Executive Summary:
The PEMBeyond project, funded by FCH JU, joins together VTT (Finland), PowerCell AB (Sweden), Genport srl (Italy), Fraunhofer IMM (Germany) and University of Porto (Portugal), with the aim to develop and demonstrate a bioethanol fuelled proton exchange membrane (PEM) fuel cell based integrated power supply for backup and off-grid applications.

Fuel cell technology has already proven competitive against conventional diesel generators, but the availability of hydrogen fuel and its logistics to remote locations is still hindering widespread use. To seek reductions in greenhouse gas (GHG) emissions while still allowing simple fuel logistics, the consortium partners decided to develop a fuel cell based system that uses crude bioethanol as its primary fuel. Bioethanol may be produced sustainably and locally also in developing countries, where the need for back-up power is growing rapidly.

The concept developed in PEMBeyond combines a high pressure ethanol fuel processor together with a pressure swing adsorption (PSA) unit, producing a hydrogen stream usable in reformate compatible fuel cell systems. Moreover, due to the high-pressure hydrogen generator, the hydrogen can be stored into an intermediate buffer tank. This allows the fuel cell system to start producing electricity immediately on demand, which is unique for any reformer-based solution.

The beauty of the concept is that the hydrogen generator and the fuel cell system can be operated as a single reformed ethanol fuel cell system, but both of the units may also be used separately, making this a very flexible platform. The potential applications range from short and extended back-up to off-grid applications and distributed hydrogen generation. Due to the flexibility of the steam reformer based fuel processor and PSA, the process can also adapt to other biofuels, such as methanol or methane.

During the course of this project, the consortium has developed reformate capable proton exchange membrane (PEM) fuel cell stacks,
four fuel cell systems in 5 kW range, and a crude bioethanol fuelled hydrogen generator designed for 2 kW continuous fuel cell power output. Moreover, the hydrogen generator was integrated into a 10 ft container together with a fuel cell system and demonstrated in a relevant environment. Although the ethanol steam reforming catalyst was extremely stable during a 1,000 h laboratory test, the reactor did not last as long in the field. The exact reason is still under investigation.

However, the fuel cell stack proved to be very robust, not only by tolerating hydrogen with up to 20 ppm of carbon monoxide (CO), but also due to its freeze start-up capability down from -25 °C. In addition to the main targets, the consortium has also developed non-noble metal based LT-WGS catalysts and PSA adsorbents surpassing any commercial alternatives. The latter can be applied to produce automotive grade hydrogen (<0.2 ppm CO) from reformate streams at a very low cost.

According to the life-cycle assessment, 50 % reductions in GHG emissions may be reached with a reformed ethanol fuel cell compared to diesel generators in off-grid applications. The initial cost of the system was estimated to be 18% higher than diesel generator, but total costs are in favour of the reformed ethanol fuel cell. However, further verification is needed regarding the ethanol steam reforming catalyst, to pursue with commercialization of the concept.

Project Context and Objectives:
Main objective of PEMBeyond project (http://pembeyond.eu/) is to develop an integrated Proton Exchange Membrane Fuel Cell (PEMFC) based power system for stationary back-up and off-grid power generation with the following targets:

• Using crude (80-95%) bioethanol as primary fuel
• Cost-competitive (complete system < 2 500 €/kW @ 500 units)
• Energy-efficient (> 30% overall system efficiency)
• Durable (> 20 000 hours system lifetime in continuous operation)

Back-up and off-grid power generation is one of the strongest early markets for fuel cell technology today. Wireless communication systems are rapidly expanding globally, and the need for reliable, cost-competitive and environmentally sustainable back-up and off-grid power is growing, especially in developing countries.

Fuel cell technology has already proven to be competitive with conventional technologies - diesel generators or batteries - in these applications in terms of total cost of ownership (TCO). However, the growth of the fuel cell industry in this sector has been modest at least partially due to high initial investment cost and fuel logistics problems. Cost-competitive PEM fuel cell power system compatible with crude bioethanol would allow direct use of easily transported and stored, locally produced sustainable and low-emission fuel also in developing countries, further adding value and increasing the number of potential applications and end-users for fuel cell and hydrogen technology.

As presented in Figure 1, the Reformed Ethanol Fuel Cell (REFC) concept developed in PEMBeyond project will consist of the following functions integrated as a one complete system:

1. Reforming of crude bioethanol in Fuel Processor (FP),
2. Hydrogen purification in Pressure Swing Adsorption (PSA) unit,

Optimized overall system design combined with use of improved system components and control strategies will lead to improvements in cost, efficiency, and durability throughout the complete system. Latest automotive reformate compatible PEMFC stacks will be used, possessing high potential to reducing stack manufacturing costs. On top of this the stacks, as a part of a low-grade H2 compatible fuel cell system design, will allow both FCS simplifications (e.g. no anode humidifier needed) and complete system simplifications (e.g. higher CO ppm and lower H2% allowed) leading to decreased cost. Optimizing the target H2 quality will be an important task with the regard to overall system cost, efficiency, and durability. An extensive techno-economic analysis and life-cycle assessment will be carried out throughout the project to ensure attractiveness of the concept. A roadmap to volume production will be one of the main deliverables of the project.

In addition to the complete REFC system, development of separately utilizable subsystems is another main outcome of the project. This includes PEMFC system for back-up and off-grid application using low-grade hydrogen directly as a fuel, low-cost state-of-the-art PEMFC stack for various applications, and crude bioethanol processing unit for distributed hydrogen generation (e.g. at hydrogen refuelling stations).

Serious market penetration of fuel cell technology and renewable fuel into back-up and off-grid power generation will provide
significant reductions in particulate and greenhouse gas emissions worldwide. Use of crude bioethanol as fuel would enable the use of low-cost, easily transported and stored, and locally produced sustainable and low-emission fuel also in developing countries.

PEMBeyond consortium consists of five partners from 5 different European countries:
1. VTT Technical Research Centre of Finland (VTT) – coordinator
2. PowerCell Sweden Ab (PCS)
3. Genport srl (Genport)
4. Fraunhofer Institute for Microengineering and Microsystems (Fraunhofer IMM)
5. University of Porto (UPorto)

The overall project schedule is shown in Figure 2, and a summary of the objectives for each work task (and the responsible partner) are given below:

• System specifications (VTT)
  o Setting the initial specifications for the subsystems
  o Verification of stack CO tolerance, H2 quality specifications
• Fuel cell stack development (PCS)
  o Development and manufacturing of reformate compatible automotive type PEMFC stacks
  o Stack validation and testing, including gas composition and freeze start-up
• Fuel cell system development (Genport)
  o Development and manufacturing of low quality H2 compatible fuel cell system prototypes in the range of 5 kW
  o Evaluation of ejectors for fuel cell system anode gas recirculation
• Reformer development (Fraunhofer IMM)
  o Development of steam reforming catalysts for crude bioethanol
  o Design and manufacturing of an integrated fuel processor module
  o Development of low temperature water gas shift (LT-WGS) catalysts
• PSA development (UPorto)
  o Acquiring or developing a PSA prototype for integration with the fuel processor
  o Evaluation of commercial adsorbents in a lab-PSA unit
• Complete system integration (VTT)
  o Design and implementation of subsystem integration, including higher level control system and containerization suitable for field trial
• Testing and field-trial (VTT)
  o Initial testing of the subsystems against specifications, including Fuel Processor, PSA unit, and Fuel Cell System
  o Complete system commissioning and field trial
• Techno-economic and environmental analysis (Genport)
  o Market analysis and techno-economic tool development
  o Life-cycle assessment

Project Results:

System specifications

The project was started by conducting a review of operation requirements in telecom base transceiver stations (BTSs), which were seen as the prime application for reformed ethanol fuel cells. The review was conducted by evaluating the currently available options and interviewing companies involved in telecom and energy security industry.

The energy security industry in general is conservative and new solutions need to be proven reliable in the field before large investments. Fire safety, theft protection, and low maintenance, low heat loads, fire safety and theft protection were also found to be important.

In addition to the application, the requirements for each subsystem were negotiated within consortium to find a balanced solution. As a result, the specifications, summarized in Table 1, set the targets for the stack and subsystem development tasks, and specified the system outer boundaries and critical interfaces between the three subsystems, required for successful integration of the complete system.
Table 1: Initial specifications for the reformed ethanol fuel cell system (REFCS).

The integrated fuel processor (FP), based on ethanol steam reformer (SR) and water gas shift (WGS) reactor, was targeted to produce a reformate gas stream with 60-70 vol-% hydrogen (H₂), and less than 1 vol-% of carbon monoxide (CO), at a maximum of 10 barg pressure. The pressure swing adsorption (PSA) unit, taking care of the final polishing, was set to produce a hydrogen stream containing below 20 ppm of CO based on a literature review.

The fuel cell system (FCS) was specified to give a 5 kW net electric output in 48 VDC, when gas is available on the H₂ buffer tank, and then drop to 2 kW power corresponding to H₂ generator output. A total efficiency of 30 % was targeted. This kind of arrangement was seen favourable for back-up applications, as the H₂ generation system could be downsized to bring down overall costs.

After setting the main system specifications, work continued with stack development and experimental research for optimizing and setting the final H₂ quality specifications. Reformate membrane electrode assembly (MEA) samples from PCS were evaluated in a single cell setup with anode gas recirculation, with varying CO and CO₂ concentrations. The results were somewhat shocking, as the MEA about to be used in the project were only able to tolerate 5 ppm of CO, as opposed to the 20 ppm seen in the literature. This may seem like a small difference, but at the time, the whole concept was put into jeopardy, and it was not known if it is possible bridge the gap.

Fuel cell stack development

The stack development work was started with fairly ready repeating unit design, consisting of the automotive type stainless steel bipolar plates and reformate MEAs. The goal in this project was to finalize and validate the Balance of Stack (BoS) design, including the clamping mechanism, gas manifolds, and power connector. Along with the BoS development, VTT prepared test benches to facilitate the fuel cell stack and system testing.

Figure 3: Product version of the S2 stack employed in the project, with 100-cells and 9 kW nominal power.

The first generation BoS was completed within six months, with first prototypes tested at PCS and also sent to VTT for validation. However, severe problems were observed while testing the first assembled stacks, both at VTT and PCS, and the design as taken back to the drawing board.

After corrective actions taken into the second round of stack design, the results were more promising. The final product version stacks (Figure 3) have been validated including leaching, shock, vibration, and a 1,500 h degradation test.

Figure 4: The S2 stack on impurity tolerance measurements (left) and under thermal stabilization preceding freeze start-up (right).

As shown in Figure 4, VTT carried out freeze start-up trials with a 10-cell S2 stack, and successful start-up was achieved from -25 °C with no stack heating, insulation, or protection from wind chill. The stack CO tolerance was verified at VTT to be 5 ppm, which was later improved to 20 ppm by introduction of new MEAs. In total 5 short and 8 large stacks, summing up to 67 kW of nominal power has been delivered by PCS to project partners Genport and VTT.

Fuel cell system development

While the delivery of first 100-cell took longer than expected, Genport had already started their work by developing a simulation tool to help with the fuel cell system design and dimensioning. Within the first six months, the design for the first breadboard prototype system was completed and main components purchased. The components were characterized, assembled into subsystems, while developing the control algorithms.

With the first stacks delivered to Genport, the breadboard system was up and running after 18 months. Based on the functional breadboard system, the development of a more industrialized version was started, which would also include an integrated li-ion battery pack for UPS capability and more importantly, power electronics system suitable for the 48 VDC telecom loads. The development and testing work took one more year, after which the prototype system was delivered to VTT for testing and integration into the final reformed ethanol fuel cell system.
After this, development work was started for a third 7 kW system, aiming to demonstrate a more cost optimized design. In total, three 7 kW fuel cell systems were built by Genport, as shown in Figure 5.

Figure 5: Breadboard FCS prototype (left), industrial FCS prototype used in REFC system (middle), and cost-optimized FCS prototype (right).

As another objective, VTT was evaluating the use of ejectors for fuel cell anode gas recirculation together with Aalto University. Ejectors were considered to be a low cost, low power and long-life solution compared to mechanical pumps. The work was started with simulations, and the ejector was dimensioned to give a broad operation range for the FCS, so that in a stationary application, using a single ejector would be sufficient. After some experiments with commercial ejectors, custom 3D-printed ejector was manufactured and characterized, and the results compared against simulation models.

Figure 6 - Fuel cell system operated with 3D-printed ejector and discrete controller.

Due to the excellent results, the fourth FCS built in the project, was used to demonstrate the 3D-printed ejector in action as part of a 4 kW PEMFC system. Moreover, a low cost discrete ejector control solution was demonstrated, and the system was proven to be capable of very fast power transients. The work was continued in a national EL-TRAN project, to evaluate the fuel cell system capabilities in grid stabilization applications. Figure 6 shows the ejector installed as part of a FCS.

Reformer development

During the first year of the reformer development task, different bioethanol samples, both crude and pure, were obtained and analysed. The first modified bimetallic catalyst samples for the fuel reformer were prepared and tested under the expected conditions regarding activity, long term stability and low selectivity towards methane formation. The best catalyst was proven stable for 1,000 hours time on stream, with full conversion and a stable reformate composition.

However, the availability of crude bioethanol (distilled but not purified) was turning out to be a big problem. Small samples were easy to obtained, but for the field trial, over 1,000 kg of crude bioethanol would be needed. Fortunately, Alcia from Finland was supplying an ethanol grade suitable for our specifications, ETAX-B. To verify the steam reforming catalyst, another 1,000 stability test run was completed, and as shown in Figure 7, the catalyst was proven stable with ETAX-B.

Figure 7: Stability test of ETAX-B crude bioethanol steam reforming over catalyst IMM 1474e. Species concentrations in the reformate: pressure, 8 barg; temperature, 750 °C; feed S/C ratio, 4.1; feed flowrate 100 mL/min; mass of catalyst in screening reactor, 17 mg.

The fuel processor design was started by setting up a simulation model using ASPEN Plus. The work continued with detailed engineering of the microstructured components, and development of reformer control strategy. The high temperature required for ethanol reforming together with the high pressure turned out to be a tricky task, which too more effort than anticipated, but functional design withstand these conditions was accomplished.

Figure 8: Fuel processor during installation of reactors and thermocouples at Fraunhofer IMM (left), and fuel processor installed to test bench at VTT (right).

After manufacturing of the single components, the fuel processor was integrated in two stages, by first testing the reformer/afterburner reactor, and next by also including the WGS-reactor, as depicted in Figure 8. After validation of the fuel processor in start-up and steady state operation and was delivered to VTT for integration into the reformed ethanol fuel cell system.

Alongside with the fuel processor development, UPorto built developed and prepared Cu-based catalysts for low temperature water gas shift (LT-WGS) reactions. Preliminary physicochemical characterization was done, and the samples were tested in an experimental setup built to test the catalytic activity. As a result of the work, a highly performing and stable Cu45ZnGa LT-WGS catalyst was developed, which is significantly more efficient than the benchmark Hi-Fuel W-220, particularly below 200°C.

PSA development

To carry out the PSA development task, UPorto started to design and build their own lab-scale PSA system, for in-situ characterization
of available PSA adsorbent. As UPorto did not have the facilities for manufacturing and testing of the prototype scale PSA, several companies were contacted for a quotation of suitable PSA unit. A prototype PSA unit (Figure 9) was delivered to the project by HyGear under a collaboration protocol with UPorto.

Figure 9: Lab scale PSA unit at UPorto (left) and prototype PSA unit by HyGear (right).

Meanwhile, the assembly of lab PSA unit (Figure 9) was completed. The characterization of selected activated carbons for hydrogen purification was performed and the most promising adsorbent, was further characterized. Several zeolites, especially selectives to CO, were acquired and characterized. VTT also conducted a literature study of Pd-membranes as an option for H2 purification.

Based on the results with the lab PSA, it was noticed that none of the commercial adsorbents were able to meet the project specifications, especially for the 5 ppm limit, and UPorto took the additional task of developing their own adsorbent. This venture turned out to be very successful, through establishing a Cu-modified activated carbon adsorbent that using the lab-scale PSA unit produces streams with < 0.2 ppm of CO with a recovery > 75 %, enough to reach the automotive hydrogen fuel specifications (ISO 14687-2).

Also during the initial testing of the PSA unit, performed by UPorto and VTT, it was concluded that the unit could not meet the targeted 20 ppm CO concentration at 75 % recovery. A vacuum pump was installed for operation in vacuum pressure swing adsorption (VPSA) mode and the targets were met. In addition, a design of experiments (DoE) approach was used to model the prototype PSA unit, both in PSA and VPSA operating modes, which allowed find the optimal operating conditions according to the desired product specification, maximizing the recovery for a given CO concentration.

Initial testing of the subsystems

The initial testing of the subsystems were started at VTT in August 2016, with the first subsystems delivered. Figure 10 shows the FP and PSA units installed for tests. All the subsystems were individually characterized against the set initial specifications with personnel from each partner (Fraunhofer IMM, UPorto, Genport) visiting. Based on the initial characterization, it was already seen that not all the requirements are fully met, but the quality of the gas along the production and purification line was proven to be adequate, so that the integrated system would be able to operate. At this point we already took careful note on how the problems could be solved, given another development round.

The testing activities were continued in 2017 along with the iterative FP+PSA integration, while at the same time negotiating for possible field trial locations nearby VTT.

Complete system integration

Work with the system integration was started by designing and acquiring the higher level control system (HLCS) and site for the integration. The integration design and operation routines (start-up, steady-state and shut-down) were negotiated and agreed upon the consortium. The first full piping and instrumentation diagram was published in August 2016. The planned REFCS container layout is shown in Figure 11, and a simplified process flow diagram in Figure 12.

Figure 11: Rendered images of CAD model from REFC system container, H2 buffer tanks, and control room container.

Figure 12: Simplified process flow diagram of the reformed ethanol fuel cell (REFC) system.

After the initial testing of all the subsystems were completed in January 2017, the FP and PSA were integrated together, first by integrating the main process gas line, and secondly the tail gas lines. In addition, automated control algorithms were developed for the FP to allow autonomous operation of the system during field trial. Along the way, the HLCS was prepared for the integration.

In May 2017, the integrated FP+PSA was deemed to work well enough to proceed with the full system integration to container, taking place in an industrial hall at VTT facilities. The integration was completed in July 2017, except for the minor modifications done during commissioning. The integrated system is shown in Figure 13.
Commissioning and field trial

In June 2017, with the full system integration on the way, the REFCS commissioning was started. The commissioning proceeded by first testing the FP heat-up procedures, then moving to reformate gas production and finally running the full hydrogen production system. The commission took longer than expected, due to rather fundamental problems in FP product gas filtration, condensing as well as the fuel supply system.

In October 2017, a successful 7.5 hour run with the hydrogen generator was completed, stopped by the operator after the H2 buffer tank was full, as shown in Figure 14. However, after routine inspections, serious problems were detected with the steam reformer, and continuing the operation was not possible. However, the hydrogen produced while the system was operational, was of good quality and the FCS was operated using the gas without any particular problems, as shown in Figure 15. Thus the concept of producing electricity from ethanol using fuel processing, PSA purification and a fuel cell, was proven to work.

Based on the operation data and experiences, an advanced concept study was completed, suggesting improvements to the REFCS concept go beyond the 30 % efficiency target, and reduce the physical footprint and raw material needs for manufacturing. Investigations are still on-going to pinpoint the exact reason for reformer decay.

Techno-economic and environmental analysis

The techno-economic and life-cycle assessment task have been running along with the technical tasks during the whole duration of the project.

A market research was conducted for the global fuel cell telecom backup market. A tool for techno-economic was developed and this has been used to identify the potential market penetration and a roadmap for volume production of the system has been developed. The initial cost of the system was estimated to be 18% higher than diesel generator, but total costs are in favour of the reformed ethanol fuel cell. Based on the techno-economic tool, a microgrid simulator with web-backend was published: [http://microgrid.demorooms.com/appStatic/simulator/index.html](http://microgrid.demorooms.com/appStatic/simulator/index.html)

Furthermore a life-cycle assessment has been done, comparing the REFCS against diesel generator. Based on the study, the concept allows GHG emission reductions in off-grid and long back-up applications (200+ h/year), but for pure back-up applications, the prototype use of materials would need to be reduced. In the off-grid scenario, 50 % reductions in GHG emissions may be reached with a reformed ethanol fuel cell compared to diesel generators.

Both the techno-economic and LCA results are available as public reports.

Potential impact:

The main result of the project has been the development and demonstration of a crude bioethanol fuelled power system, and the concept has been developed from TRL3 to TRL6. However, harvesting the full commercial potential would definitely need further verification of the system durability, followed by re-engineering based on operational experience.

Other key results is that PCS has been able to get the S2 stack into production, enabling sales of the stacks and other systems where the S2 platform acts as the centre. Genport has also been able to extend their product portfolio to 7 kW range (G7000 HPS) and to demonstrate their GENIOL Li-ion battery pack.

As a highlight of the low TRL activities, UPorto is preparing to start a spin-off company to produce the improved adsorbent and PSA units. If successful, this concept can significantly reduce the cost of producing automotive grade hydrogen dictated the fuel standard (ISO 14687-2:2012). The non-noble metal based LT-WGS catalyst also surpassed any commercial products. These together open very
interesting possibilities from producing hydrogen from biomass feedstock.

The ejector fuel supply expertise developed at VTT has lead to work carried out in other commercial and jointly funded projects, and Fraunhofer IMM has been able to develop and demonstrate high differential pressure and temperature capable microchannel reactor designs. The techno-economic simulation tools developed by Genport have also been released for public use, for students and other people interested in energy generation solutions in microgrids.

Thus, although the main goal was not fully achieved, other results from the project have been remarkably useful.

The project results have been presented in 7 international scientific conferences and 4 peer-reviewed papers have been published so far. An Industrial Advisor Group (IAG) was formed and four workshops have been held for bi-directional information exchange with the relevant stakeholders.

The project has also been in close collaboration to HyCoRA-project, dealing with hydrogen fuel impurities, also with EL-TRAN project regarding the ejector development for grid-stabilization applications. The system integration and LCA expertise developed in the project is currently in use MARANDA, EVERYWH2RE, and HY-STOC projects.

All project partners have benefited from the publicity through conferences and workshops, which have sparked a lot of interest towards the activities. Moreover, the publication of scientific articles have aided in the completion of doctoral studies. Furthermore, through the information exchange and the workshops organized, the consortium has been able to promote different fuel cell based solutions to the industry, gaining wider acceptance for fuel cell and hydrogen technologies in general, and paving the way for technologies with reduced particulate and greenhouse gas emissions worldwide.

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