Deliverable 5.3
Report on system demonstration in relevant conditions

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1. Introduction

Summary of the project scope

The objective of the project is to develop and demonstrate a compact and highly efficient micro combined heat and power (CHP) system based on high-temperature proton exchange membrane fuel cell (HT-PEMFC) technology and a methanol steam reformer. The developed micro-CHP system is intended as a back-up solution for sequential or simultaneous cogeneration of electricity and thermal energy in rural areas with unstable or zero grid availability. A core focus on thermal integration and waste-heat recovery enables high fuel utilization, high electrical- and CHP efficiency, and dynamic load response and fast start-up for flexible integration with intermittent renewable energy sources.

Purpose of the document

The objective of this deliverable is to comprehensively capture the initial plan, modifications, and the actualization of the testing phase within the EMPOWER project. Initially, the complete testing and demonstration of the CHP system were intended to take place at the end user's site, spanning a minimum of 2000 hours over a period of 6 months.

2. Description on revised demonstration activities

As detailed in Deliverable 5.2, the commissioning activities encountered challenges at the designated demonstration site. While a few successful startups were achieved, the proceedings did not advance to a stage where initiating long-term testing would have been practical. The characteristics of these successful start-ups and operations under load are concisely outlined in Section 3 of this report.

In response to encountered challenges with commissioning work in Finland, a essential shift in the approach to demonstration activities within the EMPOWER project was deemed necessary. The re-evaluation and subsequent modifications were the outcome of extensive discussions held among project partners, seeking innovative solutions to address the challenges faced during the commissioning work. These modifications, crucial for obtaining all required operational data for the final integration, were carefully discussed through and subsequently approved by the Project Office. This adaptive approach underscored the project's commitment to overcoming obstacles and ensuring the success of the overall demonstration activities.

The execution of demonstration activities within the EMPOWER project were planned to ensure a systematic and efficient process that aligns with the project's objectives. The following text outlines the key steps and considerations in the execution of these activities.

Updated demonstration plan

The revised demonstration plan was a hybrid solution, in which testing activities were divided in two parts. The first part was planned to be executed in Denmark, and the second in Finland. The details and advantages of this plan are represented below.

Testing phase in Denmark

In the first phase of testing at Blue World Technologies in Denmark, the main goal will be to comprehensively assess the FC module's performance. This will involve evaluating it under various conditions, addressing integration challenges, and confirming its reliability. The testing phase will explore different operational scenarios to understand, how the FC module behaves under varying conditions, including assessing degradation, reliability, and responses to different loads.

Throughout the testing period, detailed data should be continuously collected, forming the basis for a deep analysis that provided valuable insights into the FC module's reliability and performance. The duration of this phase will be determined by achieving satisfying validation results across the explored operational scenarios.

The knowledge gained during the Denmark testing phase will play a crucial role in the second part of demonstration activities. This process aims to enhance the smooth reintegration of the FC module into the complete mini-CHP system. The optimization phase has been designed to address challenges identified during initial testing, ensuring a smooth integration process and ultimately improving the overall performance of the mini-CHP system. Findings, operational data, and insights will be documented and reported as part of Deliverable 5.3.

Testing and integration phase in Finland

After covering the testing scope in Denmark, the FC module will be transported back to Finland for the re-integration process at the demonstration site in Nokia. During this phase, the module will be re-integrated into the container, incorporating insights gained from the Denmark testing phase.

The focus will then shift to demonstrating the entire mini-CHP system in a real-world setting. This phase will involve conducting cold start-up testing, assessing dynamic operations under varying load conditions, and testing the system in an industrial building environment to meet electricity and heat needs.

Detailed data will be collected during the Finland testing and integration phase, similar to the Denmark phase. This data will be analyzed comprehensively to evaluate the overall performance of the mini-CHP system.

Outcomes of revised demonstration activities

As outlined in greater detail in Deliverable 5.3, significant efforts were dedicated to initiating test runs, resulting in the demonstration of the fuel cell module in Denmark. However, due to multiple delays in the system startup throughout the process, the consortium collectively decided to consolidate the entire demonstration phase in Denmark. This decision was grounded in the importance of obtaining crucial data for the project's durability objectives. Ensuring close proximity of fuel cell experts in Denmark to the operational system was deemed essential to guarantee effective maintenance for the unit. This choice was made in order to increase the success rate of meeting the KPI regarding the hours of operation. This was proven to be the right choice as multiple challenges arose during the demonstration activities.

3. Field tests in Finland

Before the testing protocol for demonstration activities underwent revisions, substantial progress was made in commissioning work at the original demonstration site located in Nokia, Finland. During active commissioning, multiple successful heat-ups were conducted for the developed CHP system. However, due to the need to safeguard the fuel cell module, only a few of these instances were extended to a phase where the system operated under load. The following highlights the most noteworthy operational periods:

The first successful field test transpired from January 2nd to January 7th, 2023. The initial days involved installation and testing, with the final days dedicated to refining communication between the fuel cell system and the developed container. Throughout this period, the system was operational in conjunction with the final integration. The total operation time under load was approximately 7 hours, with load points ranging from 0.07 to 0.2 A/cm^2, generating power outputs from 1 to 5 kW.

The second successful field test took place on February 8th, with strong collaboration among partners. During this test, the system operated under load for approximately 2 hours, with load points ranging from 0.07 to 0.2 A/cm^2, resulting in power outputs between 1 and 5 kW.

4. Description on test facilities in Denmark

In order to conduct the demonstration activities at Blue World Technologies facilities, a test facility was built. A schematic of the setup may be seen below.

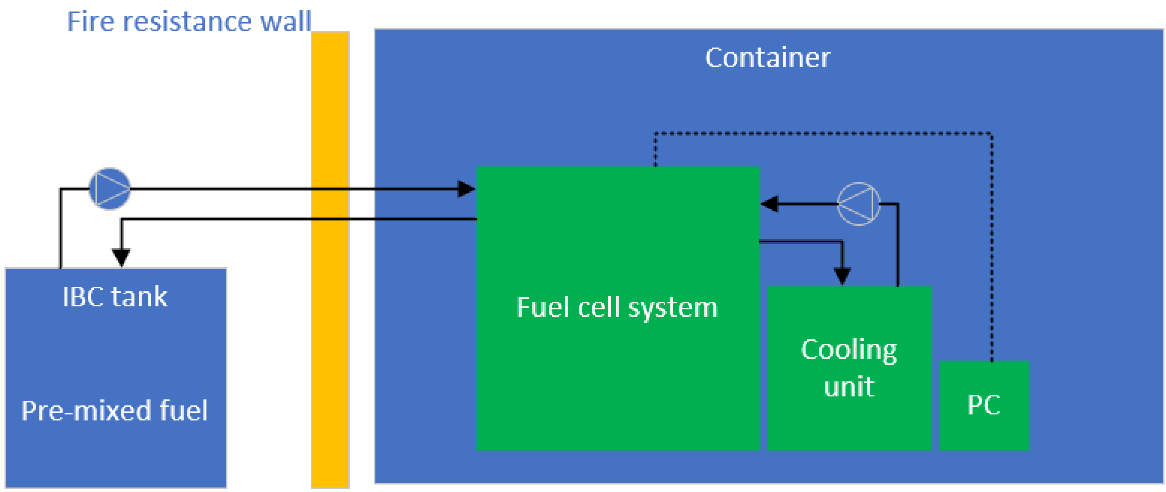

Figure 1. Schematics of the test setup in Denmark.

To enable unsupervised test, a container was chosen from which the fuel could be separated from the fuel cell system in case of an accident. In order to imitate the relative cold conditions in Finland, the container was ventilated to obtain the same ambient temperature inside the container as outside of the container. During the tests, the ambient temperature reached a minimum temperature of 5 °C. Pictures of the setup may be seen in the following pictures.

Figure 2. Test container and fuel storage.

Figure 3. Test setup under commissioning.

5. Description on commissioning activities in Denmark

Throughout the last half year of 2023, a constant effort has been made in order to approach a total operation hour count of 2000. Different challenges has occurred which has entailed a shortage of operation hours. Due to these challenges, the actual test activities differs from the planned. It was initial the plan to run the majority of the hours in Denmark and then towards the end of the project ship the system to Finland to once again to test the fuel cell system at THT's site. However, due to different challenges the desired operation hours was not obtained, from which the consortium decided to neglect the field test and focus on increasing the operation hours.

As it was of the highest priority to obtain a great amount of operation hours, the focus of the test plan became to enable a running system and then further keep it running. The dynamic response of the system was therefore not tested significantly as the system would remain at the same power output for multiple days before changing. However, simultaneously with the EMPOWER project, a lot of effort has been made from Blue World Technologies investigating the dynamic behavior of the fuel cell. It has been proven that the dynamic response has no influence towards the lifetime of the fuel cell, whereas the influence of the operation hours are still relatively unknown from which continues operation was of high interest for the EMPOWER project.

6. Performance data and overview on FC module performance

A summation of the key results may be seen in the table below.

Table 1. Summary of demonstration results.

Fastest startup	<40min
Peak electrical efficiency	53.7% - stack temperature at 160 °C
Peak system efficiency	38.1% - stack temperature at 160 °C
Approximately start/stops	70
Approximately power production	1.8MWh
Run time	350hours
Degradation rate	1.06% / 1000hour

Startup time

It was stated in the project proposal that the startup time must be less than 10 minutes. This is however not a realistic target as the reformer provided from Blue World Technologies has a startup time of 18min. The startup time for the fuel cell stack can however be less than 10 minutes if sufficient heat is supplied. In order to reach the desired startup time another reformer is therefore needed.

Efficiency

It was stated in the project proposal that an electrical stack efficiency at 180 °C of 55% based on the LHV should be obtained. From the table above it may be seen that an electrical efficiency of 53.7% was obtained. This efficiency was however measured at 160 °C and not 180 °C. In the figure below the cell voltage of the MEA used in the fuel cell stack utilized in the EMPOWER project may be seen as function of different temperatures.

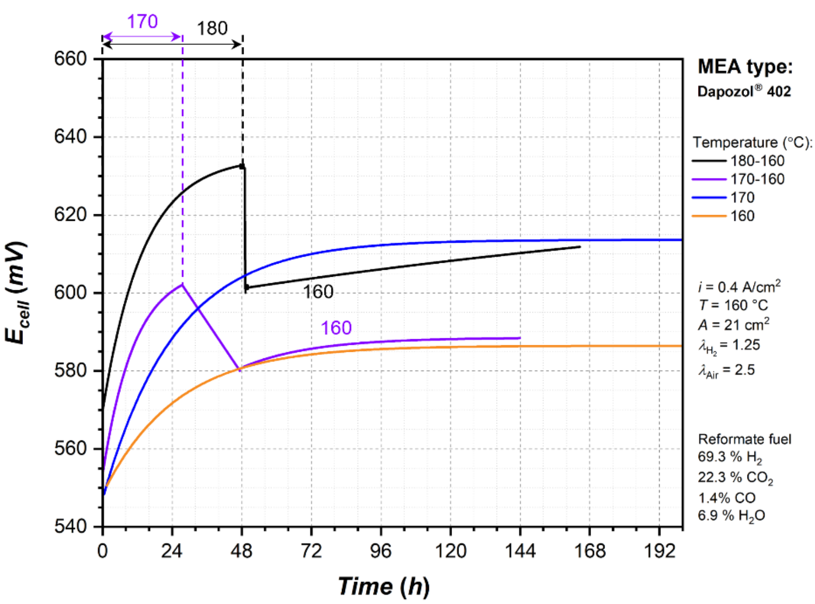

Figure 4. Background information, MEA performance under different temperatures.

It may be seen that the cell voltage increases by 5% when increasing the temperature from 160 °C to 170 °C. The cell voltage is proportional to the power output and thereby also the efficiencies. Even though the cell voltage would further increase from 170 °C to 180 °C, the increment from 160 °C to 170 °C would be enough to exceed the target of 55%. The stack was however at all time operated at a temperature of 160 °C as the increasing temperature has a relatively high impact on the lifetime of the fuel cell stack.

It was stated in the project proposal that system efficiency at 180 °C of 50% based on the LHV should be obtained. A significant enabler of this high efficiency was the aqueous phase reformer, which however turned out not to be working. Despite of this, the system peak efficiency was however only 38.1%, from which the 50% would not have been reached even with the aqueous phase reformer. The performance of the system may be seen in the table below.

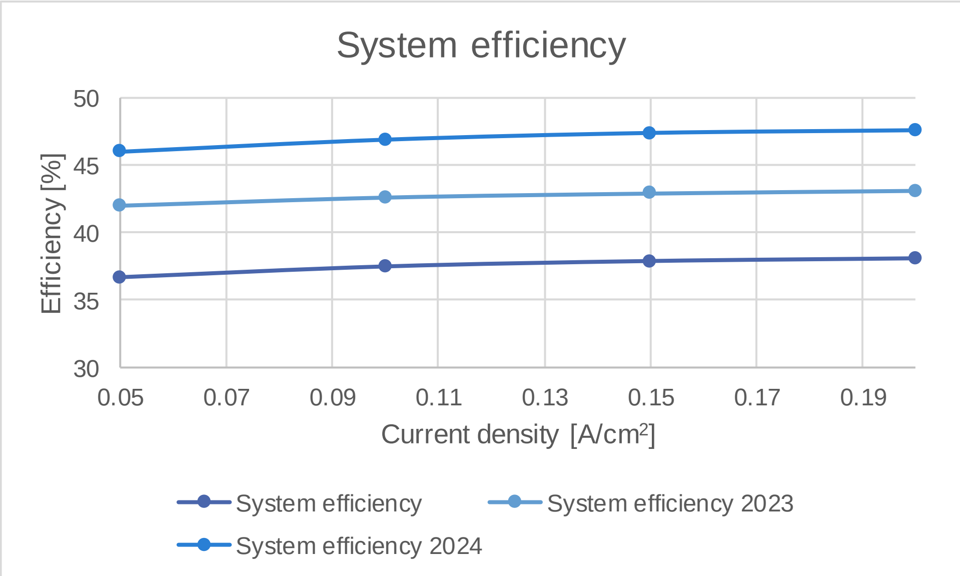

Figure 5. System efficiency comparison.

Since the EMPOWER system was build other fuel cell systems have been built by Blue World Technologies, all with higher efficiencies than the EMPOWER system. If the EMPOWER system is correlated with the build of plant power consumption from one of these systems, the EMPOWER system efficiency would be as presented in the graph above from the line called "System efficiency 2023". The major differences between these systems are the compressor, pumps and DC/DC converter. The compressor used in the EMPOWER project is a screw compressor which are known not to be very efficient compared to a centrifugal compressor, which is the type used in these new systems. In addition, the cooling pump used in the EMPOWER system is a gear pump which are also known to have a much greater power consumption compared to a centrifugal pump, which is used in these new builds. The last major component which differs from the EMPOWER system and these new systems is the DC/DC converter. The DC/DC converter use in these new systems are somewhere between 2-3% more efficient than the one used in the EMPOWER system. Therefore, an optimization of these 3 components, yields an efficiency increment of 5%.

The graph also illustrates a third line called "System efficiency 2024" which represent the EMPOWER efficiency if correlated with the improvement planned for 2024. These improvements imply customized compressor and DC/DC converter.

Run time

As presented in the table above the system was only in operation for 350 hours whereas the target was 2000 hours. Multiple factors affected the end number of operation hours, however, it seemed that once the system was in operation it was functioning without any problem. By end October 2023 the system was enabled and ran for 13 days straight, before an external error triggered a shutdown. In the weeks prior to this long run, the system was turned on 5 days in a row in the morning and shut down in the afternoon without any problems.

Degradation rate

It was stated in the project proposal that a degradation of 0.4% / 1000hour should be obtained. The actual cell degradation at a constant load point may be seen in the figure below.

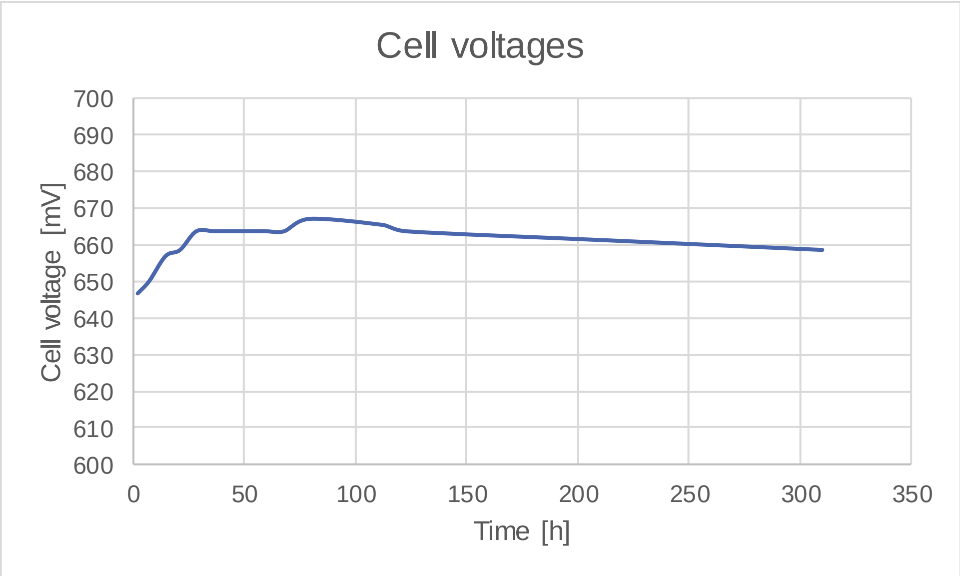

Figure 6. Mean cell voltage performance.

Initially the stack has a break-in period which is roughly up to the point of the 75th hour. If linearly regression is applied from that point, the cell voltage will be 639.8mV at the 1000th hour, whereas it starts at 646.6mV. This yields a degradation rate at 1.06% / 1000 hour being approximately 2.5 times larger than the target. A lot of internal work conducted at Blue World Technologies shows however that unplanned shutdowns has a significant negative influence toward the cell voltage. It is safe to say that this system has experienced multiple of these from which the current cell degradation must be seen as a great result.

7. Conclusion

Based on the text above it can be concluded that the system might have been ahead of its time as the components used to build this system was not designed for fuel cell application which yielded in multiple complications and reduced efficiencies. Regardless of this, the system shown relatively good results which will make the foundation for similar upcoming projects.