Work Package 7

Deliverable 7.8

Final report with strategic learnings from performance reporting, business case analysis

Public

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1. Introduction & Approach

1.1 About the HyBalance project

HyBalance is a project that demonstrates the use of hydrogen in energy systems. The hydrogen is produced from water electrolysis, enabling the storage of cheap renewable electricity from wind turbines. The plant is located in Hobro, Denmark being a leading country within integration of renewables into the energy systems. The unit helps balance the grid which is essential for the stability in electricity systems. The hydrogen produced is used to supply industrial customers as well as the network of hydrogen refuelling stations in Denmark.

The project is a technology showcase for sustainable development pathways in Europe.

The production of green hydrogen based on wind power using electrolysis is a well-known and proven technology, but the HyBalance project implements advanced key technologies. It will not only validate highly dynamic PEM (Proton Exchange Membrane) electrolysis technology and innovative hydrogen delivery processes involved but also demonstrate these in a real industrial environment by applying high pressure hydrogen production and delivery equipment.

The project is led by Air Liquide and the Copenhagen Hydrogen Network (CHN) together with partners Hydrogenics (electrolyser supplier), Centrica Energy Trading (Danish electricity and natural gas trading company formerly known as Neas Energy), Hydrogen Valley/CEMTEC (Danish business incubator), and Ludwig-Bölkow-Systemtechnik (LBST, research institute and consultancy).

The HyBalance project budget totals € 15 million. The project has received € 8 million in funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH2-JU) as well as € 2.6 million in funding from the Danish EUDP program.

1.2 Key objectives

HyBalance participates to the improvement of the whole hydrogen value chain with the following objectives:

- **Experimentation under industrial conditions** of the PEM technology which is characterized by a high efficiency, a smaller footprint and better capability to operate under flexible operations. These characteristics make PEM technology an excellent candidate to balance renewable power, and the PEM technology presents a high cost reduction potential through mass production.

- **Environmental benefits :** the HyBalance project is one of several initiatives to help transform energy systems from fossil dependency to relying on renewable and local energy sources by utilizing the potential of hydrogen. The project aims to demonstrate that hydrogen from electrolysis lowers significantly the environmental impact of conventional means of production.

- **Business case :** the HyBalance setting is unique in demonstrating the multiple applications of Power-to-Hydrogen Technologies, including how hydrogen can be used in multiple high value markets such as industry and clean transportation. The project will help validate business models for these applications including the potential revenues from the storage of cheap renewable energy from wind turbines and grid balancing services.

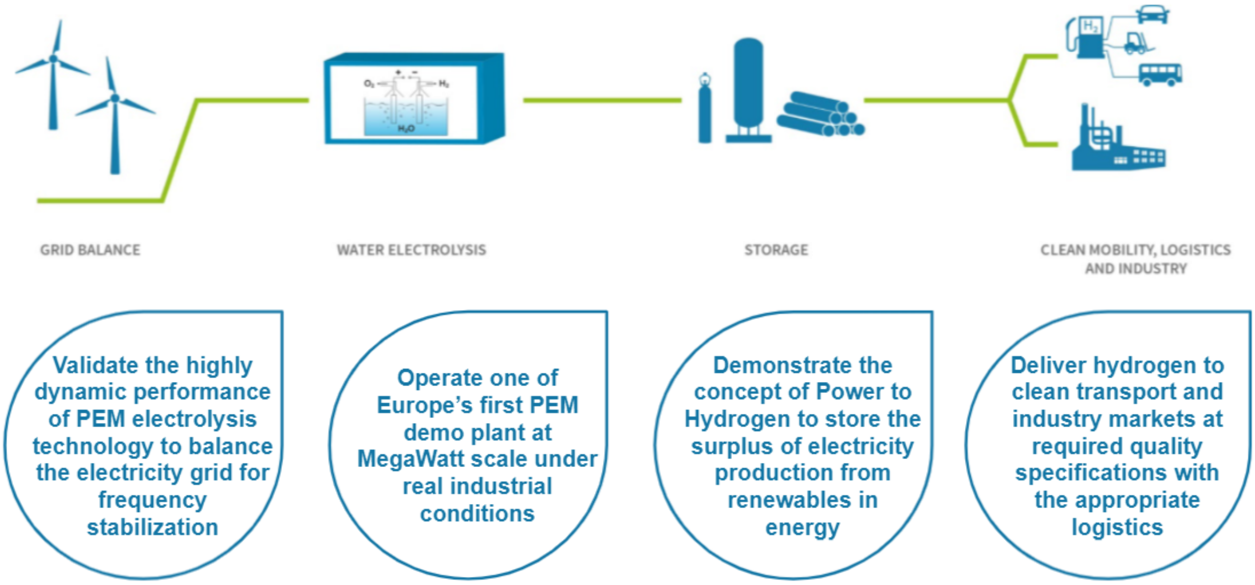

Figure 1: Hybalance actions over the global hydrogen value chain

2. Main achievements of the HyBalance program

The HyBalance facility is the first of its kind in Europe. It has demonstrated that power-to-hydrogen is a valid path to balance the grid, to store renewable energy and to serve clean transportation and industry.

Figure 2: Hybalance facility overview

HyBalance program has achieved numerous milestones and positive results along the program duration.

Below is a summary of the achievements.

- Facility inauguration on 3 September 2018
- Successful integration into the supply chain logistics of Air Liquide Denmark delivering hydrogen by pipeline to a nearby customer in Hobro and trucked-in at other customer sites.
- Generation of a nominal flow of hydrogen (230 Nm3/h) at required pressure
- Very high level of H2 purity qualified by industrial and clean mobility customers (above 99.998%)
- Efficiency of the water electrolysis[1] process at target : 56,5 kWh/kg (target of the FCHJU MAWP 2017 : 58 kWh/kg)
- Reactivity : Hot idle ramp-up and ramp-down in less than 10 seconds with a continuous hydrogen production flow
- Flexibility: Hydrogen production rate adjustable at any level from 10% to 100% of the nominal in daily operation mode
- Homologation by the Transport System Operator to provide grid balancing services on all frequency reserves market (primary - 15 seconds response time requirement, secondary and tertiary)
- High availability considering the pilot nature of the systems running 16 000 hours[1] on a 24/7 operation mode
- More than 120 tons[2] of hydrogen since the start-up
- Participation on the energy trading market to make available power capacities for Frequency Containment Reserve (primary frequencies restoration)

2. TECHNICAL LESSONS LEARNT

The plant design includes several subsystems :

- 1,25 MW PEM electrolyser composed of dual-stacks and several ancillaries : water filtration system, cooling unit, dedicated electrical substation…
- Compression unit to pressurized the hydrogen output from the electrolyzer
- High and medium pressure storage acting as regulation buffer capacities between upstream production and downstream demand
- Power transformer connected to the grid including the activation box for balancing services
- Pipeline connection for direct supply to a nearby customer
- Tube filling center for trucked-in delivery at customer sites

Hybalance equipment have proven their proper functioning in specific modes defined in the specifications, both at factory test before delivery and for the commissioning after installation on-site.

[1] Specific energy consumption includes the electrolyzer and its ancillaries
[2] from the start-up in February 2018 to September 2020

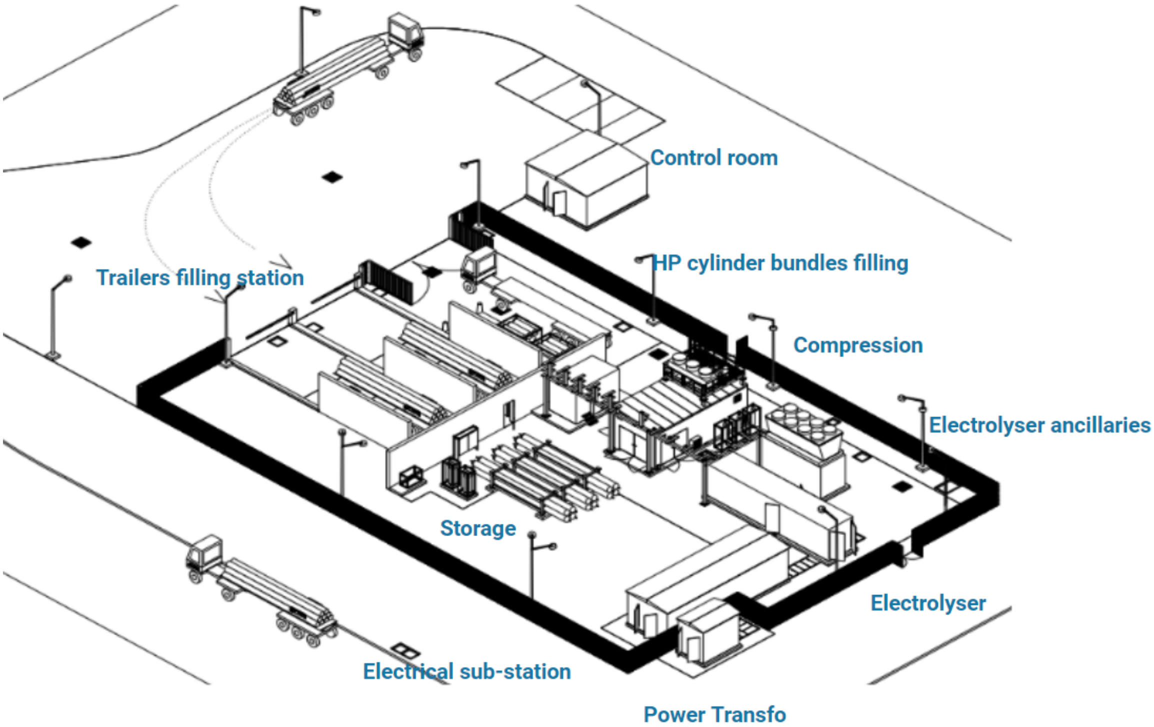

Figure 3: HyBalance subsystems layout

The operational performance is also in line and deemed very satisfactory considering the pilot nature of the installation:

- Production is stable delivering hydrogen at required flow, pressure and quality per E&C and CHN specifications
- Availability is very good, thanks to a strong service focus during the first hours of operation
- First estimation of the durability of the cell stack is in line with the forecasts

Even if Hydrogenics has a significant experience on alkaline electrolysis solutions and more recently with the PEM, HyBalance first of Its kind is a major step toward the validation of the technology.

Plenty of lessons learnt have been gathered on the electrolyser design manufacturing process as well as installation and testing protocols. The execution of the project and operation of the unit provided insights on many aspects (safety rules and risks assessments, operation management ...). All the experience gained by partners could be replicated to future site deployments.

Lessons learned consist mostly of a large number of technical details. Some of the most relevant knowledge acquisitions are detailed below:

- Containerized solutions for electrolyzer and ancillaries enable quick and easy installation on-site as well as a small footprint. Design has been enhanced to easily fit within the size of respectively 40 feet and 20 feet.

- Establishing test protocols to detect defaults before installation on-site e.g during manufacturing or Factory Acceptance Test

- Sizing of the compressor and storage capacities is obviously a key element to ensure a consistent back-up to (i) reserve production capacities for grid services and continue H2 customers supply during load down regulation, (ii) perform maintenance services on electrolyzer without stopping the H2 supply to customer or on other equipment without stopping the electrolyzer production, (iii) buffer H2 consumption peak over short period of time.

- Electrical connection to the grid and quantification of harmonics generation within the grid shall be anticipated during the early preparation phases of the project.

- Enhancement on the electrolyzer design and especially the stacks and also the process flow definition (components material, pressure regulation, flow measurements, instrumentation devices qualification...)

- Implementation of a program logic controller to pilot all the systems together appears more efficient for the monitoring and the remote access of the plant.

3. Environmental Performance

The main target behind the HyBalance project is to demonstrate that hydrogen, as a vector of energy, will help to decarbonize the industry and mobility activities. The expertise work conducted in the frame of the program issues very positive results on the efficiency of using water electrolysis Power to H2 plant against fossil based production scheme. Power-to-hydrogen is a key building block for energy system integration, notably via demand side management for grid connected electrolysis plants.

The methodology relies on the LifeCycle Assessment approach considering "Well-to-tank" boundaries in order to fit with the same scope as the HyBalance project i.e. :

- primary energy sources data about the fuel input for electricity for the process
- production and storage of hydrogen
- distribution to the point of use via H_2 pipeline or trucked-in delivery

The assessment builds on actual HyBalance performance data gained from both dedicated measurement regimes (part load behaviour) as well as simulations of plant operation regimes (demand curve, grid carbon intensity). This data is complemented with typical values for value chain elements up and downstream the HyBalance plant, such as the GHG footprint of electricity grid mix or hydrogen transport via truck/pipeline.

Four pathways (i)Hydrogen via steam methane reforming of natural gas with truck transport from Germany (current case from Germany for high quality), (ii) Hydrogen via steam methane reforming of natural gas onsite industry premises (sites are connected to a natural gas grid), (iii) water electrolysis production from grid mix Denmark and (iv) 100 % wind power have been analyzed.

The results of Greenhouse gas emissions in terms of global warming potential (GWP) expressed as CO2-equivalents[3] are shown in figure 4.

Concretely,

- The **break-even with GHG emissions** "well-to-tank" between SMR production from natural gas in Germany and PEM electrolysis connected to the Danish grid was reached when **renewable share counted for more than 60%** of the electricity mix). Looking at the case of Denmark: According to [AIB 2018], in 2017 Denmark had a renewable electricity production share of 71.6% (2016: 61.7%) and no nuclear power component.

- The GHG emissions from the supply of hydrogen via electrolysis using the **Danish grid mix** is based on an emissions factor for the Danish power plant mix of a**bout 235 g of CO_2 equivalent per kWh of electricity in 2017,** about 165 of CO_2 equivalent per kWh of electricity in 2019, about 63 of CO_2 equivalent per kWh of electricity in 2029 including upstream GHG emissions for fuel supply and non-CO_2 GHG emissions. This provides an interesting trigger to evaluate the environmental benefits of implementation of PtH2 in other countries.

- Increasing the **share of renewable electricity** and increasing the **efficiency of the electrolysis** plant would lead to a further decrease of GHG emissions.

[3] The greenhouse gas emission balance is performed in general accordance with ISO 14044/67, using principles in accordance with JRC / EU Renewable Electricity Directive (RED) methodology. Greenhouse gases considered in this study are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Other greenhouse gases are CFCs, HFCs, and SF6, which are, however, not relevant in this context. See HyBalance Deliverable D7.6 Final Environmental Performance Report for more details.

- Using **100% wind** power for hydrogen production results in GHG emission reductions of close to 100% compared to the fossil reference pathways. Considering the target climate objectives of Denmark, there is room to increase by a factor 3 the CO2 savings by 2030 as the electricity mix will get closer to the best scenario, 100% wind energy case.

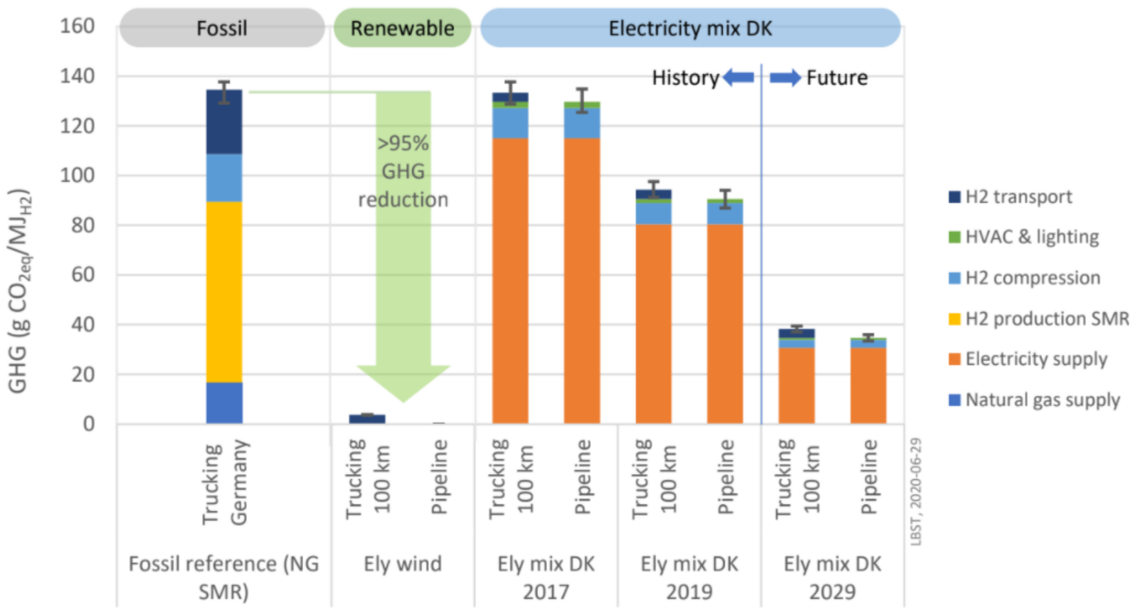

Figure 4: Greenhouse gas emissions from the supply of hydrogen

- Analyses of Energinet data showed that low grid prices strongly correlate with low CO_2 emissions in the Danish grid at current electricity market design. Thus, there will be a correlation between the environmental performance and economical profitability with an active participation on energy trading markets to produce H2 when renewables generate an excess of production.

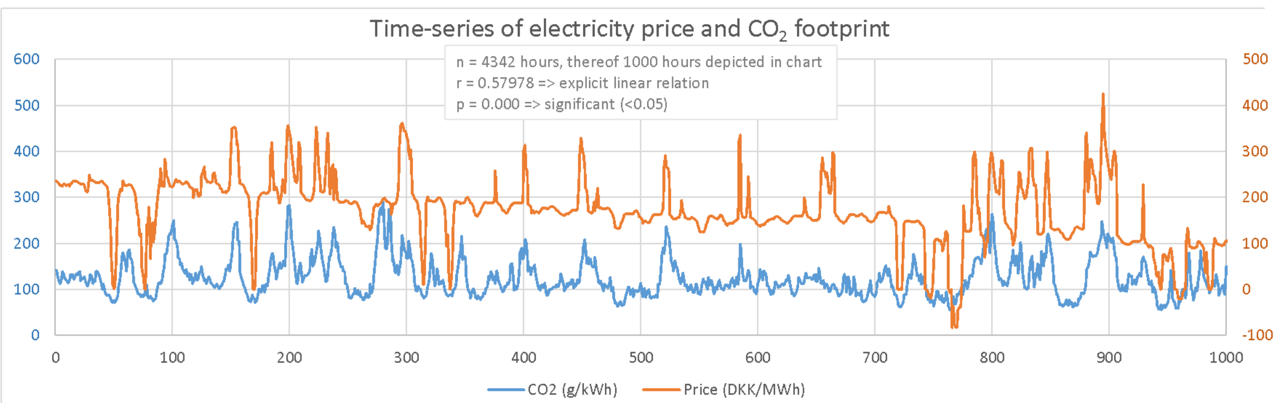

Figure 5: Correlation analysis of 1st half 2020 (thereof 1000 h depicted in chart)

4. Business case study

From an economical point of view, different cases have been assessed in order to evaluate the components of hydrogen production costs for such innovative hydrogen energy systems :

- 1,25 MW scale electrolysis (similar configuration as HyBalance)
- Large scale electrolyzer of 20MW
- Very large scale 100MW demo project

Analysis is based on market trends per 2020's state of the art and does not include conditioning and transport costs. **Electricity represents the major components of the total costs of hydrogen** produced by water electrolysis Even if its share will be reduced if we consider the well-to-tank scope,

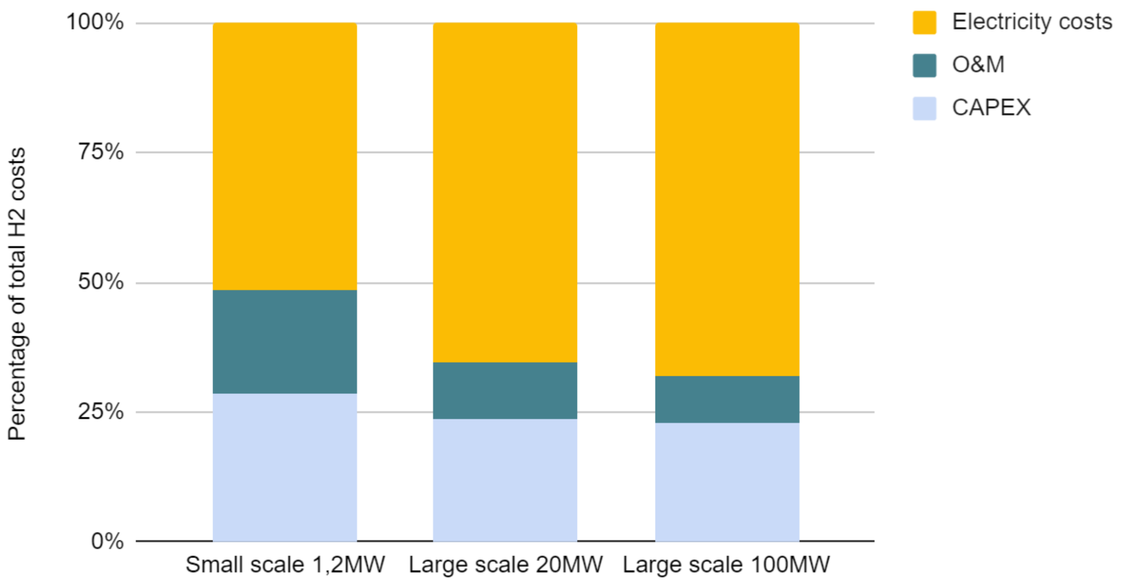

Figure 6: Percentage share of hydrogen cost of sales components

The capital cost of the HyBalance PEM electrolyzer is around 1800 €/kWh. The investments required are expected to decrease at a **target of 1000 €/kWh including EPC** in the next few years due to several reasons :

- The increase of knowledge will help to reduce the number of engineering hours for the project definition and execution.
- A design to costs approach with a rationalization and standardization of components could help to reduce the prices of equipment (stacks, compressors, valves…).
- The industrialization of components at a larger scale is also seen as a lever assuming that the raw material costs do not fluctuate significantly.

However construction and electrical connection to energy systems will still significantly weigh in the investment's balance.
In conclusion, the price of the electrolyzer is an important item in the total investment budget but the other parts of the installation have to be carefully estimated during the project preparation.

O&M costs are estimated between 2 to 3% of the hardware investments in the MAWP. Operational results on the HyBalance plant are aligned with this hypothesis.

Even if the current subsidies mechanism decreasing the impact of CAPEX facilitates the emergence of projects, other mechanisms will be required to limit OPEX (i.e. electricity) and reach competitive prices on the market especially for industrial applications.

The improvement of the efficiency of the electrolysis process is also a way to reduce the energy consumption per kg of H2. The efficiency achieved during the HyBalance program on the electrolyzer and its ancillaries (water cooling & purification…) is 56,5 kWh/kgH2. The recent product optimizations will permit an efficiency of around **52 kWh/kgH2**.

Grid services for electrolysers can offer a great potential of cost reduction for hydrogen production by electrolysis.
The energy trading markets obey quite complex rules which depend on the area (primary energy sources for electricity production, tax policies, purchase agreement between regions/countries...). The reduction of fees in Denmark and finally exemption of the PSO tax is an example of the regulation mechanism which can positively or negatively affect the competitiveness of one country from another.

Two sources of revenues can be activated with bids on the energy market:
1. Lower electricity prices on the **spot market** (day ahead or intraday) than the imbalance cost
2. **Payment against reserve capacities** set at disposal of the TSO who decide to activate them or not

HyBalance assessment and similar case simulations show that grid balancing services could generate **revenues equivalent to 15 % to 25% of the electricity costs** on average, even reaching negative costs of electricity during certain periods. With forecast prices of energy on the rise, there will be more and more benefits to optimize the energy trading strategy for new deployment.

Based on these results, conclusions can be made for the future business cases :

- Excellent production planning is needed to maximise the possible revenue from grid balancing. For grid balancing to work well in operation, it is necessary to **be able to produce based on interesting electricity prices instead of based on demand**. There is a need for operations optimization tools to pilot production according to demand, storage capacity and grid forecast. Then the impact on operations remains low.

- In the first deployment phase of an electrolyser, when the demand is still low compared to the production capacity, the reserves revenue will allow the system to increase its profitability;

- Different strategies could be applied for small and large size installations. The first case will require H2 sales volume close to the nominal in order to amortize CAPEX then less capacities can be reserved for grid balancing. Large scale plants can take advantage of more flexibility due to higher production capacity to limit the impact of OPEX. However this is also dependent on the available renewable energy and needs to balance the grid in the area. The reserve capacity offered on the market may be very limited, which makes these bidding strategies difficult to carry out on larger scale plants;

5. CONCLUSION

HyBalance, one of Europe's first facilities for the production of hydrogen by PEM water-based electrolysis on an industrial scale has demonstrated that producing hydrogen to store energy is technically and economically viable.

The project has achieved a number of important results in terms of technologies, operations, safety business case and integration of Power To H2 plant within the energy systems. It represents a great step toward the demonstration of performance on the field, exceeding at some points the benchmark of 2017 state of the art.

Air Liquide will continue to operate the site and produce hydrogen to supply its customers. Industry enabled a quick ramp-up of the production and distribution to clean mobility is expected to grow with the market deployment of FCEV's in Denmark sustained by the government policies.