Final report

1. Project details

Project title	SafePtx
File no.	64021-2081
Name of the funding scheme	EUDP
Project managing company / institution	Energy Cluster denmark
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Project partners	Sulfilogger Green Hydrogen System DBI
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2. Summary

Project summary

The project developed a hydrogen sensor for detecting traces of hydrogen in oxygen, enhancing safety in alkaline electrolysis systems. It addressed the need for safer hydrogen production. The sensor was advanced from TRL 4 to TRL 6, validated in industrial environments, and featured internal diagnostics for high SIL, long-term stability, and resistance to harsh conditions.

Most important results:

- Developed a hydrogen sensor capable of detecting trace amounts of hydrogen in oxygen, achieving TRL 7 with over 3200 hours of operation in a full-size alkaline electrolyzer system.
- Demonstrated the sensor's ability to replace current sensors, addressing issues like flow dependency and measurement in startup/shutdown scenarios.
- Implemented an internal diagnostic algorithm to check the sensor's state-of-health, aiding in SIL 2 certification.
- Conducted pressure tests showing the sensor's capability to withstand pressures up to 100 bar.
- Demonstrated the sensor's effectiveness in both oxygen and nitrogen environments, showing no flow dependency.

Future use of results: The hydrogen sensor will be used by system integrators and architects in hydrogen-related processes, especially in humid, wet, or liquid environments. The technology will support safer and more efficient operation of electrolysis systems, contributing to the hydrogen business segment of Sulfilogger. The project has paved the way for further development and commercialization of the sensor.

Expected effects of the technology: Enhanced safety and operational efficiency in hydrogen production, reducing the risk of explosions and ensuring gas purity. Lower maintenance costs and improved long-term stability of hydrogen sensors in harsh environments. Support for Denmark's energy policy objectives by enabling the production of green hydrogen, contributing to decarbonization and energy security.

3. Project objectives

The project aimed to develop a novel hydrogen sensor for detecting traces of hydrogen in oxygen and demonstrate its feasibility in alkaline electrolysis systems producing green hydrogen. The developed sensor featured internal diagnostics for a high Safety Integrity Level (SIL), long-term stability to reduce maintenance costs, and the ability to withstand harsh environments, including high humidity. It aimed to achieve SIL 2 without needing gas handling and conditioning, simplifying system complexity and enhancing safety.

The project advanced the sensor from Technology Readiness Level (TRL) 4 to TRL 6 by developing modifications and signal algorithms for SIL 2 certification and validating the sensor in industrial environments. Additionally, it explored using the same technology for oxygen measurements, though this remained at TRL 4.

Given the nascent stage of the hydrogen industry, the project also addressed regulatory challenges, particularly for SMEs, by building knowledge on relevant standards and guidelines for commercializing hydrogen-related components. This included identifying regulatory gaps and providing a roadmap for engaging with standards at various TRL stages.

Overall, the project not only advanced the hydrogen sensor technology but also provided valuable insights and guidance for SMEs entering the hydrogen market, helping to pave the way for safer and more efficient deployment of hydrogen-based energy solutions.

This sensor technology developed addressed several critical sensing needs in the hydrogen production industry, including enhanced safety, long-term stability, and the ability to operate in harsh environments.

Alkaline electrolysis is a pivotal technology in the transition to green energy systems. Alkaline electrolysis can be powered by renewable energy sources such as wind, solar, and hydropower. This integration allows for the storage of excess energy produced during peak times, which can then be converted into hydrogen and stored for later use. This capability is essential for balancing the intermittent nature of renewable energy sources. Compared to other electrolysis technologies, alkaline electrolysis is more cost-effective due to its use of non-noble metal catalysts and mature technology.

The safe operation of alkaline electrolysis systems is paramount for several reasons:

- Risk of Explosion: Hydrogen is highly flammable, and any leaks or improper handling can lead to explosions, the lower explosion limit (LEL) is extremely low LEL_{H2} = 4%, thus even small leaks can be hazardous.

- Gas Purity: The separation of hydrogen and oxygen gases is critical. Any contamination can lead to the formation of explosive mixtures. Cross-over in electrolysis systems is a well-know risk that needs to be constantly monitored.

- Operational Efficiency: Safe operation ensures that the system runs efficiently, reducing downtime and maintenance costs. This efficiency is vital for the economic viability of hydrogen production.

- Regulatory Compliance: Adhering to safety standards and regulations is essential to avoid legal and financial repercussions. Compliance ensures that the system operates within the prescribed safety limits, protecting both the operators and the environment.

In summary, alkaline electrolysis is a cornerstone of green energy systems due to its ability to produce clean hydrogen, integrate with renewable energy sources, and stabilize the power grid. However, the safe operation of these systems is essential to prevent accidents, ensure gas purity, maintain operational efficiency, and comply with regulations. By prioritizing safety, we can harness the full potential of alkaline electrolysis in our transition to a sustainable energy future.

Hydrogen sensors play a crucial role in the safe and efficient operation of alkaline electrolysis systems. It is essential to continuously monitor the concentration of hydrogen in the process environment, detecting any leaks that could lead to hazardous situations such as explosions. By providing real-time data, hydrogen sensors enable prompt detection and response to leaks, ensuring the safety of both the equipment and personnel. Overall, hydrogen sensors are essential for optimizing the performance and safety of alkaline electrolysis systems, contributing to the reliability and sustainability of green hydrogen production.

4. Project implementation

The main goal of the project was to develop a hydrogen sensor, on TRL 6, capable of detecting trace amounts of hydrogen in oxygen within electrolysis systems. This goal was achieved and even demonstrated on TRL 7 having clocked more than 3200 hours of operating in a full size alkaline electrolyzer system. In that sense the project was a major success.

Specifically, it was demonstrated in the project that the developed sensor could replace the currently used sensor, which have significant drawbacks such as flow dependency and unable to measure H2 in N2 as is needed in startup / shutdown scenarios.

A risk identified in the project was that the sensor failed to operate in the harsh industrial environment of the electrolyzer, to mitigate that risk, early testing was initiated. The risk of a sensor that often-required maintenance / service was also mitigated by enabling early industrial testing.

An important outcome of the project was the implementation of an internal diagnostic algorithm for periodically checking the state-of-health of the sensor. The algorithm both ensures a generally lower production failure rate of the sensor as it allows for better failure detection during the sensor production but is also an enabler for the SIL approval as this generally lowers the undetected failures from operating the sensor. Although the SIL2 approval was not obtained in the project period, significant steps were made towards having a SIL2 approved solution and it is expected that the approval will be acquired within 2024.

Although, the sensor was only tested in a side stream of the main O2 stream, it was demonstrated from the pressure tests conducted, that it certainly is possible to operate the sensor in the main O2 stream.

5. Project results

One of the main objectives of the project was to modify the Sulfilogger sensors to achieve SIL 2 certification. As of October 2024, the SIL 2 certification has not yet been obtained, but it is expected to be achieved later this year. The SIL process turned out to be more complex than anticipated and was further delayed when the responsible project partner, DGC, had to leave the project early on, before the SIL process had started. Sulfilogger then took over responsibility for this deliverable, which made sense given that the certification process requires a deep understanding of the product. Although the SIL 2 certification process is delayed it is important to mention that preliminary findings suggest that is indeed possible to achieve SIL 2 with current sensor, mainly due to the internal diagnostics methods developed in this project. The main work in the SIL certification process is to make compliant firmware code for the sensor.

The other main goal of the project was to test the sensor in a relevant industrial environment to min. TRL 6. Early in the project a sensor was manufactured for test purposes and installed in the test facilities at GHS on their A-series full scale electrolyzer (450 kW). The sensor has thus been in operation for more than 3200 hours on the GHS test facility. Even more test data could have been obtained if the project, the initial sensor was somewhat delayed due to the global electronic chip crisis in 2022. Sourcing was a major issue both at GHS and Sulfilogger at that point in time.

A subgoal of the project was to demonstrate that a Sulfilogger can be used at elevated pressures. Consequently, pressure tests were conducted on over 10 sensors. Preliminary results showed that the Sulfilogger is significantly more pressure-resistant than the nominal 3 bar of a standard sensor. Special chips and a reinforced sensor head revealed that the sensor can withstand pressures well over 100 bar, see “Appendix 1: Pressure plots normal sensor heads”.

The pressure test results exhibited a large spread in data. More tests are needed, and the pressure-bearing components of the sensor need to be reviewed and improved in quality to achieve more stable results.

Another subgoal was to demonstrate an oxygen sensor at TRL level 4. An oxygen sensor requires different electrode materials for both the working electrode and the reference electrode, as well as a different electrolyte. Progress on this task has been limited due to challenges in the nanofabrication process at the DTU Nanolab clean room. The special chips needed for these tests were made very late in the project, and resources for testing the chips were depleted and redirected to other tasks, such as the SIL 2 approval. Consequently, the validation tests remain to be done. However, these tests are expected to take place in the latter part of 2024.

During the project a benchmark test of the Sulfilogger sensors vs. a commercial competitor (BGA: binary gas analyser) was performed. From the test it was clear that the Sulfilogger sensor had some clear advantages:

- **No flow dependency:** A BGA is highly flow dependent. As the tests below shows for 100% oxygen the BGA outputs a signal even if the gas contains no hydrogen, whereas the Sulfilogger sensor is not affected by the flow. In the case of gas containing hydrogen (1.2%) in oxygen, the BGA shows large flow dependency even within its nominal flow range. Again, the Sulfilogger sensor displays no flow dependency, see “Appendix 2 – Varying flow rate measurements”.

- **Inert to N2, especially important during start-up and shutdowns:** A BGA is used to differentiate the composition between two difference gasses, hence the name Binary gas analyzer. Thus, when introducing another gas like Nitrogen into the gas composition, the BGA measuring principle is challenged. Nitrogen is often used in Electrolysers during start-up and shut-downs to flush the system for gasses. In the test conducted two gasses containing hydrogen, one with hydrogen (1.2%) in oxygen and one with hydrogen (2%) in nitrogen are alternated. As the BGA used is setup to measure hydrogen in oxygen it has severe challenges in measuring correctly for hydrogen in nitrogen. In fact, it greatly underestimates the hydrogen concentration. On the contrary the Sulfilogger sensor has no problems with detecting the correct gas composition in the two cases, see “Appendix 3 – H2 concentration measurement”.

- **Pressure dependent but shows linear coherence to pressure.** Both the Sulfilogger sensor and the BGA is pressure dependent. However, the BGA outputs a signal even if there is no hydrogen present in the gas if the pressure is increased, as the test data shows in the graph below. In a gas composition with hydrogen present (1.2 % hydrogen in oxygen), both the Sulfilogger sensor and the BGA display an increase in signal when the pressure is increased. The signal from the Sulfilogger sensor is however directly proportional with the pressure and can thus be compensated for, see “Appendix 4 – Hydrogen concentration”.

From a market perspective, the project has confirmed the need for better hydrogen sensing technology for electrolyzer applications. This applies to both alkaline electrolysis and other electrolysis technologies such as PEM electrolysis. Especially players within PEM electrolysis have shown great interest in Sulfilogger. For SulfiLogger technology, the PEM technology is considered an easier application due to its less aggressive environment compared to the KOH environment of alkaline electrolysis. Another interesting application is the e-boiler segment, where water is heated using high voltages. The high voltages are known to generate hydrogen causing hazardous incidents. This market is considered very mature. Common to all these applications is that the Sulfilogger sensor benefits from being capable of measuring either directly in liquid or in very humid/condensing environments.

Early in the project a report was published to present the project and later a press release was published to present the project and its preliminary findings, i.e. 1200 hours of operation on a full scale electrolyzer.

Based on the findings from the project a tech talk took place in October 2024 as the main dissemination event. Two publications have also been produced during the project:

- ATEX guidelines: Brief introduction for SME’s on how to get started with an ATEX product certifications process.

- SIL guidelines: Brief introduction for SME’s on how to get started with an SIL product certification process.

6. Utilisation of project results

The results obtained from this project are expected to benefit system integrators and system architects designing hydrogen related processes. Especially humid / wet / liquid process streams containing hydrogen concentrations reaching the lower explosion limit (LEL) will have a new tool available to ensure safe and efficient operation of their processes. As electrolysis application exactly matches the above description, the hydrogen sensor developed in this project is a good match. Thus, electrolysis partners, that is; end users, system integrators and system builders will be key accounts for the hydrogen business segment of Sulfilogger.

For Sulfilogger the SafePtX project has been a key steppingstone for the hydrogen business segment. During the project period 10 mio. DKK of capital was raised by the Sulfilogger shareholders to invest further into the hydrogen segment and strengthening the organization. During the project, 4-5 people have been employed in Sulfilogger as a direct impact of the hydrogen business investment and Sulfilogger have received increasing interest from different market players and sales have been completed in 2023 with selective partners. In 2024, with the employment of a global business lead for hydrogen, Sulfilogger has significantly increase its appearance as supplier of hydrogen sensing equipment.

The market is a niche market with players typically supplying a wide range of different types of sensors. Competitors in the hydrogen sensor space all use bypass solutions, as many of these sensors are only capable of withstanding atmospheric pressure, limited temperature range and must be installed in a dry environment. Below is a non-exhaustive list of competitors:

- Dräger
- MSA
- Michell
- H2Scan

The Sulfilogger measurement technology represents a new measurement method compared to traditional hydrogen sensors found in industrial methods. Traditionally, sensors require a high degree of conditioning of the process gas before it can go into the analyzer. Sulfilogger aims to completely remove the need for conditioning, so that the sensor can be installed directly in the process stream, in which high pressures, temperatures, humidity and challenging corrosive conditions may occur. This project represents a big step towards that goal. The Sulfilogger way of measuring, is thus a sales barrier that requires a very close dialogue with the customers and their system architects. The project has therefore confirmed that close customer partnerships is a necessary sales approach, to enable market entry.

As this project is supporting electrolysis development it aids in advancing Denmark’s energy policy objectives by enabling the production of green hydrogen from renewable energy sources like wind and solar. This green hydrogen can be used to decarbonize various sectors, including transportation, industry, and heating, aligning with Denmark’s goal of becoming fossil fuel-free by 2050. Additionally, electrolysis supports energy storage, balancing the grid by storing excess renewable energy and releasing it when needed. This contributes to energy security and efficiency, key components of Denmark’s National Energy and Climate Plan. By integrating electrolysis, Denmark can enhance its renewable energy share, reduce greenhouse gas emissions, and lead in sustainable energy innovation.

7. Project conclusion and perspective

During the project period, Sulfilogger has made significant advances towards maturing their hydrogen sensing technology. Highlights of the project is implementation of a redundant sensing system with internal diagnostic capabilities, which has been pivotal for the ongoing SIL 2 certification process. The sensor developed in the project has proved to be a durable and reliable solution for detecting hydrogen trace amounts in the oxygen gas line of a full scale commercial alkaline electrolyzer system. On several parameters it has outperformed the competitor analyzer used as benchmark at an internal test at Sulfilogger.

A better hydrogen sensor is important for the improvement of the electrolyzer technology. A better sensing technology will enable more low-load operation of the electrolyzer systems as operation can take place closer to the LEL of hydrogen in oxygen as illustrated in "Appendix 5 – load operation". Due to cross over in the diaphragms of the stack low load operation can be difficult but is important for the overall utilization of the system.

Going forward, the most important goal is to get the SIL 2 certificate in place. During the project, from dialog with potential customers, it has been made very clear that this is absolutely mandatory if the sensor is to be used as safety component in industrial hydrogen process applications. There are also applications in the market where SIL approval is not required, e.g. surveillance of process conditions, however the majority of applications require SIL approval.

For the sensor to be more attractive to the electrolysis segment, measurements closer to the stack is on the wishlist of all the manufacturers of electrolysis systems. This will enable better detection and faster detection of hydrogen cross-over in the stack. Too late detection can mean very costly repairs of the stack. To operate closer to the stack several main specifications of the sensor must be improved:

Temperature:
Most electrolysis stacks operate at elevated temperatures close to the boiling point of water. Operating an electrolysis process at elevated temperatures is beneficial from a thermodynamic point of view. The current maximum operating temperature of the Sulfilogger sensors is 60 °C and thus under the current operating temperature of alkaline and PEM electrolysis stacks, which often operate within 70-90 °C.

Increasing the temperature limit of an electrochemical sensor is a challenging task. Besides the basic material temperature limits of mainly the polymer used in the sensor construction, the main problem is the electrolyte employed in the electrochemical sensor. Changing the electrolyte is a significant R&D task that requires extensive screening and testing of novel electrolyte candidates.

Pressure:
During the SafePtX project it has been shown that the current Sulfilogger sensor pressure rating can potentially be raised significantly. Results from the pressure tests did however show that the pressure resistance varied a lot among the samples tested, therefore improvements in the production are needed to obtained better reproducibility of the pressure resistance. Increased pressure combined with elevated temperatures also need further investigation of potential consequences.

Corrosion resistance:
Alkaline electrolysis represents a very harsh corrosive environment having highly concentrated KOH at elevated temperatures. Thus, materials used in this environment are obviously challenged in terms of durability. From tests conducted in the project, it is known that the membrane material will deteriorate over time in this environment. Therefore, new membrane candidates must be found that have sufficient durability and adequate permeability for hydrogen.

Lastly, it is found that there is a sustained general interest for an oxygen sensor. In the project chips for an oxygen sensor were manufactured, however assembly and test of the sensor needs to be conducted.

8. Appendices

- Appendix 1 - Pressure plots normal sensor heads
- Appendix 2 - Varying flow rate measurements
- Appendix 3 - H2 Concentration measurements
- Appendix 4 - Hydrogen concentration
- Appendix 5 - Load operations