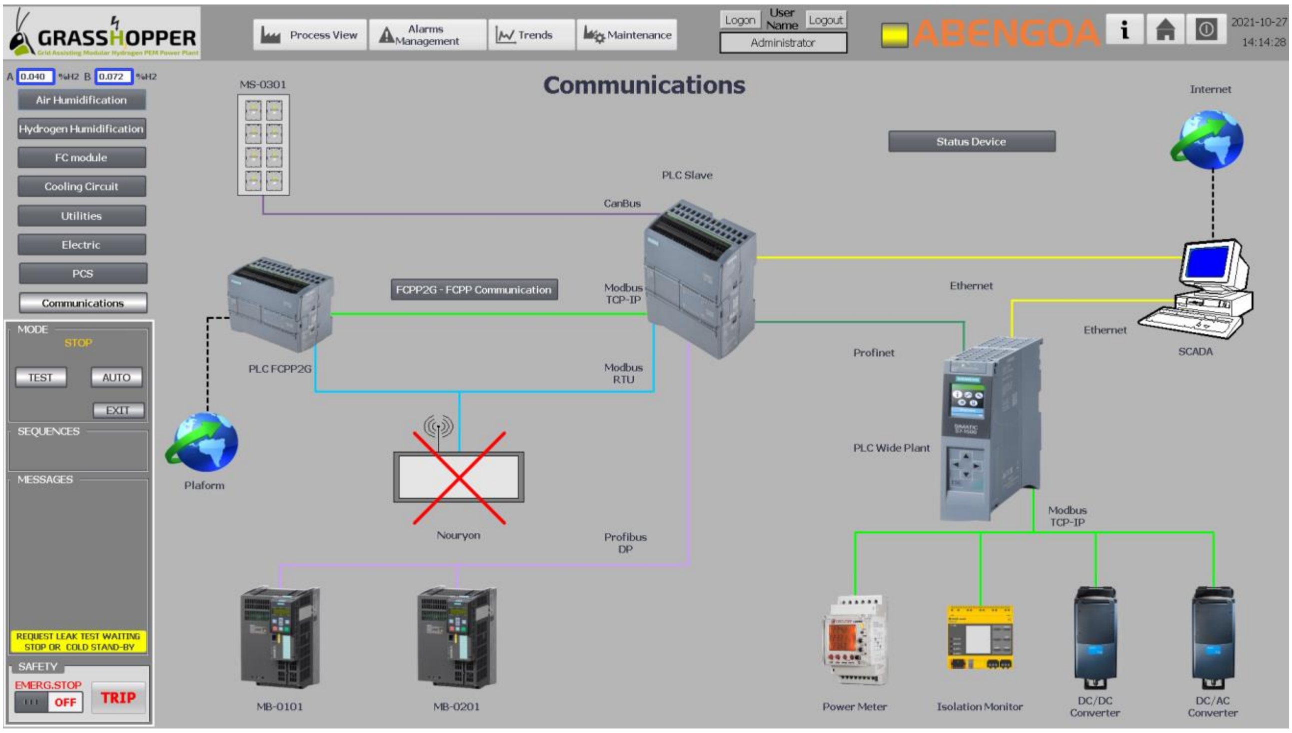

Figure 5: FCPP GUI

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The values exchanged between FCPP2G and FCPP are shown on the following Figure 6.

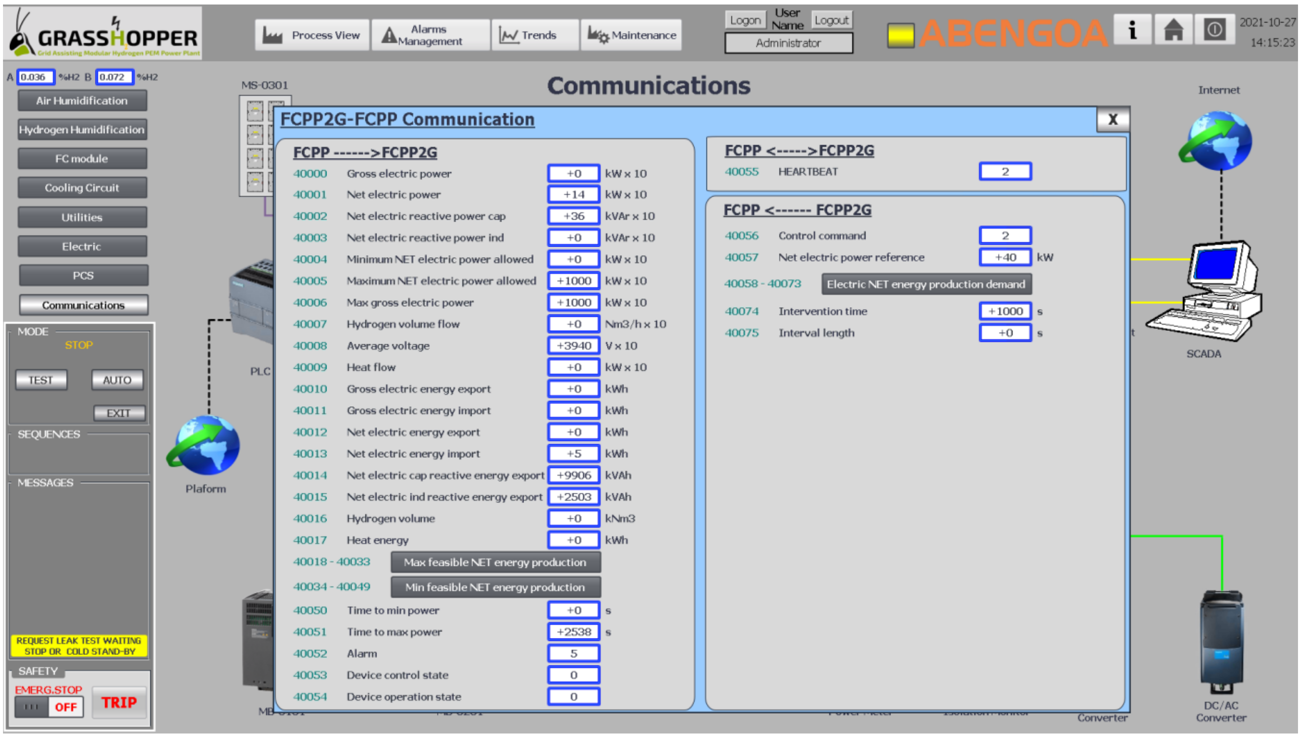

Figure 6: FCPP GUI

2.2 FCPP2G - VPP/DSM data exchange

Communication between VPP/DSM flexibility service and FCPP2G was partially tested and reported in D7.2. Furthermore, we continued testing the measurements that are sent to collection service for monitoring purposes. FCPP2G collects electric energy data from accounting electricity meter, which measures energy flow from/to electric distribution grid. Data is sent periodically (default 1 minute) to VPP/DSM services, which is configurable.

VPP/DSM services are monitoring the operation of the FCPP2G controlling the FCPP. On the collection service GUI, we presented few dynamically changing diagrams where we can observe the system's response. Through those diagrams we can confirm successful communication with the Collection service.

On the first two graphs presented on Figure 7, the power limits of the FCPP operation are being shown, representing the real limits (received from FCPP) vs. limits set (manually set in FCPP2G), as well as Net-power vs gross- power. The data provided on the diagrams is the data being simulated in the testing environment, since the real FCPP in Seville was not operational most of the time.

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Figure 7: Monitoring power limits and gross-net power

The parameters that being observed on Figure 8 are the power setpoint written from FCPP2G to FCPP, net power, gross power and power limits on FCPP. All those values are also graphically shown for easier monitor.

Figure 8: Monitoring FRR parameters

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3 Validation of the control commands

To validate the FCPP2G-FCPP interface design and technology in a relevant environment for overall operation flexibility, it is tested in simulated environment, where FCPP response is simuilated. Purpose of the tests is to examine if FCPP2G meets the specifications, and if it is suitable to control the FCPP for balancing purposes and VPP/DSM services on the electricity market.

The tests were performed directly on FCPP2G by manually changing the modes according to the table provided in Appendix: 8.5 and state event diagram provided in 8.6.

3.1 Shut down - control state 0

Control command set to "0" – shut down, no power set-point, as given in Figure 9. When changing the control command to 0 – shut down, we were able to validate control state of simulated FCPP via GUI, successfully following the control command and changing through transient state (shut down) for 5mins, to stable state cold stand by – value 10 and power drop to minimum, net power below zero. That can be visualized on the following picture:

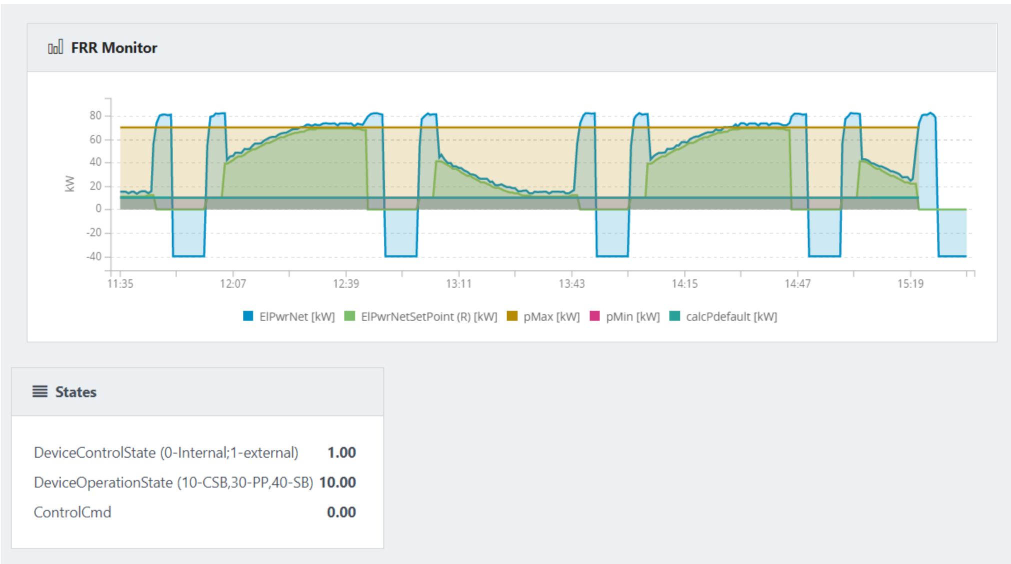

Figure 9: Changing of the Pnet and device operation state when shut down command executed

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3.2 Stand by – control state 1

Control command set to “1” – stand by, no power set-point, as given on Figure 10.

When changing the control command from FCPP2G to 1– stand by, we were able to validate control state of FCPP via GUI, successfully following the control command true transient state and changing to stable state warm stand by –FCPP state changed to 20 (Warm-up, transient state) and power changes to maximum as shown on the upper part of Figure 10. After 5mins FCPP state changes to 50 (Warm stand by, stable state) and power drops, as shown on the lower part of Figure 10:

Figure 10: Changing of the Pnet and device operation state when stand by command executed

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3.3 Power set point – control state 2

Control command set to "2" – power setpoint, set point set to 20kW, as given on Figure 11.

When changing the control command from FCPP2G to 1– power setpoint, we were able to validate control state of FCPP via GUI, successfully following the control command and changing to 30 - power production stable state and following the set point of 20kW, as shown on Figure 11:

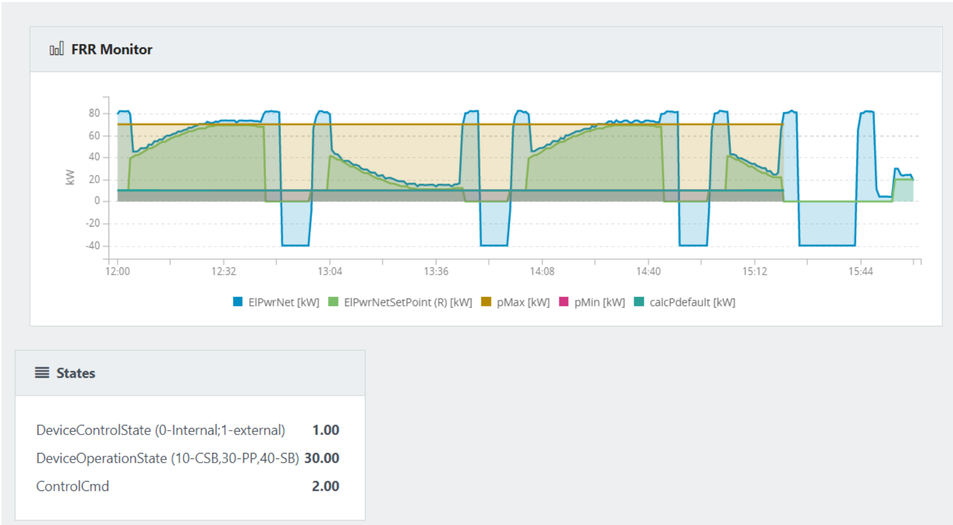

Figure 11: Changing of the Pnet and device operation state when command for power set point executed

3.4 Short summary of the results

Previously given tests are presented shortly in the following Table 1, where control command and the response of FCPP can be observed.

Estimated worst delay because of communication between FCPP – FCPP2G – VPS/DSM services, in both direction is 4 minutes. Response time of the FCPP was not possible to estimate due to FCPP unavailability.

Table 1: Results

Control command	Command description	FCPP response
0	shut down	FCPP state changed to 40 (shut down), after 5 mins, state is changed to 10 (cold stand by).

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1	stand by –zero power	FCPP state changed to 20 (Warm-up) and power changes to maximum. After 5mins FCPP state changes to 50 (Warm stand by) and power drops.
2	power set point	FCPP state changes to 30 (Power production), FCPP starts to follow the set point.

However, due to unavailability of the FCPP, the tests were executed using simulated FCPP.

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4 Validation of automatic operation of FCPP2G

4.1 Mode control

There is a possibility for the operator of the FCPP to change the operation, to enable and disable the grid support, between 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 set-points received by the VPP/DSM services.
- Combination of power and energy flexibility.
- Disable VPP/DSM services (local schedule, as defined by FCPP operator)

The FCPP2G is offering flexibility when in Power flexibility mode, Energy flexibility mode or combination mode. Appropriate control command is determined based on the VPP/DSM services. The FCPP is changing operation states according to the control commands from FCPP2G.

4.2 Power flexibility

Power flexibility is offered when power flexibility is enabled by the FCPP operator - FCPP supports grid services (FRR Services). Power set point (absolute power set-point within the offered power limits) is received and is being sent to the FCPP in agreement with specifications. Current operation and safe operation of the FCPP is also considered.

FCPP2G is designed to control more FCPP units and received power-set point is distributed among them. Example of power flexibility offered by FCPP2G to VPP/DSM services:

"powerFlexibility": {
  "lowerBound": 10,
  "upperBound": 70 }

FCPP2G received power set point from VPP/DSM services and was properly executed by FCPP as shown in the Figure 12. The green line is referring to the power set point and blue line is representing the FCPP power.

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When VPP/DSM services is disabled, FCPP2G sends a command for shutting down the FCPP. This can be observed on the Figure 12, when power is not following the set-point (at the end of the graph), due to shut down process. The same applies during start up process (beginning of the graph).

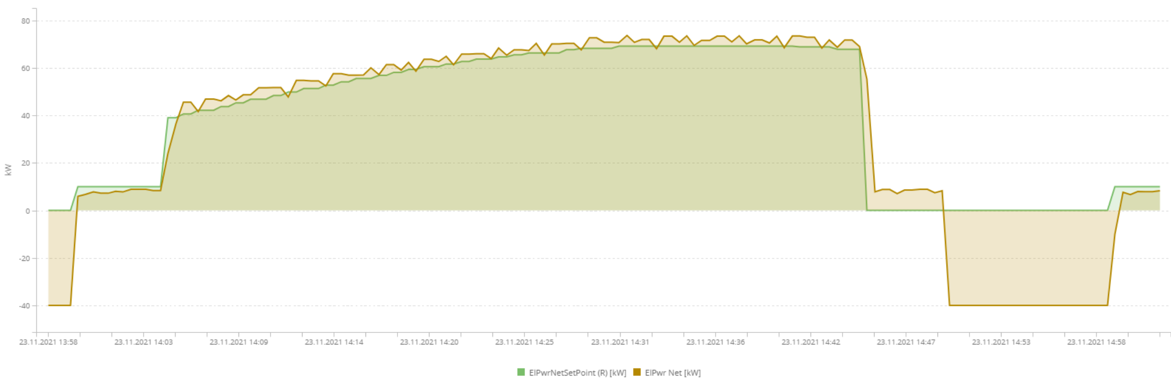

Figure 12: Changing of the Pnet according to the set point

During the test FCPP was turned off, because of the set point received by FCPP2G it was turned on and followed the set-point. At the end of the test, it was turned off again.

4.3 Energy flexibility

Energy flexibility is offered when energy flexibility mode is enabled by the FCPP operator – FCPP supports energy trading. While FCPP is in energy flexibility mode, FOs are sent to the grid supporting services, and If energy is requested, energy demand is received on the FCPP2G. FCPP2G converts energy demand into power set-point, that is sent to the FCPP.

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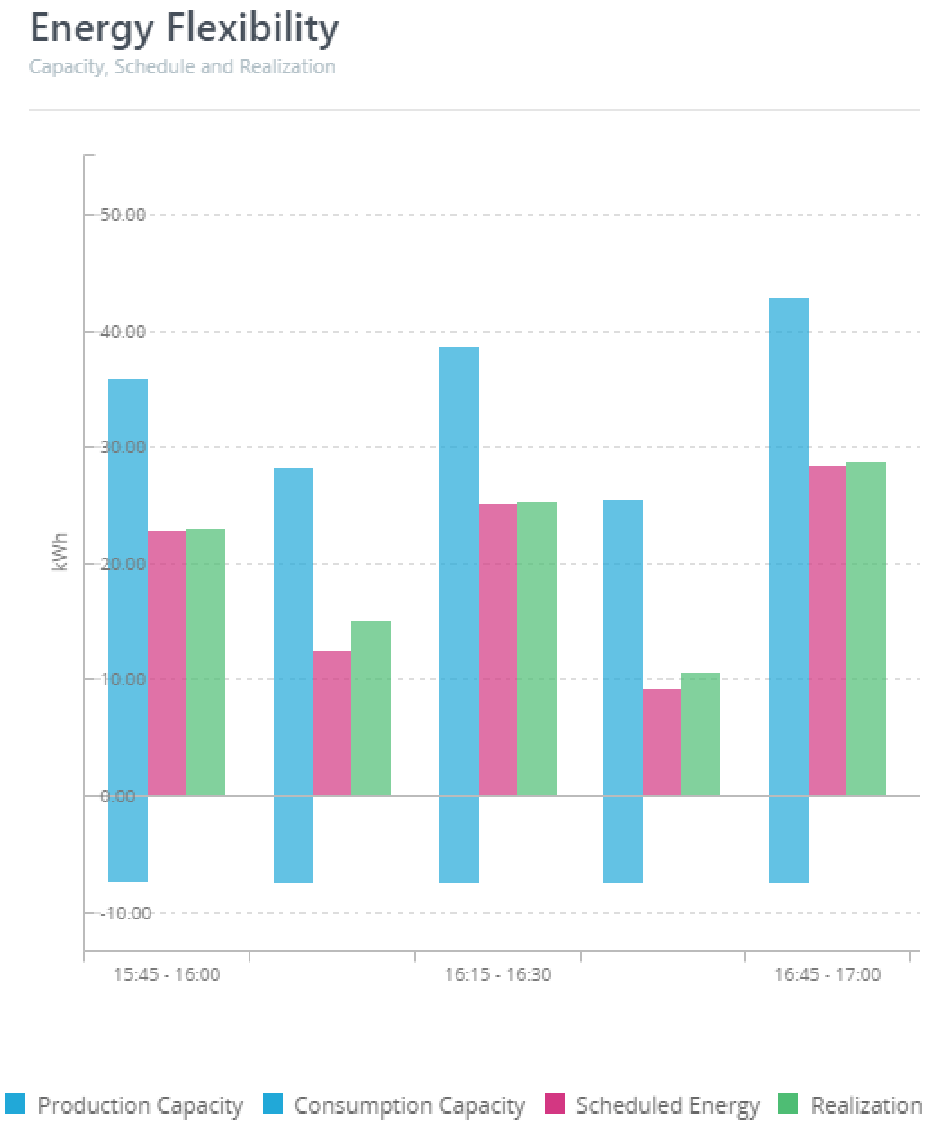

Figure 13: Realization and schedule

On the plot we can observe the energy flexibility, which was offered to the market, requested from the energy market and realized by FCPP.

4.4 Summary of the results

Executed tests are shortly presented in the following Table 2, in case of power flexibility, energy flexibility, combination of both (energy and power flexibility) and in case VPP/DSM services are disabled. When power flexibility is offered, only power FO is being created and offered by FCPP2G. When energy flexibility is offered, only energy FO is being created and offered by FCPP2G. In both cases, if requested by VPP/DSM services, the request is transformed by FCPP2G into power set point control command for FCPP. In case of power and energy flexibility offered, power flexibility request has priority before energy request. When VPP/DSM services are disabled, no flexibility is being provided by FCPP2G and consequently no request to FCPP.

Table 2: Results

Power flexibility		**Energy flexibility**		**Combination of Energy flexibility and power flexibility**		**Disable VPP/DSM services**	
Expected result	**Result**	**Expected result**	**Result**	**Expected re-sult**	**Result**	**Expected result**	**Result**
Power FO offered to VPP/DSM services.	OK	Energy FO offered to VPP/DSM services.	OK	Power and Energy FO offered to VPP/DSM services.	OK	NO flexi-bility pro-vided.	OK
Power is re-quested from the VPP/DSM services. FCPP2G transform it into power-set point for the FCPP.	OK	Energy is re-quested from the VPP/DSM services. FCPP2G transform it into power-set point for the FCPP.	OK	If two sched-ules are re-ceived from GO, power flexibility schedule has priority be-fore Energy schedule.	OK	NO Schedule from GO, no power set point executed from FCPP2G to FCPP.	OK

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5 FAT tests results

The FAT test aims to evaluate the technical correctness of the FCPP2G interfaces, as a conclusion of different aspects being already tested. Two tests were performed:

- FAT test with simulated FCPP
- FAT test with real FCPP

5.1 FAT test with simulated FCPP

The FAT test on simulated FCPP covered the proofing of implementation of both interfaces a) FCPP2G – FCPP interface and 2) FCPP2F – network/market operator. The test contains the functionality of energy trading as well as usage the FCPP for system services through power control.

Table 3: FAT tests results

Test case	Objective	Test procedure	Acceptance criteria	Test results
Parameters available on FCPP	Availability of the parameters on FCPP2G.	The parameters listed in data exchange table need to be checked if available on the FCPP.	Data is available on FCPP.	OK
Variable data-exchange test	Test the data-exchange between FCPP2G-FCPP.	The data listed as R(read) in the data-exchange table is changed on FCPP a few times and observed on FCPP2G. The data listed as W(write) is changed on FCPP2G and observed on FCPP.	The data from the data exchange table to be read and written as described in the table.	OK
Power flexibility Offer on FCPP2G	Creation of power flexibility Offer based on the conditions in the FCPP	Reserved capacity introduced to FCPP2G and check if an Offer is being created respecting the capacity being reserved.	Reserved capacity to be available in the Offer created by FCPP2G.	OK

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	and capacity reserved.			
Energy flexibility Offer on FCPP2G	Creation of energy flexibility Offer.	FCPP2G needs to create energy flexibility Offer.	Energy flexibility Offer created on FCPP2G.	OK
Communication test FCPP2G – VPP/DSM services.	Test the communication between FCPP2G – VPP/DSM services.	Operational info to be send from FCPP2G.	Operational info received by grid supporting service.	OK
Power set-point when request from grid service support.	Calculated power set point by FCPP2G is in agreement with requested power.	Execution of power set-point by FCPP2G when requested from grid service support.	Power-set point to be in the limits of the offered capacity on FCPP and request is fulfilled.	OK

5.2 FAT test with real FCPP

The FAT test on real FCPP proofs the correctness of the implemented interface FCPP-FCPP2G on both side. Additionally the test contained sending the control commands to FCPP to change its operation state and monitoring the speed of power response on various rapid power set-point changes.

Table 4: FAT tests results

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Test step	Action	Result	Test results
0	Initial state	FCPP is in cold stand by. The power reflects the consumption for its internal operation	OK
1	Command "power setpoint" and setpoint = 57kW	FCPP net power is increased to intermediate setpoint then gradually changed to the target	OK
2	Change the setpoint to half power (30kW)	The power follows the setpoint	OK
3	Change the setpoint to max power (58kW)	The power follows the setpoint	OK
4	Change the setpoint to zero	The power follows the setpoint	OK
5	Change the setpoint to max power (58 kW)	The power follows the setpoint	OK
6	Send the 'shut down' command to put the FCPP into the cold stand by state	The FCPP goes into initial state.	OK

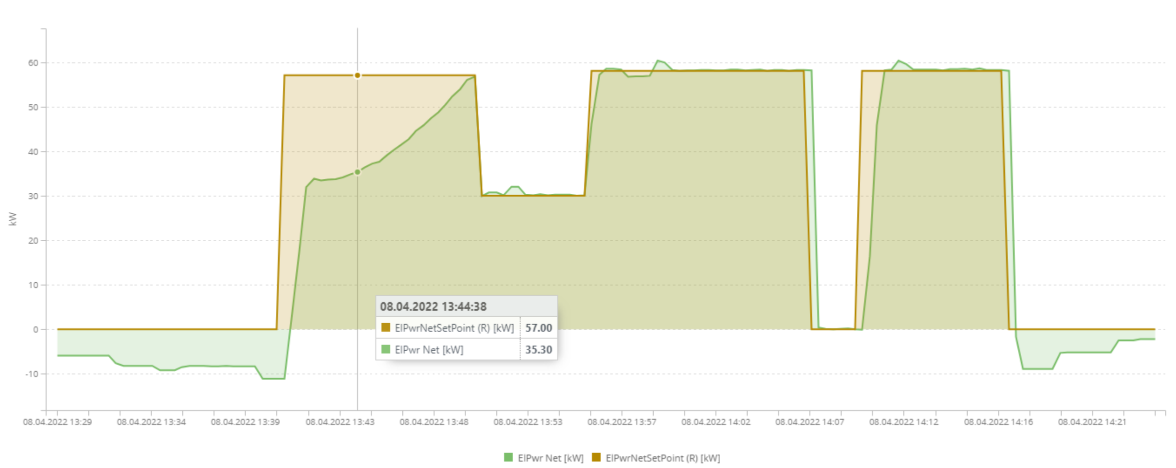

Figure 14: FCPP net power with setpoint through FAT test

6 Conclusion

The validation of the FCPP2G contains successful testing of the communication toward the FCPP as well to network operator, what proofs that it is a tool for aggregators or Grid Operators that enables them to use FCPP operation flexibility for grid support services and energy trading.

The end-to-end test of FCPP on the simulator proved that the FCPP2G meets the project's objectives which are 1) integration of communication protocol which efficiently exploits the fuel cell characteristics of fast start up and power response and b) combines two areas of usage such as energy trading and power setpoint. These characteristics enables user various usages and business cases for FCPP.

The FAT on the real plant validated the FCPP2G-FCPP communication protocol and confirmed that technical characteristics are within expectations. From the FCPP2G point of view the product is ready for the shipment and installation on the destination, where the post project validation period can be performed.

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7 References

D7.1 “Conceptual architecture and requirements”

D7.2 “Prototype of FCPP2G integration interface”

D6.1 “Design of modular, low cost 100kW pilot plant”

D5.1 “Report on workshop results on review of plant key features and definition of performance optimization criteria”

D5.2 “Simulations of layouts and report on operating conditions as support for 100 kW unit engineering”

D5.3 “Final report on stationary simulations and optimization of the 100 kW prototype and MW scale plant”

D5.4 “Final report on dynamic simulations and optimization of operation strategies for flexibility”

D5.5 “Report on prototype data analysis, validation and refinement of the optimal layout and operation, multi-MW plant expected performances”

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D6.3 “FAT reports of 100 kW pilot plant”.

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8 Appendix

8.1 Data exchange table

After technical discussions and alignments between partners on the project, resulted in update of exchange table for Modbus communication. Last version of exchange table is presented in the following Table 5.

Table 5: FCPP – FCPP2G variables exchange table

	Data name	Availability	R/W	Range	Unit	Format	Address	Description
1	Gross electric power	FCPP	R	0..100	kW	int x 10	40000	Total electric power measurement from DC/DC converter[1]
2	NET electric power	FCPP	R	-20..100	kW	int x 10	40001	From network analyzer. Alternative via pulse signal
3	NET electric reactive power cap	FCPP	R	-20..100	kVAr	int x 10	40002	From network analyzer. Total capacitive reactive power
4	NET electric reactive power ind	FCPP	R	-20..100	kVAr	int x 10	40003	From network analyzer. . Total inductive reactive power
5	Minimum NET electric power allowed	FCPP	R	0..100	kW	int x 10	40004	From PLC
6	Maximum NET electric power allowed	FCPP	R	0..100	kW	int x 10	40005	from PLC
7	Max gross electric power	FCPP	R	50..100	kW	int x 10	40006	From PLC
8	Hydrogen volume flow	FCPP	R	0..30	Nm3/h	int x 10	40007	from PLC (analog signal)
9	Average voltage	FCPP	R		V	int x 10	40008	From AC/DC converter
10	Heat flow	FCPP	R	0..200	kW	int x 10	40009	From heat meter[3]
11	Gross electric energy export	FCPP	R		kWh	int	40010	from DC/DC converter[2]
12	Gross electric energy import	FCPP	R		kWh	int	40011	From DC/DC converter[2]
13	NET electric energy export	FCPP	R		kWh	int	40012	From network analyzer
14	NET electric energy import	FCPP	R		kWh	int	40013	From network analyzer
15	NET electric cap reactive energy export	FCPP	R		kVAh	int	40014	From network analyzer
16	NET electric ind reactive energy export	FCPP	R		kVAh	int	40015	From network analyzer
17	Hydrogen volume	FCPP	R		KNm3	int	40016	From PLC

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18	Heat energy	FCPP	R		kWh	int	40017	From heat meter[3]
19	Max feasible NET energy production	FCPP	R	Array[16] 0..25	kWh	int	40018 ……. 40033	From PLC Estimation of the maximum feasible energy production in next set of intervals
20	Min NET energy production	FCPP	R	Array[16}0..25	kWh	int	40034 ………. 40049	From PLC Estimation of the minimal (necessary) energy production in next set of intervals
21	Time to min power	FCPP	R	0..200	s	int	40050	From PLC Estimated time needed to reach min power (from current power)
22	Time to max power	FCPP	R	0..200	s	int	40051	From PLC. Estimated time needed to reach max power (from current power)
23	Alarm	FCPP	R	0..10		int	40052	From PLC – see corresponding table
24	Device control state	FCPP	R	0..10		int	40053	Status of FCPP sent to FCPP2G – see corresponding table
25	Device operation state	FCPP	R	0..10		int	40054	Status of FCPP sent to FCPP2G – see corresponding table
26	HEARTBEAT FCPP-> FCPP2G	FCPP, FCPP2G	R / W	0..15		int	40055	Communication check signal. FCPP increases internal counter every second, FCPP2G will reset this counter (send 0) every 5 secs if communication is OK.
27	Control command	FCPP	W	0..10		int	40056	See corresponding table
28	NET electric power reference	FCPP2G	W / R	0..100	kW	int	40057	NET power reference for the FCPP from the FCPP2G
29	Electric NET energy production demand	FCPP2G	W / R	Array[16] 0..25	kWh	int	40058 ……….. 40073	NET electric energy production demand in time in next set of intervals. It is updated every 15 min – number of intervals are reduced.
30	Intervention time	FCPP	W	0.. interval length	s	int	40074	Time in seconds from the energy production demand. It is reset at every interval length.
31	Interval length	FCPP	W	0..3600 (default 900)	s	int	40075	Interval length in seconds

8.2 Alarm table

Table 6: Alarm table (element #23 in Table 5)

Value	description
0	no alarm
1	maintenance
2	operation error (out of hydrogen, internal error, …)

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3	bad power setpoint
4	bad energy demand

8.3 Device control state table

Table 7: Alarm table (element #24 in Table 5)

Value	description
0	internal control
1	external control

The values are controlled by FCPP PLC.

If value = 0 → external commands are disabled. I.e. used at maintenance.

8.4 Device operation state table:

Table 8: Alarm table (element #25 in Table 5)

Value	description
10	Cold standby
20	Warm-up
50	Warm Standby
30	Power Production
40	Shutdown
60	Oxygen Depletion
Any other	Ignore this value

8.5 Control command

Table 9: Alarm table (element #27 in Table 5)

Value	description
0	shut down
1	stand by –zero power

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2	power set point
3***	energy demand

Control commands are in power only when the device control state is in “external control”.

***For practical reasons energy demand is converted into power set point on FCPP2G. If a proper use-case will be defined, possibility to implement in next version of FCCP and FCPP2G.

8.6 State event diagram

State FCPP	State type	Control state	Value of variable
Init	Transient	External control	1
Cold standby	Stable	External control	10
Warm-up	Transient	External control	20
Warm Standby	Stable	External control	50
Power Production	Stable	External control	30
Shutdown	Transient	External control	40
Oxigen Deplition	Transient	External control	60
Ignore this value	-	-	Any other

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