Flagship Project
H_2Giga

The hydrogen flagship project H_2Giga

Water electrolysis for green hydrogen on a gigawatt scale

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Dear readers,

Many of you know about the potential uses of hydrogen from your work. When produced renewably, it can bring together three important aims: energy security, climate neutrality, and competitiveness. This makes hydrogen the opportunity of the century, and also one of our priority policy areas at the Federal Ministry of Education and Research.

It is our aim to scale up the technology as rapidly as possible. In future, sufficient amounts of hydrogen will be needed to supply numerous areas of application, such as the chemical and steel industries. In order to achieve this, Germany – as a business location – now needs visionary approaches like the flagship project H_2Giga.

As part of this project, more than 120 partners have come together to prepare large-scale electrolysers for mass production. And they have been very successful: the first large-scale electrolysers have already been used for the first time, and pilot plants are being set up.

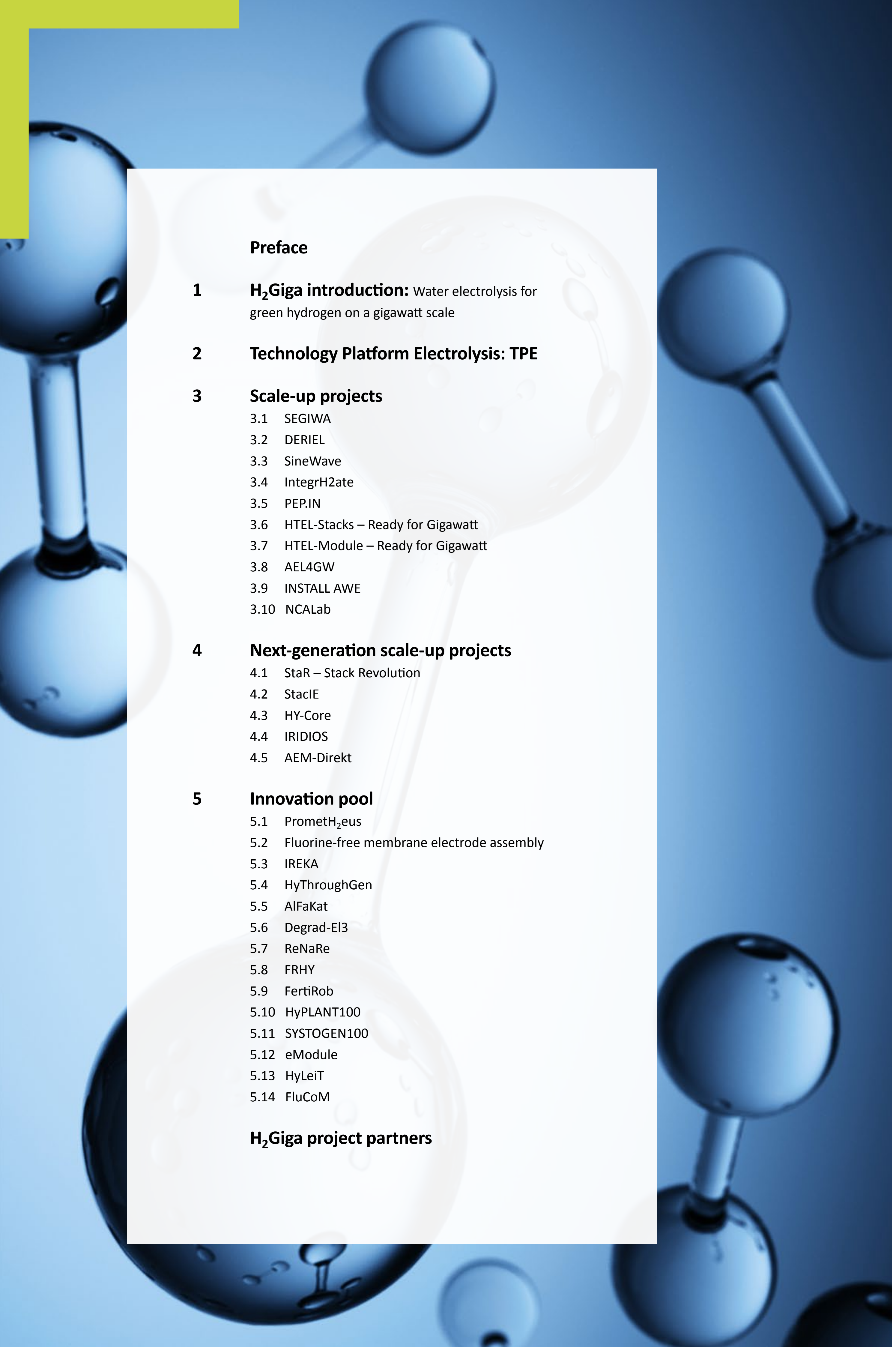
As the project grows, the network of H_2Giga partners is growing too. Established manufacturers of electrolysers work hand in hand with suppliers, universities, and scientific institutions. Together, they put findings from the world of research into practice right away. This means that solutions are found which can be used in industry without delay.

Our aim is clear: we want to make Germany a hydrogen republic – with the help of innovation. The National Hydrogen Strategy defines the framework for this, and gives all involved the security to be able to plan ahead.

Germany already has a strong research and industry landscape, and the field of hydrogen is no exception to this. However, particular effort is needed for us to be able to compete on the international stage. We want to become a leading market for hydrogen technologies, and to make them an export leader with the label "Made in Germany". In this context, I see the role of the Federal Ministry of Education and Research as paving the way for developments, but also setting their pace. We are investing more than 700 million euros in our three hydrogen flagship projects alone. This will contribute to green hydrogen developing its full potential for the energy transition and climate protection.

Over the next few pages, you are invited to get an impression of this for yourself. I wish the flagship project continuing success in its upcoming endeavours!

Bettina Stark-Watzinger
Member of the German Bundestag
Federal Minister of Education and Research



1 H_2Giga

Water electrolysis for green hydrogen on a gigawatt scale

Water electrolysis for the energy transition

In the global search for sustainable and environmentally friendly energy sources, hydrogen from renewable energy sources (“green hydrogen”) plays a key role in overcoming the challenges of climate change. Hydrogen can be utilized in versatile applications and is more than just an energy carrier: Besides its function to store renewable energy, hydrogen can be used directly as a fuel for mobility and heating. Through Power-to-X technologies, hydrogen enables the production of synthetic fuels as a replacement for today’s fossil fuels. Furthermore, it is an important reducing agent and reactant in the chemical industry and steel production. In the latter, it can replace coke to reduce iron ore in the blast furnace. In a fuel cell or in a hydrogen power plant, it can generate power or be used to generate heat. Green hydrogen therefore represents a bridge between renewable energies and energy-intensive sectors in which decarbonization through direct electrification is difficult or even impossible.

According to Germany’s National Hydrogen Strategy, which has been updated in 2023, the country’s green hydrogen generation capacity should reach around 10 gigawatts by 2030. The ambitious climate targets require an increase in the electrolysis capacities currently available for the generation of green hydrogen by almost two orders of magnitude, i.e. a factor of 100. The flagship project H_2Giga, funded by the Federal Ministry of Education and Research (BMBF), is laying the foundation for this massive ramp-up by developing technologies for the serial production and upscaling of electrolyzers. Around 120 partners, including electrolyzer manufacturers, plant manufacturers, engineering companies, precious metal suppliers, start-ups, research institutes and universities, are researching and developing modern production technologies, new materials, and improved components. Leading German electrolyzer manufacturers, such as Siemens Energy, Linde, MAN-ES/H-TEC, thyssenkrupp nucera and Sunfire, are all part of H_2Giga. In cooperation with their research partners, they are working on projects to upscale electrolysis technologies.

H_2Giga is open to scale-up and industrialize all water electrolysis technologies, covering alkaline electrolysis, PEM electrolysis (PEM: proton exchange membrane) and high-temperature electrolysis, as well as the next-generation technology AEM electrolysis (AEM: anion exchange membrane). Alkaline water electrolysis (AEL or AWE) is an established technology with a high degree of technical maturity and proven long-term stability. Alkaline electrolyzers are already available on a larger scale. This technology has the advantage of using low amounts of precious metals and the disadvantage of a lower flexibility for partial-load operation. By comparison, PEM electrolysis offers high electrical efficiency and better dynamic properties. However, this method requires high amounts of precious metals as catalysts, in particular iridium. The third technology, high-temperature electrolysis, can achieve very high conversion efficiency levels by using process heat or waste heat as an additional energy source when coupled with industrial processes. However, it is technologically less mature than AEL and PEM and not suitable for dynamic start-stop operation, since the required temperature cycle would be too large. The youngest electrolysis technology, the AEM electrolysis, combines specific advantages of alkaline and PEM electrolysis: For example, no precious metals are required as catalysts and the polymer membrane is more suited for serial production than AEL separators. However, from a technical point of view, AEM electrolysis is at a significantly lower level of maturity, in particular compared to AEL and PEM.

Electrolysis technology depends on specific application requirements, available resources and underlying economic conditions. In summary, H_2Giga provides the whole spectrum of technological possibilities, which are essential to achieve hydrogen production on a gigawatt scale.

Project objectives:

A sufficient supply of efficient, durable, and scalable electrolyzers is needed to enable the hydrogen ramp-up in line with the goals of Germany's National Hydrogen Strategy. Although there are already large electrolyzers on the market today that work efficiently and over long periods of time, their production is at least partly manual. This is time-consuming, cost-intensive, and prone to errors. This is where H_2Giga enters the picture: our project partners are researching and developing technologies for the industrialization and upscaling of water electrolysis – a prerequisite for producing green hydrogen on a gigawatt scale.

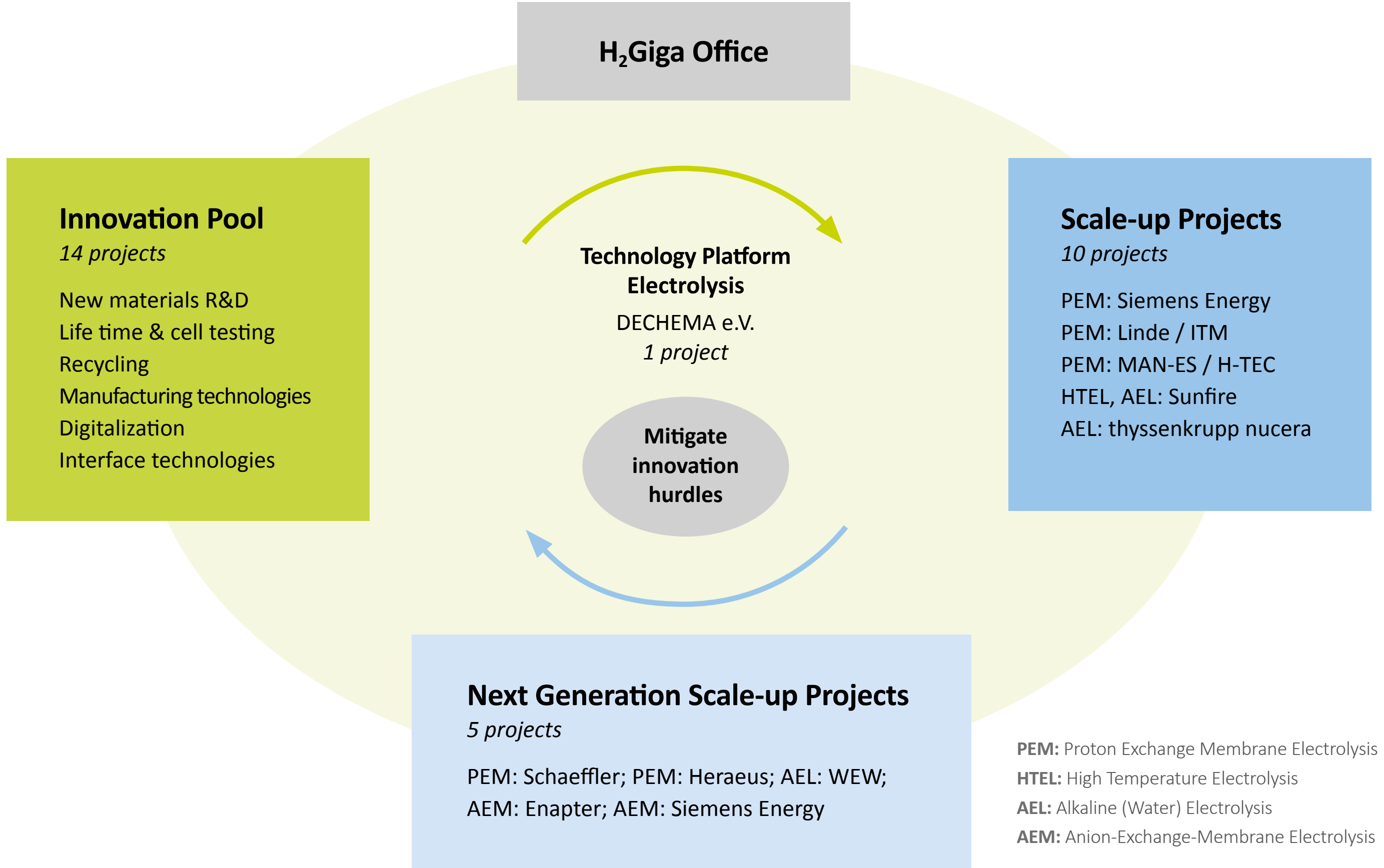
Thematic priorities within H_2Giga:

- Manufacturing technologies
- Automation and robotics
- System and process integration
- Re-design for production, maintenance, recyclability
- Support of technology development through digital plant and product twins
- New materials (e.g. membranes and catalysts)
- Testing methods, quality control, lifetime analysis and prediction
- Set-up of a reference factory
- Recycling concepts
- Norms, standards, and approval processes for electrolyzers
- Professional training on electrolysis/hydrogen technologies

120+

partners are involved in the hydrogen flagship project H_2Giga to work towards a greener future

Photo ©: Siemens Energy AG, thyssenkrupp AG, H-TEC Systems GmbH, ITM Power Linde GmbH, Sunfire GmbH (from top left to bottom right)



Project structure

H_2Giga consists of 30 independent projects in which over 120 partners are researching and developing modern production technologies, new materials and improved components for electrolyzers. Electrolyzer manufacturers, plant manufacturers, engineering companies, precious metal suppliers and start-ups as well as research institutes and universities work together within their projects in order to move the technology towards an industrial scale. The H_2Giga projects are divided into three groups: scale-up projects, next-generation scale-up projects and innovation pool projects.

In the scale-up projects, electrolyzer manufacturers and their project partners are researching technologies to enable upscaling and serial production of electrolyzers. They aim to produce large modules of the electrolyzers with a high degree of automation, thereby achieving huge increases in throughput and production capacity. The ten independent scale-up projects cover alkaline, PEM and high-temperature electrolysis. All aim to prepare their technology for implementation on a gigawatt scale.

In the next-generation scale-up projects, more innovative electrolysis technologies are being further developed and scaled up. This group also covers advancements in core components, such as the stack or the membrane electrode assembly. The results will pave the way for the electrolysis technologies of tomorrow and beyond.

The academic innovation pool projects work on overarching research topics relating to electrolysis – from new membranes and catalysts to testing methods and manufacturing technologies.

The independent projects are clustered in six research areas, which range from material development to peripheral elements of electrolyzer plants.

The **Technology Plattform Electrolysis** hosts an ongoing dialogue between research and industry. This information exchange helps to close knowledge gaps and supports the research partners in considering the future applicability of research topics right from the beginning of their work. The platform project also covers general, non-technical topics such as training programs or approval procedures for the installation of electrolyzers.

2 H_2Giga

Technology Platform Electrolysis

2 Technology Platform Electrolysis: TPE

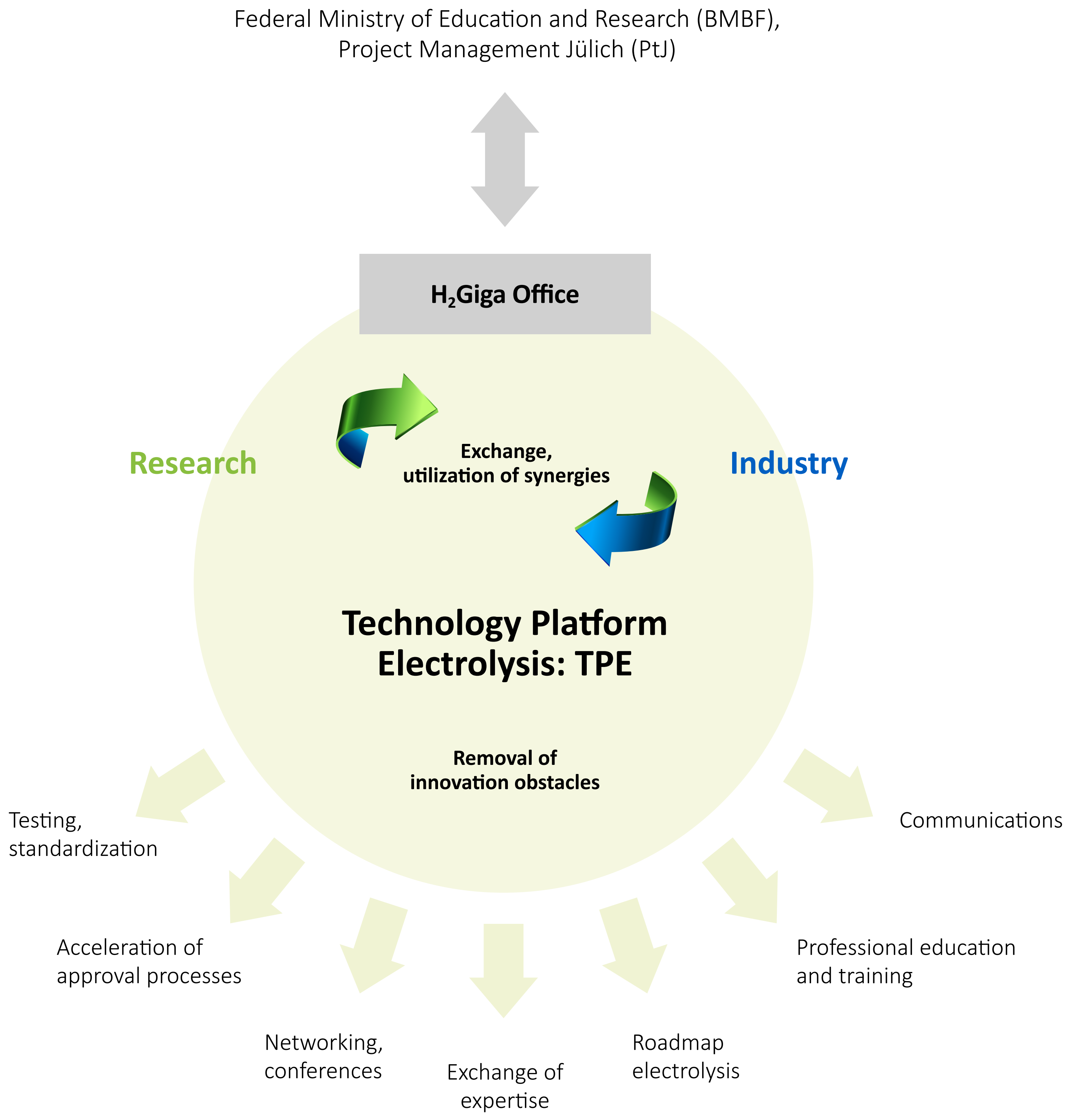
Interaction between research and industry

The network project Technology Platform Electrolysis (TPE) is the central point of contact for all stakeholders in the H_2Giga projects, as well as for external inquiries and requests. DECHEMA e.V. coordinates the TPE and provides a platform for information exchange between the currently 30 independent H_2Giga projects. TPE additionally functions as the interface to the project sponsor, the Federal Ministry of Education and Research (BMBF), via Project Management Jülich (PtJ). Within H_2Giga, various exchange formats support the continuous flow and exchange of information between research and industry. This ensures that synergies are optimally leveraged. TPE also manages the flagship project's communication and public relations campaigns. It organizes trade fair presences and annual status conferences for H_2Giga, the latter being excellent networking opportunities for experts and stakeholders across the flagship project.

The TPE project also works on non-technical topics in order to overcome innovation obstacles. Examples include standardization issues and acceleration of approval processes for the installation of electrolyzers. The latter are analysed from a practical standpoint. In direct interaction with approval authorities, the partners identify defined and transparent procedures enabling a fast and effective process from application to approval. An additional TPE work package focuses on professional education and training on electrolysis and other hydrogen technologies. The partners develop and implement professional training courses both for the basics of electrochemistry and to impart more specific knowledge of electrolysis technologies.

One highlight of the TPE project is the elaboration of the Roadmap Electrolysis. This summarizes the scale-up status of all electrolysis technologies in H_2Giga, lists open technological challenges and further research requirements, and proposes implementation paths to reach the gigawatt scale.

Coordinator: **DECHEMA e.V.**



3 H_2Giga

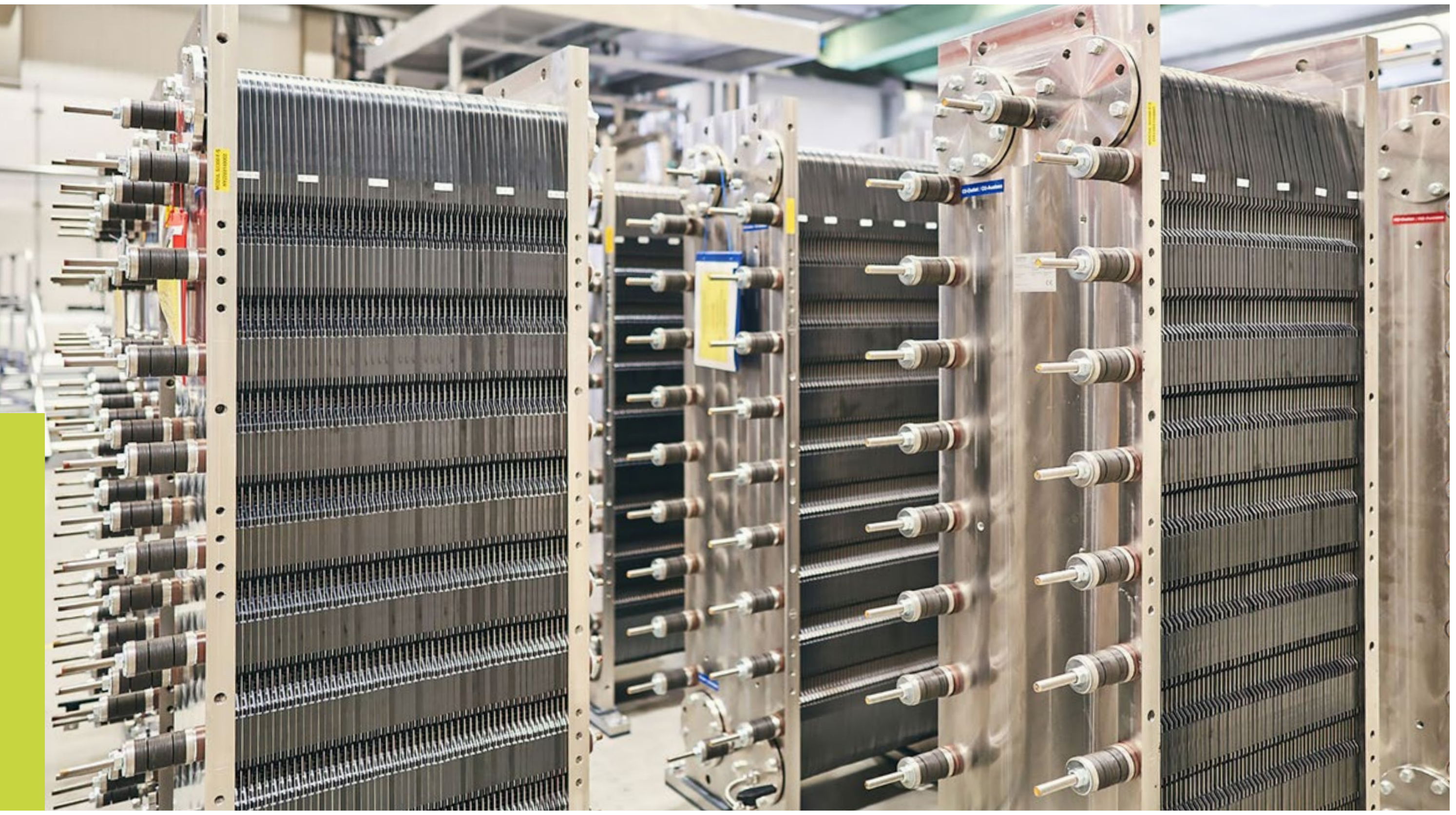
Scale-up projects

3.1 SEGIWA

Serial production of gigawatt-scale PEM electrolyzers

Within SEGIWA, the partners are laying the foundation for an automated serial production of PEM electrolyzers and thus for the expansion of production capacities in the gigawatt range. From basic materials, e.g. catalysts, through membrane electrode assembly (MEA) and stacks right up to entire electrolysis modules, the partners are working on technologies to fully automate production and assembly. During the research phase, many decisions need to be made: from basic construction, dimensioning of the cell size and number of cells per stack, supplier selection, mode of operation all the way up to the design of the entire plant. All this information flows into the realization of a production line for the gigawatt range. The development is supported by studies on digital twins, in particular a digital fleet twin, which can analyse numerous plants that are in operation. From this, concepts are designed with learning systems for detailed monitoring and a predictive maintenance process in real time. Overall, SEGIWA aims to lay the foundation for transforming the Silyzer® 300 technology platform from manual assembly to automated serial production at the best possible quality standard. Here, a plant consists of individual 0.75 MW modules offering a total output of 17.5 MW and a hydrogen production of 340 kg/h (4000 Nm³/h).

Coordinator: **Siemens Energy Global GmbH & Co. KG**



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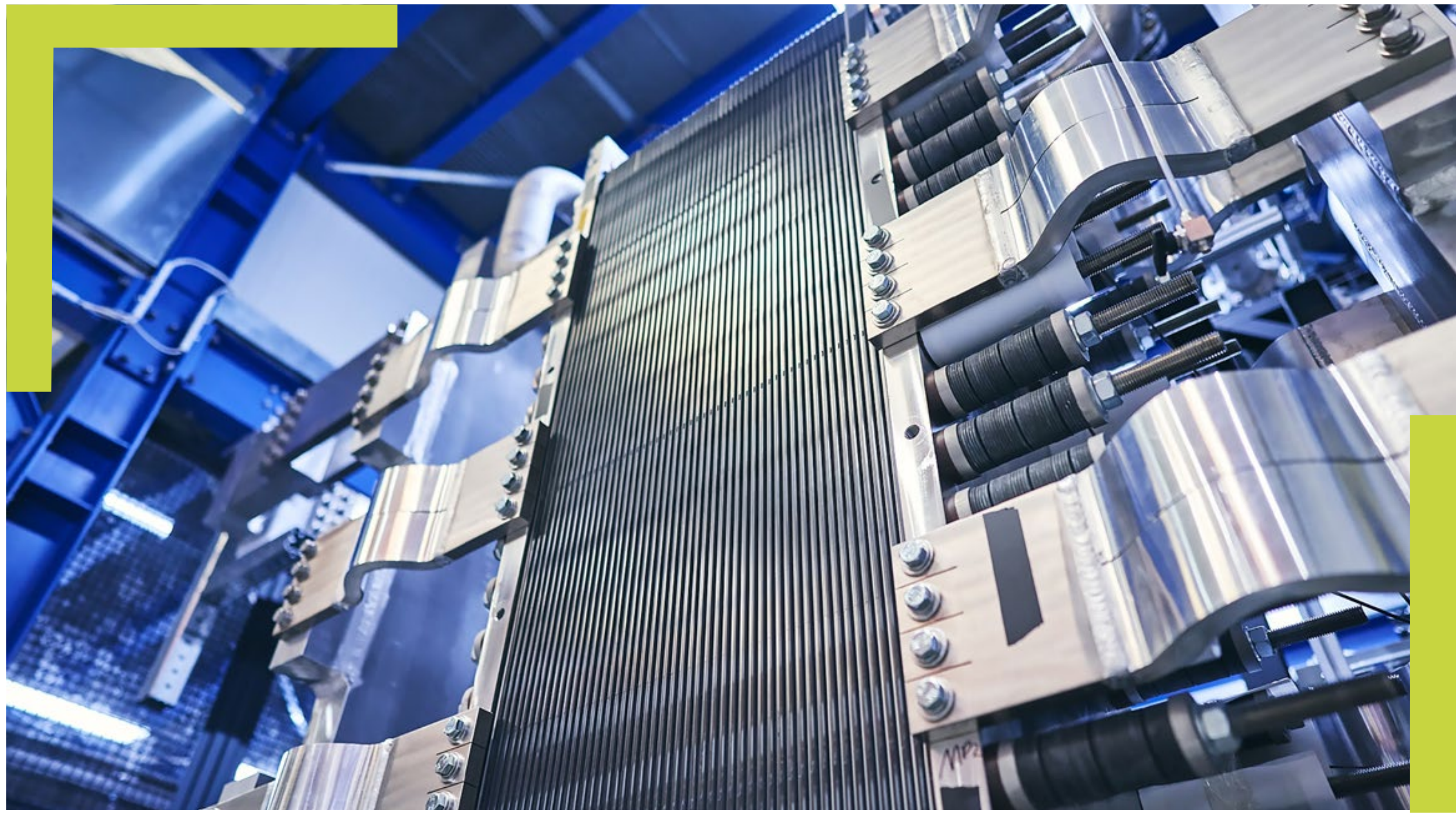
3.2 DERIEL

De-risking for PEM electrolyzers

De-risking, or the minimization of risks, means increasing the operational reliability of electrolyzers. Operational reliability becomes increasingly important as the systems grow bigger and their technical maturity improves. To this end, partners from research and industry work together in the DERIEL project to establish a basic understanding of degradation and failure mechanisms in PEM electrolyzers. The studies cover a spectrum ranging from small individual laboratory cells up to application-oriented test stations in the megawatt range. From these results, the partners develop measures for preventing or minimizing degradation. Such measures typically include selecting and defining suitable operating windows and defined protocols for special operating conditions, such as start/stop, load change or emergency shutdown. The partners analyse aging mechanisms by means of both electrochemical characterization and complex analytics. Computer tomography, electron microscopy, NMR and RAMAN spectroscopy, are used to compare materials before and after their use in the electrolyzer. Degradation processes, such as particle growth of the catalyst or changes in the electrode structure, can be monitored and analysed quantitatively. The aim is to achieve a fundamental understanding of the underlying processes of failure and degradation modes. This is a basis to optimize the entire system according to the Pareto principle in a time- and cost-effective manner.

Coordinator: **Siemens Energy Global GmbH & Co. KG**



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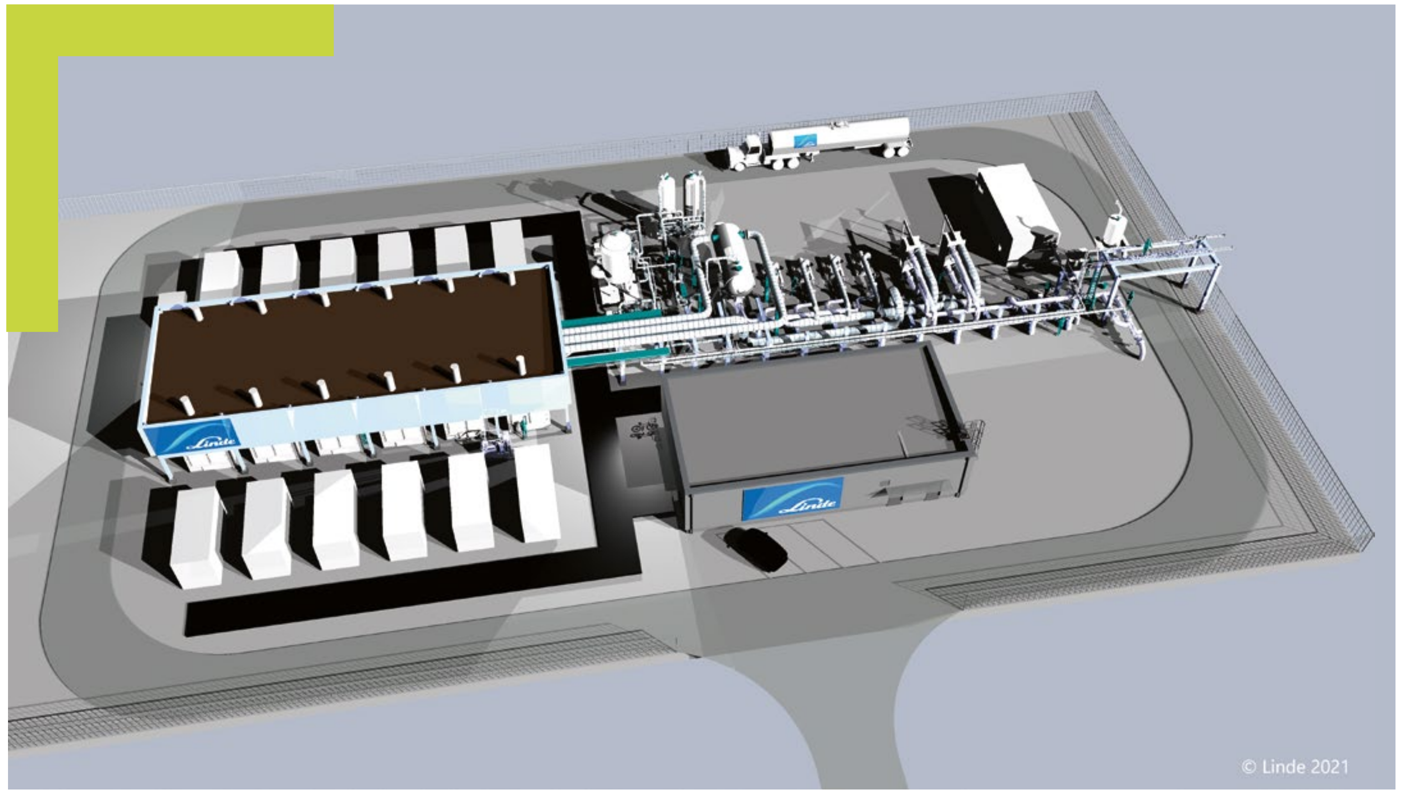
3.3 SineWave

Innovative sector-coupled electrolysis systems

In SineWave, the partners are working on optimizing the entire electrolysis plant, in particular the periphery components. The aim is to research a technology base for plants that can be applied to different electrolyzers, independent of their power class. Additionally, the partners develop tailored plant components, for example for separating oxygen and water. Here innovative technologies, for example additive manufacturing, are used to test new methods to efficiently separate oxygen and water in the PEM anode cycle. Test stands are set up for material development and to analyze degradation behavior on short stack level. The overall system gets optimized in terms of its suitability for scale up. Another important part of SineWave is the process integration of the electrolyzer, e.g. in plants for the production of methanol or ammonia, or the combination with conventional plants for steam methane reforming. The project team develops digital solutions for safe operation of the electrolyzer and intelligent controlling of the entire system. As a result, the total costs for the system and the ongoing operating costs (OPEX) can be reduced.

SineWave includes the following work packages:
WP 1: Digital solutions
WP 2: Smart materials and equipment
WP 3: Water/oxygen separation
WP 4: Performance measurements and process integration
WP 5: Education and training

Coordinator: **Linde GmbH**



3D plot plan of 24 MW electrolysis plant © Linde GmbH

3.4 IntegrH2ate

Operating electrolyzers with added value

The large-scale implementation of electrolysis plants is currently lagging far behind expectations. One of the main reasons for hesitant investment decisions is their low profitability. Therefore, there is an urgent need to optimize the OPEX/CAPEX of large-scale electrolysis plants in order to improve the profitability of such plants. As a step towards profitability, concepts for the effective utilization of the by-products oxygen and heat are being developed and researched. For oxygen utilization, new processes for oxygen treatment and compression are being analysed and concepts as well as simulations for suitability for potential customers are being developed. For heat utilization, the waste heat from the electrolyzer will be upgraded to a higher temperature level in a scaled demonstration plant using a heat pump. This allows the heat to be used more effectively at a production site (e.g. in chemical parks, refineries or municipal utilities). In addition, the project is researching concepts for conditioning water and sewage from electrolyzer plants.

IntegrH2ate includes the following work packages:
WP 1: Research into large-scale electrolysis plants up to 1 GW
WP 2: Purification and effective utilization of oxygen as a product of electrolysis
WP 3: Extraction and effective utilization of heat as a by-product
WP 4: Water conditioning

Coordinator: **Linde GmbH**

Leuna chemical site © Linde GmbH

Scale-up projects

Planned gigafactory "H-TEC SYSTEMS Stack Manufacturing & Development Center" in Hamburg-Rahlstedt © MAN Energy Solutions

3.5 PEP.IN

Industrialization of PEM electrolysis production

The aim of PEP.IN is to manufacture electrolyzers competitively in large quantities. For this, the partners are developing production technologies and methods that do not exist on the market yet. Knowledge from the field of fuel cells in the automotive sector serves as a starting point for the development of automation and upscaling of electrolysis. Therefore, car manufacturers and component suppliers play an important role in this project. Further development and cost reduction extend across all value-added steps in the production of electrolyzers. Serial production processes are being developed to be applied in a giga factory. Stack design is also being adapted for suitability in automated production (“design for production”). In parallel, the partners are conducting research on a “stack of the future”, which will serve as a basis of future electrolyzer generations. For the current stack generation, the partners are working on making the assembly fully automatic and reproducible by using specifically developed grippers and assembling robots. Various procedures for designing the assembly lines are being examined from an academic and industrial point of view.

Intelligent monitoring options for electrolyzer operation are also being integrated into the manufacturing process. This ensures optimal usage of the electrolyzers across their entire lifetime. The monitoring technology considers subsequent maintenance: smart systems for predictive maintenance help to ensure a longer life and efficient deployment of maintenance resources. Last but not least, the partners are developing logistic concepts for a qualified supply chain that is suitable for mass production. Due to the work in PEP.IN, production of one gigawatt electrolysis capacity per year should be enabled in the medium term.

Coordinator: **MAN Energy Solutions SE**

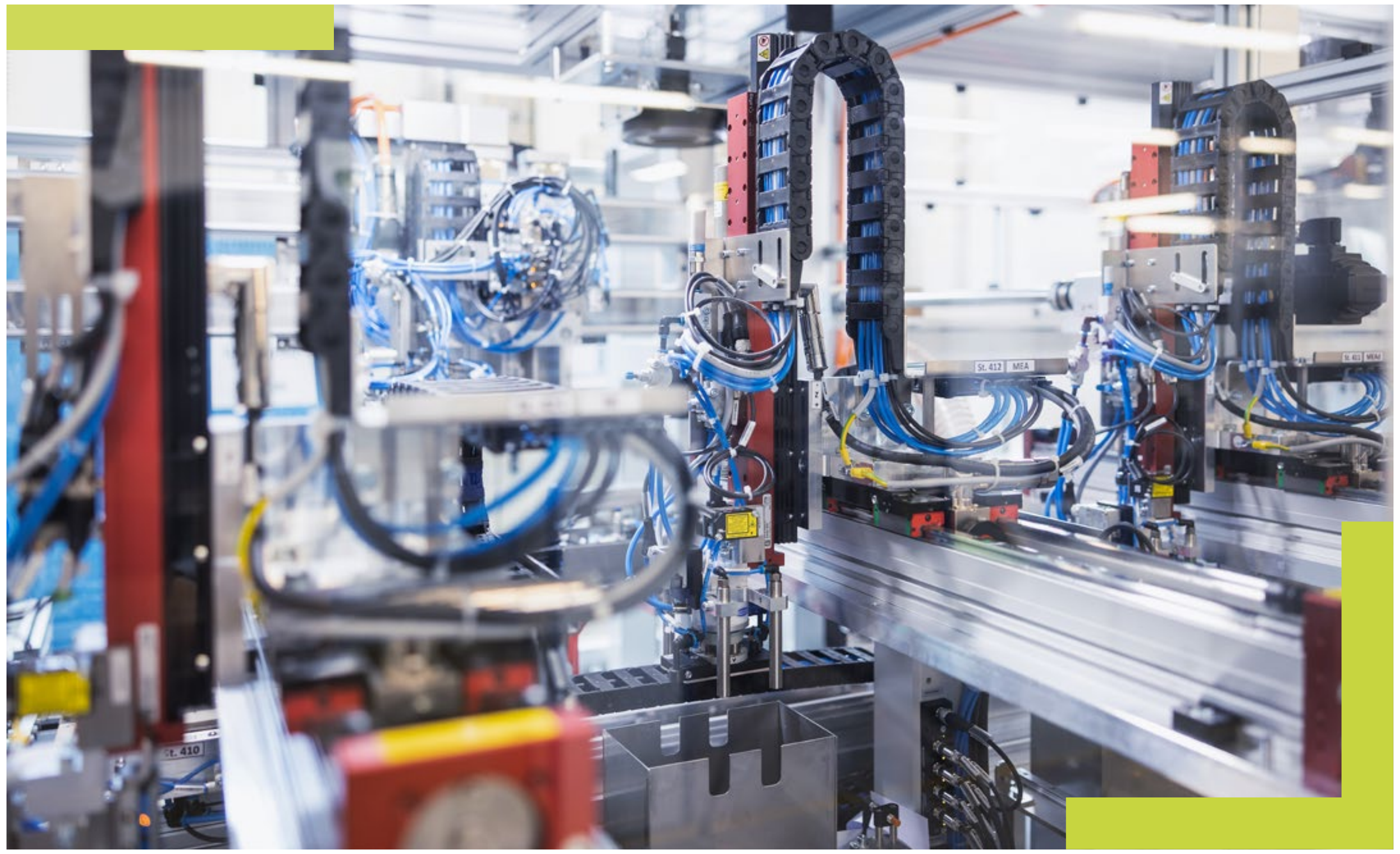
3.6 HTEL stacks – ready for gigawatt

Stacks for high-temperature electrolysis in the gigawatt range

The high-temperature electrolyzer (HTEL) is the preferred electrolysis solution for industrial applications in which water vapor is available. By using industrial waste heat as an additional source of energy alongside electricity, the HTEL achieves a far higher conversion efficiency than other technologies. As a result, considerably more hydrogen can be produced from the same electrical power consumption. The core element in the production of green hydrogen using an electrolyzer is the HTEL cell, with numerous cells being combined to form a stack.

This project puts an emphasis on scaling up the stack technology to the gigawatt range. For this, the partners are focusing on further development steps regarding lifetime, material costs, efficiency, production technologies and ramp-up of production. Innovations in the cell and in the stack will improve performance and long-term stability and optimize their suitability for automated production in the future (“design for automation”). With the development of plant technologies, for example an automatic stacker, and the design of a logistics network, the foundations will be laid for future industrial serial production of the HTEL stacks at gigawatt scale.

Coordinator: **Sunfire GmbH**



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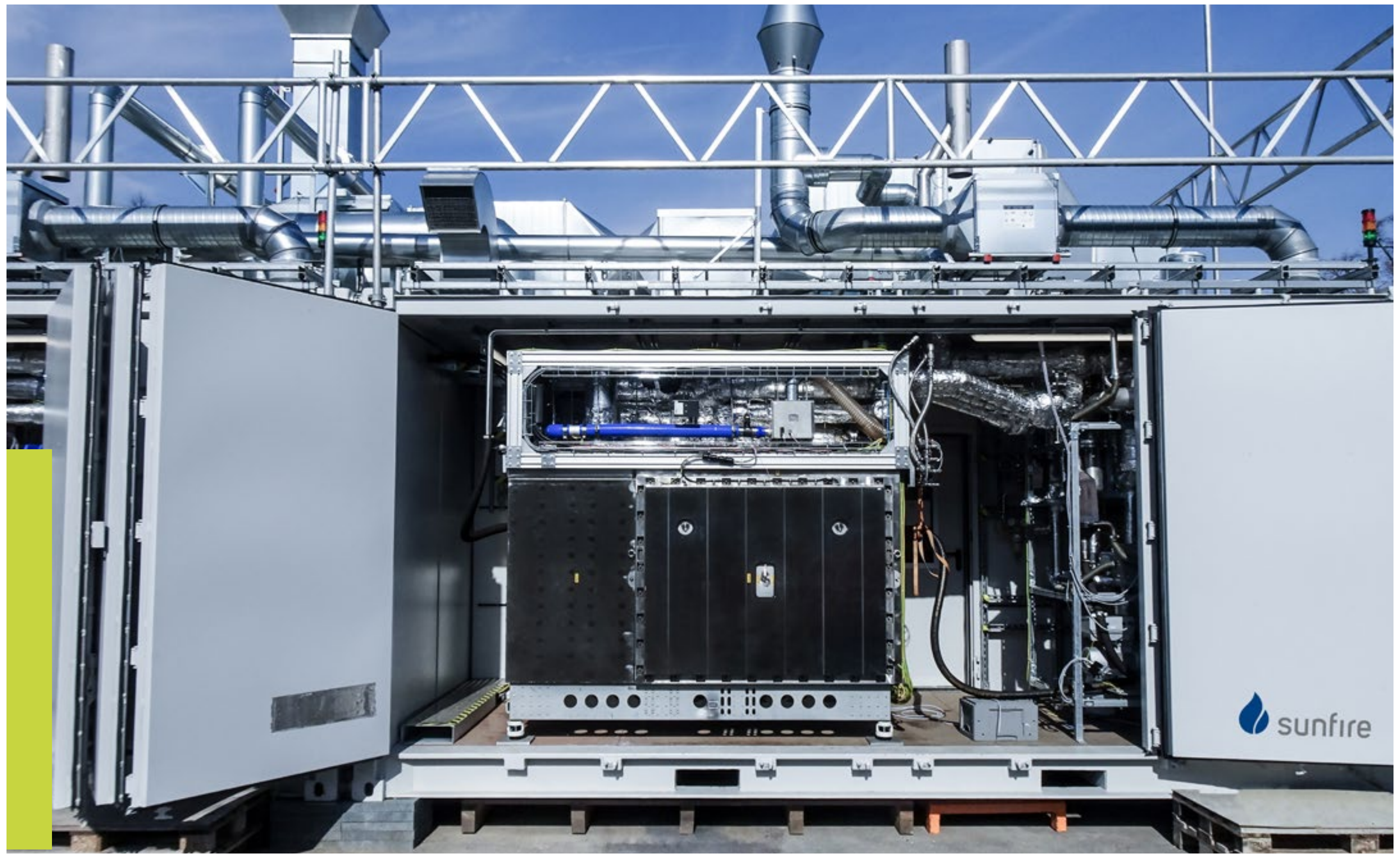
3.7 HTEL modules – ready for gigawatt

High-temperature electrolyzers on an industrial scale

An electrolyzer consists of the stacks, its core, and peripheral components. In a HTEL module, HTEL stacks of HTEL cells are combined with the components for carrying reactant and product streams, including thermal energy management and electrical power management. Through multiplication, modules can be connected to form scalable electrolysis plants. In order to be able to serve the rapidly growing market for water electrolyzers economically, the partners are developing new generations of HTEL modules that can be produced in large quantities and at a considerably lower manufacturing cost than those of today. To achieve this, the scalability of this technology is being optimized to reduce costs through economies of scale (“design to cost” approach). The cooperative work on research and development topics in the project aims to realize a new generation large-scale HTEL module, as well as corresponding production processes and operating strategies. As a result, the project will help to economically serve the fast-growing market of water electrolyzers. HTEL technology can produce hydrogen particularly efficiently in applications in which water vapor is available and thereby effectively contribute to saving CO_2 emissions.

Coordinator: **Sunfire GmbH**



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3.8 AEL4GW

Alkaline electrolysis for the gigawatt scale

Alkaline water electrolysis (AEL or AWE) is a particularly mature and robust technology. However, there are still numerous unanswered technological questions regarding the further development of industrial-scale alkaline electrolysis modules. Especially for industrial serial production, it is necessary to rethink the modularity of the functional components of the electrolyzer and develop production processes suitable for the gigawatt scale. The AEL4GW project addresses the challenge of developing a new generation of alkaline water electrolyzers for 30 bar (g) operating pressure. Those are not only more efficient than the current state of the art, but also enable cost-effective large-scale production. Examples of technical innovations in this project include powerful and scalable coating technologies for electrodes, automated processes for manufacturing and joining seals, and the modeling of electrochemical processes in the cells.

In the first project stage, the consortium will adapt the existing technology – namely the cell, stack and system – to the current requirements and develop a new generation of alkaline water electrolyzers. Upscaling will be performed based on this, including the development of associated production and logistics processes. The new configurations will be validated. Process development and factory planning are carried out up to the gigawatt range. In the second project stage, electrolyzers are interconnected to develop and plan multi-megawatt electrolysis plants in detail. Taking location factors into account, concepts for large plants to produce green hydrogen are being developed based on an established techno-logy. The result is a central element for hydrogen ramp-up and the decarbonization of important branches of industry.

Coordinator: **Sunfire GmbH**

3.9 INSTALL AWE

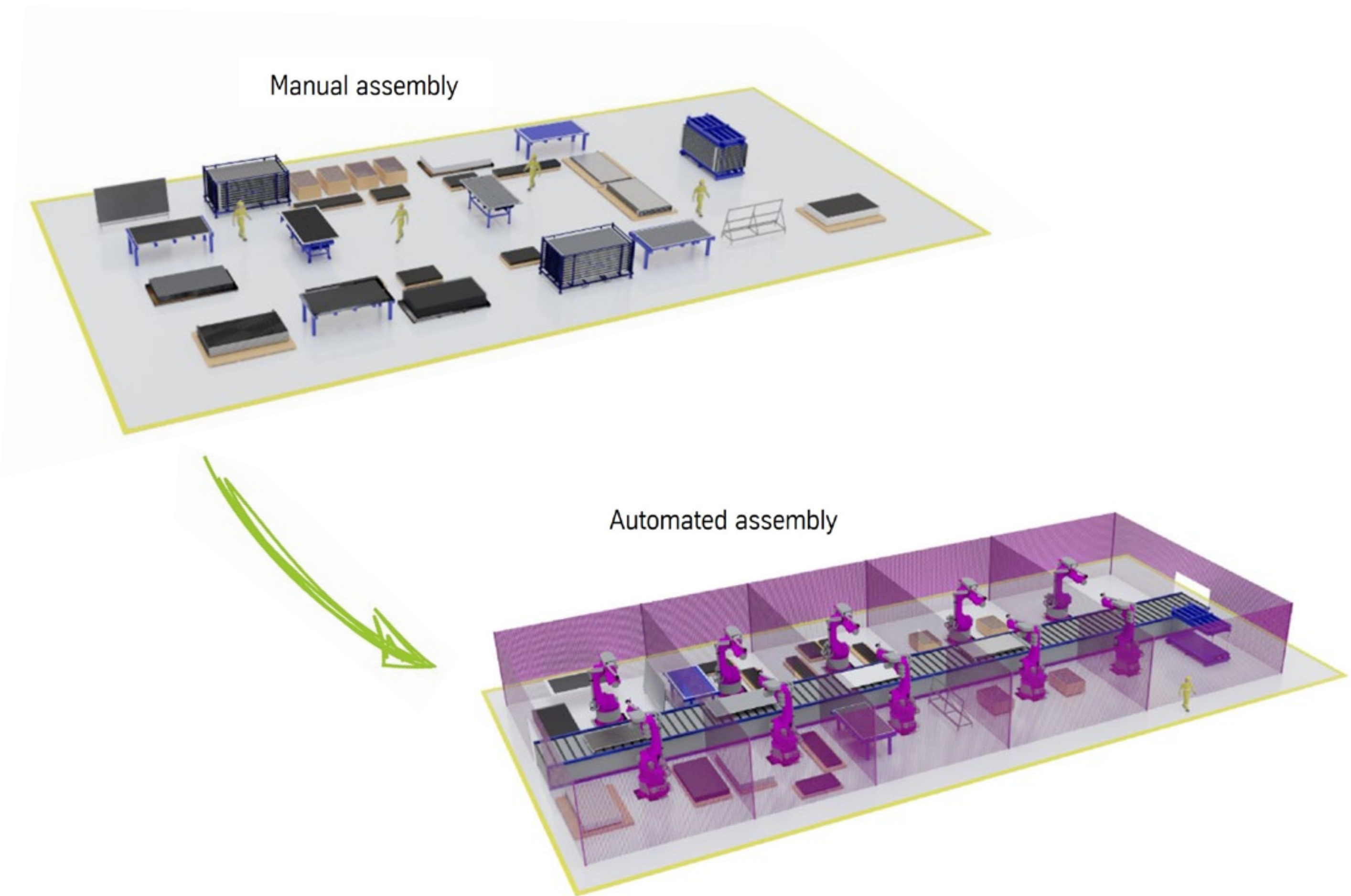
Industrialization of alkaline water electrolysis

The collaborative INSTALL AWE project is driving the industrialization of alkaline water electrolysis forward at various levels. The partners are conducting research into a completely new stack and cell development for the next technology generation of alkaline electrolysis. This new cell design is to be specially optimized for producibility. The partners are developing technologies for a fully automated assembling process of the stack and electrolysis module. Both production of components and assembly (the latter is currently still manual) will be optimized using robotics. In addition, the partners are working on improving the supply chain to meet the requirements of industrial serial production. The aim of the project is to hugely increase electrolysis production capacities and, at the same time, reduce the manufacturing costs.

Coordinator: **thyssenkrupp nucera AG & Co. KGaA**

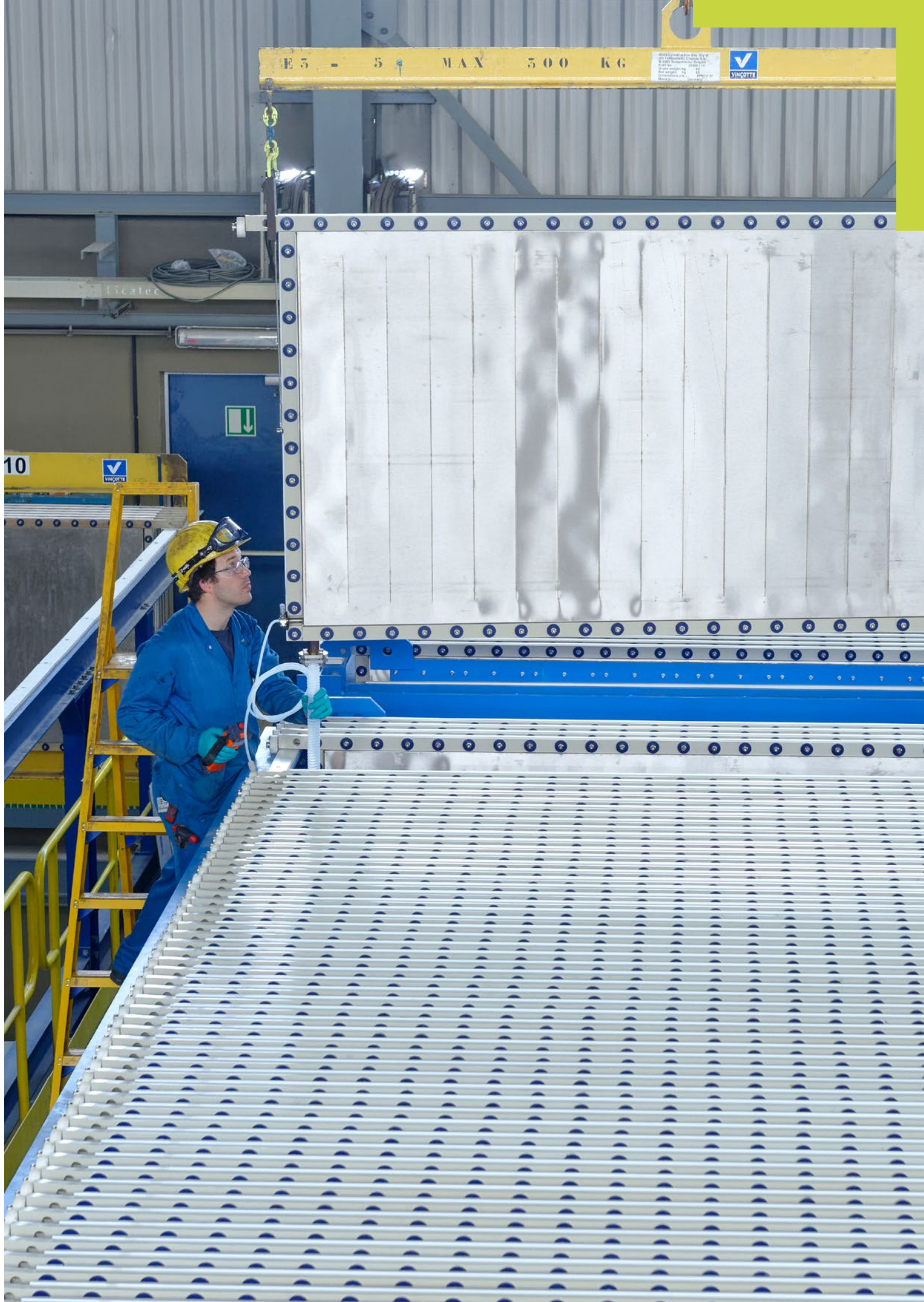
3.10 NCALab

Nucera assembly lab for alkaline electrolyzers



While INSTALL AWE develops serial production technologies for the medium- and long-term run-up of AWE, NCALab is working on short-term implementation measures. Within the short timeframe of two to three years, the aim is to improve processes through targeted use of industrial automation solutions so that ongoing electrolysis projects can already benefit from them. Individual improvements and semi-automation will lead to higher throughput, better reproducibility, and lower costs in processes that currently involve manual cell assembly. Supplementing INSTALL-AWE, the results of NCALab will concretize the future large-scale assembly of AWE cells. Furthermore, information is being gathered about the achievable degree of automation and reachable production key figures.

Coordinator: **thyssenkrupp nucera AG & Co. KGaA**



4 H_2Giga
Next-generation scale-up projects

Next-generation scale-up projects

Picture of the 150 kW test field with the installed WEW stack at the Research Center for Energy Storage Technologies in Goslar. © die drehen (diedrehen.de)

4.1 StaR – Stack Revolution

Innovative stack design for alkaline electrolysis

Alkaline water electrolysis is the longest established type of electrolysis. Its advantages are a high degree of technical maturity and long life. Nevertheless, this technology presents particular requirements for a serial stack production. Fragile materials with large cell areas must be joined together with high precision. Precision, a precondition for high reproducibility and low failure rate, is extremely important, particularly since large electrolysis plants are needed to generate huge quantities of hydrogen at acceptable prices.

The investment costs for the heart of future water electrolysis plants, i.e. the stack, should be drastically reduced by developing a revolutionary stack design, using low-cost materials and highly automated production processes. In order to experimentally test the short stacks developed and produced in the StaR project, a test field was set up at Clausthal University of Technology in Goslar. In this self-developed test field, short stacks with a scale of 1:1 can be installed and examined at pressures of up to 1.4 bar (a), temperatures of up to 90 °C and a maximum load of 150 kW. Stacks are tested under application-oriented conditions that include common disruptive factors and dynamic operation. Previous work has shown that the new stack design combines low manufacturing costs with a competitive efficiency level and operational flexibility.

Coordinator: **WEW GmbH**

4.2 StacIE

Scale-up for the PEM electrolysis stack

The "Stack Scale-up – Industrialization of PEM Electrolysis" project, StacIE for short, is developing technologies to prepare mass production in the gigawatt range p.a. for PEM stacks. The stack is the core component in an electrolyzer. It consists of several electrolysis cells which are stacked on top of each other. The 'heart' of each cell is the catalyst-coated membrane, consisting of a membrane coated with catalyst layers, where the electrochemical reactions take place. In combination with the bipolar plates and the porous transport layers, this catalyst-coated membrane forms the electrochemical cell. StacIE is optimizing the interplay between these components, which naturally interact strongly with each other. The project is working to develop ideal combinations that are not only cost-effective and efficient, but also suitable for industrial mass production. StacIE is also developing new processes for mass fabrication of the stack and its components. To prepare for large-scale serial production, several demonstrators in test environments have been set up and installed. One central element of investigation in the electrolysis cell is the transfer of functionalities of the porous transport layer to the bipolar plate. This enables a more compact and less complex system design. Aligned combinations of material, coating and substrates permit an industrial scale production of electrolysis cells. Furthermore, the cell becomes more robust and durable, which leads to a sustained reduction in costs. The provision of stack technology suitable for mass production and standardization at stack and stack component level will contribute significantly to the industrialization of PEM electrolysis. Identifying optimum component properties is a precondition for preparing the necessary availability in supply chains for expected large-serial demands.

Coordinator: **Schaeffler Technologies AG & Co. KG**

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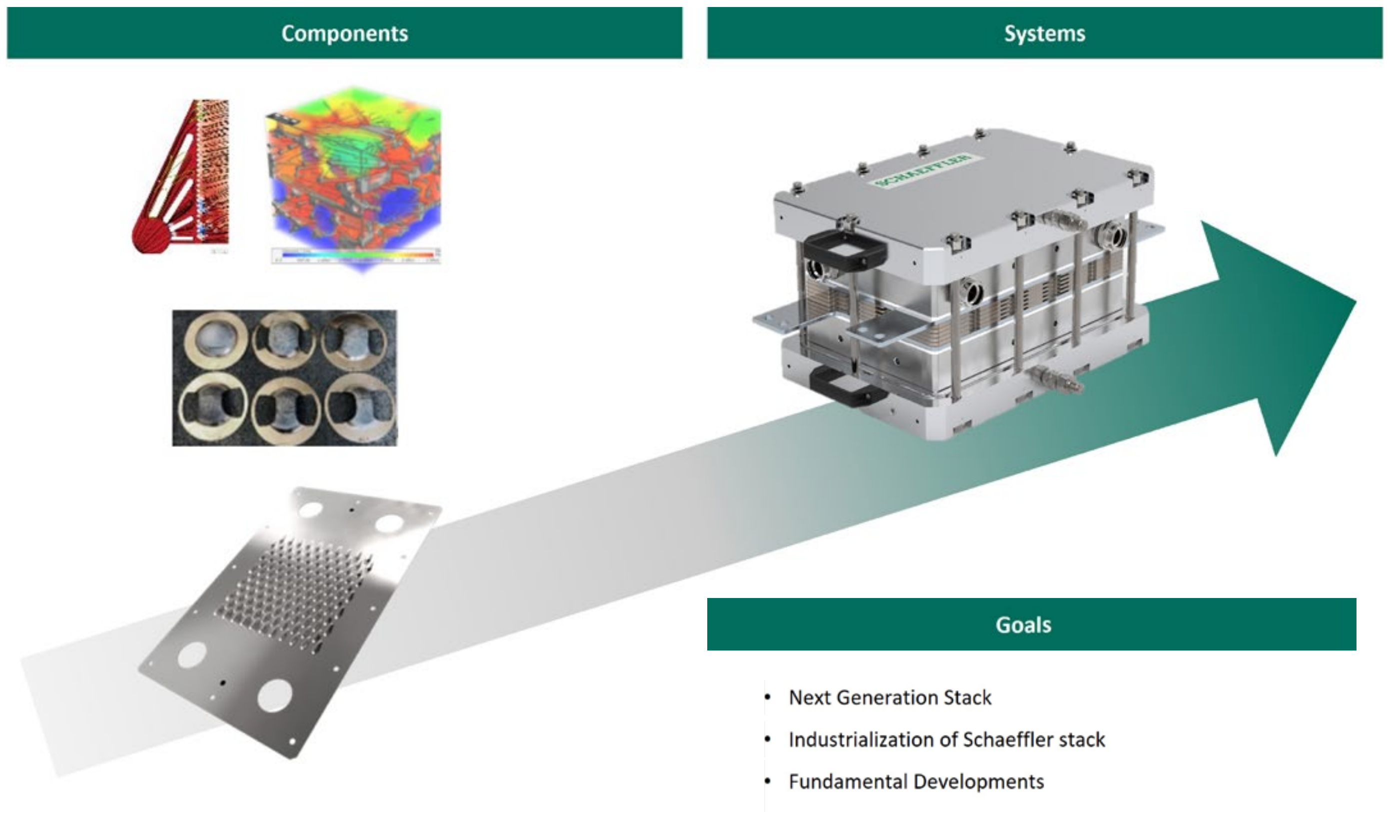

4.3 HY-Core

Scale-up of AEM electrolysis

AEM electrolysis (AEM: anion exchange membrane) is the most recent electrolysis technology. It aims to combine the advantages of PEM electrolysis with those of alkaline electrolysis. The former benefits from the advantages of a polymer membrane, the latter from the possibility to operate without expensive precious metals as catalysts. HY-Core is working to scale up AEM technology from today's laboratory level to megawatt applications. The entire system will be optimized for resilience and operational stability. A modular structure, with the numbering-up of many small stacks that can be switched in as needed, provides for a particularly flexible operation of the megawatt electrolyzer. As a result, the system is adaptable to fluctuations in the electricity supply or hydrogen demand. With AEM electrolysis, large-scale, resource-friendly, and cost-efficient generation of hydrogen directly at the renewable energy source will be realized.

Koordinator: **Enapter AG**

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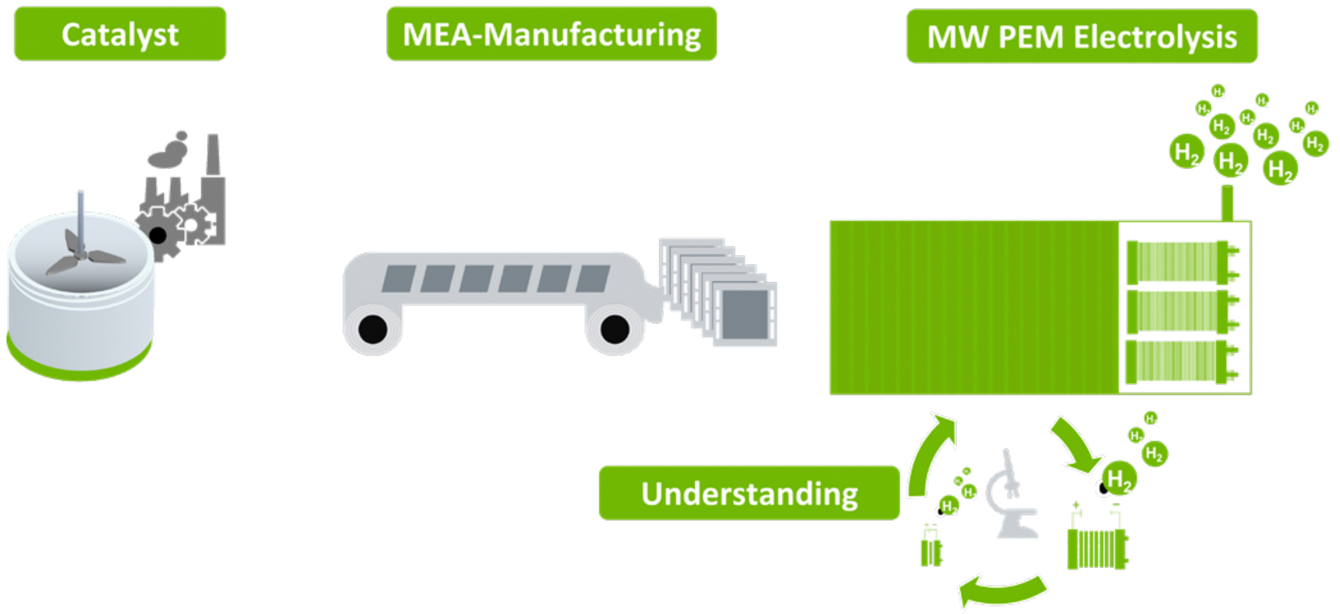
4.4 IRIDIOS

Using the precious metal iridium more efficiently in PEM electrolysis

Iridium is a crucial part of the catalyst layer in PEM electrolyzers. By extrapolating the planned quantities of green hydrogen and assuming that a large proportion will be produced using PEM technology, the required iridium quantities reach the magnitude of today's global market and outreaches by far the partial amount accessible for the PEM technology. Of course, the iridium from electrolyzers will be recycled and reused. However, especially during the PEM electrolysis ramp-up phase, sparing and efficient use of this rare metal is an important lever to achieve the desired gigawatt capacities. IRIDIOS addresses this topic from both the material and the component perspective. The project is based on successful work from a previous research project, where the partners developed membrane electrode assemblies (MEAs) with low iridium content on a laboratory and pilot scale. Within H_2Giga, the partners are researching the functionality and stability behavior of these low-iridium MEAs under application-relevant conditions on three scales: laboratory-scale, pilot scale and, finally, industrial scale. Project topics are component scaling, stack testing and identification of operating effects with accompanying laboratory tests. In all these areas, the transition from laboratory/pilot scale to the industrial "megawatt range" will be completed within IRIDIOS. To ultimately prepare for the gigawatt expansion towards 2030, the production of catalysts and MEAs is being driven forward. The entire process chain is being examined with regards to ecological as well as economic impacts.

Coordinator: **Heraeus Deutschland GmbH & Co. KG**



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4.5 AEM-Direkt

Direct coating of AEM membranes for large-scale electrolyzers

This project is devoted to material development for the highly innovative AEM electrolysis (AEM: anion exchange membrane). AEM-Direkt focuses on technology development for coating membranes with catalyst layers. The partners are testing and developing suitable low-cost, high-volume direct coating methods for depositing electrocatalysts on coated membranes and current collectors. They are comparing various methods, in particular gas-phase processes with coating methods from the liquid phase. Examples of gas-phase processes include sputtering, arc evaporation and thermal spray coating. Examples of liquid-phase methods are coating with particle-based pastes by means of a blade or slot die, as well as electrochemical or solvothermal deposition. The project is initially addressing key research issues relating to these technologies, in order to then launch further activities for larger cell areas. These will start from a small pilot scale and lead to an industrial scale with an active area of around 5,000 cm². Ideally, AEM technology should provide a meaningful supplement to today's electrolysis technologies and combine the advantages of PEM electrolysis with those of alkaline electrolysis.

Coordinator: **Siemens Energy Global GmbH & Co. KG**

Test facility for slot nozzles for direct coating of AEM membrane samples for 25 cm^2 cells in the round-robin experiments of AEM-Direkt. The two pictures on the right show two anode catalysts: nickel iron hydroxide with double layer structure (brown) and nickel hydroxide (green). The circles depict suction units.
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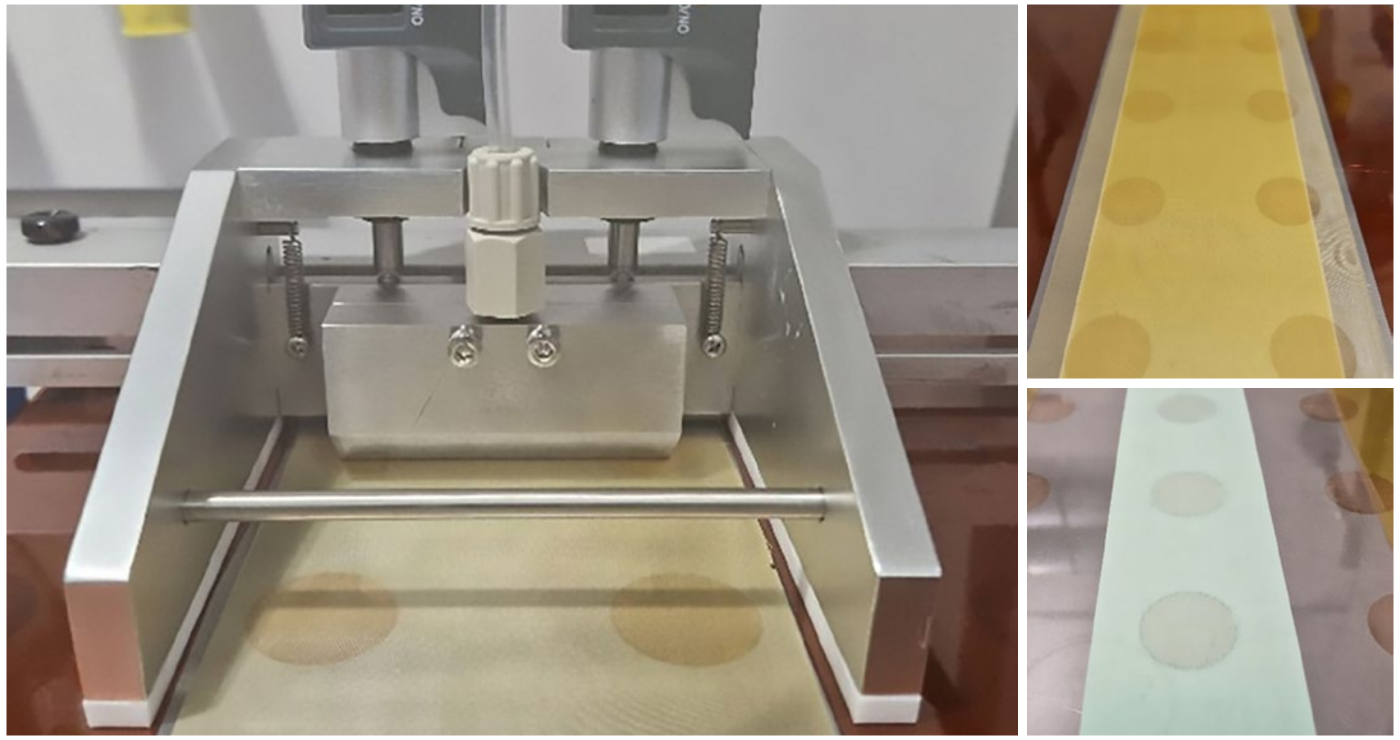
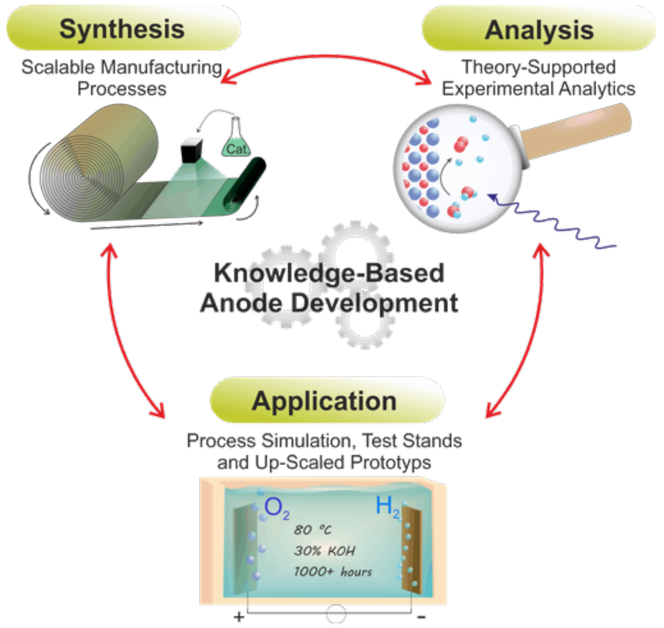


5 H_2Giga
Innovation pool projects

5.1 PrometH$_2$eus

Application-oriented anode development for alkaline electrolysis



The oxygen evolution reaction at the anode – which, in combination with the cathode and the separator, forms the core of an electrolysis cell – has a significant influence on the performance of alkaline water electrolysis. Therefore, the PrometH$_2$eus research focuses on the anodic side. The project aims for the identification of how the development of an anode material must be designed from the outset to ensure an efficient and long-term stable industrial application later on, hence, bridging fundamental research with applied research and application. Material synthesis is supported by state-of-the-art *operando* analytic and simulation methods, which are continuously optimized with regard to their application under technically relevant conditions. Following this, the upscaling methods will be refined for promising material candidates. They will be initially tested on a laboratory scale with an electrode size of 100 cm², focusing on technically relevant measurement conditions. The technically most promising material candidates will be subsequently processed to prototype electrodes and validated in industrial test stands.

In this project, a total of 26 partners from industry and science combine their expertise in synthetic procedures and analytical methods. The knowledge generated in the project will additionally be made available to the scientific community for future research in a guideline for application-oriented electrode development.

Coordinator: **RWTH Aachen University – Chair of Electrochemical Reaction Engineering**

Innovation pool: Material research

5.2 Fluorine-free membrane electrode assembly

Research for next-generation electrolysis cells without fluorine-containing materials

The membrane electrode assembly, or MEA for short, is the heart of the electrolysis cell. In PEM electrolysis, membranes based on perfluorosulfonic acids (PFSA) are commonly used. This material can be envisaged as PTFE (polytetrafluorethylene, trade name e.g. Teflon®) with attached acid groups. The latter ensure proton conductivity, while the PTFE-backbone ensures mechanical stability and integrity. Perfluorosulfonic acids also provide high chemical stability and withstand the aggressive conditions in the electrolysis cell. However, they also have disadvantages: the complex fluorine chemistry makes them expensive to produce. Disposal or recycling of the membrane itself or the adjacent catalyst layers are more difficult due to the presence of fluorinated materials. Therefore, a desirable solution would be a proton-conductive membrane that is not fluorinated but still offers high performance and long-term stability. The “Fluorfreie-MEA” project researches and develops such membrane materials. The latest membranes based on fluorine-free polymers have already shown promising results. They have far lower gas permeability than PFSA membranes and ensure high efficiency in hydrogen production. In the “Fluorfreie-MEA” project, partners from industry and science develop high-performance fluorine-free MEAs using scalable technologies, thus contributing to efficient and low-cost next-generation water electrolyzers.

Coordinator: **Hahn-Schickard-Gesellschaft für angewandte Forschung e.V. – Institute for Microanalysis Systems**

5.3 IREKA

Less iridium with equivalent performance in PEM electrolysis

PEM electrolyzers use iridium as a catalyst on the anode, usually in the form of iridium oxide (IrO_2). This rare and expensive precious metal has often been regarded as unavoidable in such application because of its unique stability against the highly acidic and oxidizing conditions in the catalyst layer over a long period of time. In view of the massive ramp-up that is planned for hydrogen technologies, the predicted demand for PEM electrolysis will make up a considerable proportion of the total global iridium market. Even assuming that most of the iridium is recovered after use in the electrolyzer, such high demand is expected to lead to a corresponding rise in prices.

In order to use less iridium in PEM electrolysis while maintaining the same performance and stability, the IREKA project is conducting research on new catalyst materials. The aim is to reduce the amount of iridium on the PEM anode while preserving the catalytic activity. This can be achieved, for example, by using supported iridium catalysts with particularly homogeneously distributed catalytically active centers. As a result, a large catalytically active surface is generated with a lower iridium loading. Other approaches include adding an additional metal (e.g. through alloy formation) and specifically improving the morphology. Alternative synthesis routes and the possibility of increasing corrosion stability by doping the carrier material are also being researched. In addition to developing materials, the IREKA partners are working on methods for manufacturing new catalytically active coatings.

Coordinator: **Leibniz Institute for Catalysis**

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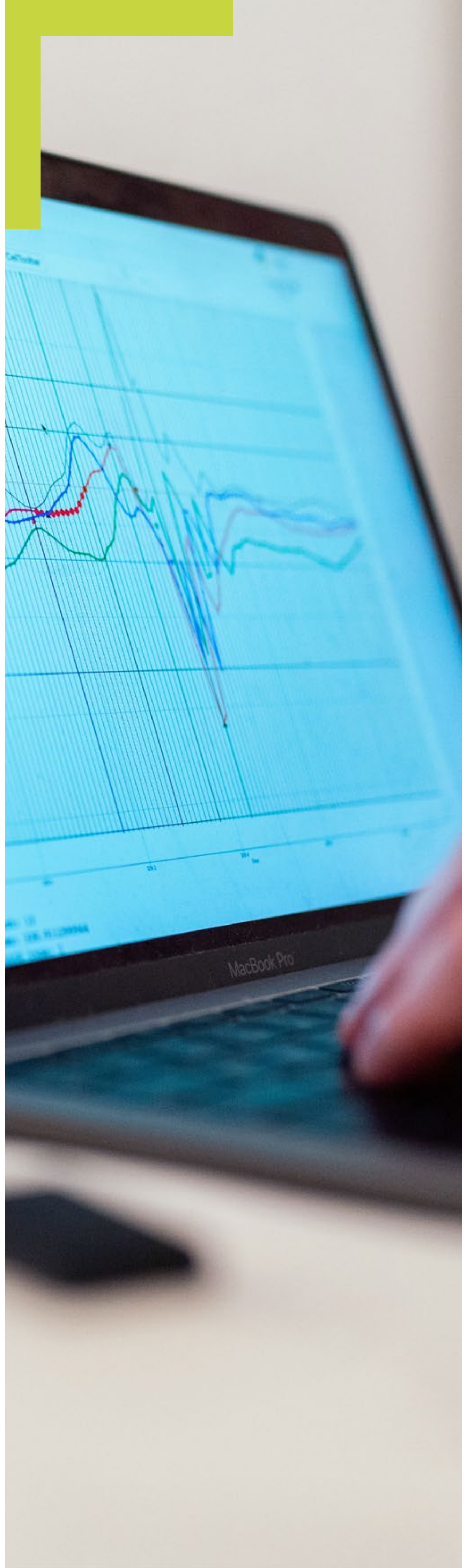
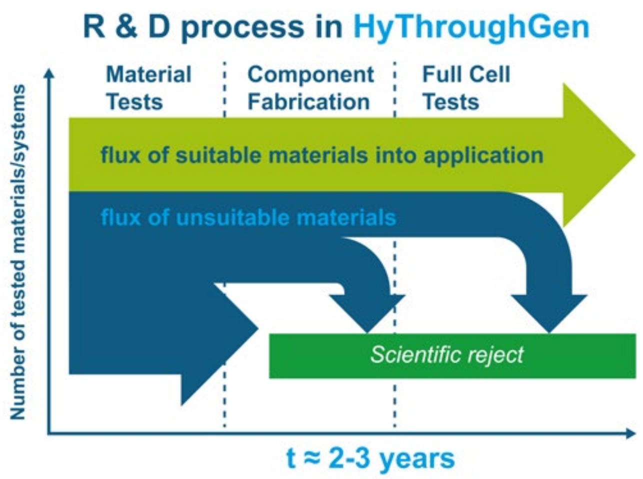


5.4 HyThroughGen

Accelerated development cycles for PEM electrolysis using high-throughput methods

New materials for electrolysis typically have development cycles of up to 10 years. In the future, these processes need to go faster. To this end, the HyThroughGen project researches and develops high-throughput methods for the evaluation of new materials and key cell components in PEM electrolysis. Research is conducted on membrane and electrode materials and the membrane electrode assembly, the heart of the electrolysis cell. Using high-throughput methods, the partners create material libraries and component libraries and characterize the materials based on their performance and long-term stability. Experiment, analysis, and simulation are combined so that promising configurations can be identified and validated particularly quickly. The aim of HyThroughGen is to evaluate new, improved materials and components for their suitability in water electrolysis within two to three years, instead of the usual 10.

Coordinator: **Forschungszentrum Jülich GmbH - Helmholtz Institute Erlangen-Nürnberg for Renewable Energy**



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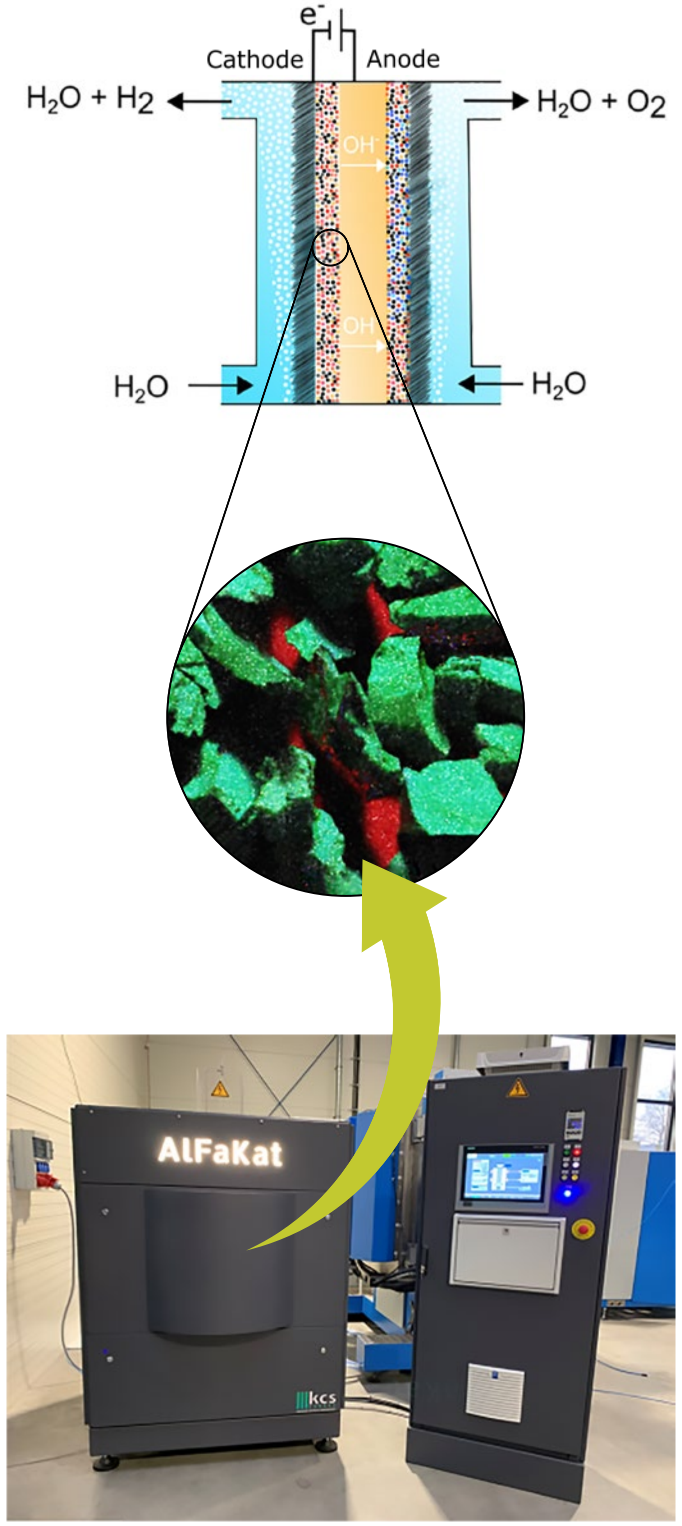
5.5 AlFaKat

New catalysts for AEM electrolysis

This project develops electrochemical catalysts for AEM electrolysis (AEM: anion exchange membrane). In addition to material development, the project focuses on research into manufacturing methods for large-scale, continuous catalyst production. PVD (physical vapor deposition) powder coating is the chosen method. This enables the production of core-shell catalysts by applying the catalytically active component onto a carrier substrate. The catalysts are turned into electrodes and are ultimately processed to form membrane electrode assemblies. Those are tested in individual cells under application-like conditions. The easily scalable PVD technology combined with the use of non-precious transition metals as an active component aims to facilitate low-cost, large-scale catalyst production for AEM electrolyzers.

Coordinator: **The hydrogen and fuel cell center ZBT GmbH**

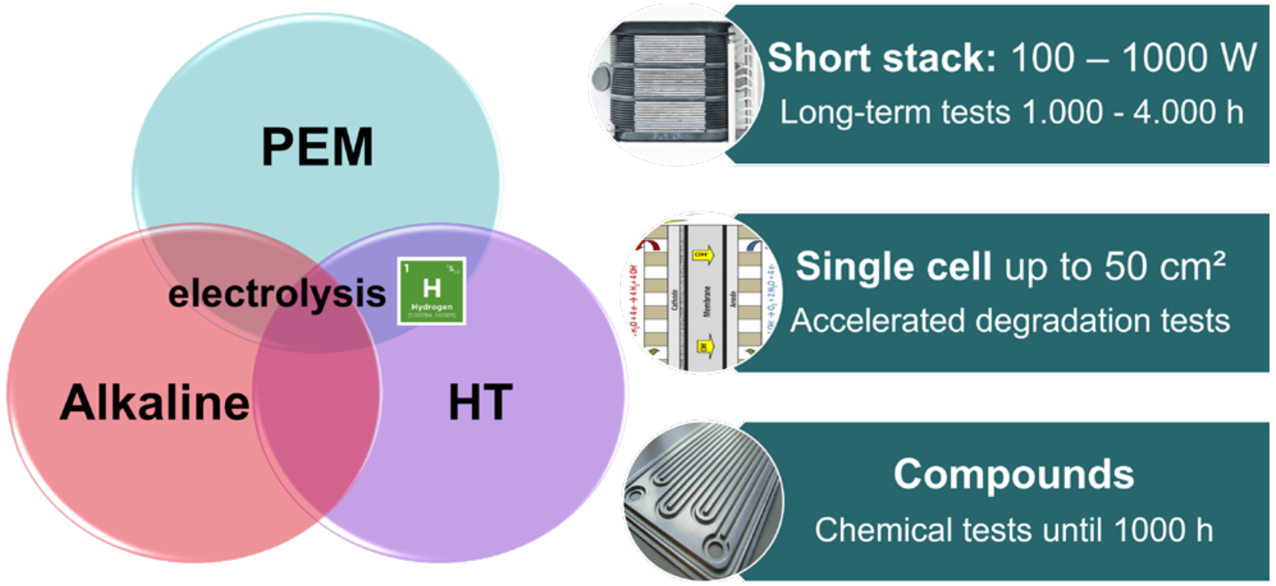


5.6 Degrad-El3

Degradation mechanisms and lifetime prediction for the various electrolysis technologies

Electrolysis cells should not only produce hydrogen efficiently, but also be stable over a very long period of operation (10-15 years). However, material tests under real conditions over such a long period are extremely time-consuming and not straightforward. As an alternative strategy to a real-time test, an accelerated test procedure might help to identify some degradation mechanisms within a short period (e.g. 1.000 h) so that expected life of certain materials can be predicted with a reliable accuracy. In that context, the Degrad-El3 project aims at investigating the correlation between some degradation mechanisms and the expected long-term performance of the three electrolysis technologies – PEM, alkaline and high-temperature. Accelerated experimental stress procedures include chemical and electrochemical tests of materials and components under aggressive conditions in chemical solutions, single cells and short stacks. Some aging protocols reflect particular steps during electrolyzer operation such as startup/shutdown, dynamic behavior, failure and contaminated water. Systematic in-situ and post-test analysis are carried out for providing relevant information about the various degradation mechanisms. In addition to the experimental work, artificial neuronal networks, quantum computing and hybrid machine-learning methods have been implemented for analyzing the experimental data pool and predicting the lifetime of some critical compounds regarding to a specific degradation mode. Moreover, the Degrad-El3 project results should contribute to a faster development of more efficient and stable materials for water electrolysis processes.

Coordinator: **DECHEMA Research Institute**

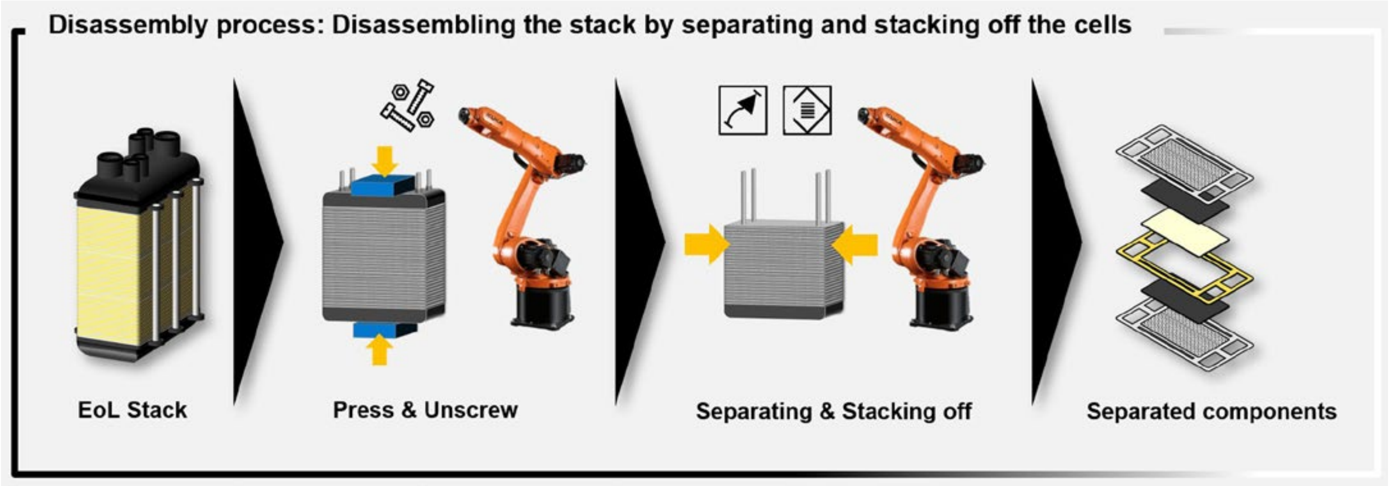


5.7 ReNaRe

Recycling – sustainable use of resources

Electrolyzers do not run forever, and what happens at the end of their life is the subject of the ReNaRe project. The partners are developing technologies to recycle PEM and high temperature electrolyzers by dismantling the stacks and separating the components/materials. Technological approaches from the fields of functional materials, automated disassembly, mechanical and sensor-based recycling, and metallurgy are combined. Together, partners from research and industry provide the missing link between the end-of-life phase and the synthesis of new materials to keep valuable and critical raw materials in a closed-loop material cycle. A suitable process scheme will be developed for the above-mentioned electrolysis technologies, which in principle allows recycling on a technical scale. In order to be able to respond to current and future technological developments, this process scheme should also be sufficiently adaptable. Technology assessments in the form of life cycle and techno-economic analyses will be carried out to provide quantitative data on the benefits of recycling in terms of sustainability and cost efficiency.

Coordinator: **TU Bergakademie Freiberg – Institute of Mechanical Process Engineering and Processing Technology**



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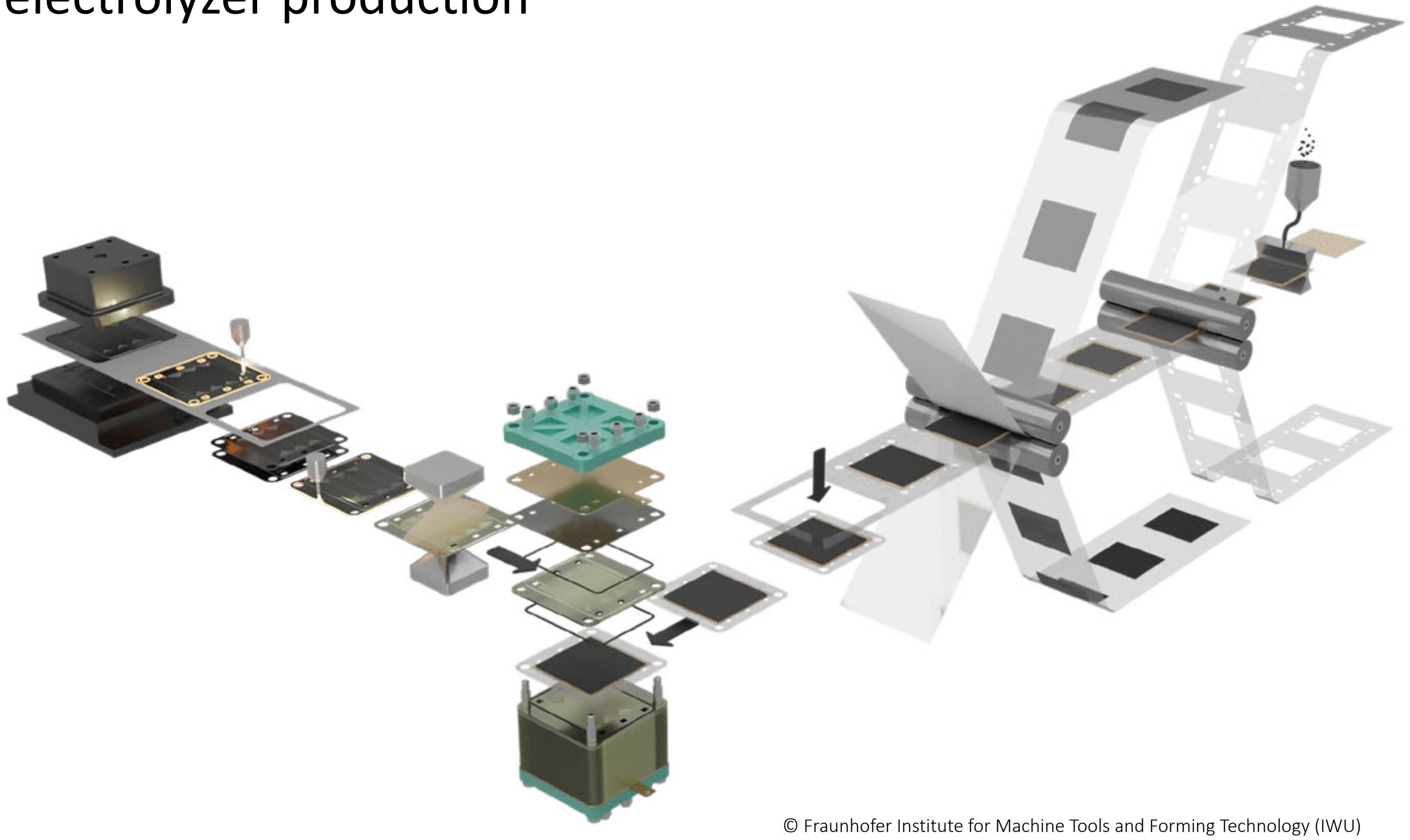
5.8 FRHY

Reference factory for high-rate-capable electrolyzer production



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The reference factory designs solutions for the large-scale production of PEM electrolyzers. To this end, new production and test modules are being developed. In parallel, the corresponding digital images are created, which are then linked in a central virtual architecture. The result is a technology kit in which individual processes can be directly compared in terms of production quality, scalability and costs. This modular system can be used to compile and compare product variants from the individual process steps right up to the entire value chain. As a result, it is possible to compare strategies on parallelization, automation and production depth and establish a basis for decision-making. Thereby, not only can investment costs be validated, but also statements about returns on investment, based on the planned production quantity.

The kit facilitates the manufacturing technology design of individual cell components, e.g. the catalyst-coated membrane and bipolar plate. These components have been combined in an innovative cell and stack design. A reference stack has been assembled to test and validate the new developments and their interaction with each other. The reference stack is based on components that can be produced using high-rate capable methods. This includes roll-to-roll processes for membrane coating (inkjet) and forming bipolar plates by rolling. The project thus makes an important contribution to enabling scalable, cost-optimized, continuous production processes, as well as significantly improving technical and economic product properties.

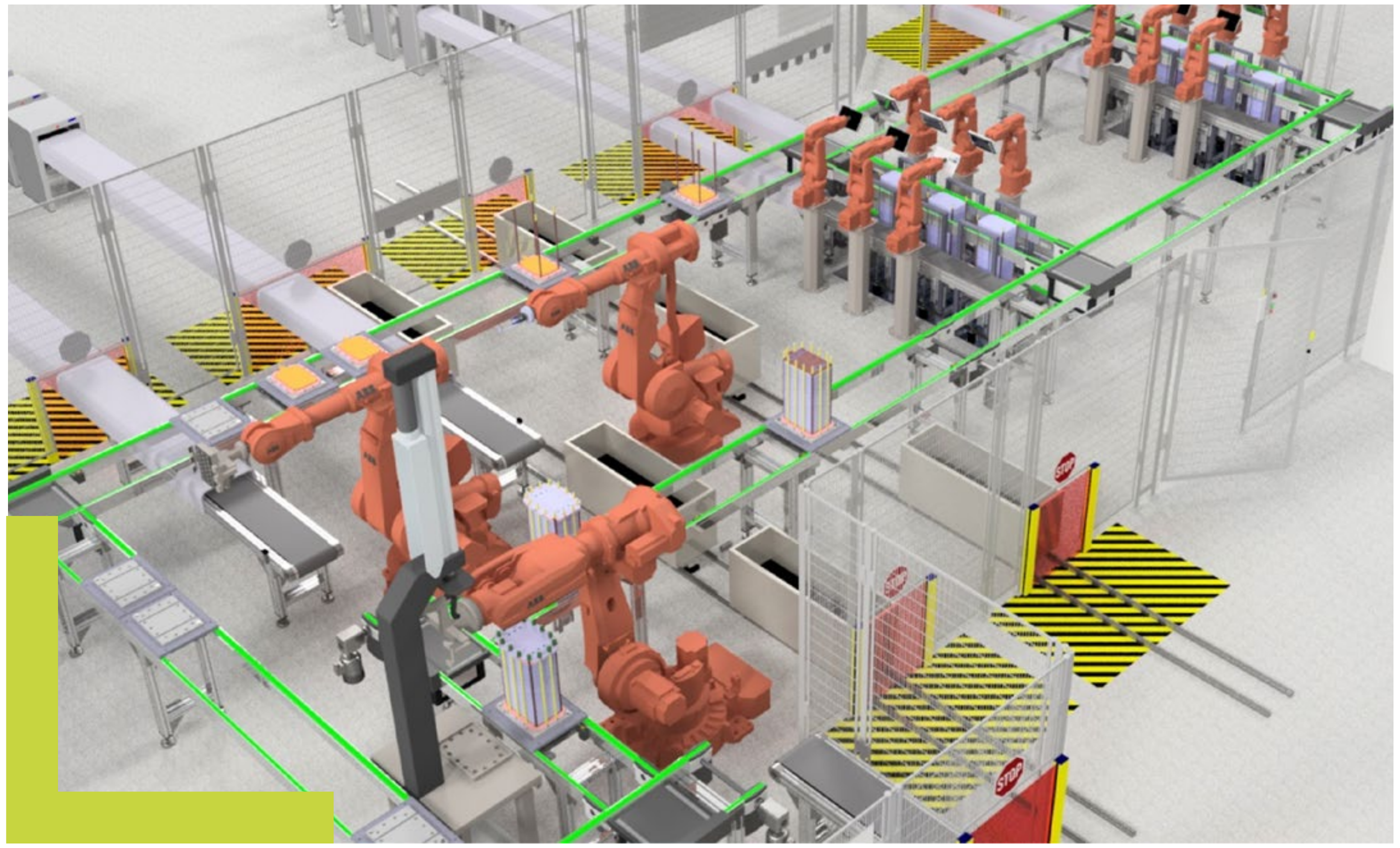
Coordinator: **Fraunhofer Institute for Machine Tools and Forming Technology (IWU)**

5.9 FertiRob

Manufacturing and robotics

The serial production of electrolyzers requires technologies that enable a (partially) automated assembly of the produced units. The FertiRob project develops solutions for this. It considers not only the physical components, e.g. the structure of different demonstration plants for various technical subprocesses, but also the digital aspects of a production plant. Plant design is supported by a module-based approach with the aid of a configurator. Both a digital product twin and a plant twin are created. These can be enriched with real data during operation, which supports quality assurance and tracking. The use of digital twins provides a material- and cost-saving way of achieving particularly rapid results. In this way, a complete architecture for a scalable plant can be created and virtually tested before the costly building of the hardware begins. The technologies developed in FertiRob should help to increase the production volume of key assemblies through automation.

Coordinator: **Ruhr University Bochum – Faculty of Mechanical Engineering – Chair for Production Systems**



Scalable system for the production of hydrogen electrolysis stacks © Ruhr University Bochum – Faculty of Mechanical Engineering – Chair for Production Systems

Innovation pool: Manufacturing technologies

5.10 HyPLANT100

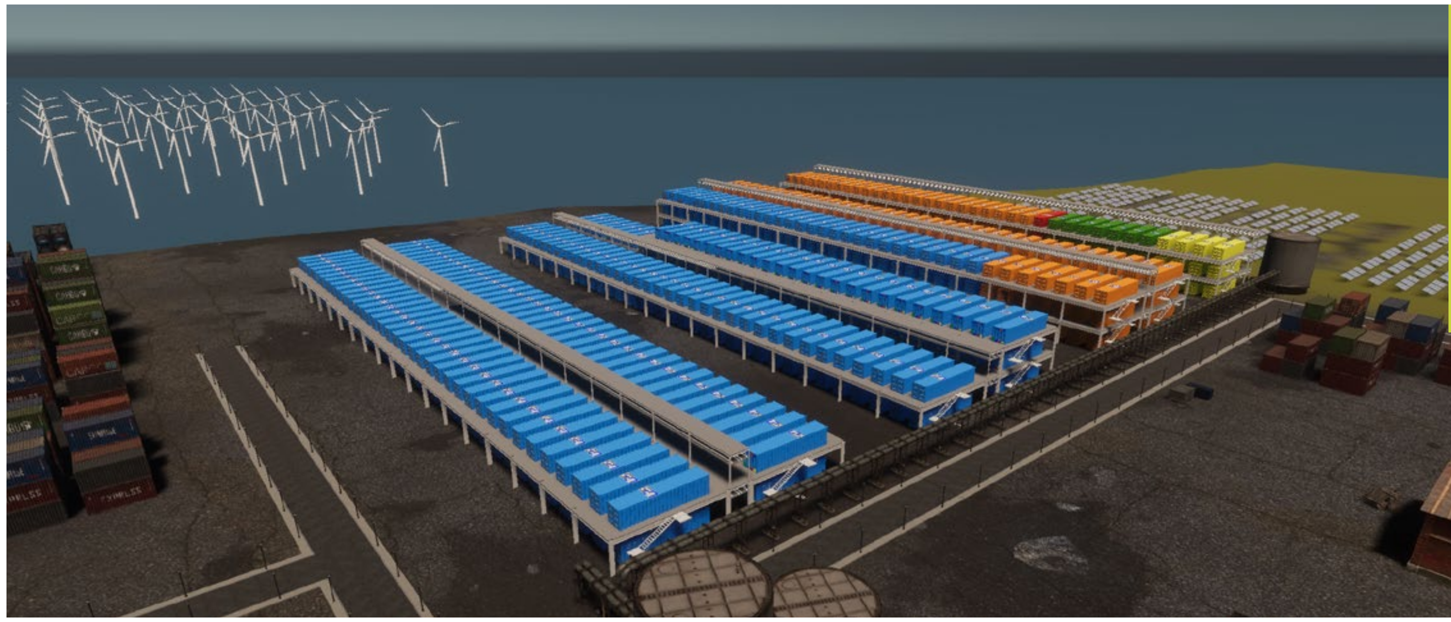
Boosting efficiency in the planning and production of large-scale electrolysis plants

The HyPLANT100 project researches and develops optimized and automated processes for the construction of large electrolysis plants. In H2Giga, the HyPLANT100 project closes the gap between the development and production of basic electrolysis units – the smallest modules – and the complete, large-scale electrolysis system ready for operation at the installation site. The relevant basic electrolysis units are first put together to form modular assemblies, so-called skids, in a (partially) automated preproduction step. Research here focuses on identifying processes in which robotics can be deployed, also in the context of a human-machine collaboration (HMC). A further objective is to digitize and provide intelligent support for the assembly processes by means of sensors, controllers and mobile robotics. This includes the preassembly of the skids and installation at the construction site and aims to enable automatic documentation of the assembly progress and quality information, for example.

These skids are then combined to form a complete system on the construction site. The aim of modularization is to make it possible to vary the system configuration, such as the total output or the underlying conditions for installation and operation. This will allow the specific requirements of the location to be met. Particular emphasis is placed on the lowest possible land sealing and thus a space-optimized structure.

Across the entire scope – from skid assembly to the complete system – the partners are working on the overarching issues of standardization and qualification. With regard to standardization, the partners are developing standardization recommendations for components, processes and interfaces. These enable a reduction in installation effort and costs and achieve openness in terms of manufacturers and technologies. Regarding qualification, the partners are identifying training content and formats to train experts and prepare them for the challenges of the hydrogen sector.

Coordinator: **Entwicklungsagentur Region Heide AöR**



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5.11 SYSTOGEN100

Complete orchestration of system components for an efficient green hydrogen infrastructure

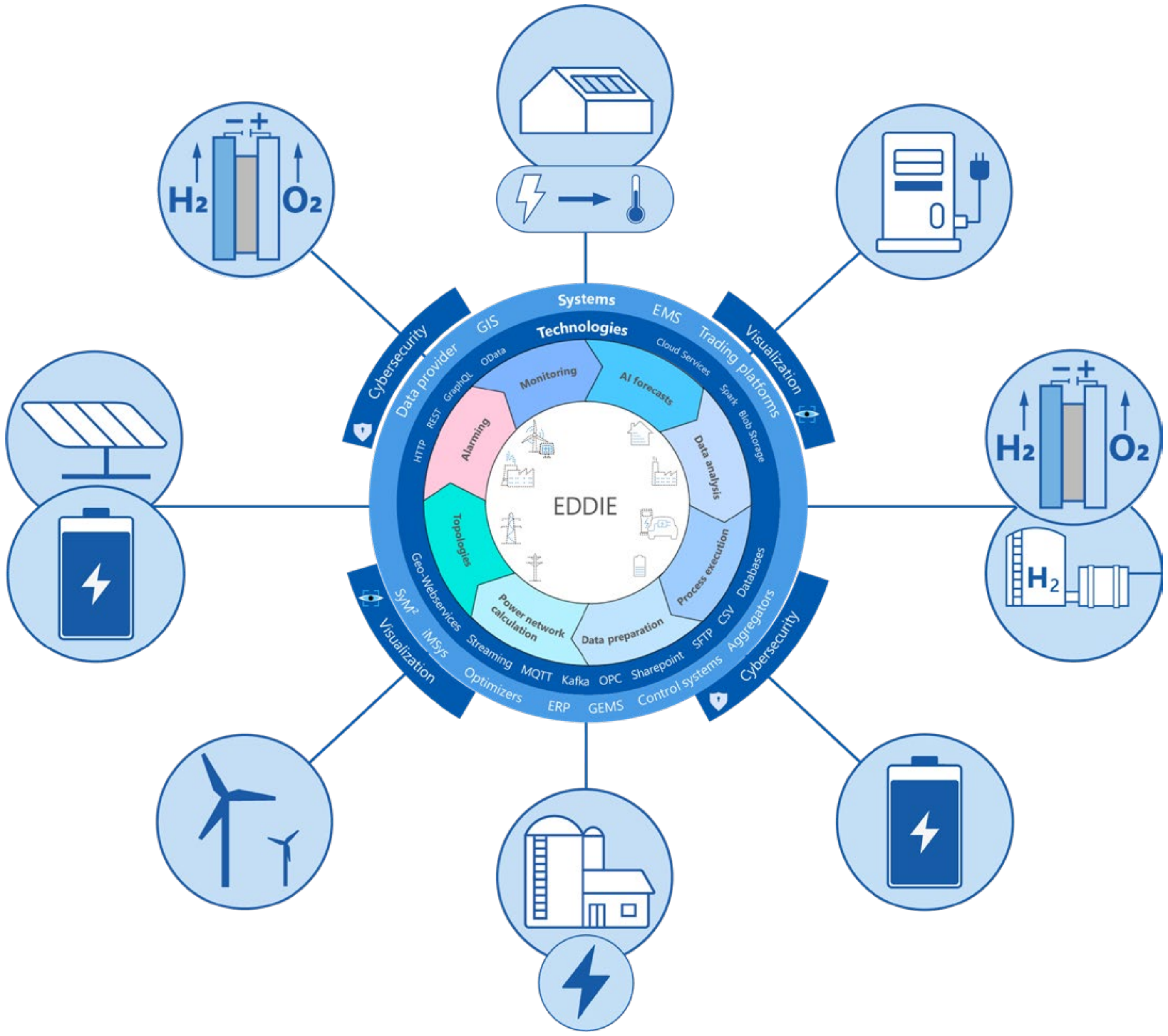
It is not only the amount of electrical energy that plays an important role in the sustainable energy system of the future, but also when and where this energy is available or required. Intelligent, large-scale solutions for a fluctuating green-electricity supply are needed and must be reconciled with the timely meeting of demand for hydrogen-based energy products. SYSTOGEN100 aims at orchestrating energy systems with electrolyzers to improve the efficiency of the hydrogen economy.

In this project, a software platform is being developed to orchestrate large-scale electrolyzers and other components in modern energy systems. This enables their optimized operation and design, also paying attention to environmental compatibility, grid security and economic efficiency. The optimization is also dependent on a number of external factors and parameters, such as weather forecasts, load, feed or price predictions combined with real-time field information like measurement data. All this information is integrated and processed by the software platform Fichtner EDDIE which is the central data hub in SYSTOGEN100.

Furthermore, SYSTOGEN100 is developing a capital market tool which will enable dynamic risk modeling for long-term investment decisions. This addresses an important step on the way to a hydrogen economy by creating transparency and supporting private investors in their investment decisions.

SYSTOGEN100 is also compiling recommendations of action in the legal context for the energy system transformation. This will ensure that technically and operationally optimized system solutions do not fail due to the legal framework.

Coordinator: **Entwicklungsagentur Region Heide AöR, Fichtner IT Consulting GmbH**

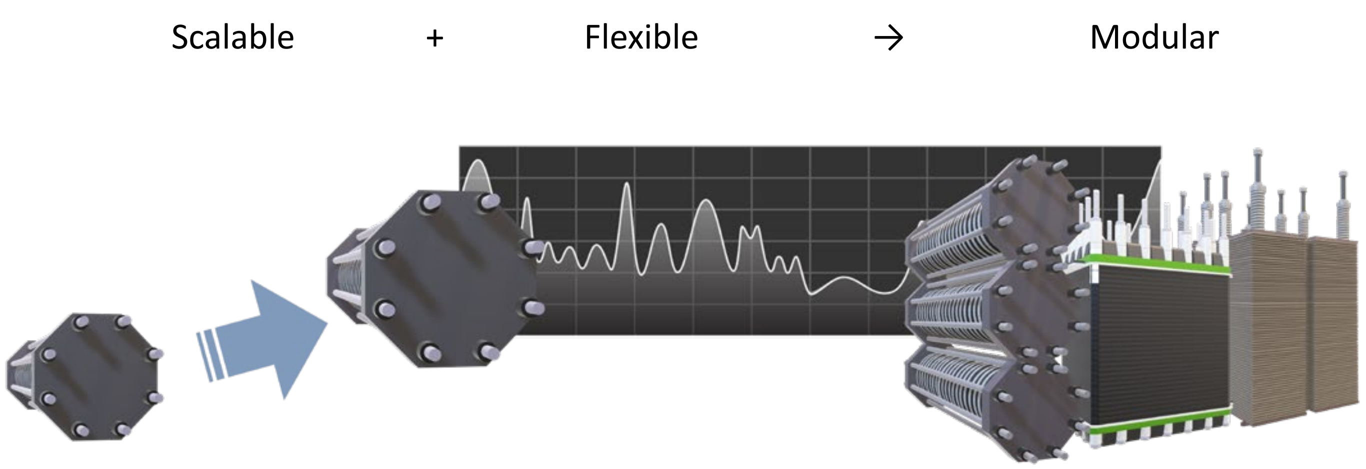


5.12 eModule

Modular concepts for the operation and automation of large electrolysis plants

An electrolysis plant always interacts with its operational environment. Plants that generate hydrogen locally and flexibly in the direct vicinity of consumers must be able to respond to dynamic time- and location-based requirements. To this end, the eModule project researches and develops concepts that address how the modular and scalable operation of electrolyzers can be supported through an appropriate automation. New process control concepts are being drawn up for the optimization, scaling, and integration of electrolyzers into one plant. Digital twins of these plants are being created and their efficiency optimized through knowledge- and data-based methods. This work is very closely interconnected to the modeling and simulation of the behavior of a plant with a power input greater than 100 MW as a reference plant. The behavior of the entire value chain is mapped. The eModule project aims to develop a manufacturer-, process- and largely technology-independent description standard for water electrolyzers. The intention is for it to be possible to identify potential weak points in industrial-scale plants in advance. This will enable plants to be integrated into the power grid without unnecessary test loops and green hydrogen to be produced in an energy-optimized manner.

Coordinator: **Technical University Dresden – Institute for Automation Technology (IfA)**



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5.13 HyLeiT

Cost-optimized system technology and grid integration of systems for the generation of green hydrogen

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Potentials for significant efficiency improvements lie not just in the electrolyzer itself but also in adjacent components. The connection of the electrolysis plant to the power grid and electrical energy conversion between the power grid and the electrolysis stack play an important role here. The HyLeiT project works on electrical system technology of electrolysis plants, focusing on converter technology as the link between grid and electrolyzer. The project aims to achieve a significant cost reduction in power electronics, and to improve the direct-current quality at the electrolyzer, which in turn has a positive impact on reliability and lifetime of the stacks. A further aim is the provision of system services for the electricity grid during operation of the electrolysis plant. The partners are researching and developing an adapted and optimized converter technology using power semiconductors optimized for specific applications. The cost reduction targets will be achieved primarily by leveraging experience and solutions from large-volume device production in the photovoltaic industry and significantly increasing the power density with state-of-the-art power semiconductors and topologies. At the same time, comprehensive system services are to be exploited and reliability maximized. A further approach uses new circuit topologies with SiC semiconductors (SiC: silicon carbide) for electrolysis rectifiers to achieve the stated aims. Real-time-capable simulation models of the power grid and electrolysis stacks are created to test and optimize the converters in the system context. These models are then fed into a “power hardware in the loop” platform to test the converter designs under various grid conditions and stack configurations. The focus is on the interaction of the converter with both the electrolysis stack and the power grid. Scenarios for operating the plants in grids with high shares of renewable energies are extremely important here. In order to increase efficiency and reliability, the electrical connection technology in electrolyzer rectifiers is being optimized as well, by particularly focusing on the thermal design and tests on contact and long-term behavior. Developments are accompanied by investigations on new protection concepts for the electrical system technology. Faults must be reliably detected and independently clarified, whereby an increased system robustness is achieved.

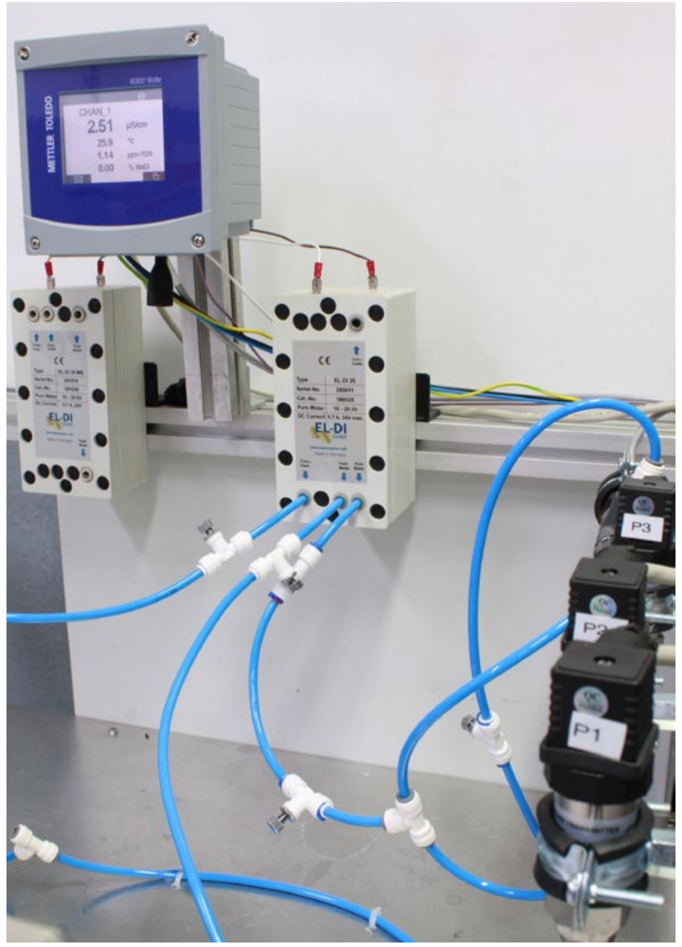
Coordinator: **Fraunhofer Institute for Energy Economics and Energy System Technology (IEE)**

5.14 FluCoM – Fluid Condition Monitoring

Purification and monitoring of process water in the electrolyzer

Electrolyzers split water into its elements hydrogen and oxygen. This water is initially introduced into the system from the outside, but is then circulated until it is consumed. While circulating, this water – the so-called process water – is in contact with electrolyzer components, such as the electrolysis cell, pipes, or pumps. This can lead to process water contamination and impair the electrolyzer's operation. The best-known impurities that have been found to cause disruptions are metal ions. Their concentration can be constantly monitored based on the conductivity of the process water. Silicon and silica gel acids can also enter the process water cycle and cause adverse effects. Alternative monitoring methods are needed for these substances and are being developed in this project. FluCoM is examining the effects of various water qualities on the effectiveness of the purification systems. The project is developing contaminant-specific monitoring methods for the process water input stream. One key project objective is to detect and identify contaminants and define the minimum qualities required for safe operation of the electrolyzer. This will contribute to reliable hydrogen production over a long lifespan of the electrolyzer.

Coordinator: **TEC4FUELS GmbH**



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Overview project partners

H_2Giga

Project partners

ABB AG
Advanced Training Technologies GmbH
Alantum Europe GmbH
University of Freiburg – Department of Microsystems Engineering
AUDI AG
AUTOMATION W + R GmbH
Autoproc GmbH & Co. KG
BIAS – Institute of Applied Beam Technology
Boll Automation GmbH
Kiel University – Institute of Inorganic Chemistry
DBI – Gastechnologisches Institut gGmbH Freiberg
DBI Gas- und Umwelttechnik GmbH
De Nora Deutschland GmbH
DECHEMA Research Institute
DECHEMA Society for Chemical Engineering and Biotechnology
German Aerospace Center (DLR) – Institute of Engineering Thermodynamics
German Aerospace Center (DLR) – Institute of Networked Energy Systems
EIFER – European Institute for Energy Research
EKS InTec GmbH
Enapter GmbH
Entwicklungsagentur Region Heide AöR
West Coast University of Applied Sciences
Fest GmbH
FFT Produktionssysteme GmbH & Co. KG
FH Münster – Energy · Building Services · Environmental Engineering
Fichtner IT Consulting GmbH
Institute for Industrial Management (FIR)
Forschungszentrum Jülich GmbH – Helmholtz Institute Erlangen-Nürnberg for Renewable Energy (HI ERN)
Forschungszentrum Jülich GmbH – Institute of Energy and Climate Research (IEK)
Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems IEG
Fraunhofer Institute for Electronic Nano Systems (ENAS)
Fraunhofer Institute for Energy Economics and Energy System Technology (IEE)
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Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM)
Fraunhofer Institute for Ceramic Technologies and Systems (IKTS)
Fraunhofer Institute for Microstructure of Materials and Systems (IMWS)
Fraunhofer Institute for Manufacturing Engineering and Automation (IPA)
Fraunhofer Institute for Production Technology (IPT)
Fraunhofer Institute for Solar Energy Systems (ISE)
Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT)
Fraunhofer Institute for Machine Tools and Forming Technology (IWU)
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Helmholtz-Zentrum Dresden – Rossendorf e. V. – Helmholtz Institute Freiberg for Resource Technology (HIF)
Helmholtz-Zentrum Dresden - Rossendorf e. V.
Helmut Schmidt University – Universität der Bundeswehr Hamburg – Institut für Automatisierungstechnik
Heraeus Precious Metals GmbH & Co. KG
Hochschule Bonn-Rhein-Sieg – Departement of electrical and mechanical engineering and technical journalism (EMT)
Rhine-Waal University of Applied Sciences – Faculty of Communication and Environment
Hoedtke GmbH & Co. KG
Hoeller Electrolyzer GmbH
HORIBA FuelCon GmbH
HYPION GmbH
IBG Automation GmbH
IBG Technology Hansestadt Lübeck GmbH
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inpro Innovationsgesellschaft für fortgeschrittene Produktionssysteme in der Fahrzeugindustrie mbH
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Karlsruhe Institute of Technology (KIT) – Institute for Applied Materials - Electrochemical Technologies (IAM-ET)
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KCS Europe GmbH
keep it green gmbh
KERAFOL Keramische Folien GmbH & Co. KG
Kontron AIS GmbH
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RWTH Aachen University – Surface Engineering Institute (IOT)
RWTH Aachen University – Welding and Joining Institute
RWTH Aachen University – Institute of Technical und Macromolecular Chemistry
RWTH Aachen University – Electrochemical Reaction Engineering
RWTH Aachen University – Metallurgical Process Engineering and Metal Recycling (IME)
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XENON Automatisierungstechnik GmbH
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