Deliverable 5.2

Report on initial system validation

Author: THT Control Oy

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Dissemination Level		
PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
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1. Introduction

1.1 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.

1.2 Purpose of the document

The purpose of this deliverable is to document the construction of the FC system, the container structure and its components. The system aimed to showcase its performance in a real setting for at least 2000 hours over a six-month period. The demonstration planned to incorporate stress tests, quick start and stop cycles (15 minutes each), proving the system's durability in temperature changes and its ability to respond rapidly to power adjustments.

2. Pre-testing period

This section covers preparation tasks and relevant aspects of the CHP system equipment.

2.1 Preparation tasks

The testing phase serves as a preparatory stage, encompassing tasks essential for ensuring the success of the upcoming tests. In practical level this means inspecting all devices and the various components associated with the system.

When testing fuel cell systems, safety comes first. Therefore, prior to testing, a notification of small-scale activities involving methanol has been made to the rescue authorities. This preparatory procedure was started several months before the test was planned to be performed. The EMPOWER project received permission for small-scale operations and the equipment was inspected in early December 2022.

At the end of the test phase, data on the functionality of the device under a wide range of operation conditions was targeted to be collected. The data was planned to be analyzed and conclusions could be drawn based on overall data and findings gained.

2.2 Container

The fuel cell was inserted into a small movable container. The container cell developed during the project allows the fuel cell to be moved behind the car. This allowed the container to be used in a variety of locations.

Figure 1. Developed container in the forest.

2.3 Fuel tanks

The applied fuel was a mixture of water and methanol. During testing time, IBC tanks were selected to act as the main fuel storage. In practical terms, this involves three IBC tanks, each containing one cubic meter of fuel. The cleanliness of the tanks was verified by the manufacturer, which ensured that no excess dirt could drift into the fuel cell.

Figures 2 and 3. IBC tank, and water purification system.

2.4 Fuel manufacturing

As the fuel of the developed CHP system, a methanol-water mixture was used. The mixing ratio of the blend was 54.24 w-% methanol and 45.76 w-% water. Pure methanol and water were used for this mixture. The electrical conductivity value of water was decreased as down as possible. This was made possible with the help of VTT's water purification equipment.

2.5 Fuel supply

The CHP container's fuel supply is facilitated by transferring fuel from an IBC tank to a 250-liter tank located inside the fuel cell space of the container. During operation, the fuel cell draws its fuel from this tank. Additionally, at startup, the fuel cell utilizes pure methanol, which is stored in a small (5-liter) tank within the FC space.

Figure 4. 250-liter methanol tank.

2.6 Sensors

Sensors were installed inside the fuel cell module and in the space where the fuel cell module was located. This subsection describes only the sensors attached to the outside of the fuel cell module. These sensors were used to monitor surrounding conditions and the status of the fuel cell room.

Temperature sensor

The European standard EN54-5:2000 classifies heat detectors according to the highest ambient temperature in which they can safely be used without risk of false alarm. The applied Orbis IS heat detectors have an open-web casing which allows air to flow freely across a thermistor which measures the air temperature every 2 seconds. A microprocessor stores the temperatures and compares them with pre-set values to determine whether a fixed upper limit for alarm level has been reached. In the case of rate-of-rise detectors the microprocessor uses algorithms to determine how fast the temperature is increasing.

Static heat detectors respond only when a fixed temperature has been reached (80 °C). Rate-of-rise detectors have a fixed upper limit, but they also measure the rate of increase in temperature. A fire might thus be detected at an earlier stage than with a static detector so that a rate-of-rise detector is to be preferred to a static heat detector unless sharp increases of heat are part of the normal environment in the area protected by the heat detector.

Gas sensor

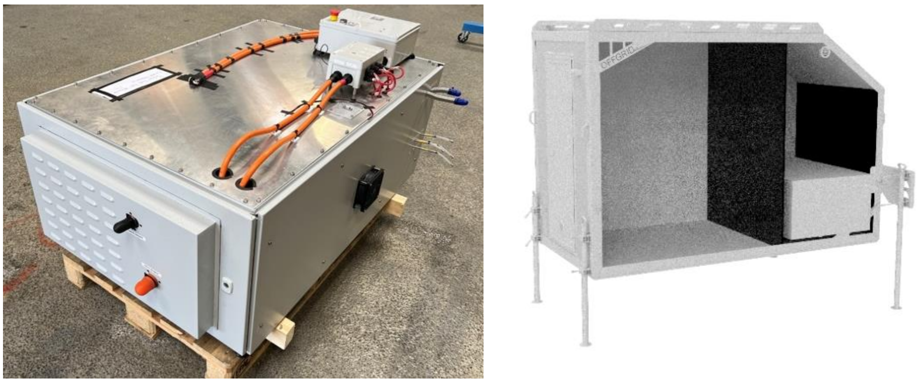
GAM-5 series sensors are modern microprocessor-based relay output sensors for flammable and toxic gases measurement. Controller automatically calibrates the bottom end of the measuring range, so that slow changes in background concentrations as well as measuring errors due to zero drift are automatically corrected. This significantly reduces the change of the false alarms. LED lights on the sensor cover inform the user about the operational status of the sensor.

2.7 Air to water heat pump

The EMPOWER demonstration enabled the use of energy output of the fuel cell module for heating of an industrial building. This experiment was planned to take place under winter conditions in Finland, during which all the electricity and heat generated by the system were used to warm the property. The fuel cell system was planned to heat a 1000 m^2 industrial building. To enhance heating efficiency, an air-to-water heat-pump solution was developed during the project, converting all available energy into heat. As a result, more than 20kW of thermal energy could be obtained from the continuous input of the 5-kW fuel cell device. This would have significantly multiplied the efficiency of the fuel cell utilized by the system.

2.8 Safety

During the EMPOWER project, the fuel cell module was installed in a container structure on top of the developed trailer. The total weight of the container was less than 1,000 kg. Inside the container were electrical installations, fuel cell and pumps. The container has fire detectors, gas detectors and an emergency stop system. Upon triggering an alarm, a red light illuminates atop the container's lighthouse.



Figures 5 and 6. Fuel cell module and structure of trailer.

Following safety related actions and clearances were executed during preparation phase:

- THT prepared risk assessments for the storage and handling of hazardous chemicals, covering all stages of the production process. The results of the risk assessments have been taken into account in the guidelines and trainings. Recommendations for hazard and risk assessment measures were also implemented.
- Instructions for use and maintenance were prepared for the use, handling and storage of hazardous chemicals. Instructions were available to the staff. The operating company ensures that the operating personnel has received sufficient training and guidance on hazardous chemicals and the plant area layout and is familiar with the instructions. The operating company supervises that the personnel act in accordance with the instructions.
- A rescue plan was drawn up for the building and site. Instructions for action in accidents and hazards involving chemicals was included in the rescue plan.
- The explosion hazard assessment was prepared for flammable liquids and gases and the measures required for the assessment were implemented.
- A pre-service and maintenance system was developed for the plant, covering equipment, pipelines, tanks, etc. for handling and storing hazardous chemicals in working order, as well as regular verification of the operation of alarm systems and safety devices. Records were kept of the inspections, tests and measures carried out.
- It was defined, that workers must have access to appropriate protective equipment.
- Appropriate containment equipment was procured for the plant to quickly collect any leakage and prevent spreading to the environment.
- The initial extinguishing readiness was made such that in the event of a fire, effective initial extinguishing would be possible, and the spread of the fire could be prevented.
- Equipment, tanks, pipelines, and chemical storage facilities and locations were equipped with markings necessary for safe operation and for preparing for accidents. Pipelines are equipped with markings indicating their contents and direction of flow.

Details on the test environment:

- Equipment:
  - CHP system / one container
  - Thermal container / one container
  - Fuel container / IBC tank x 3 / in 20 ft storage container
  - Connections between containers and the building (electric/heat)
- Safety Equipment:
  - Fire extinguishers near containers in the test area, at the entrance to the building
  - Contact with the local rescue authorities (Nokia Rescue Service, locating 1 km away from the test site)
  - Personal protective equipment: rubber gloves, gas mask and overalls for refueling
- Staff:
  - EMPOWER project staff
- Environment:
  - Fenced open outdoor space
  - Distances to buildings are consistent with safety distances
  - The soil at the test location is rocky, gravelly and sandy soils.
  - Safety distances to the thoroughfares follow instructions given by authorities.

Figure 7. Testing site.

- Aquifer areas:
    - The nearest aquifer is located at Maatialanharju (A location presented in Figure 8). From the test location, the distance is about 1.5 km to the aquifer. In case of drifting into the ground, the methanol mixture does not pose a risk from an aquifer perspective.

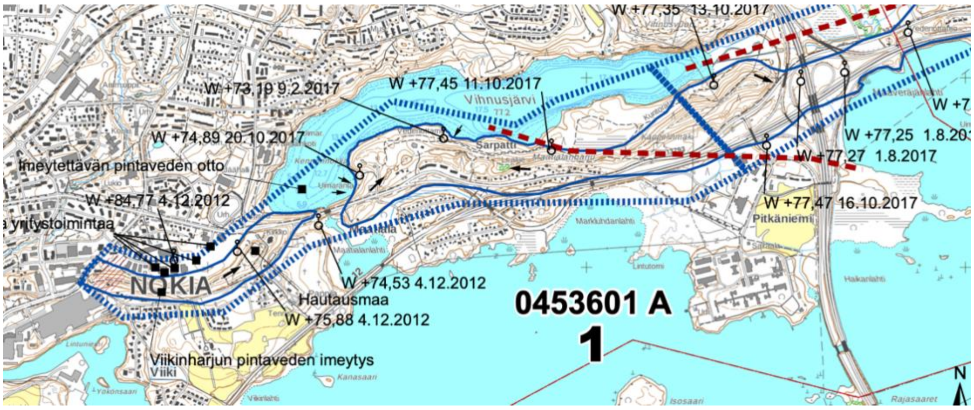


Figure 8: Aquifer area.

Risks associated with testing activities exist in each of the following cases:

- Case 1 - Dealing with methanol fuel as risk and associated risk factors
    - In practice, this means spillage or evaporation of methanol or methanol liquid mixture into the breathing air in the fuel transfer and mixing situation. This can be prevented by suitable fuel tanks and personnel protection.
- Case 2 - Normal risk factors associated with the use of the device
    - During demonstration testing, the equipment is located in a fenced-off area within a controlled testing environment. It has undergone a HAZOP analysis facilitated by VTT, effectively minimizing all risk factors associated with its operation.
- Case 3 - Device is used normally
    - The risk associated with this stage is greatest when changing the fuel tank of the device. This is protected in the same way as in case 1. The device has gas and temperature sensing, as well as emergency stop buttons. When sensing detects hydrogen gas or elevated temperatures, it automatically shuts itself off. On the roof of the device there is also a beacon (light and sound) that notifies extinction.
- Case 4 - All separate parts are dismantled from the equipment and here the protection instruction is the same as in case 1.

- THT Control Oy is responsible for the design and construction of the device “safety” system.

2.9 Original timetable for testing activities

The long-term test was planned to start on 9 January 2023. The goal of the test was to produce an understanding of the function of the fuel cell module in long-term use. The test target was set at 2,000 h. This meant that the test was supposed to be running continuously. The long-term test was targeted to cover the operation of the fuel cell at temperatures min. -30°C. At the final stage of the test, various individual tests were planned to carried out. These would have included at least start-up tests, operation under different load points, and emergency stop tests.

3. Testing period

3.1 Container design

As the foundation for container design, the aim was to create a mobile space capable of accommodating a fuel cell, fuel tank, battery, automation, safety systems, and potentially a workspace for winter testing. The mobile space needed to be transportable behind a car, ATV, or even a snowmobile. The objective was to establish an independent system adaptable for various applications.

The container structure was designed to allow one person to detach it from the trailer. Once detached, the container stands on its own, and the trailer can be pulled out from underneath, enabling convenient storage with its own support.

Given the limited space, careful compartmentalization and installation of security devices were essential. THT opted to place a methanol-water mixture tank at the front of the container structure and a fuel cell space on top. This entity was isolated from the working and electrical spaces by airtight walls, ensuring proper ventilation and equipping it with gas sensors.

A movable base structure was constructed for the methanol-fuelled fuel cell system, facilitating easy serviceability. This design allowed the fuel cell to be pulled out of the container for maintenance work outside.

The interior housed automation, batteries, and electrical equipment. A roof-mounted fan was installed for system cooling, and a desk was incorporated for the computer. Safety system sensors and switches were strategically placed, with a security beacon on the roof providing status indications through a flashing light.

Figures 9 and 10. Commissioning work on-going in Nokia.

3.2 Description on activities

As part of the EMPOWER project demonstration, THT committed to creating a mobile container space capable of housing the necessary equipment. In the initial 8 months, THT developed a prototype to assess the feasibility of a mobile workspace as a container for the EMPOWER project. The positive experience led to proceed with the chosen model.

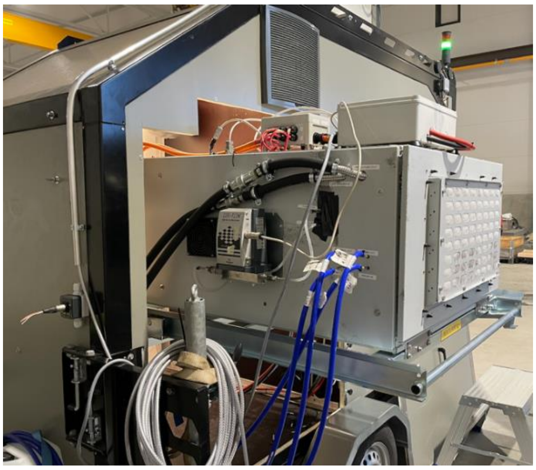
Road and off-road testing of the container structure took place in May 2021, confirming its suitability for both road traffic and challenging terrains.

Throughout the project, the placement and size of the equipment underwent several changes, presenting challenges to the design of the container structure spaces. As a result, the installation of equipment in the container spanned an extended period, with the fuel cell module arriving in Finland during the summer 2022. The fuel cell installation commenced in August but faced delays due various occurred difficulties. The cooling and safety systems were installed as the final steps before testing and starting the fuel cell.

In January 2023, BWT and THT collaborated in Nokia, Finland, for a week to complete final installation work before the test run.

After a week of collaboration, the fuel cell was started up once, followed by several unsuccessful attempts. Over the next two months, efforts were actively made to identify and address bugs causing start-up issues. However, the challenges persisted, posing obstacles to progress.

After failed startup attempts, it became evident that new approach towards demonstration activities was required. The following section will focus on revised demonstration plans.



4. Revised demonstration activities

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.

4.1 Updated demonstration plan

The revised demonstartion 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 demonstartion 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.

4.2 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.

5. Conclusions

In conclusion, the integration of the fuel cell module into developed CHP system in Finland was comprehensive, involving significant efforts. However, challenges encountered during the commissioning work prompted a revision of the demonstration activities. Consequently, the decision was made to initially test the fuel cell module in Denmark to achieve comprehensive validation for the unit. While the revised plan included a second phase for integrating the FC module into the developed CHP container, the demonstration activities in Denmark evolved in a way that rendered the progression into the final integration phase unfeasible.