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Sustainable SoluTions FOR recycling of end-of-life Hydrogen technologies

Deliverable D2.6

Report on the evaluation of MEA including recycled materials in PEMFC stack (Public)

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Abbreviations

B4HyCCM	CCMs manufacture in the BEST4Hy project
BPP	Bipolar Plate
CCM	Catalyst Coated Membrane
CEA	French Atomic Energy and Alternative Energy Commission
EK-FCDLC	EKPO Fuel Cell Durability Load Cycle
EKPO	EKPO Fuel Cell Technologies GmbH – Joint Venture between ElringKlinger and Plastic Omnium
EoL	End-of-Life
FC	Fuel Cell
GDL	Gas Diffusion Layer
MEA	Membrane Electrode Assembly
OCV	Open Circuit Voltage
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PHT	Performance and Homogeneity Test
RefCCM	Reference CCM
SOFC	Solid Oxide Fuel Cell

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Executive Summary

This document reports the work carried out under the last task of work package 2 (WP2 – *Characterization and evaluation of recycled materials in single cell and stack PEM configuration*) of the BEST4Hy project. This includes the testing and evaluation of catalyst coated membranes (CCMs) manufactured by project partner CEA (French Atomic Energy and Alternative Energy Commission) with the catalyst obtained from the platinum recovered from end of life (EoL) polymer electrolyte membrane fuel cells (PEMFCs) provided by EKPO. Therefore, five project CCMs (B4HyCCMs) (D2.4) were assembled to membrane electrode assemblies (MEAs) and stacked parallel[1] to five MEAs, containing commercial CCMs (RefCCMs) as reference, resulting in a 10-cell short stack of industrial size (NM5-evo).

Manufacturing and testing of the fuel cell stack was carried out by EKPO. Data evaluation was then subsequently done also by EKPO.

Fuel cell stacks comprising of components differing from each other, are commonly referred to as “rainbow stacks”: their advantage is that different cells are tested under the same conditions supporting their direct comparison of the performance. They are commonly used in industrial settings when trialing new components.

1 Introduction

The BEST4Hy project focused on the evaluation, development, and characterization of recycling technologies for end-of-life fuel cells. In focus, concerning fuel cell technologies, were polymer-electrolyte membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs).

WP1 (*Existing and novel technologies of PEMs: proof of concept*) and WP2 are covering the PEMFC technology, whereas the SOFC technology is being addressed in WP3 and WP4.

End-of-life (EoL) components of PEMFC stacks were the starting point of material flow in the project. Therefore, a variety of materials of different integration levels were supplied, starting from catalyst coated membranes (CCMs), to MEAs up to entire fuel cell stacks. The component of major interest – from an ecological and economical point of view – is certainly the platinum containing CCM, which is typically available in varying degrees of use, meaning different number of operating hours.

Different processes for the recycling of materials were investigated, whereby the main focus was initially set on platinum. This is a highly valuable and at the same time, a significant environmentally impacting material. Geopolitical factors apparent in poor security of supply and limited deposits support the focus on this material.

[1] Parallel use of MEAs/cells here is meant from a supply-by-media point of view, whereas from an electrical point of view, the MEAs/cells are connected in series.

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Successful and efficient recovery of platinum by Hensel Recycling / IDO Lab at lab scale (D1.1 and D1.2), and subsequently up to TRL5 (D1.5), resulted in platinum salt, that served as precursor for the catalyst synthesis at CEA (D2.1 and D2.2 – both confidential). Further process steps, explained in D2.3, resulted in the manufacturing of CCMs. Different CCM sizes were produced to be tested mainly for electrical performance, from small scale single fuel cells over medium scale single fuel cells up to industrial sized fuel cell stacks.

In this deliverable, the main outcomes of task 2.4.2 - *Evaluation in stack PEMFC* is presented, addressing the objective of *CCM manufacturing at industrial stack design and validation in stack operation*.

The report is structured as follows:

- chapter 2: testing of fuel cells at EKPO
- chapter 3: building of short stack
- chapter 4: testing of short stack
- chapter 5: conclusion

2 Testing of fuel cells at EKPO

EKPO is developing and producing fuel cell stacks and fuel cell stack modules, all of the type PEMFC. Fuel cell stack modules in comparison to fuel cell stacks have further integrated functionalities, like sensors (e.g. temperature sensor, pressure sensor), actuators (e.g. valves for purge and drain) or passive components like water separators or a housing. Latter supply the connections to the cell row assembly (stacked single cells of a fuel cell) only, inlets and outlets for hydrogen, oxygen and coolant, as shown in Figure 1. The power connection is realized through conducting end plates, whereas in fuel cell stack modules, dedicated paths for the power to be fed into a system is realized via power connectors.

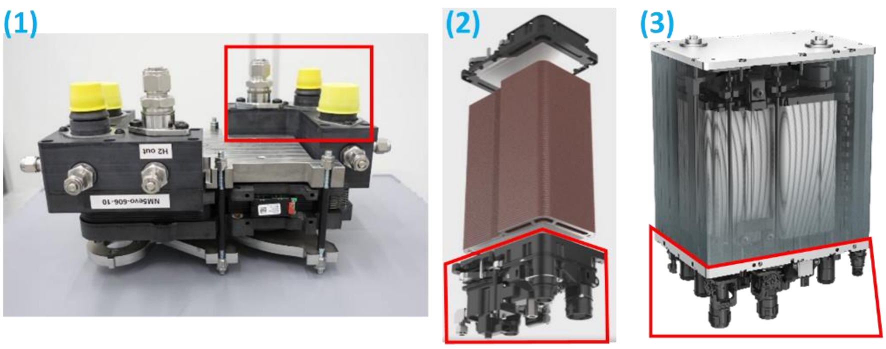

Figure 1: Short stack with media connectors (1), fuel cell stack with media supply assembly (2), fuel cell stack module with media supply assembly and housing (with transparency effect) (3)

There are different purposes for testing FCs. In the frame of this project, a component should be tested and compared to another component to evaluate relative performance, in

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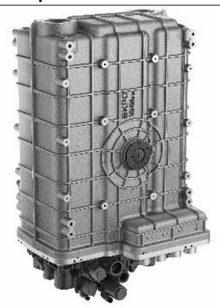
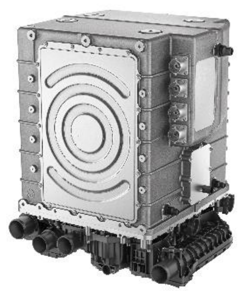
this case considering the use, in the CCMs, of catalyst manufactured with recovered Pt vs. a commercial component. This component is the CCM.

Component development for research purposes is often carried out in small sized fuel cells, medium sized fuel cells, seldomly in industrial size fuel cells. However, for testing and benchmarking components in an industrial environment and for the commercial market, ready-for market designs are used.

At EKPO, different so-called platforms have been developed, offering different power ranges, addressing different applications and concepts, trying to cover the entire market. These platforms developed are NM5, NM12 and NM12 twin (Table 1). In BEST4Hy, NM5 EoL material from development tests was used, thus the NM5-evo platform has been selected for carrying out the test of the project CCMs with recovered platinum material.

With the aim of testing the BEST4Hy project CCMs (B4HyCCMs) in an as-close-as-possible or as-close-as-feasible setup compared to a commercial fuel cell stack, a short stack was chosen over a single cell. In commercial applications, fuel cell stacks often comprise of many cells, stacked to a cell row assembly, resulting in a desired power output for the targeted application. The short stack thus is a reasonable choice, being just in between a single cell and a full-sized stack. Hereby the short stack already represents the characteristics of a full-size stack without showing border effects of the single cell. The drawback is that more components and thus more CCMs (and Pt) is needed to build the stack. However, the advantage is that a direct comparison between the CCMs in one test specimen is possible. Using the concept of a rainbow stack, meaning to integrate several components of different characteristics into one stack distributed over different cells, guarantees a fully comparable operation of the components to be evaluated. All cells are operated under the same conditions, which enhances the comparison.

Table 1: Fuel cell platforms at EKPO

NM5-evo	NM12 single	NM12 twin
15 - 76 kW	123 kW	205 kW
up to 335 cells	up to 359 cells	up to 598 cells
		

3 Building of short stack

The CCMs produced by CEA (Task 2.3.2, Deliverable D2.4) were assembled at EKPOs prototype shop into a NM5-evo fuel cell short stack (Figure 2). Therefore, EKPO NM5-evo standard components for the cell assembly were used, such as gas diffusion layers (GDLs) and bipolar plates (BPPs). The NM5-evo's concept uses GDLs with an injection-molded

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gasket, so no separate seals or sub-gaskets needed to be used (Figure 3). The CCMs supplied by CEA came, as agreed, in slightly larger size than needed for the stack to be processed. The CCMs were cut to the right size.

Cell 1 to cell 5 from the short stack inherited the project CCMs, also referred to as B4Hy-CCMs with an average total loading of about 0,55 mgPt/cm². For cell 6 to cell 10, EKPOs' reference components were used. The only difference between the cells were therefore the CCMs, which are, especially considering the parameter of catalyst loading, both in the same range, with the B4HyCCMs eventually containing slightly less catalyst mass and probably different catalyst type and membrane.

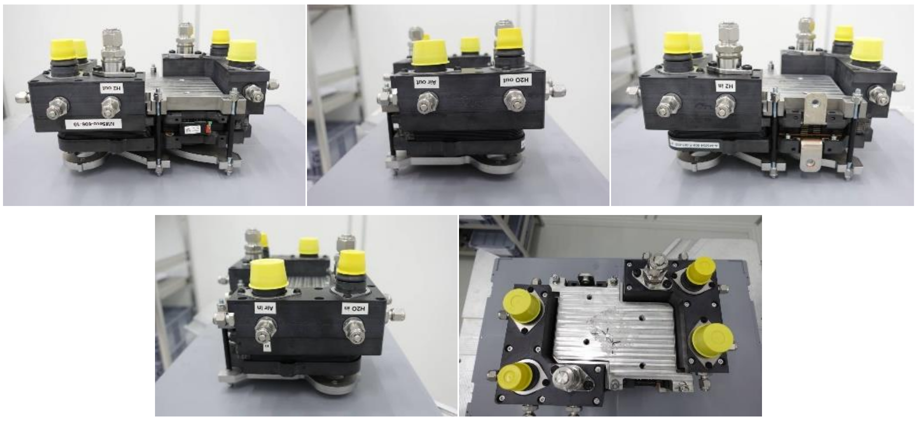

Figure 2: Different views on the NM5evo fuel cell short stack (rainbow stack) produced at EKPO for the BEST4Hy project

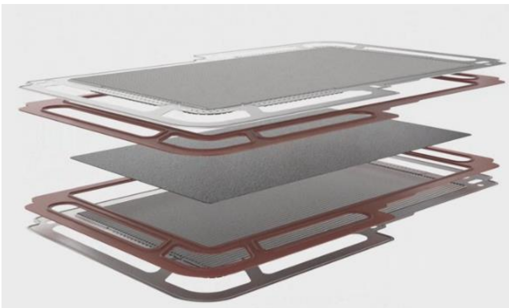

Figure 3: EKPO NM5 cell concept with BPPs, seals and MEA (GDLs and CCM). The seals, which appear separated here, are however injection molded onto the GDLs

However, when the single membrane electrode assemblies (MEAs) were assembled, it was noticed that the B4HyCCMs, produced by CEA had certain defects. Placing the CCMs on a light table, bright dots were observed on the CCM sheets. The areas where light came through seemed to have no catalyst coating on both sides of the membrane, enabling light to pass through (Figure 4). These defects of coverage are coming from a lack of one electrode transferred in front of the agglomerates present in the other electrode, without damaging the membrane. An optimization of the ink for the manufacturing of the large CCMs could have increased the quality of the CCM. Due to the limited quantity of synthesized catalyst, only one batch of ink has been produced for the manufacturing of the

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10 CCMs for the project. The defects were small spots of a maximum of 1 mm size. There were some few (below 10) up to 50 or more of these spots per CCM. Due to a previous process step, i.e., the cutting of the CCMs, the conditions of the CCMs (spots) were only recognized right before assembling the MEAs. The CCMs with the best coverage were selected for the test.

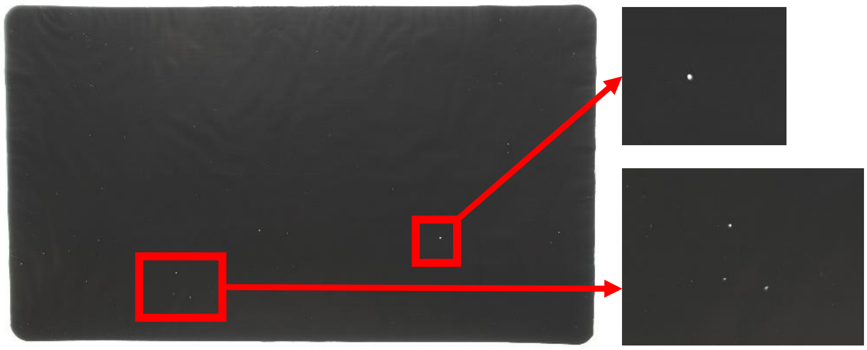

Figure 4: spots with no coverage of catalyst layer on both sides of BEST4Hy CCMs

Even though small spots of uncovered areas of the B4HyCCMs were present, the final MEAs assembled and built into the short stack beside the RefCCMs resulted in an overall gastight stack (no anode to cathode leakage).

EKPO commonly performs an end-of-line testing of built stacks. These are of different categories like optical and mechanical checks, but also a leakage test (pressurization of single media chambers or a combination of these) and an electrochemical test on the testbench, called Performance and Homogeneity Test (PHT, explained later) just to mention some of the routines. The tests and checks offside the testbench showed no further abnormalities, so the stack was approved ready for testing.

4 Testing of short stack

For running a fuel cell test, a test bench is needed. At EKPO facilities, different test benches are available.

To be able to examine the CCMs the best way possible, a test bench for component tests was chosen. This test bench also had the capability to be operated in open-end mode for the anode side, compared to other test benches at EKPO, having a closed-anode-loop configuration. Being able to set parameters on anode side is of high interest for component tests, especially when cell components are being tested.

For the test procedures, several meetings with CEA were conducted. Being aware of the limited budget and the circumstances of the test, a test plan was made. The budget limitation already set the boundary for the overall testing time on the test bench. Calculations projected an all-in-all test duration up to 500 hours, which was considered more than sufficient to undertake the operational and functionality testing of the recovered Pt to demonstrate close-loop recycling efficiency. A lifetime or durability test (requiring at

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least a range of some thousand hours of testing) was not planned in the project due to lack of time, considering the effort in all the processes of recovery of Pt, synthesis of catalyst with said material and manufacturing of new CCMs. Nevertheless, a durability test would be of high interest for the industry to get insights into the stability over lifetime of the CCMs produced with recovered Pt.

It was agreed on a test plan as shown in Table 2:

Table 2: Test plan Short Stack test at EKPO

Test	Time needed (h)	Comments
Break-in	2-3	Conditioning of stack
PHT	4	Performance and Homogeneity Test
Polarization Curves	3*2 = 6	Per polarization curve 2-3 + System polarization curve
Performance analysis (DoE D-optimal test plan)	24	Wide parameter space
Max duration of EKPO-FCDLC[2]	~500	According to budget and availability of test bench and resources

4.1 Test design and test setup

Table 2 shows the single sequences planned for the test. This is composed of:

- A break-in
- A PHT
- Polarization curves
- EKPO performance analysis
- The EKPO Fuel Cell Dynamic Load Cycle (EK-FCDLC).

4.1.1 Break-In

Commonly, fuel cells are being conditioned with a break-in procedure, which is the initial operation of a fuel cell. This brings the cells in a stack to their nominal power output after manufacturing. Also, a homogenization of single cell voltages is aimed for with this procedure.

4.1.2 PHT - Performance and Homogeneity Test

At EKPO the procedure called PHT is an end-of-line procedure, to check the quality state of the fuel cell, namely performance and cell-to-cell homogeneity of the stack. Therefore, four specific load points are set, to get the corresponding voltage response of the individual

[2] From "The Fuel Cell Dynamic Load Cycle, (FC-DLC), which is derived from the New European Driving Cycle (NEDC) modified for fuel cell applications extended by a hill climb load point held for 60 minutes at moderate current density.

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cells in the stack (Table 3). These load points can be classified in two low pressure and two high pressure load points. Low pressure means that cathode and anode side gases are not, or not significantly pressurized (pressure equal to 1 bar_a), whereas pressurized operation occurs at around 1.5 bar gauge above ambient. Each pressure level has a maximum load point (PHT2 & PHT3), where around 0.6 V per cell as an average voltage is aimed to be achieved. The partial-load load points (PHT1 & PHT4) aim for low power output in the corresponding pressure level. These four load points were empirically established to supply a time efficient and sufficient method to evaluate the states of performance and quality for each stack and cell produced at EKPO.

Table 3: EKPO PHT Load Points

Load Point Name	Current density (A/cm²)	Pressure (bar_a)
PHT1	0.79	2.5
PHT2	2.00	2.5
PHT3	1.37	Atm.
PHT4	0.11	Atm.

PHTs being quite quick in time and easy to implement are a suitable method to monitor the evolution of the performance of the fuel cell stack over time if placed accordingly over the testing sequence, e.g. after break-in and as end-of-test. A first comparison of these results can already give some easy interpretable first insights into the cells or stack behavior.

4.1.3 Polarization curve

Polarization curves are a common method to evaluate fuel cells and their components. Hereby some parameters, e.g. the pressure level of anode and cathode gases, are maintained at a fixed value, supporting an easy evaluation by keeping some of the operating parameters constant while stepping through several current steps. Some polarization curves were for this reason integrated into the test plan.

4.1.4 Performance Analysis

Another suitable test method is a test designed according to the method of statistical design of experiments (DoE), called performance analysis at EKPO. With that method, the result is a mathematical model which covers the resulting responses (in the fuel cell this is voltage), that can be expected when setting parameters to a certain value. These parameters are obviously the current or current density and all the ones being integrated into the DoE, typically pressures, flows, humidification, temperatures of media. Interpolation in the observed and examined parameter space can give accurate results if the parameters for the DoE were set accordingly.

A performance analysis has been implemented in the test plan, which comprises of 73 load points with varying parameters in a certain range as can be seen in Table 4.

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Table 4: parameters and range of DoE

EKPO Performance Analysis – 73 test points			
Variable	Unit	Min	Max
Current density	A/cm²	0.3	2.5
Pressure	bar_a	0.9	2.5
Coolant inlet temperature	°C	60	85
ΔT coolant between inlet and outlet	K	1.7	13
Relative humidity cathode inlet	%	40	80
Air stoichiometry	-	1.5	2.6
Relative humidity anode inlet	%	40	80
Hydrogen stoichiometry	-	1.5	3.9
Volume percent nitrogen anode inlet	%	0	50

4.1.5 EK-FCDLC

For durability analysis, a load cycle, called the EK-FCDLC (EKPO Fuel cell Dynamic Load Cycle) was used. This is which is a derivative from the "Fuel Cell Dynamic Load Cycle" (FC-DLC) to be found in the publication "EU HARMONISED TEST PROTOCOLS FOR PEMFC MEA TESTING IN SINGLE CELL CONFIGURATION FOR AUTOMOTIVE APPLICATIONS" (1) adjusted to EKPOs products and requirements.

The EK-FCDLC, in comparison to the FC-DLC, is extended by a load point which is held for 60 minutes at a moderate current density (1 A/cm²). The whole load cycle is less dynamic than its template FC-DLC. Additionally, the concatenation of the EK-FCDLCs is interrupted by one polarization curve per day. Furthermore, one shutdown per week of the fuel cell stack is done with optionally a leakage and cell voltage drop test.

4.2 Results and interpretation

Some delays in the start of the test were experienced due to internal constraints in capacity of stack building and testing. This delay in the start limited the overall testing time, which reached a total of about 200 hours (Figure 5) but was considered sufficient to understand the performance of the CCMs manufactured with recovered Pt.

The test that had to be cut was the durability test, i.e. the repetition of the EK-FCDLC. An analysis of the different phases of the test is reported below.

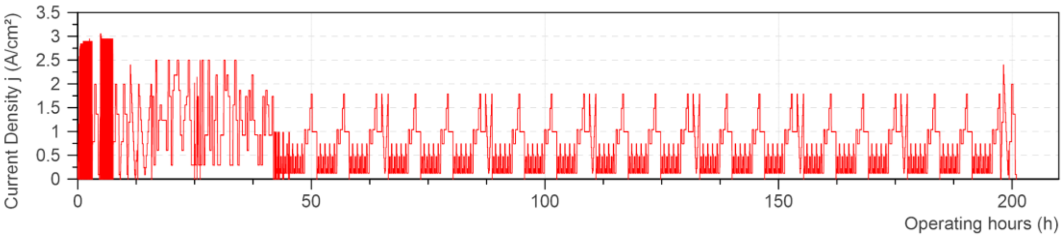

Figure 5: overview over short stack test time displaying the current over operating hours

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4.2.1 Break-In

The break-in procedure is basically a voltage cycling between open circuit voltage (OCV), so with no load, and different load points of higher currents, resulting in different cell voltages. This proprietary cycle between different potentials is repeated several times until a certain level of cell performance is reached.

As already described, the break-in procedure happens after manufacturing usually as the very first electrical operation of the fuel cell (stack). For making a statement on the result of the break-in procedure, it is suitable to evaluate the PHT.

4.2.2 PHT

The two PHTs (after the break -in and after 200 h of operation) show only very little difference, considering the plots seen in Figure 6. You can see the corresponding averaged voltage of the cells containing the B4HyCCMs, referenced as U_avg in green (Cell 1-5) and the RefCCMs referenced as U_avg (Cell 6-9) in blue in the plot.

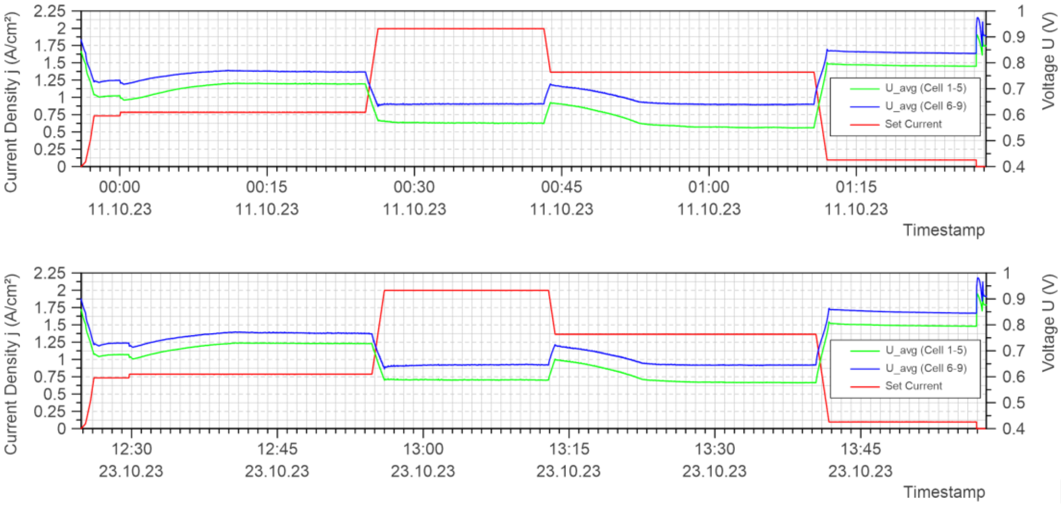

Figure 6: PHT after break-in procedure (top diagram, after ~7.5 operating hours) and PHT at end-of-test (bottom diagram, after ~200 operating hours).

Evaluating the four load points in another view (Figure 7), gives clearer insight into the data. The values shown are averaged over the last 60 seconds of each load point in the PHT, after keeping a dwell time for at least 15 minutes for every load point to reach quasi steady-state conditions and before targeting the next load point. Comparing begin to end of test, the project CCMs still gain voltage in every load point comparing the PHT after about 7 hours of operation to the last PHT after about 200 hours of operation (up to ~5%, considering the 260 A load point), whereas the RefCCMs from EKPO gain less voltage and thus performance (~1%). The improvement over time for a replicable load point can have different reasons e.g. the B4HyCCM not being fully conditioned yet. Also, the overlay of an already occurring degradation mechanism could be contained in this short time of operation already, which lowers the voltage.

The second obvious takeaway examining the graph is, that the B4HyCCMs are constantly lower in voltage compared to the RefCCMs. This is also recognizable, when having a look

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at open circuit voltage of the single cells, like in Figure 9. The reasons for this can be multiple, which could be better classified with a more detailed analysis and further tests.

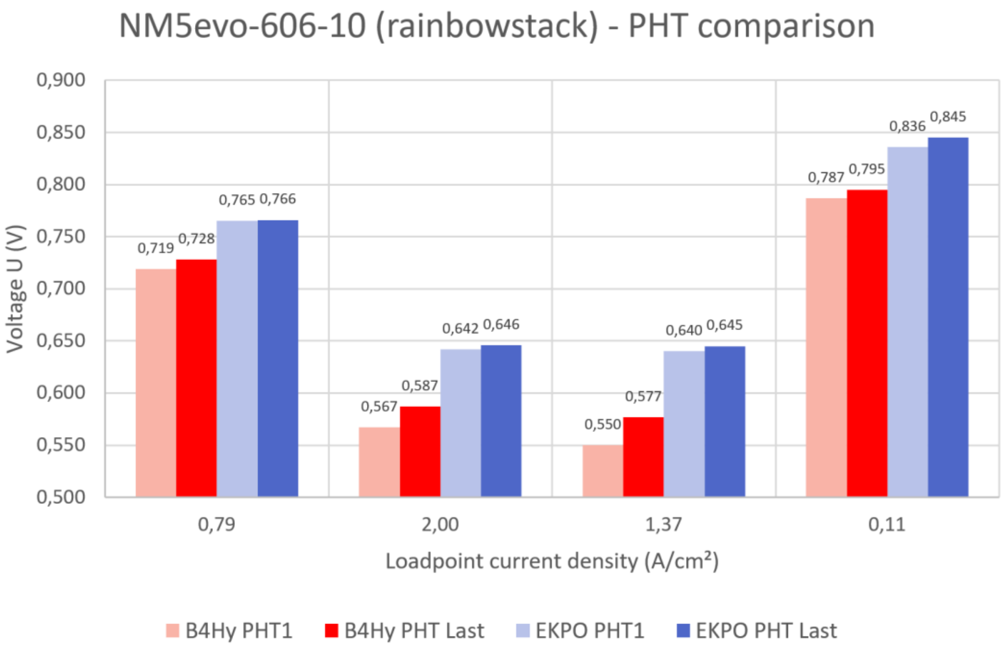

Figure 7: Comparison of PHT results categorized by load points

4.2.3 Polarization curves

Several polarization curves were recorded during the test, one is evaluated here in further detail (Figure 8), since the behavior of the other polarization curves are quite similar. It can be noticed that both CCM types have similar performance and show a quite constant offset between their average voltages. Hereby the B4HyCCMs are constantly 50-70 mV less in voltage and thus minor in power output than the RefCCMs. The difference in voltage between the two types of CCMs could have been slightly reduced if the break-in had been longer, to fully condition the B4HyCCM.

Another interesting point would be to have a look at the open circuit voltage (OCV) of both CCM types. In Figure 9, an offset between the two cell types is clearly visible. In the frame of the project, no further analysis was possible, but it is worth to mention that this “offset effect” is visible throughout the entire operating time, even in OCV.

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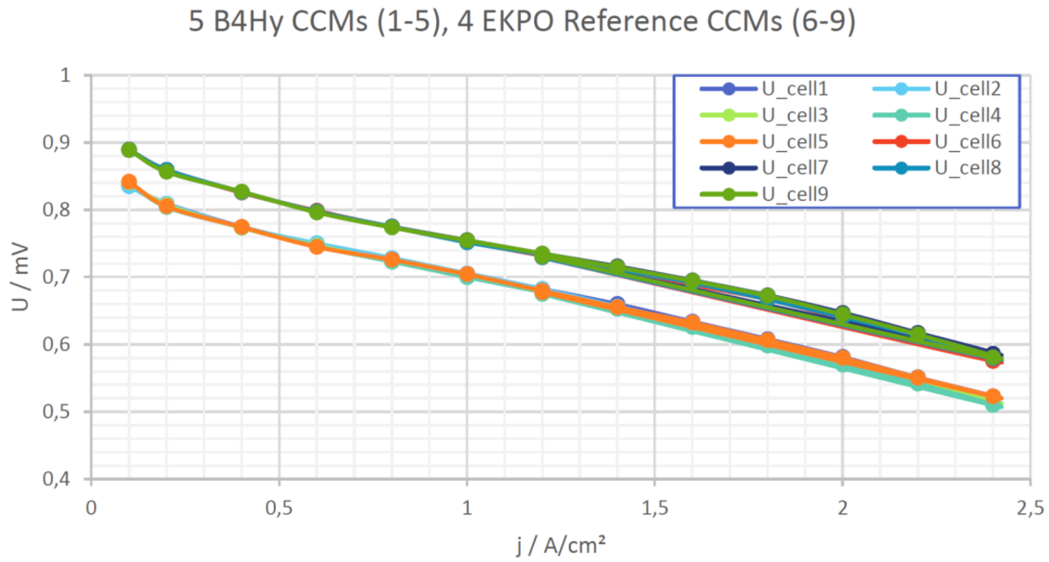

Figure 8: one exemplary polarization curve from short stack testing displaying single cells, B4HyCCMs being constantly lower in voltage. Operating parameters to be found in the annex (Table of Operating Parameters of exemplary polarization curve).

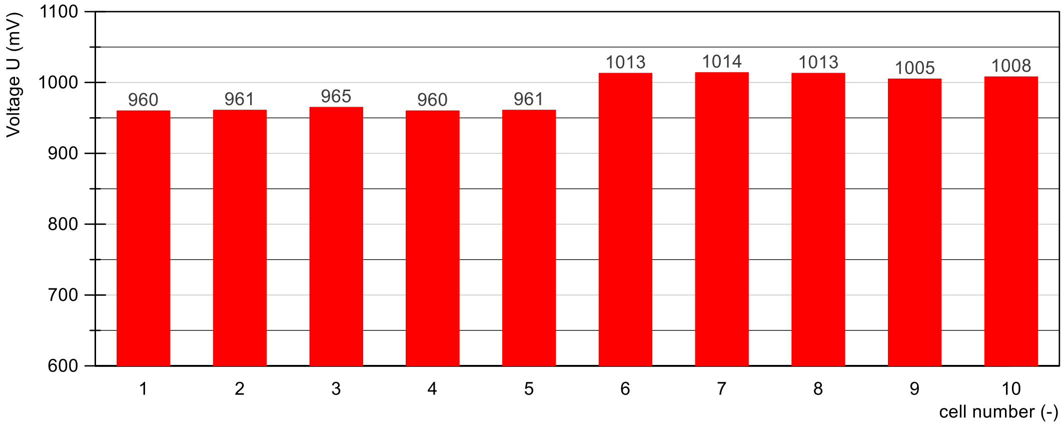

Figure 9: Open circuit voltage of short stack single cells with B4HyCCMs (1 to5) and RefCCMs (6-10).

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Performance Analysis

The performance analysis shows the behavior of the cells containing the B4HyCCMs. Exemplarily, the predicted responses (voltage) are shown for one parameter combination in Figure 10 for the B4HyCCMs at an exemplary current density of 1.5 A/cm^2.

The plots show an obvious and linear dependency between air stoichiometry and responding voltage, which agrees well with findings from literature. A higher air flow and thus oxygen supply to the catalyst express in a higher voltage with given drawn current density. With even higher effect, the same applies for the cathodic pressure (the anodic pressure is equally leveled) which logarithmically rises, according well with Nernst's Law.

Having a look at the relative humidity on anode and cathode side, an increase translates only slightly visible in voltage gain, which leads to the conclusion, that with the other parameters set, a higher humidification leads to a slightly higher protonic conductivity of the membrane and thus to a lower electrical cell resistance.

The behavior of decreasing voltage with increasing coolant temperature delta could be explained with more inhomogeneous temperature and thus humidity conditions along and in the CCM, while the optimal temperature with given parameters seems to be at around 70 °C.

Neither further comparison nor model data to/for EKPO RefCCMs can be disclosed due to IP restrictions.

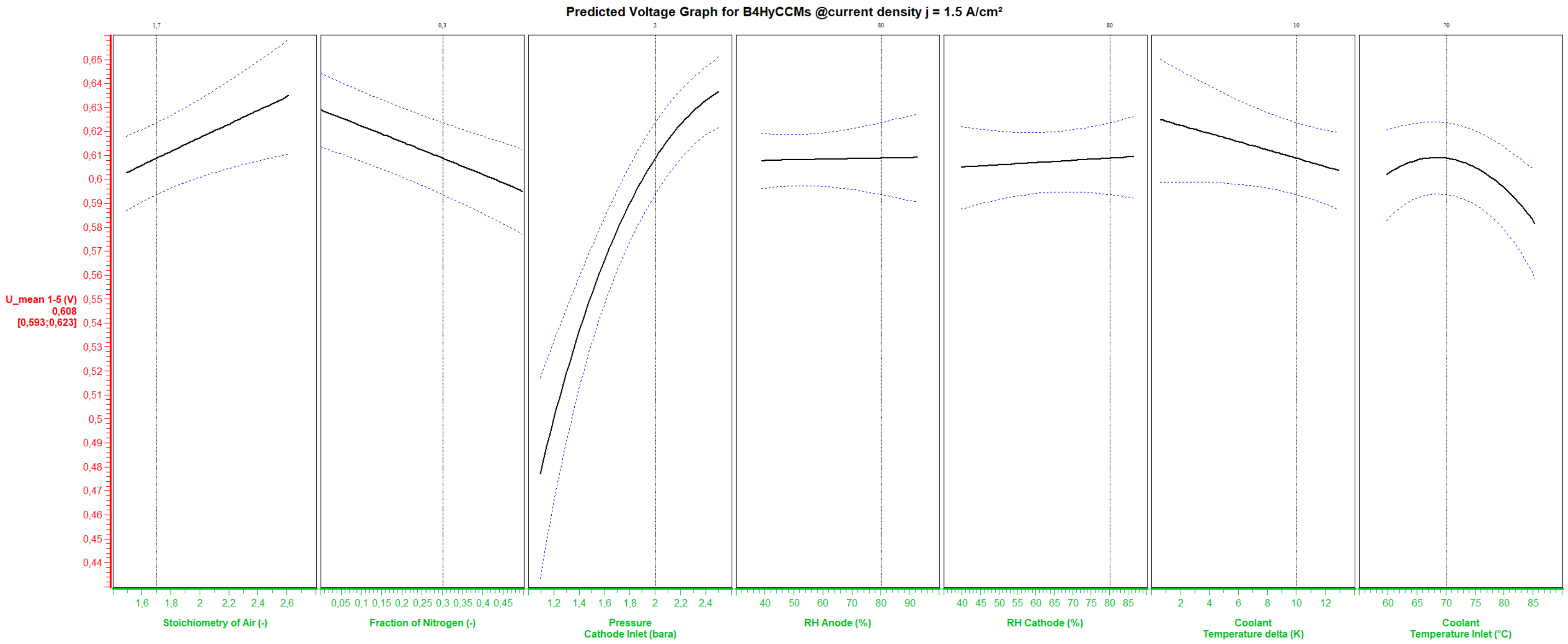

Figure 10: Predicted response graph for the averaged cell voltages of cells containing B4HYCCMs in reference to different factors. Factors fixed to one exemplary operating point at a current density of 1.5 A/cm².

4.2.4 EK-FCDLC

The evaluation of the EKPO fuel cell dynamic life cycle (EK-FCDLC) can just give a qualitative statement of the long-term durability of the B4HyCCMs / cells of the short stack. In the short time that was available for testing, CCMs might not have been fully conditioned, thus cells can still show an improvement of performance. This could be seen in the evaluation of the PHTs conducted at the beginning and the end of test.

Just considering the durability test (EK-FCDLC), in a first interpretation, it becomes visible that both cell types are already degrading slowly. The B4HyCCMs are degrading a bit faster than the EKPO RefCCMs (different degradation rate for every load point), as can be seen in the slope of the linear trendlines of the corresponding figures (Figure 11 - Figure 14: B4HyCCMs are represented by the black rhombus, RefCCMs by the red triangles). The degradation in V/cell/h is given by the slope of the linear trendline (e.g. in the 340 A point: 1,01E-05x + 6,21E-01 means a degradation rate of about 10 µV per Cell per hour). It is to notice, that the degradation rates are unexpectedly high, especially for the EKPO cells, which could have various reasons, that couldn't be examined in the frame of this project.

The higher degradation rate of the B4HyCCMs could be attributed to a mismatch with the EKPO standard operating conditions.

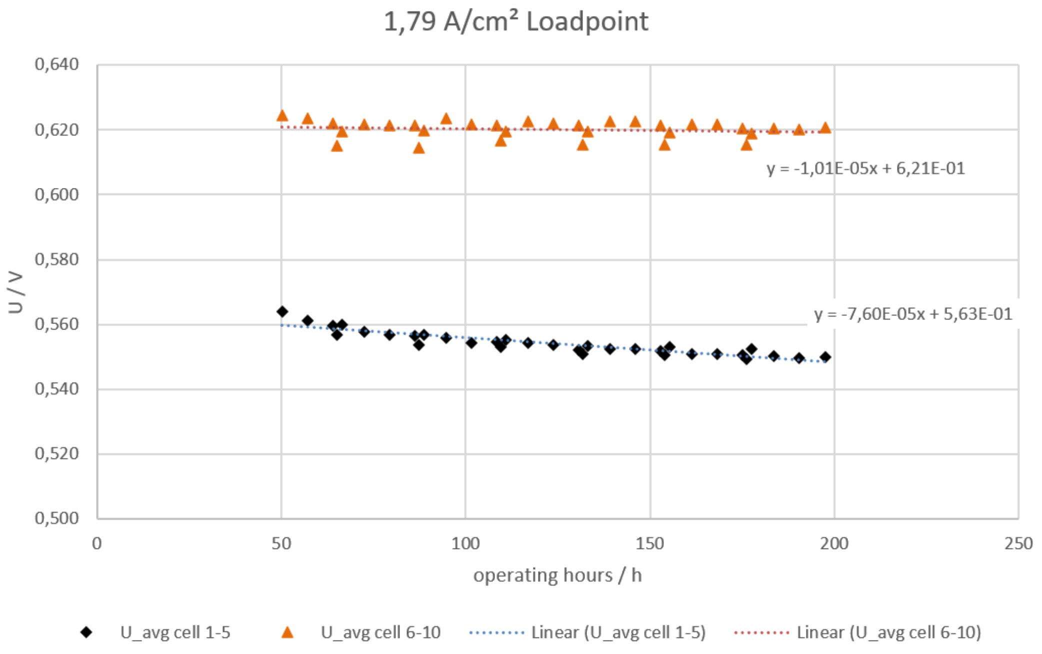

Figure 11: Evaluation of 1.79 A/cm² load point of durability load cycle

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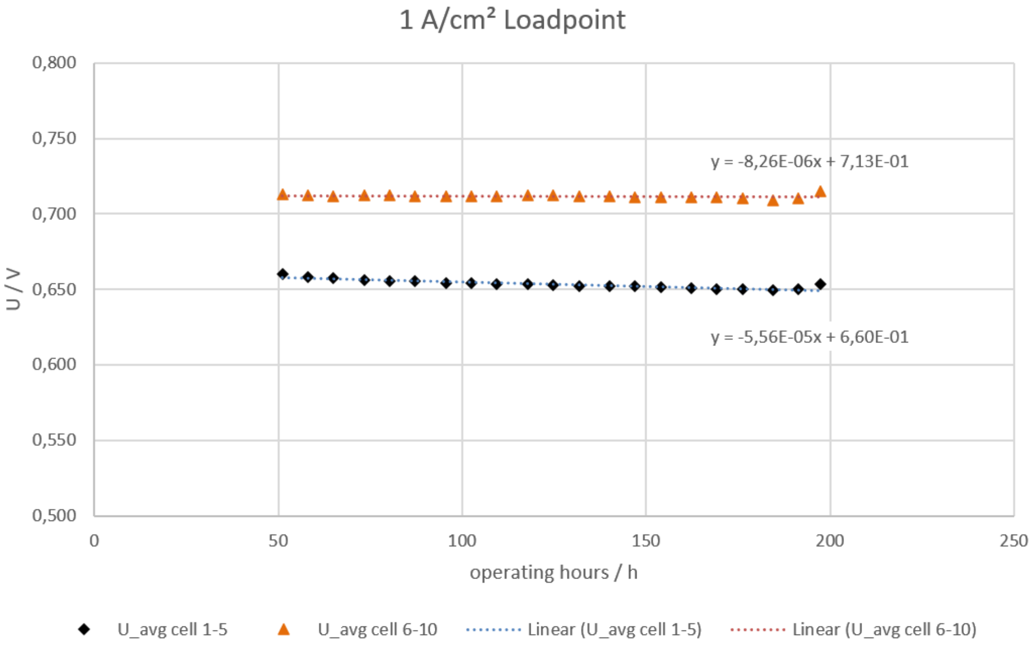

Figure 12: Evaluation of 1 A/cm² load point of durability load cycle

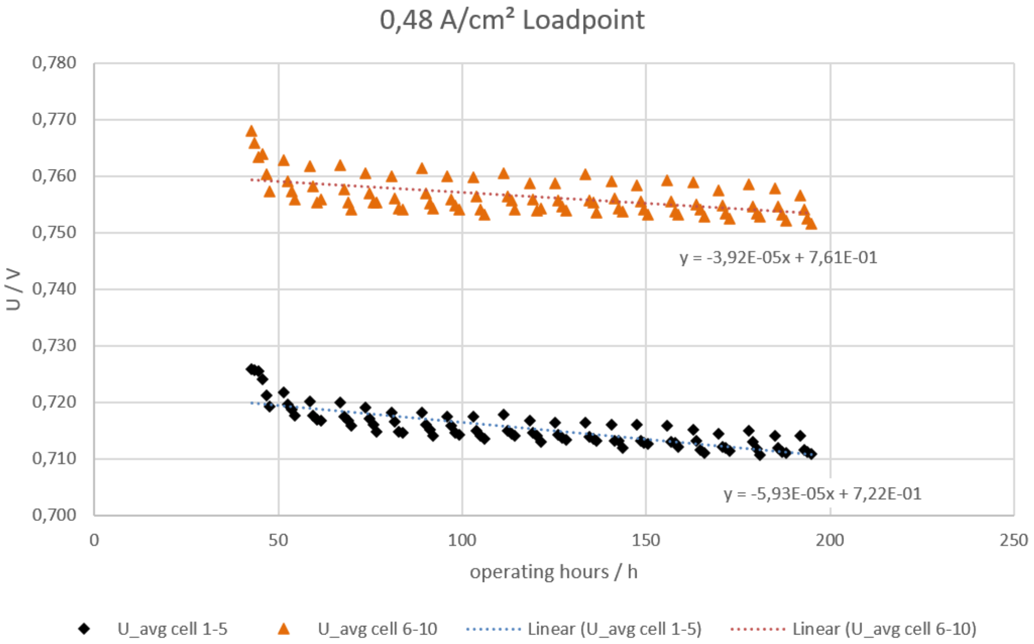

Figure 13: Evaluation of 0,48 A/cm² load point of durability load cycle

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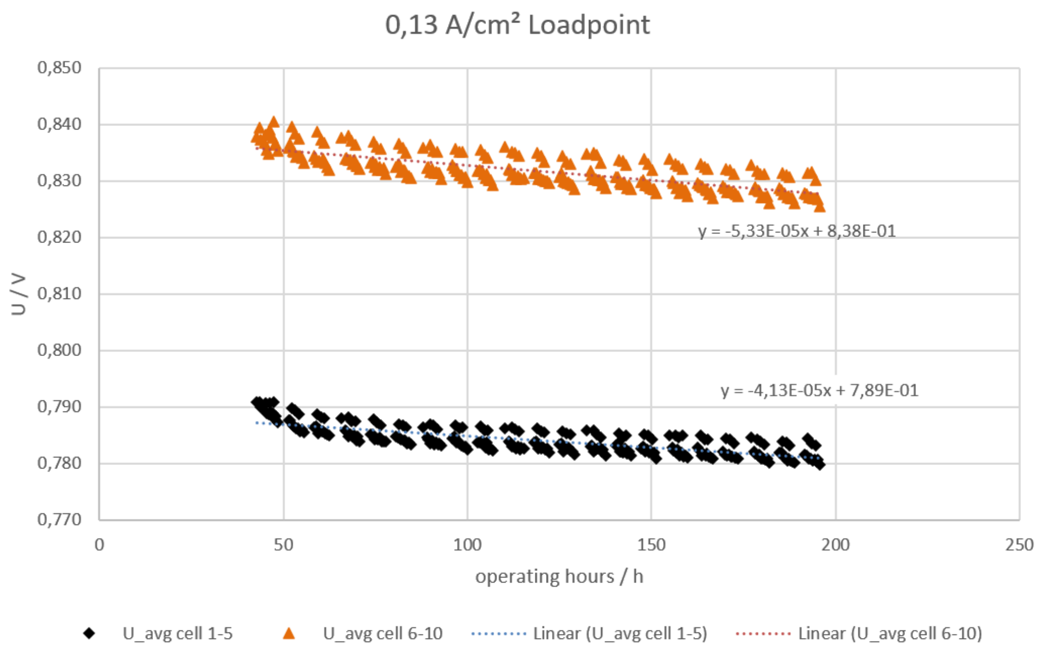

Figure 14: Evaluation of 0,13 A/cm² load point of durability load cycle

4.3 Discussion of the results: comparability, limitations, validity

The test plan agreed within the Best4Hy consortium, considered that the CCMs to be compared would be most probably different in many parameters, starting from materials used, like membrane, ionomer, catalyst carbon support, catalyst loading, catalyst etc. up to production processes and production environment. EKPO purchases state of the art, commercially available CCMs, meeting EKPOs product requirements in terms of loading, performance and operating conditions. CEA was able to design and manufacture a CCM (B4HyCCM) comparable to EKPOs CCMs (RefCCMs) based on these requirements. A comparison between the B4Hy-CCMs and the RefCCMs can only give an overall understanding of the functionality of the project's CCMs vs. commercial ones but it must be considered that far too many factors between the CCMs to be compared are different.Considering the % of recycled material used, the project went for manufacturing the test CCMs using the catalyst produced with only the Pt salt recovered from EoL stack, i.e. 100 % recycled Pt. Although EKPO does not have specific information on the CCMs it buys in and the origin of the platinum used within, it is assumed that most of it is virgin material. There is a possibility that recycled Pt accounts for a share in the range of 15-30 % of the Pt used in the manufacture of "virgin material" CCMs, considering market data provided by our project partner Hensel Recycling[3]. This % is not however declared explicitly by the manufacturers, so it could not be reproduced for comparing the efficiency of the process chain from HMT down to polyol synthesis, which could be an interesting evaluation to be done. Similarly, a parametric study on the % of catalyst synthetized with recovered Pt-salt to

[3] Each year, around 25 %, of platinum supply comes from recycled auto catalysts (80%) and jewelry (20 %) (Source: Platinum Investment Council. Update March 2023)

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hit the best performance or the performance most comparable to commercial CCMs could also be of interest for the industry. This could also support a study on the influence of any impurity in the recovered salt and in turns push for improving the recovery process.

Furthermore, the EKPO's RefCCMs had a bimetallic catalyst on anode and cathode side, whereas the B4HyCCMs used Pt only. This difference can have an impact on the performance.

Finally, despite the use of commercial components (membrane, ionomer, catalyst support, i.e. the carbon black) for the manufacturing of the B4HyCCMs, they could be different from the ones used for the RefCCMs, and this, as explained before, is an unknown to EKPO themselves but can have some influence on the performance of the CCMs.

Aside from the materials used, the lab-based production methods adopted in the project cannot compare to the processes of EKPO's commercial CCM supplier, which are industrialized.

Overall, it can be said that the B4HyCCMs behave similarly to the RefCCMs in the tests performed. Even though the performance of the cells with the B4HyCCMs performed slightly worse than the ones with the RefCCMs, it was possible to show that CCMs with 100 % recycled Pt work.

5 Conclusion

The task 2.4.2 completed successfully. The CCMs manufactured in the project with the recycled platinum originating from end-of-life PEMFC material from EKPO were successfully built into one short stack of industrial size besides commercial CCMs, whereas five of each were used. The short stack passed EoL (End of Line) criteria such as tightness, mechanical and optical criteria successfully, hereby also proofing the mechanical integrity of the CCMs, although the B4HyCCMs showed optical defects due to non-optimal process parameters in the CCM manufacturing. The resulting rainbow stack was then operated successfully on a test bench with different agreed-on routines, to gather data for the evaluation of different aspects of the CCM component.

Fulfilling the scope, the short stack with its 10 CCMs was functional and delivered power. The test conducted on the testbench performed without major abnormalities. It's to mention, that differences between the B4Hy projects CCMs and the commercial CCMs used by EKPO considering performance and durability are quite noticeable and that the project CCMs can't yet compete under these aspects. They reach – considering the average voltage of the two CCM types compared – in average about 92% (between 89% and 95% considering the results of the last recorded PHT load points) of the voltage of the commercial RefCCMs.

For a closer analysis and a valid comparison between CCMs with recycled materials and commercial CCMs, a by far more detailed and on statistic-based approach would be needed, to gain further insights into properties of recycled CCMs. This applies for different parameters for the CCM to be manufactured, but also for the methodology of testing.

An important and highly interesting aspect for industry in the PEMFC business and the increasing interest for recycling topics, is the evaluation of the circularity capabilities of other crucial components and materials, such as ionomer of the CCM or bipolar plates and their

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coatings. Prioritizing life cycle assessments and sustainable product considerations can make it easier for companies to incorporate them into their strategy.

The industry has a strong interest in further exploring the potential of PEM technology in recycling.

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6 References

1. **Georgios, Tsotridis, et al.** JRC Publications Repository. [Online] 01 27, 2016. [Cited: 12 20, 2023.] https://publications.jrc.ec.europa.eu/repository/handle/JRC99115. DOI: 10.2790/342959.

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Annexes

6.1 Table of Operating Parameters of exemplary polarization curve

These parameters were set for the polarization curve in Figure 8: one exemplary polarization curve from short stack testing displaying single cells, B4HyCCMs being constantly lower in voltage.

Addon in open-end operation																
Operating step	Dwell time	Current	Current density	Coolant inlet temperature	Coolant temperature delta (outle-inlet)	Cathode inlet pressure	Cathode inlet temperature	Cathode outlet temperature	Cathode rel. Humidity	Stoichiometry air	Anode inlet pressure	Anode inlet temperature	Anode outlet temperature	Anode relative humidity	Anode dewpoint (calculated)	Stoichiometry anode
OS	t	I	j	$T_{cool,in}$	ΔT_{cool}	$p_{cat,in}$	$T_{cat,in}= T_{cool,in}+x$	$T_{cat,out}= T_{cool,out}+x$	rel. hum. cathode	λ_{air}	$p_{an,in}$	$T_{an,in}= T_{cool,out}+x$	$T_{an,out}= T_{cool,in}+x$	rel. hum. anode	Dewpoint TDP	λ_{H2}
[1]	[min]	[A]	[A/cm²]	[°C]	[K]	[bar_a]	[°C]	[°C]	[%]	[1]	[bar_a]	[°C]	[°C]	[%]	[°C]	[1]
1	20	228	1.2	75	10.0	2.5	77.0	85.0	80	1.7	2.5	87.00	77.00	40.00	63.25	2.7
2	5	456	2.4	75	10.0	2.5	77.0	85.0	80	1.7	2.5	87.00	77.00	40.00	63.25	2.7
3	5	418	2.2	75	10.0	2.5	77.0	85.0	80	1.7	2.5	87.00	77.00	40.00	63.25	2.7
4	5	380	2	75	10.0	2.5	77.0	85.0	80	1.7	2.5	87.00	77.00	40.00	63.25	2.7
5	5	342	1.8	75	10.0	2.5	77.0	85.0	80	1.7	2.5	87.00	77.00	40.00	63.25	2.7
6	5	304	1.6	75	10.0	2.5	77.0	85.0	80	1.7	2.5	87.00	77.00	40.00	63.25	2.7
7	5	266	1.4	75	10.0	2.5	77.0	85.0	80	1.7	2.5	87.00	77.00	40.00	63.25	2.7
8	5	228	1.2	75	10.0	2.5	77.0	85.0	80	1.7	2.5	87.00	77.00	40.00	63.25	2.7
9	5	190	1	75	10.0	2.5	77.0	85.0	80	1.7	2.5	87.00	77.00	40.00	63.25	2.7
10	5	152	0.8	73	10.0	2.5	75.0	83.0	80	1.7	2.5	85.00	75.00	40.00	61.52	2.7
11	5	114	0.6	72	10.0	2.5	74.0	82.0	80	1.7	2.5	84.00	74.00	40.00	60.65	2.7
12	5	76	0.4	69	10.0	2.5	71.0	79.0	80	2	2.5	81.00	71.00	40.00	58.04	2.7
13	5	38	0.2	65	10.0	2.5	67.0	75.0	80	2.6	2.5	77.00	67.00	40.00	54.55	2.7
14	5	19	0.1	65	10.0	2.5	67.0	75.0	80	2.6	2.5	77.00	67.00	40.00	54.55	2.7