FTI Initiative Energy Model Region

Publishable final report

Programme control:
Climate and Energy Fund

Programme management:
The Austrian Research Promotion Agency (FFG)

Final Report
created on
30/09/2022

Project title: HyTechbasis 4 WIVA

Project number: 868833

Call	1st. Call FTI Initiative Energy Model Region
Project Starting Date	01/04/2019
Project Ending Date	30/06/2022
Total duration of project (in months)	39
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HyTechbasis 4 WIVA

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1 Table of content

2 Introduction

HyTechbasis 4 WIVA is part of the Energy Model Region WIVA P&G. The project duration was from April 2019 to June 2022.

Project partners:

- Fronius International GmbH
- MIBA Sinter Austria GmbH
- Heraeus Deutschland GmbH & Co. KG
- HyCentA Research GmbH
- Energieinstitut an der Johannes Kepler Universität Linz
- WIVA P&G - Wasserstoffinitiative Vorzeigeregion Austria Power & Gas

The project HyTechbasis 4 WIVA aimed, to advance the industrialization of PEM (polymer electrolyte membrane) electrolysis and fuel cell systems. In order to achieve these goals a 150kW PEM electrolysis system and a stationary 10kW fuel cell system were developed (see Figure 2-1). Both systems were intended as the key components of the Fronius Solhub, a system for decentralized hydrogen production, storage and vehicle refilling. With the defined use cases for the Solhub for industries, communities, logistic and agricultural enterprises, a modular approach for the fuel cell and electrolysis systems was necessary. To further support the industrialization and for the impact assessment of these hydrogen products, the development was accompanied by socio-technical, socio-economic and macro-economic simulations.

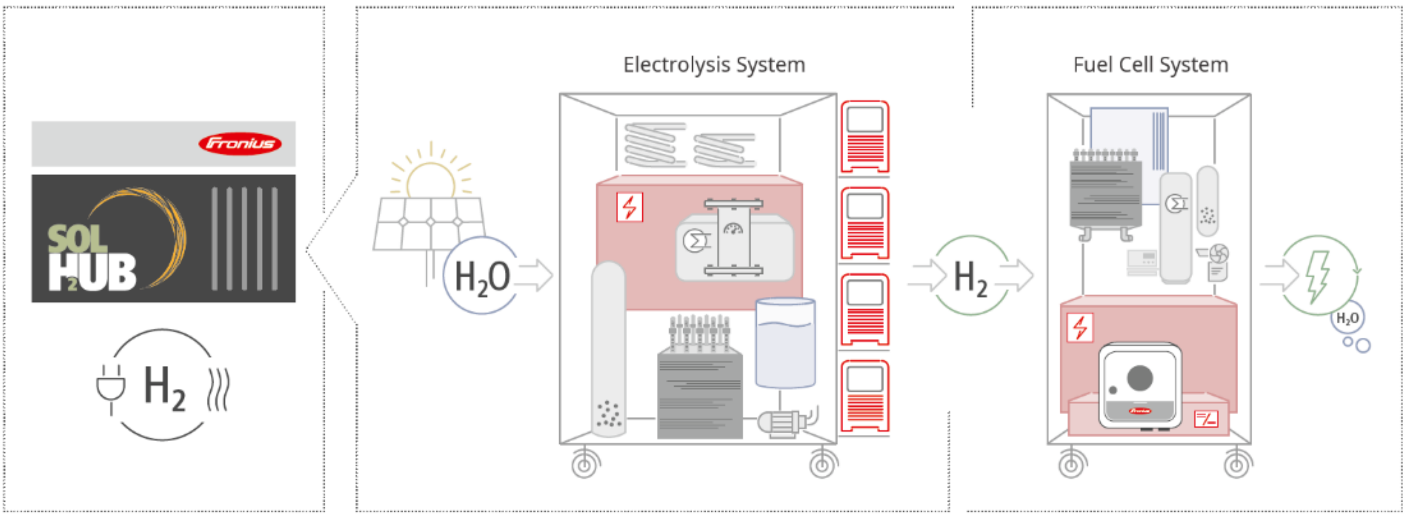


Figure 2-1: HyTechbasis System developments

WIVA P&G

The energy flagship region WIVA P&G pursues demonstrating the conversion of the Austrian economy to a largely CO2-neutral structure with the production and use of renewable hydrogen as an important component. In order to achieve this goal, the development and adaptation of WIVA P&Gs fields of innovation is an essential task. The key fields of innovation of WIVA P&G are Green Energy, Green Mobility and Green Industry. An overview description is shown in Figure 2-2.
HyTechBasis is an essential project for WIVA P&G covering multiple fields of innovation addressing central white spots of the flagship region.

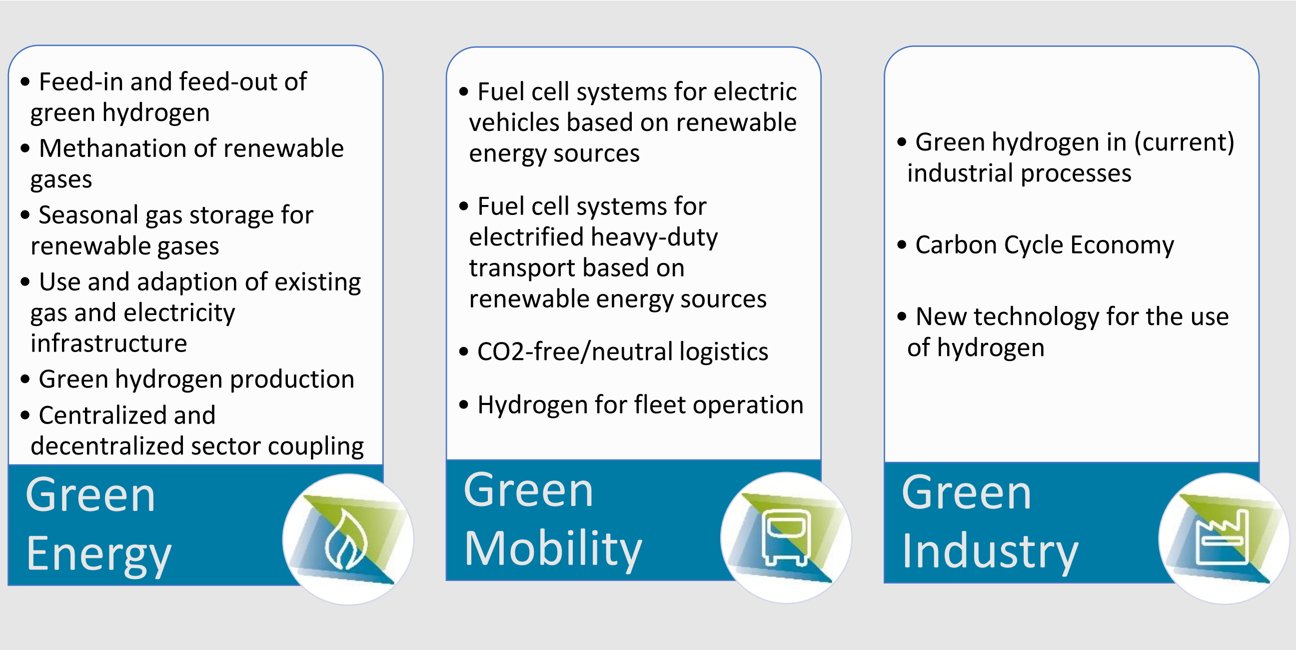


Figure 2-2: Innovation fields of the flagship region WIVA P&G

Dissemination

The relevant projects results are promoted in various dissemination activities like national and international conferences, poster exhibitions and discussion rounds to increase visibility among experts and the general public. The website www.wivat.at contains the factsheet of the project as well as a video and relevant updates. Social media (LinkedIn and Twitter) is used continuously to highlight important steps in the development process.

3 Development and industrialisation of PEM electrolysis

3.1 Content presentation

Regarding electrolysis, a holistic approach was pursued in HyTechbasis. Therefore, the development started with component tests on electrolysis single cell level. Within the single cell hardware, CCMs (catalyst coated membrane) and PTLs (porous transport layers) from the project partners Heraeus and MIBA were mainly tested. These tests defined the components that were used for the electrolysis short stack development and build up. Additionally, a complete 150kW PEM electrolysis system was developed within the project (see Figure 3-1).

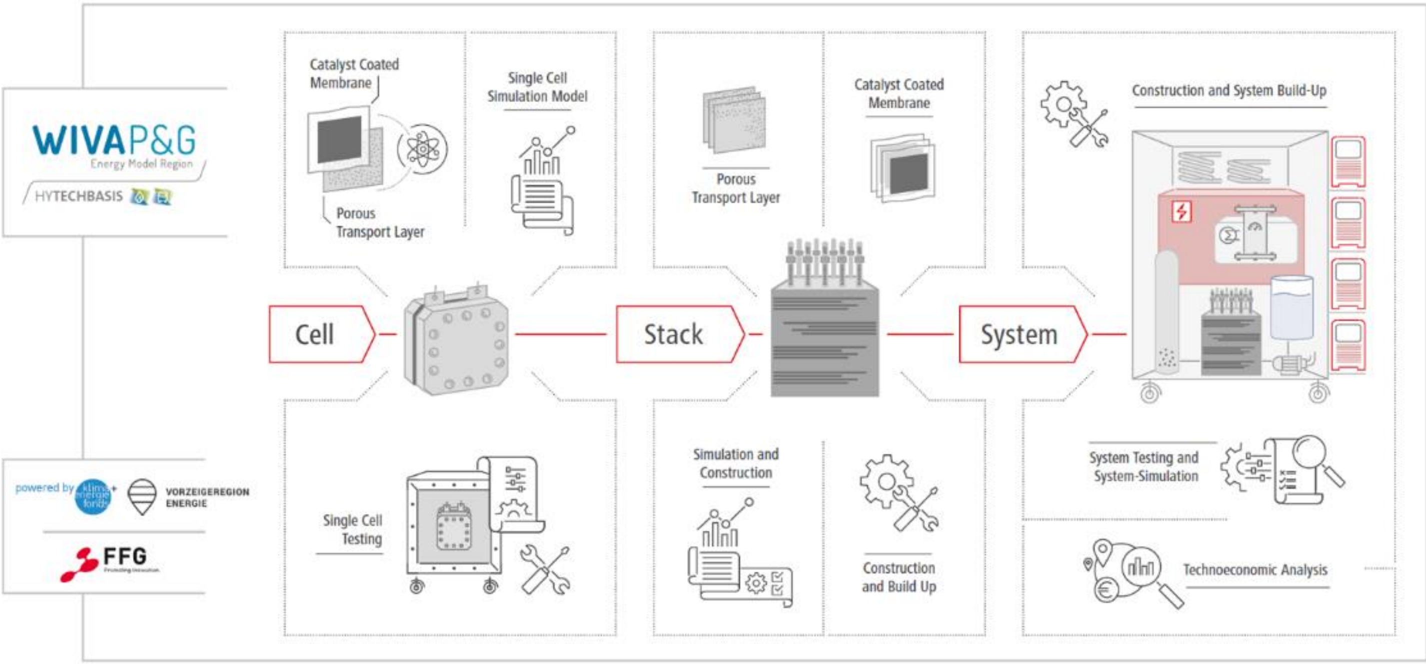


Figure 3-1: Electrolysis development path

3.2 Development of catalyst coated membrane (CCM)

3.2.1 Content presentation

The electrolyser anode catalyst portfolio at Heraeus ranges from pure metal material like Ir black over the oxidic IrO_2 and mixed oxides $Ir_xRu_{1-x}O_2$ to a supported, Ir-based material. For the cathode side, various Pt on carbon materials for H_2 generation are available.

Within the framework of the project, a cathode catalyst and electrode loading were chosen and fixed for the whole duration. Variations of the 20% Pt on medium surface area carbon were refrained from, as the main focus was on optimization of the oxygen evolution reaction on the anode side. A cathode area loading of 0.1 mg_{Ir}/cm^2 was chosen as a good balance between low electrode thickness and sufficient Pt availability for the hydrogen evolution reaction.
On the anode, Iridium dioxide IrO_2 was chosen. This dominantly crystalline material has a BET surface area > 180 m^2/g. It has the benefit that a decrease in the electrode Ir-loading can be reached without the electrode layer getting too thin. This is advantageous compared to Ir-black as well as to commercially available electrolyser OER catalysts. Thus, loadings of 1.0 to 0.4 mg_{Ir}/cm^2 are feasible.

3.2.2 Results and conclusions

Regarding CCM manufacturing, a bar coating decal process was performed at lab scale. In the process each electrode layer is coated on inert film first, applying a catalyst ink and drying. Subsequently, both electrode layers are transferred to the membrane simultaneously by applying pressure and heat.
A strong dependence on the ionomer content on the anode film transfer efficiency was observable, but not expected based on Heraeus' coating experience with Pt/C inks. The ratio of ionomer to solid as well as the best ionomer equivalent weight were investigated and optimized until reproducible results were achieved.
It was found that with an ionomer content of ca. 10% solid ink components and the use of 2-propanol instead of 1-propanol as a volatile ink component, a decal transfer of ≥ 97 wt-% can be achieved reproducibly. Also, the formation of cracks during drying of the coated layer could be significantly decreased. See Figure 3-2 for a depiction of a 5 cm² CCM, representing the Heraeus internal testing size.

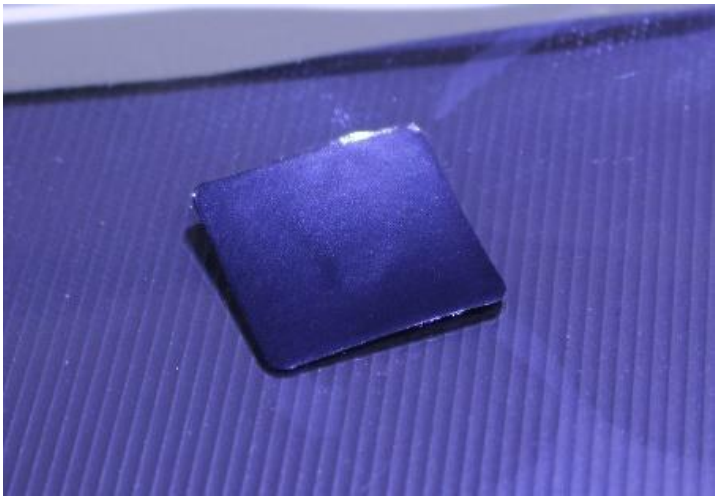


Figure 3-2: CCM active area (5 cm² test size) containing IrO2 on Nafion 117 membrane

As membrane material, Nafion N117 (178 µm thickness) and N112 (50 µm thickness) were tested. There were no significant differences in electrode transfer behaviour to the surface of the membrane. Due to better comparability with industrial standards and a lack of stability data on the thinner membrane, Nafion N117 was chosen as a standard within the project.

Cell testing concepts were developed by Heraeus and, after iterations, aligned with Fronius, where they were implemented similarly in order to get comparable results.
Those developments enabled Heraeus to conduct a first CCM manufacturing campaign in August 2020 resulting in 38 CCMs of which 34 met the loading criteria and 30 were provided to Fronius for testing. A second campaign January/February 2021 produced 35 CCMs of which 30 were provided to Fronius. The combined mean anode loading over both campaigns was 1.03 mg_{Ir}/cm^2 with a standard deviation of 0.1 mg_{Ir}/cm^2.
Internal testing of the cells at Heraeus revealed a power consumption of 1.7 W/cm² at a current density of 1.0 A/cm² when measured at 80 °C. The U-I graph showed only small deviations between 3 different CCMs even at higher current densities (deviation span < 25 mV at 1.5 A/cm²).
For reference, tests with a thinner membrane were conducted in the expectation to find higher initial activities. Indeed, CCMs with the Nafion membrane N212 (thickness 50 µm), show a more efficient power consumption of 1.62 W/cm² at 1.0 A/cm² (see Figure 3-3). Stability tests were not undertaken.

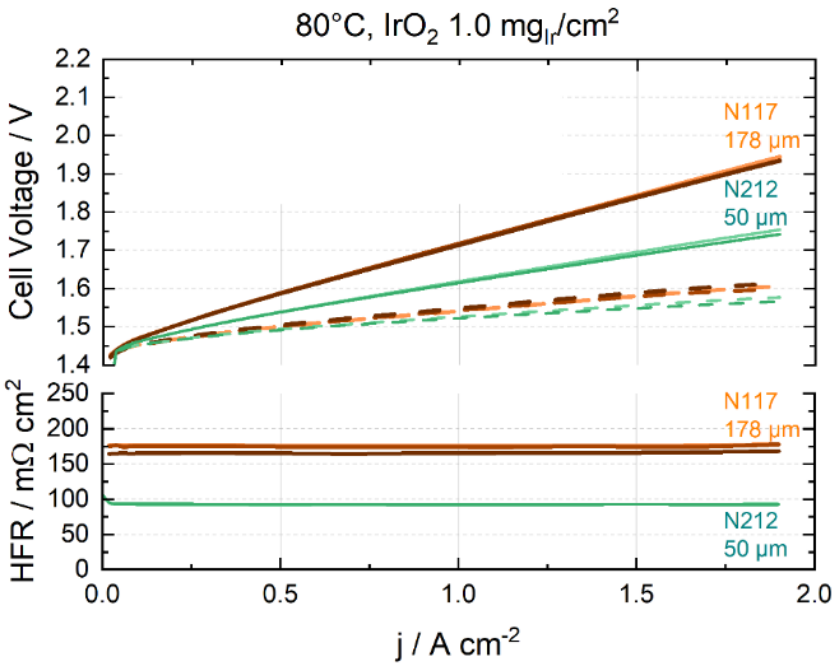
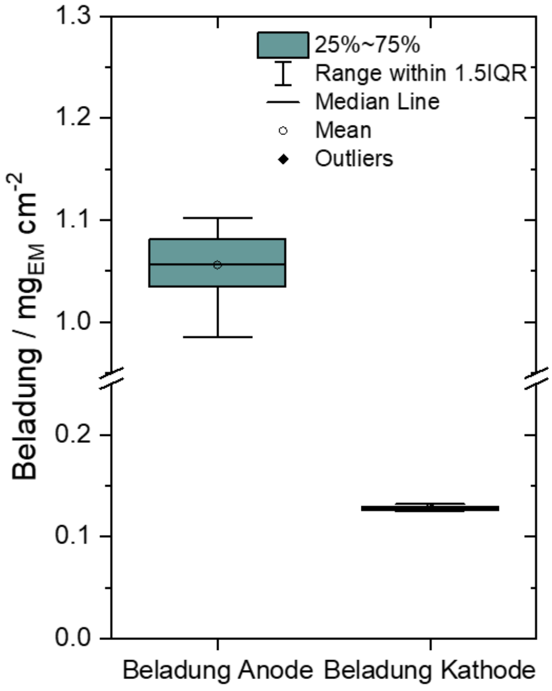


Figure 3-3: Comparison of membrane thickness and reproducibility over two batches.

Further CCM manufacturing campaigns were conducted in the first half of 2022 resulting in 45 CCMs. 15 of which were intended for the short-stack and 40 for single-cell testing at Fronius.
The combined mean loading of the anodes of the fifteen CCMs intended for the short stack was at 1.06 mg/cm² with a standard deviation of 0.03 mg/cm² confirming a reproducible coating process (see Figure 3-4). A similar observation was made for the 30 CCMs produced for single-cell testing, where the mean anode Iridium loading was measured at 1.07 mg/cm² with a standard deviation of 0.04 mg/cm².



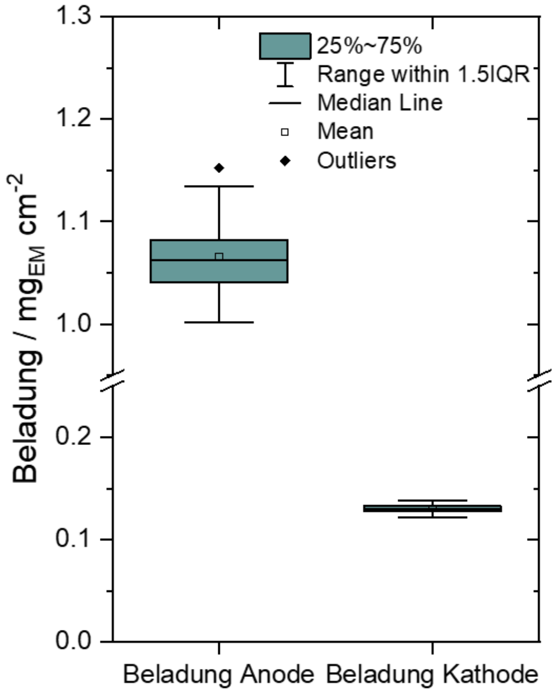


Figure 3-4: Loading reproducibility on 15 CCMs intended for short-stack (left) and 30 CCMs for single-cell testing (right).

In a separate study, Heraeus conducted Ir-loading variation experiments on the anode. The electrode thickness and therefore the amount of Ir on the electrode was varied in the coating step which resulted in two electrodes with an Ir-loading of 1.0 mg/cm² and two electrodes with an Ir-loading of 0.57 and 0.58 mg/cm². For the different loadings, the same coating ink formulation was used. With the resulting CCMs current-voltage polarization curves were measured internally at Heraeus at 80°C and ambient pressure. Notably, a thinner membrane was used for these experiments compared to the sample CCMs used at Fronius (Nafion NR212, 50 µm).
The lower anode loading resulted in a performance loss of 10 mV in the kinetic, low current-density region of the measurement (at ~ 0.1 A/cm²) and a difference in voltage at higher current densities of 53 mV (see Figure 3-5). It seems, only a part of the performance loss can be attributed to the lower Iridium amount available (kinetic loss) while the voltage difference at higher current densities points to differences in layer morphology.

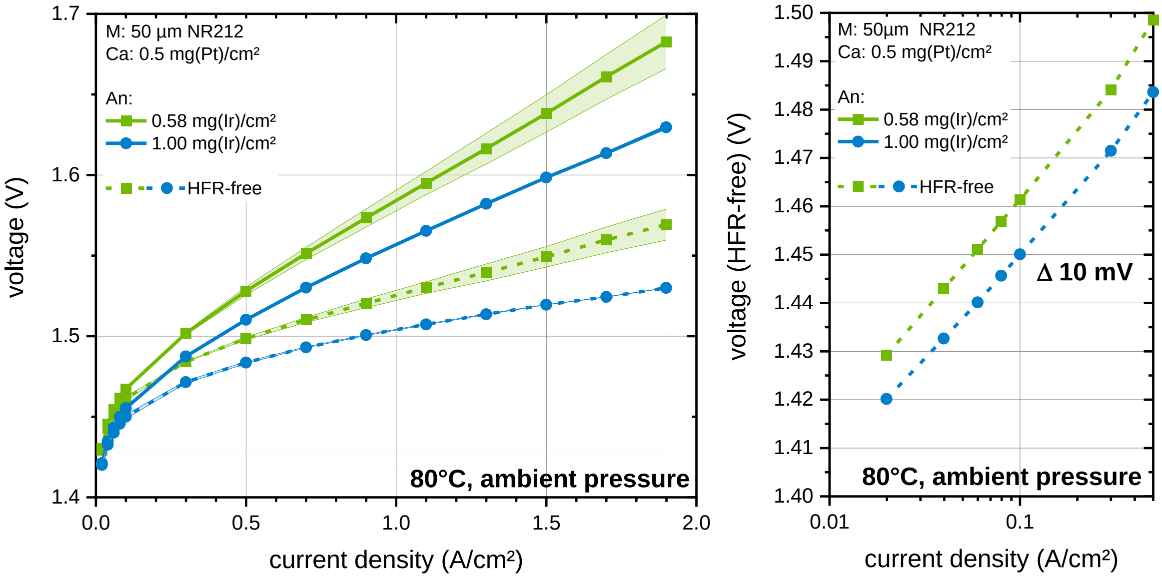


Figure 3-5: HFR-free polarization curves of 2 CCMs each with lower anode Ir-loading (0.58 mg/cm², green) and higher Ir-loading (1.00 mg/cm², blue). The graph on the right shows a magnification of the kinetic region of the curves.

3.3 Engineering of titanium cell components

3.3.1 Content presentation

Electrolysers and fuel cells are completely new applications for MIBA. Up to now, only low alloyed iron-based metal powders have been processed for automotive applications like gears and transmission components. New applications converting electricity to hydrogen by electrolysis and vice-versa from hydrogen to electricity by fuel cells requires detailed theoretical knowledge and understanding before considering possible manufacturing technologies for its components. Initially, an intensive literature study comprising scientific papers, review articles and books about the state-of-the art concerning electrolysis and fuel cells was carried out.

The relevant components for low-cost manufacturing of PEM Electrolyser and Fuel cells are the Bipolar Plate (BPP) and the Porous Transport Layer (PTL). MIBA´s goal in this project is to produce these components by low-cost industrial manufacturing technologies. In the first year, the focus was set to develop industrial manufacturing technologies for PTLs because MIBA´s expertise in Powder Metallurgy can better be used to manufacture porous rather than full dense components.

Engineering of cell components - PTLs:

Requirements specification

Based on available literature sources providing a state-of-the-art overview together with an investigation of conventional PLT components purchased as benchmark parts, the following requirements for PTLs were identified.

- The material needs to be high purity Titanium (grade 1 or grade 2)

- Titanium may need to be coated to increase corrosion resistance for longevity and long-time stability. However, as this implicates further costs, no coating will be used at the first stage.
- The porosity is to be varied between 10 – 70 % preferably 30-40 %
- The pore size is to be 10 – 30 µm, preferably 15-20 µm
- The thickness is to be 200 – 600 µm, preferably 300 µm. Homogenous thickness is crucial for the performance of the PEM EC/FC
- Surface needs to be flat and very smooth for good electrical contact and prevention of damage to the CCM

Based on existing knowledge, the following technologies were identified and will be evaluated for production of first PTL prototypes that will finally be tested in Fronius´s single test cell.

- Free sintering
- Additive Manufacturing
- Tape casting

All these technologies are based on Titanium powder feedstock. The defined approach aiming to reduce manufacturing costs is based on an increase of the used Ti-particle size available at comparable costs as smaller sized particles. Thus, three different particle size distributions of Titanium powder (P1 small, P2 medium and P3 large particles) were purchased.
Free sintering and first inhouse tape casting experiments at MIBA confirmed a promising basis for further improvement. To facilitate the tape casting process and to better control the thickness of cast foils together with a possibly improved surface quality, a self-made casting apparatus was designed, engineered, and manufactured.
According to MIBAs focus concentrating on production technologies for Titanium based PTLs the second year´s activities were strongly focused on the tape casting process. Technical possibilities and required processing parameters to meet PTL specifications were investigated. The following related questions were tried to be answered:

- What range of particle size can be used for tape casting and does the feedstock size require any slurry modification for the casting processing?
- Is a prepared Ti-slurry stable over time or does it require specific processing windows?
- Which layer thicknesses can be produced depending on the particle size of utilized powders and is there a correlation between cast green foil - and sintered PTLs thickness?
- What are the most suitable debinding and sintering atmospheres (and temperatures) to minimize the uptake of chemical impurities like carbon, nitrogen and oxygen by titanium?
- Which time-temperature profiles are required to reach PTL porosities in the range of 30-40%?
- Can PTLs having targeted porosities provide sufficient mechanical stability to be handled and used for electrolyser applications?
- What range of electrical resistivity can be obtained by our PTLs and is there a correlation between resistivity and porosity?

As most of these questions require detailed scientific investigations, a cooperation with a Research Facility was established helping to answer these questions. In this context, the two most important goals were 1) to gain and quickly transfer relevant know-how within MIBA and 2) to access the partner´s equipment for sintering of first sets of PTLs under vacuum conditions.
MIBAs equipment only allows to operate at atmospheric conditions but can´t provide high quality protective atmospheres or vacuum conditions required to sinter Titanium. In the scope of this project, one of Miba´s research furnaces was refurbished to provide high purity atmospheres and was used to evaluate the possibility of Argon to replace Vacuum sintering. This is also of relevance for other potential manufacturing technologies considered for low-cost production of Ti-PTLs such as free sintering and sinter based Additive Manufacturing.
To evaluate first PTL prototypes, an electrical test bench for in-plane and through-plane resistance measurements was developed and built up. Its correct functionality was confirmed by electrical measurement of purchased benchmark PTLs. The purpose of this test-bench was a pre-evaluation and selection of produced PTLs saving measurement time and effort at Fronius laboratories.

Engineering of cell components - Bipolar-plate (BPP):
Each titanium component of an electrolyser requires different production technologies as it must fulfil individual, specific requirements. BPP are usually CNC-machined from solid blocks as they need to effectively transport electricity, liquid, and gases. Since CNC machining is an established and efficient production technology that is used for decades, no cost-effective potential for alternative production was identified. However, since MIBA is only producing steel components, no titanium material has ever been machined before. Thus, suitable tools required for each BPP design as well as material dependent machining parameter were developed during this project.

3.3.2 Results and conclusions

MIBA´s goal in this project is to optimize production technologies with respect to low-cost manufacturing of Titanium PTLs. The most obvious approach to potentially lower production costs is to reduce material costs. Up to ten different material providers world-wide were selected to provide Ti powder. Based on a comparison of the offered powder grades, qualities and prices, a Chinese supplier offered the lowest price per kg and - most important - indifferent of the particle size of the powder. Thus, the approach to potentially lowest material costs was using bigger grain sizes of Ti powder resulting in larger material volumes due to its lower apparent density. In this way, much coarser particles will also lead to higher porosity and thus lower material consumption compared to finer particles. The first year´s work was focused on PTL production by tape casting technology using three different titanium powder grades P1, P2 and P3 differing in particle size and distribution. These powders were purchased and analysed concerning particle size distribution, chemical purity, and morphology.
Based on existing literature concerning tape casting technology and publicly available slurry preparation recipes for similar raw powders, each feedstock from P1, P2 and P3 powder could be successfully processed into a slurry and cast to green foils. It turned out that the slurry composition itself had to be slightly adjusted for each powder grade to yield slurries with similar rheological behaviour and casting properties. For all powders, a processing window of about 1,5 h was identified as well as a linear

correlation between doctor blade distance and green foil thickness, respectively, even though each slurry shows different shrinkage rates during drying.

The next step after tape casting is the debinding procedure which is needed to thermally remove the organic matrix of cast green foils. The debinding process was optimized using differential scanning calorimetry as well as thermal gravimetrical- and chemical combustion analysis. By measuring the quantity and identity of chemical impurities after the debinding and after the final sintering process, it was found that lower impurity values can be obtained when using debinding temperatures lower than 600°C, other than normally recommended in literature. An optimized debinding time temperature profile was derived and used in all further experiments.

Performing sintering experiments in the range of 900 – 1100°C on cast green foils yields metallic PTLs with different gravimetric porosity values ranging from 40-70% manufactured from each of the three selected Ti-powder fractions. As expected, the higher sintering temperature, the lower porosity values. Further investigations showed that for a given sintering temperature porosity values increase with increasing particle size. Furthermore, to reach the same porosity level, higher sintering temperatures are needed for larger particles. These results show that different combinations of particle size and sintering temperature can be exploited to tailor porosity values of Ti-PTLs with respect to increasing performance in electrolyser applications. Scanning Electron Microscopy images of PTL cross sections perfectly allow the three different particle size distributions and morphologies of each powder fraction to be visualized. Also, individual sintering necks can be seen at higher magnification and show that each powder grade could be successfully sintered to porous layers. Figure 3-6 also provides light optical microscope images of embedded and polished PTL cross-sections.

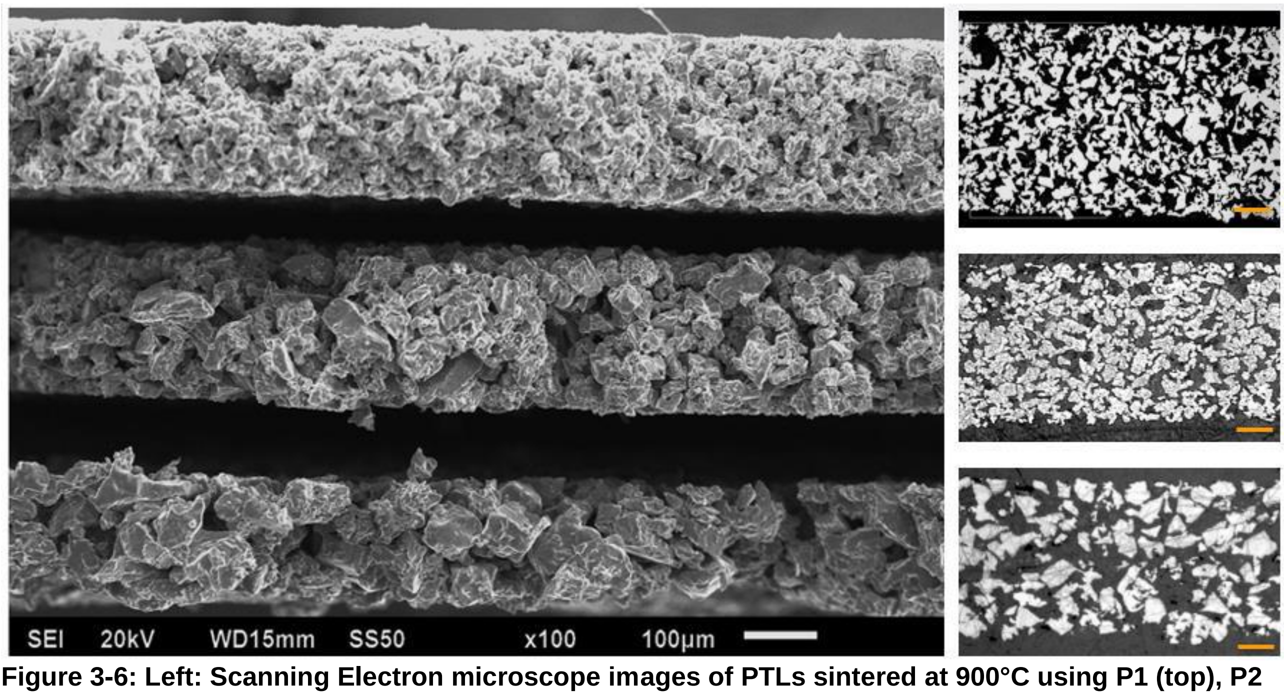


Figure 3-6: Left: Scanning Electron microscope images of PTLs sintered at 900°C using P1 (top), P2 (middle) and P3 (bottom) powder; Right: corresponding light optical images of embedded cross-sections (orange scale bar represents 100 µm)

A comparison of gravimetrically calculated and with Archimedes' principle measured porosity values show that gravimetrically determined values are up to 15% higher with a larger scattering range of ± 9% compared to only ± 3% for Archimedes values, respectively.
To further characterize sintered PTLs regarding performance in electrolyser applications, an electrical test bench for in-plane and through-plane resistance measurements was built. The purpose of this test-bench was to pre-evaluate the performance of each produced PTL saving time and effort for electrochemical characterization at Fronius' single cell test bench. Analysing each PTLs electrical resistivity value with respect to its gravimetric porosity reveals a clear correlation of increasing electrical resistivity with increasing porosity.
The influence of sintering temperatures (and correspondingly porosity values) on the mechanical stability of produced PTLs was primarily judged based on handling experience during thickness measurements. Optical inspections also revealed that too high sintering temperatures result in distorted and uneven surfaces whereas too low sintering temperatures yield PTLs not stable enough for operation within an electrolyser cell.
The thickness of each PTL was measured at least at 9 different positions in green state and after sintering. Local deviations within each PTL were determined to be ± 10 µm, however, averaged thickness values for all sintered PTLs cover a range of 220 – 445 µm. This large scattering range around the target value of 300 µm needs to be individually improved for each PTL, particle size and porosity value. The reason for these substantial deviations originates from the casting process itself which was carried out manually using a self-built casting device. Ideas for improvement were identified.
Three different PTLs produced from P1, P2 and P3 having similar porosities of about 60% were electrochemically characterized using Fronius´s self-built single cell test bench. Current-voltage curves measured at 60 and 80°C were compared to a commercially available Titanium frit delivered with the test cell purchased from the FuelCell store. Three important findings could be derived from these preliminary results.
1) The electrochemical performance of a PTL increases with decreasing particle size
2) The electrochemical performance of a PTL decreases with each test cycle, showing degradation effects.
3) The electrochemical performance of all tested PTLs with a porosity of 60% is much lower compared to the reference assembly.

Given that, the future focus was set to improve the performance of the manufactured PTLs. To improve the overall performance of our PTLs, the electrically insulating oxide layer on the titanium surface will be removed using chemical pickling solutions. The obvious degradation of each PTLs during subsequent test cycles further suggests measures to increase the chemical resistance enlarging PTL lifetime. To do so, PVD surface coatings with noble metals such as Pt can be an option.

Optimization of MIBA PTL´s cell performance

Three different kinds of PTLs produced from Ti powder P1, P2 and P3 having similar porosities of about 60% were electrochemically characterized using Fronius´s self-built test bench. Current-voltage curves were compared to a commercially available Titanium frit delivered with the test cell. The results revealed that the performance of MIBA´s PTLs was about half the level of commercially available Ti fibre felts.

Without having at least similar U-I characteristics compared to benchmark parts, the production of graded or hybrid PTL components makes no sense. Thus, the last year´s work had to be focused on increasing PTL performance.

- **A first approach** to improving the performance of sintered PTLs was pickling. Three PTLs made from P1, P2 and P3 Ti powder already tested in the single-cell test bench at Fronius were pickled at MIBA´s Laboratory using a mixture of HF and HNO3 acid. The pickling process removes the oxide layer at the Titanium surface and was immediately aborted after the acid´s colour was changing, and strong hydrogen formation was observed. The weight loss by pickling was calculated for each PTL and accounts to about 70 to 110 mg per PTL. After pickling, each PTL was rinsed in deionized water and ethanol. After drying, each PTL was individually packed and sealed for testing its electrochemical performance.
- **The second approach** to improving the performance of sintered PTLs was coating of freshly pickled Ti-PTLs with Platinum using a physical vapour deposition (PVD) process. This was done at the Technical University of Vienna. A layer thickness of 30 nm was targeted. After determining the relevant process parameter, each PTL was individually coated with the same process. Due to the weight increase, the real layer thickness can be calculated. The thickness profile in horizontal and vertical cross-section of the Pt-coating itself were analysed by optical and SEM microscopy. The achieved averaged layer thicknesses of 30 nm were found at centre position. Further outside, the layer is getting thinner, down to 15-20 nm at the edges. After Pt-coating, these three samples were again characterized in the single-cell test rig at Fronius comparing performance with and without coating.
- **The third approach** to improving the performance of sintered PTLs was Miba's idea to produce PTLs with a porosity gradient across the thickness of the PTL. The goal was having a high porosity on the side of the PTL facing the flow-field (water transport) and a lower porosity on the side facing the CCM (Hydrogen transport). Using a modified, customized tape casting process it was possible to fabricate graded green foils made up of different combinations of P1, P2 and P3 Ti powder. Even differently sized Ti particles could be successfully sintered together forming a stable, graded PTL. An SEM image of a PTL´s cross-section showing a gradient in porosity is exemplarily provided in Figure 3-7.

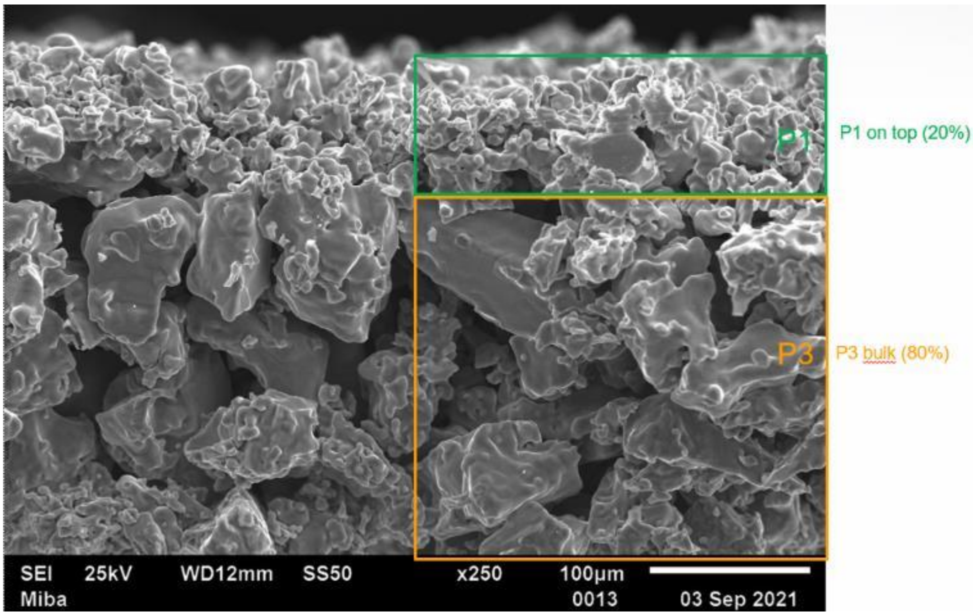


Figure 3-7: SEM images of a PTL cross-sections made up of finer P1 Ti-powder (top 20%) and coarser P3 powder (bulk 80%). In this way, a gradient in porosity was achieved.

A second option for fabricating graded PTLs is laminating different kind of tap casted green films made from either P1, P2 or P3 Ti powder. In this way, a similarly composed green foil is obtained which can be sintered to a graded PTL. Based on indicative cell performance results, several PTLs were selected and electrochemically characterized at Fronius´s test rig.

Cost reduction for PTL production

Porous PTLs were produced by tape casting green films which were subsequently sintered to pure metallic components. During the first two years, all PTLs were sintered in vacuum conditions at a pressure level of 10e-05 mbar. This requires gas tight and perfectly sealed furnaces that are expensive to purchase and operate. Currently, MIBA does not have any furnace that allows to sinter under similar vacuum conditions. The acquisition of such a furnace was neither planned nor in the budget.
MIBAs existing equipment only allows to operate at atmospheric conditions but can´t provide high quality protective atmospheres or vacuum conditions required to sinter Titanium powder. In the scope of this project, one of Miba´s research furnace was refurbished to provide high purity Argon atmospheres and was used to evaluate the possibility of Argon atmospheres to replace Vacuum sintering. In this way, existing equipment can be used, and operation costs dramatically be reduced. This is also of relevance for further potential technologies considered for low-cost production of Ti-PTLs such as free sintering and sinter based Additive Manufacturing.
Within the project seven individual sintering trials using pure Argon atmosphere were carried out. To make a long story short, none of these seven approaches was successful. After sintering, the PTLs showed cracks, crumbled apart, or were discoloured. All these results suggest that the used MIBA furnace is not gas tight and thus not suitable for high purity atmospheres required to sinter titanium powder. For a final prove of concept, identical MIBA PTLs were also sintered at a service provider - once in vacuum and once under argon atmosphere. Both sintering trials were successful and yielded good PTLs without cracks, distortion or coloration. This proves that argon sintering is possible if an appropriate

furnace is used. These PTLs were also used for an electrochemical characterization evaluating any potential difference in cell performance originating from the sintering atmosphere.

Evaluation of alternative production technologies for PTL

The last year was also used to evaluate further production technologies such as free sintering and additive manufacturing for PTL production.

According to specific requirements collected from literature and derived from preliminary experiments proofing basic feasibility first free sintering trials using different high-temperature materials as sinter moulds were carried out. Special material like Molybdenum was purchased and machined into sintering moulds. One of the biggest issues using the free sintering approach is to generate an even and homogenously distributed powdered film in the mould. Furthermore, it turned out that the mechanical strength of porous PTLs was not sufficient to remove the sintered PTLs from its mould. Different ways to do so were tested but all PTLs were damaged in the process. Therefore, free sintering had to be eliminated as a potential low-cost industrial production method for PTLs.

Sinter based Additive Manufacturing was also tested for production of porous PTLs. Using Binder Jetting technology, it was possible to print green sheets that were successfully sintered into PTLs. However, the required thickness of about 300 µm could not be realized. The minimum thickness of printed green sheets that could be successfully de-powdered after curing was about 3 mm. Since these PTLs have a thickness that is a factor of 10 higher than required, no further optimizations were made and Binder Jetting technology was also eliminated as a potential low-cost industrial production method for PTLs.

Production of bipolar plates

BPP for single cell tests: For the electrolyser single cell, a meander design for the cathode side and a new design intended for the anode side developed by HyCentA were manufactured at MIBA. The later flowfield was developed to increase the water supply and its homogeneous distribution at minimum pressure drop by 3D CFD simulations. Since titanium material has never been machined at MIBA before, suitable tools required for each design as well as material dependent machining parameter were developed during this project. Primarily, CNC machining was used to mill each design with outer dimensions of 70 x 70 mm followed by EDM wire cutting and – in some cases – a final grinding operation. A total of 3 different BPPs and two different inlays were manufactured for single cell assemblies.

BPP for electrolysis short stack: For the short stack electrolyser the same flowfield designs that were used in the single cell were also used for the stack except that here not only the flowfield (70 x 70 mm) but the entire “housing plates” having 120 x 120 mm x 4 mm as well as the double-sided polar plates with cathode and anode design on each side were fabricated. The meander design was still used on the cathode side and the “HyCentA design” on the anode side. In total, each stack is composed of 5 single cells and requires 5 double-sided polar plates, one BPP with current collector at the cathode side and one BPP with current collector at the anode side. These components are shown in Figure 3-8.

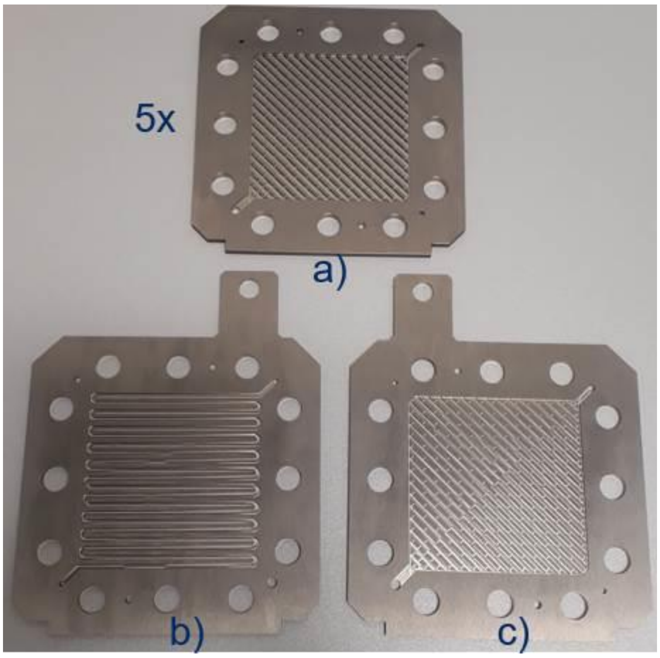


Figure 3-8: Stack components: a) double sided BPP; b) cathode polar plate with meander flowfield and current collector; c) anode polar plate with "HyCentA design" and current collector.

As two of these short stacks were fabricated - one equipped with PTLs purchased from existing suppliers and one with MIBA-made PTLs - a total of 14 Ti-components were machined. During fabrication it was found that the machining time of the HyCentA design would be reduced by 30% if the outside contour channel having a diameter of 0,5 mm. Therefore, after additional simulations, the design was changed.

3.4 Electrolysis single cell simulations

Next to development of an electrolyser system, a proton exchange membrane water electrolysis stack was developed within the project HyTechbasis. The development included the design of the single layers, the manufacturing of the components, the built-up and the testing of the stacks. Additionally, a stack test bed was designed and built-up during the project time.

3.4.1 Content presentation

The stack design was developed in cooperation with all partners. The main focus of HyCentA was laid on the flow field design of the bipolar plates (BPP). The main requirements concerning the BPP are

- Conduction of electricity from an external circuit to the cell
- Uniform distribution of reaction educts and collection of products
- Uniform temperature distribution inside the cell
- Sealing the cell

Especially the transport of water to the reaction sites and the removal of produced oxygen bubbles from the reaction sides is challenging when developing new flow field designs. Therefore, a simulation-based approach was chosen to reduce manufacturing and testing costs and time.
Several flow field variations were performed to receive the most optimised flow field as it is of major importance to reduce the abidance of the oxygen bubbles as these block the catalytic surface and therefore reduce hydrogen production efficiency. Furthermore, the pressure difference across the flow field has to be considered, so that the pressure loss is neither too high (requires more power to pump the water through) or too low (leads to an uneven water distribution among the cells). The different geometries and the oxygen distribution are shown below (Figure 3-9).

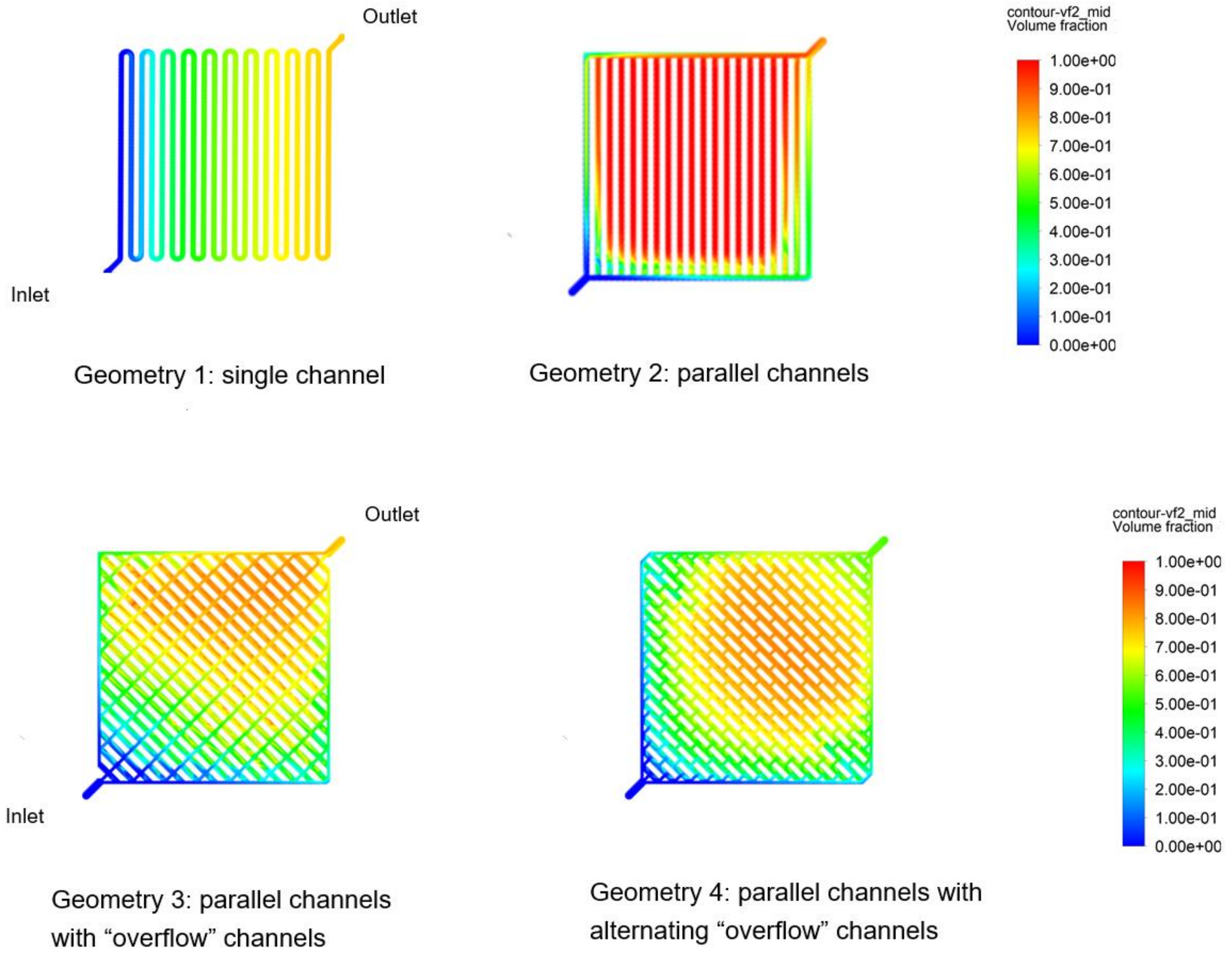


Figure 3-9: Comparison of different flow field variations showing the volume fraction of oxygen in the central plane of the flowfield

3.4.2 Results and conclusions

Geometry 4 was chosen for further improvements by adapting the alternating channel heights, see Figure 3-10.

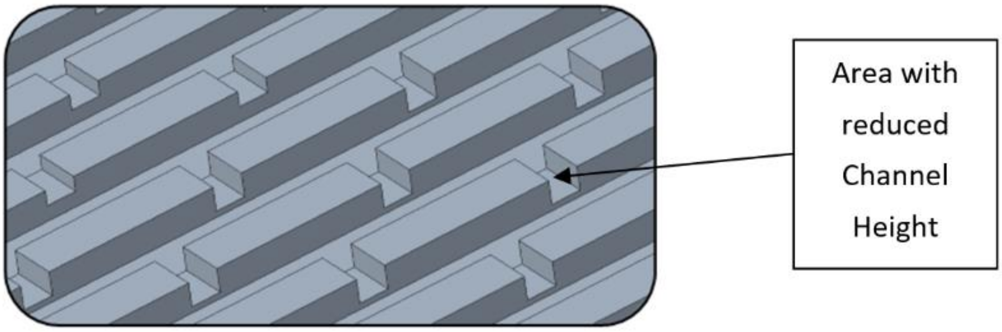


Figure 3-10: Detailed geometry with alternating channel height

Several optimisation loops considering the geometry of the flow field channels have led to an even better distribution of water and removal of oxygen bubbles, as shown in Figure 3-11. In comparison to the designs shown in Figure 3-9 the volume fraction of oxygen could be reduced significantly, which shows the improved bubble removal.

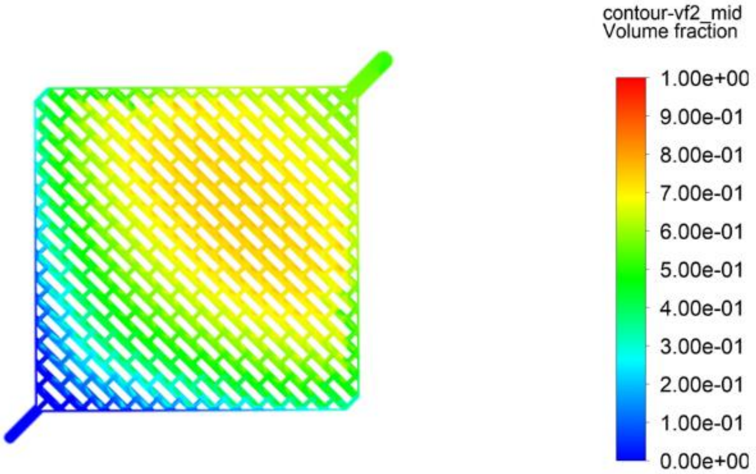


Figure 3-11: Optimised flow field design for the HyTechbasis stack with reduced maximum volume fraction of oxygen

3.5 Electrolysis single cell testing

3.5.1 Content presentation

For the testing of the CCM and PTL samples, a single cell test station was necessary. Fronius developed an electrolysis single cell test station (Figure 3-12) with the following capabilities:

- Cooling water loop with active heating and cooling
- Active cooling water flow control
- Electronic load up to 200A
- Measurement of: gas and water temperatures, water conductivity, gas pressure, water flow, H2 flow, H2 humidity
- Fully automated testing and data acquisition

Figure 3-12: Electrolysis single cell test station

For the actual electrolysis single cell, a commercially available cell and a proprietary cell design from Heraeus were used. For the testing itself a testing protocol was developed and repeated for each test at least two times or more often according to the test run specification. A large number of tests were carried out with both cell designs, as can be seen in the following statistical values:

Commercially available single cell:

- 116 single cell hardware assemblies
- >300 test runs
- Ca. 4350 operating hours

Heraeus single cell:

- 53 single cell hardware assemblies
- >153 test runs
- Ca. 2685 operating hours

3.5.2 Results and conclusions

The selection of the subsequent tests have all been tested with the Heraeus single cell hardware, Heraeus CCMs and MIBA PTLs.

With three PTL samples the effect of platinum coating was tested. According to literature, the coating of titanium PTLs with platinum has a huge impact on the performance and on the degradation rate as well. The measurements carried out were able to confirm these statements. Table 3-1 shows the used PTL samples for the tests with platinum coating.

Table 3-1: PTL samples with platinum coating

PTL sample:	SP3-009-10	SP2-008-1	SP1-007-1
Thickness [µm]	306	331	352
Porosity [%]	63	62	60

Figure 3-13 shows the results of the tests before and after the platinum coating. After the tests without the coating, all samples were pickled with a mixture of HF and HNO3 acids. Afterwards they were coated with platinum using a PVD process.
Without the platinum coating sample SP1 shows the best performance, followed by SP3 and SP2. The samples show the same order regarding the performance also after the coating, but the difference in performance is much less significant. Additionally uncoated PTLs typically degrade with during the testing. This means, that the performance for the second test run is worse compared with the first test run. The coated samples show a different behaviour: All samples gain performance from the first to the second test run. Mainly because of the different uncoated performance the improvement with the platinum coating is quite different:

- SP1: 2 times performance gain
- SP2: 5 times performance gain
- SP3: 3 times performance gain

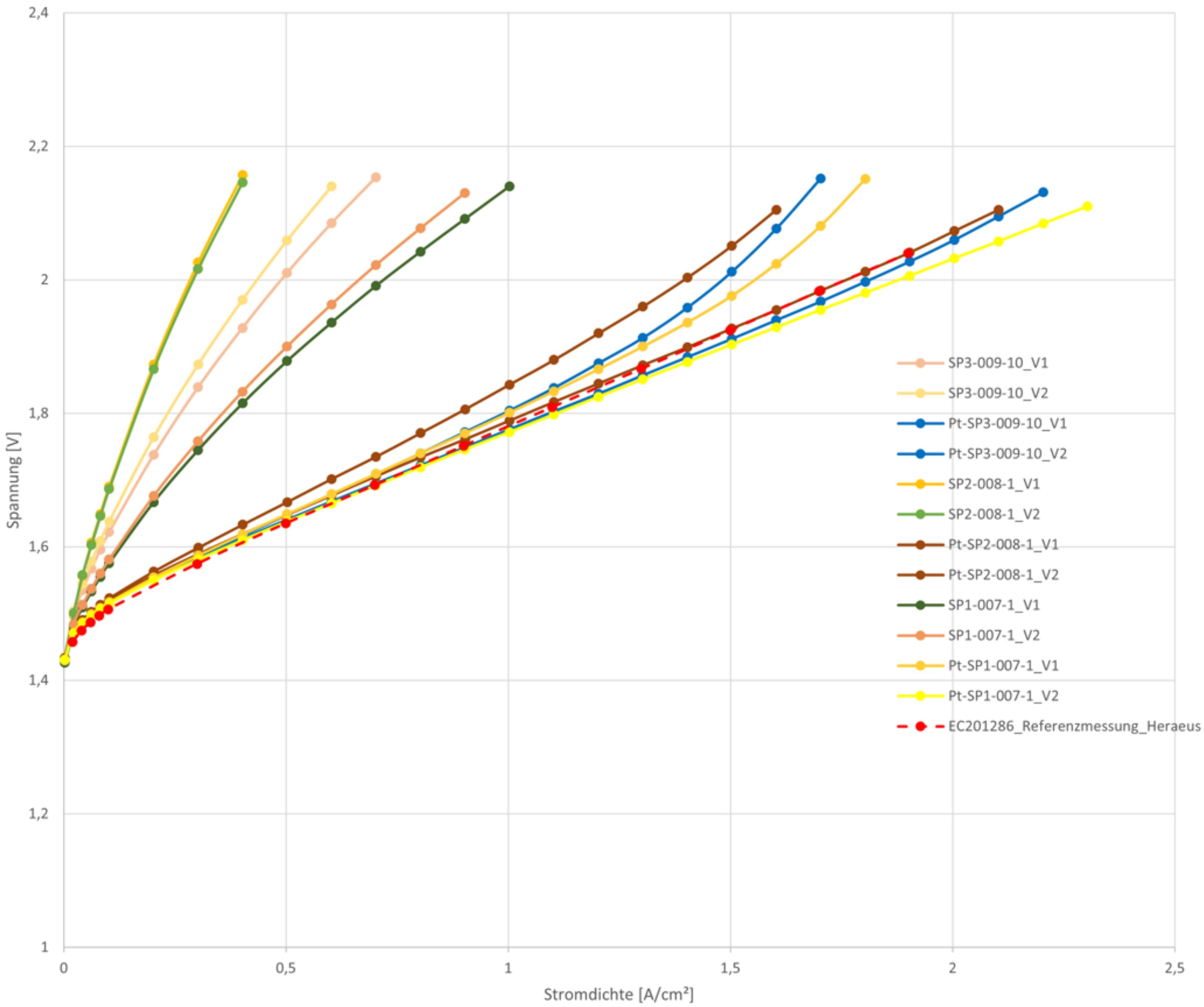


Figure 3-13: Platinum coating

As described in the above chapter “Optimization of MIBA PTL´s cell performance” additional PTLs have been tested (see Table 3-2 and Table 3-3). The samples P1 and P2 are standard PTLs with different thickness and porosity. The samples P1-BM-P2-006 and P1-BM-P2-005 are PTLs with a porosity gradient. For the sample “Laminated” two different tape casted green films were laminated together.

Table 3-2: PTLs with different sintering atmosphere

PTL sample:	P1-A	P2-A	P1-V	P2-V
Thickness [µm]	303	343	343	357
Porosity [%]	38	50,6	48,7	55,5

Table 3-3: Graded and laminated PTL samples

PTL sample:	P1-Bm-P2-006	P1-BM-P2-005	Laminated
Thickness [µm]	285	366	488
Porosity [%]	50,9	51,3	53

Figure 3-14 contains all in the above tables mentioned PTL samples. For each sample at least two full test runs (V1 and V2) have always been done. The PTL with the best performance was sample P1-V, which was the reason that this PTL was chosen for the stack assembly.
The two graded samples P1-BM-P2-006 and P1-BM-P2-005 perform less well than the standard PTLs. The laminated PTL shows the worst performance of all samples. More work needs to be carried out for the production and testing of graded PTLs. Also, the combination of the PTL together with different flow field types needs more attention.

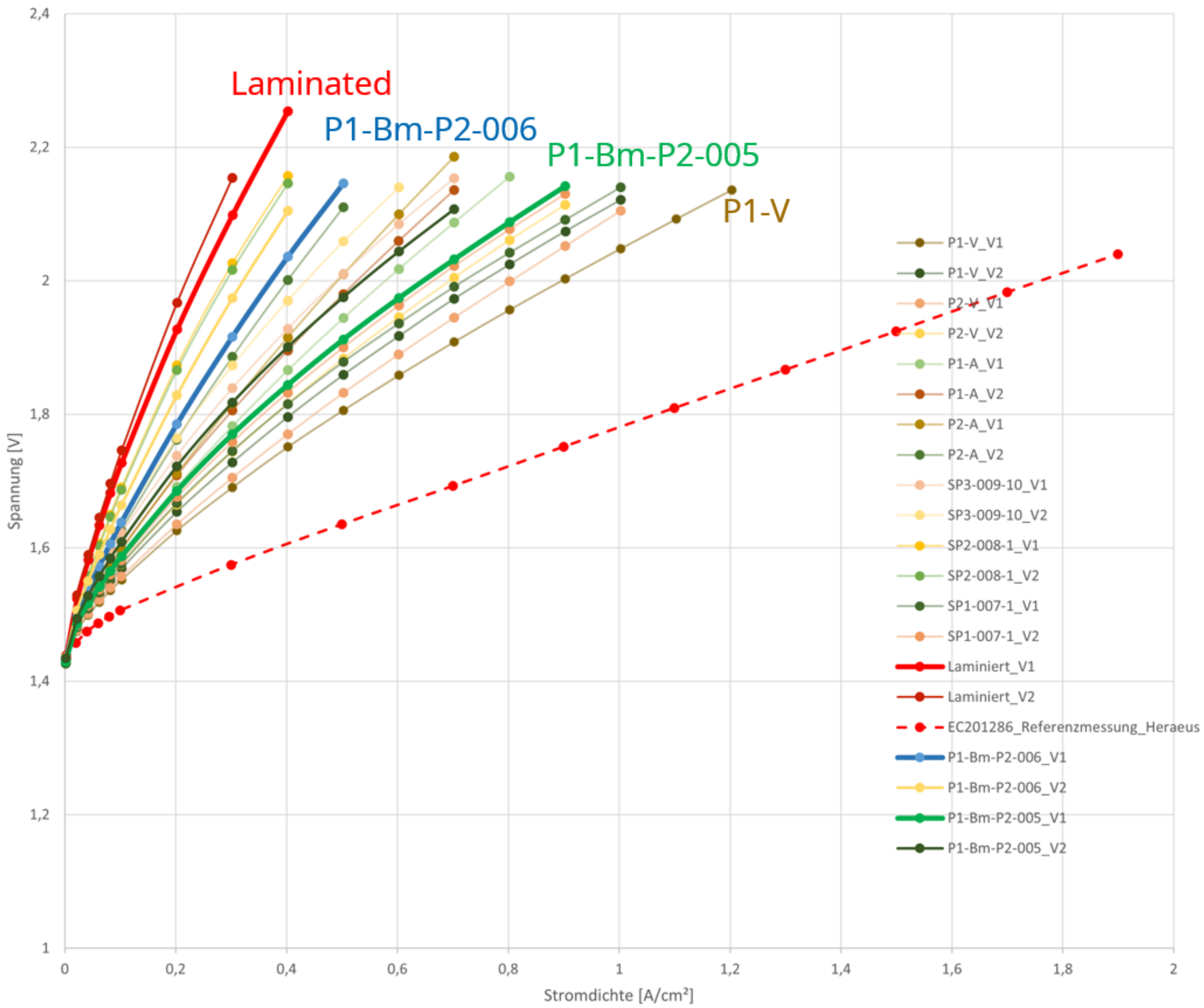


Figure 3-14: MIBA PTL measurements

During the production of the PTL samples, MIBA also tried out different atmospheres during the sintering process. The samples P1-A, P2-A and P1-BM-P2-006 were sintered in an argon atmosphere. The samples P1-V, P2-V and P1-BM-P2-005 were tested in a vacuum atmosphere. All three vacuum sintered samples showed a noticeable better performance compared to the argon atmosphere (Figure 3-15).

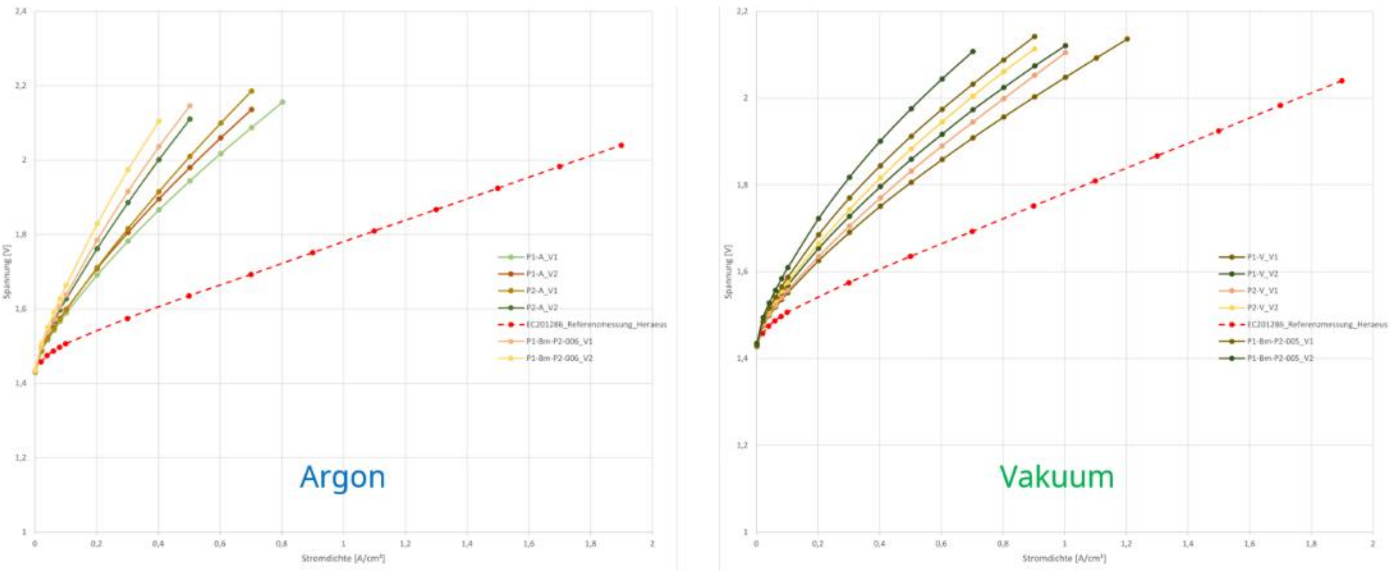


Figure 3-15: Sintering atmosphere

3.6 Electrolysis short stack

3.6.1 Content presentation

Short stack build up

For comparison reasons, the decision was made to build up two electrolysis short stacks with different components. The components itself were determined from tests with the electrolysis single cell hardware.

Components short stack HTB Gen 1:
- Anode: PTL: Titanium felt
  - Gasket: Teadit ePTFE
- Cathode: GDL: Toray Paper 120
  - Gasket: Fiberflon 280µm

Components short stack HTB Gen 2:
- Anode: PTL: MIBA P1 Vacuum
  - Gasket: Fiberflon 320µm
- Cathode: GDL: Toray Paper 120
  - Gasket: Fiberflon 320µm

Both short stacks consisted of 5 single cells. All other parts except from the above mentioned were the same. The build up of the stacks was carried out manually, with the help of specially made assembly supports (Figure 3-16 and Figure 3-17). Figure 3-18 shows the ready assembled Gen 1 short stack.

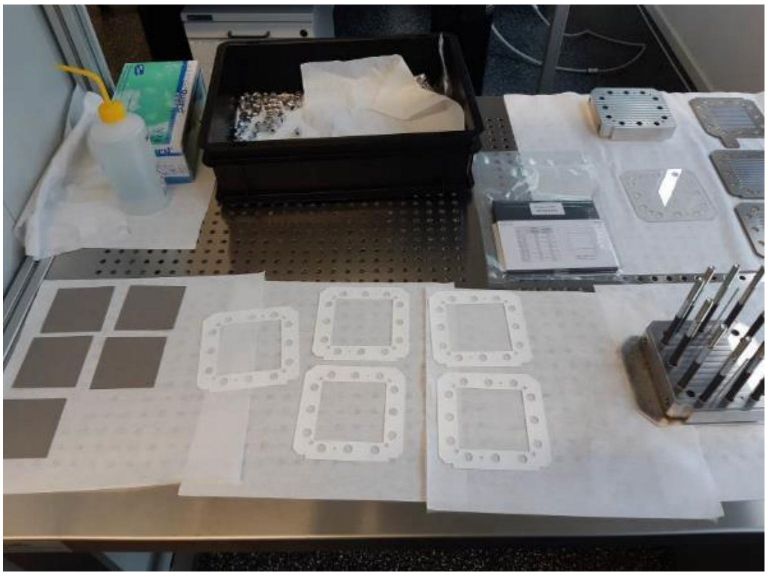


Figure 3-16: Components for stack assembly

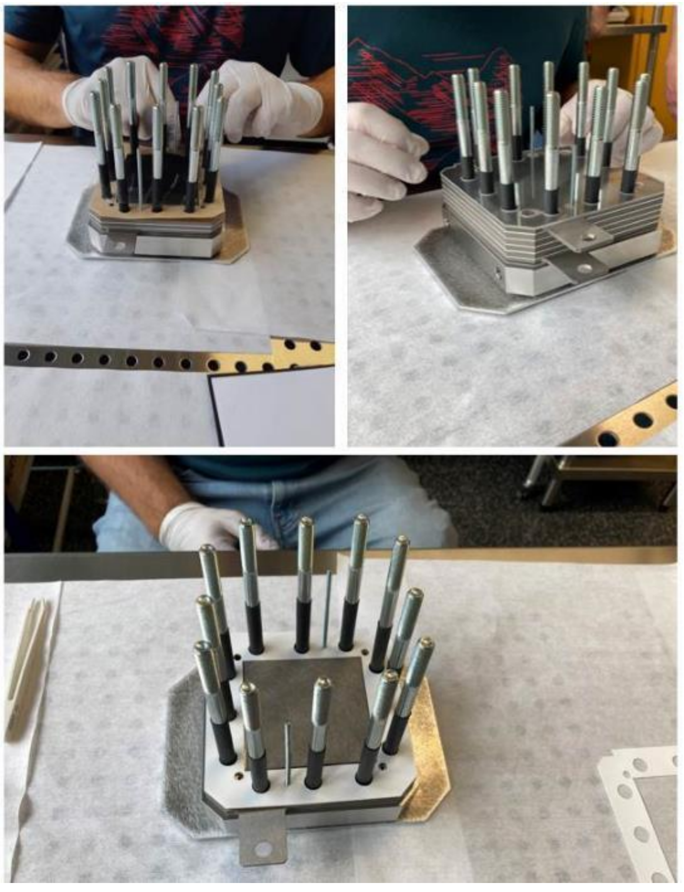


Figure 3-17: Manual short stack assembly

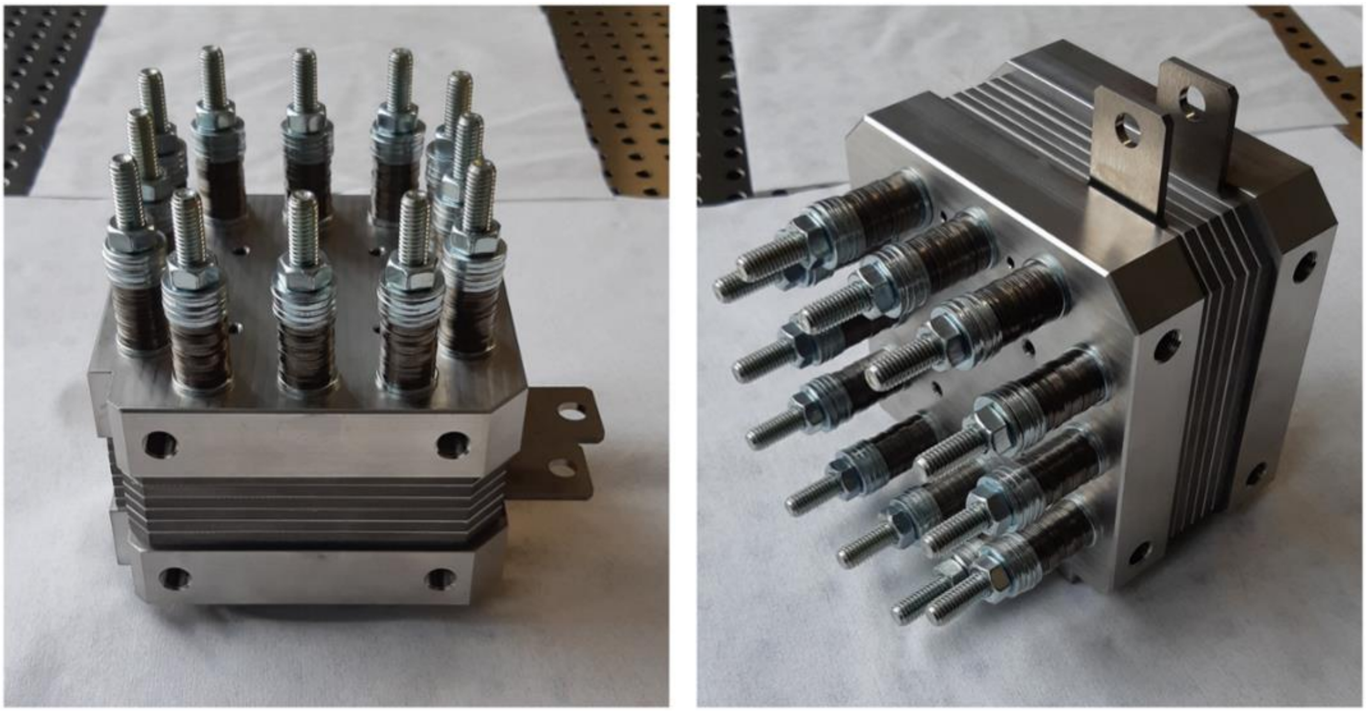


Figure 3-18: Ready assembled electrolysis short stack

Electrolyser stack test stand

To be able to test the developed stack, HyCentA developed an electrolyser stack test stand. The test bench can handle stacks from 1 to 10 kW electrical power and hydrogen pressures up to 160 bar. The process temperature can be varied between 20 and 80 °C. These wide operating ranges presented challenges for the component selection and the implementation of the control cycles. However, the deep insights gained during the development of the electrolysis system enable high quality research for stack operation and degradation mechanisms. Furthermore, the implemented control and state model allow for testing of operation strategies and optimization from component to system level.

After build-up, the test stand was validated by testing it with a commercial stack and the results showed good agreement with the manufacturer's data of the commercial stack. Therefore, the electrolyser test stand was used to test the developed HyTechbasis stack, see Figure 3-19.

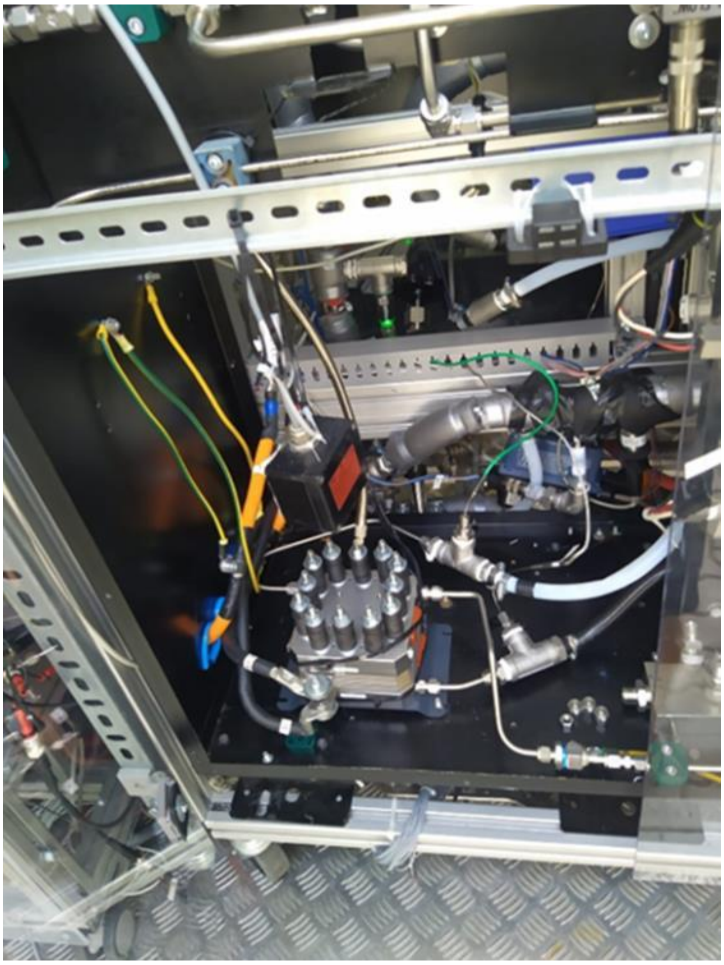


Figure 3-19: HyTechbasis stack installed at the HyCentA stack test bed

3.6.2 Results and conclusions

The testing protocol for performance characterization includes an activation procedure and the actual polarization curves at two different temperatures, 60 °C and 80 °C. To receive consistent and reliable data, three polarization curves were recorded at 60 °C and two at 80 °C for each stack.

The direct comparison of HTB Gen1 and Gen2 can be seen in Figure 3-20. As already expected from the single cell measurements, the performance of HTB Gen1 is much better than HTB Gen2. As can be seen in Figure 3-13, platinum coating would have made a considerable difference for the performance. Unfortunately it was not possible to test coated PTLs within the stack until the end of the project.

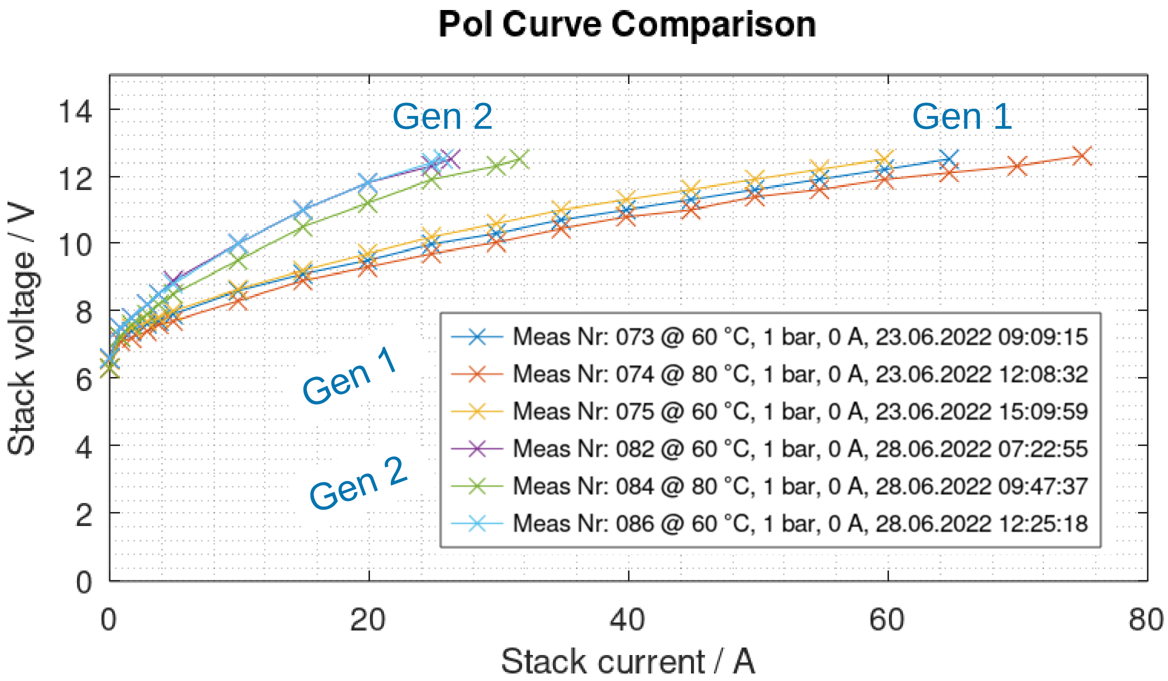


Figure 3-20: Comparison of different polarisation curves of HTB Gen1 and Gen2

3.7 PEM electrolysis system

3.7.1 Content presentation

A major task of this project was the design and engineering of the electrolysis system. Following the use cases and requirements defined at the beginning of this project, variant studies were taken out in order to determine the best solution for the electrolysis module. For all variants, a technical and economical investigation was carried out. During a separate procurement analysis, an external stack supplier was defined.
For the process engineering the following main parameters were taken into account: stack size (also cell count), number of stacks per module, build-up in separate cabinets or container integration, DI-water purification and the integration of the gas drying unit.
An investigation into the power supply identified the combination of 4 units of Fronius Selectivas 8210 as the preferred solution for each stack. This ensured a cost efficient and readily available power source and aids the industrialisation character of this project.

The result of the variant study was a modular electrolysis module, with a cabinet as housing incorporating up to two 75kW stacks and an external gas drying unit (see Figure 3-21). This combination promises the best technical and economical solution for the defined use cases.

The technical details of the electrolyser system are as follows (per stack):

- Hydrogen production: 24,8 kg/d (11,5 Nm^3/h)
- Max. electrical power: 75 kW (at the end of lifetime)
- Voltage supply: 4 x Fronius Selectiva 8210 Ely
- Max. current and voltage: 800 A, 84 V
- Hydrogen pressure: 36 bar
- Control: PLC with LabView interface

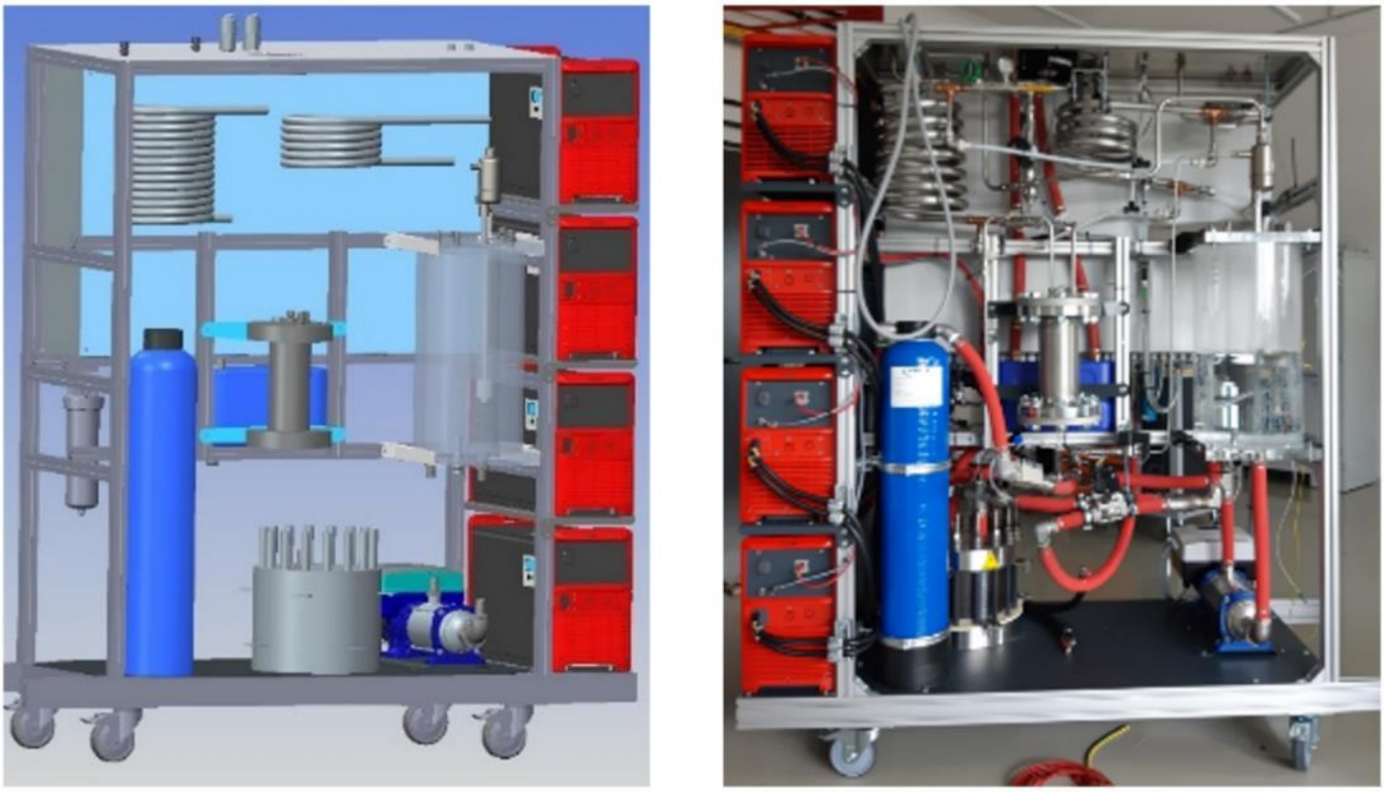


Figure 3-21: CAD drawing and ready assembled prototype of PEM electrolysis system

3.7.2 Results and conclusions

The electrolysis system developed during the project was tested at the HyCentA test bench "Schönbein". The system included one electrolysis stack with a maximum power of 67.2 kW, a maximum current of 800 A DC and was able to produce approximately 11.5 Nm^3/h.

The highly integrated fuel cell analysis infrastructure, Schönbein, at HyCentA Research GmbH, originally developed for fuel cell systems, was adapted for evaluating the electrolyser system. The test bench features a climatic chamber capable of -40 to +85 °C, two cooling circuits for different cooling power and temperatures (50 and 200 kW) and all necessary safety equipment. The only constrain was the power supply of the electrolysis system, which only allowed the operation up to 80 % (55 kW) of the actual power.

The polarisation curves were recorded at four different temperatures, i.e. 30, 40, 50 and 60 °C. Figure 3-22 shows the performance gain with the temperature.

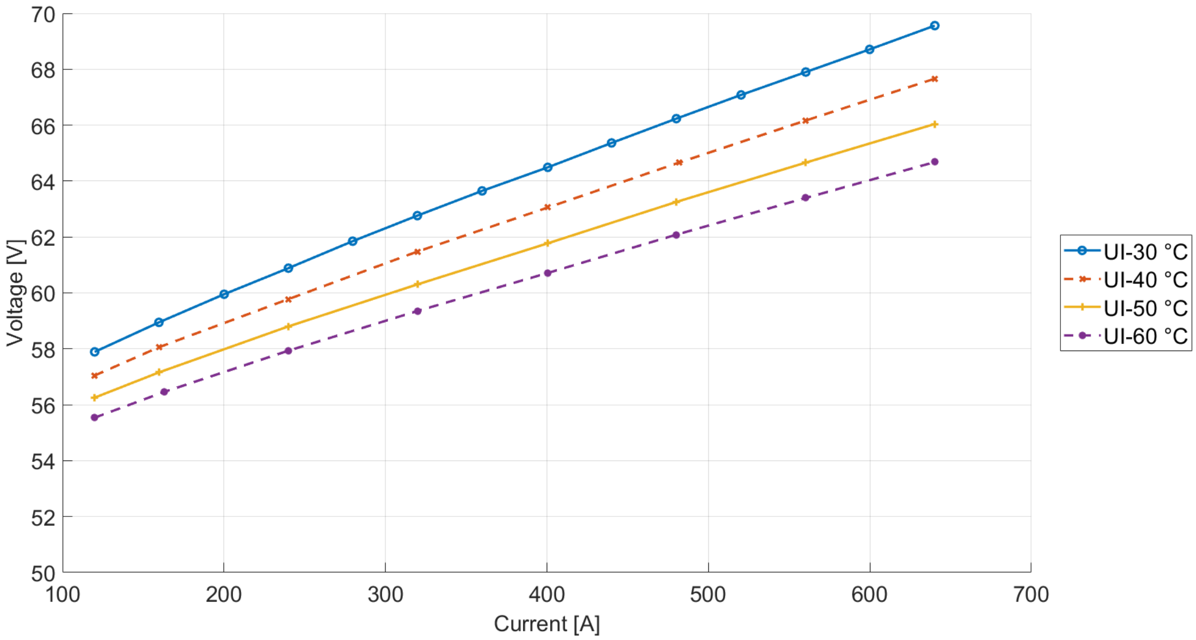


Figure 3-22: Electrolyser system polarisation curves at different temperatures measured at HyCentA

Functionality of the system was tested by increasing the cooling water temperature fed into the system in order to verify the process cooling concept.

The dynamic performance of the system was evaluated for the operation with fluctuating energy sources. Figure 3-23 shows an example of a dynamic profile, where the set power is changed rapidly, and the duration of steps is decreased along the testing period. In this case, the set power was varied from 15 to 47.5 % and the step time decreased from 720 to 45 s.

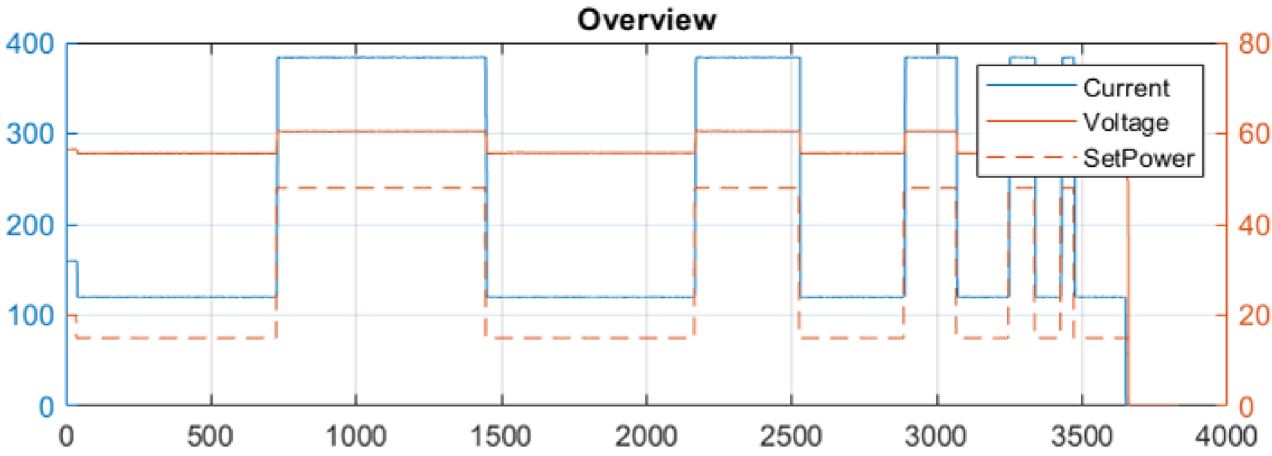


Figure 3-23: Dynamic profile based on fluctuating energy sources

The dynamic testing of the system showed a very good capability of dynamic response time as well as of operation under dynamic conditions over longer time periods.

During the tests with the electrolysis system, the efficiency of the entire system and individual components was also determined, using external, highly accurate current measuring devices (Figure 3-24).

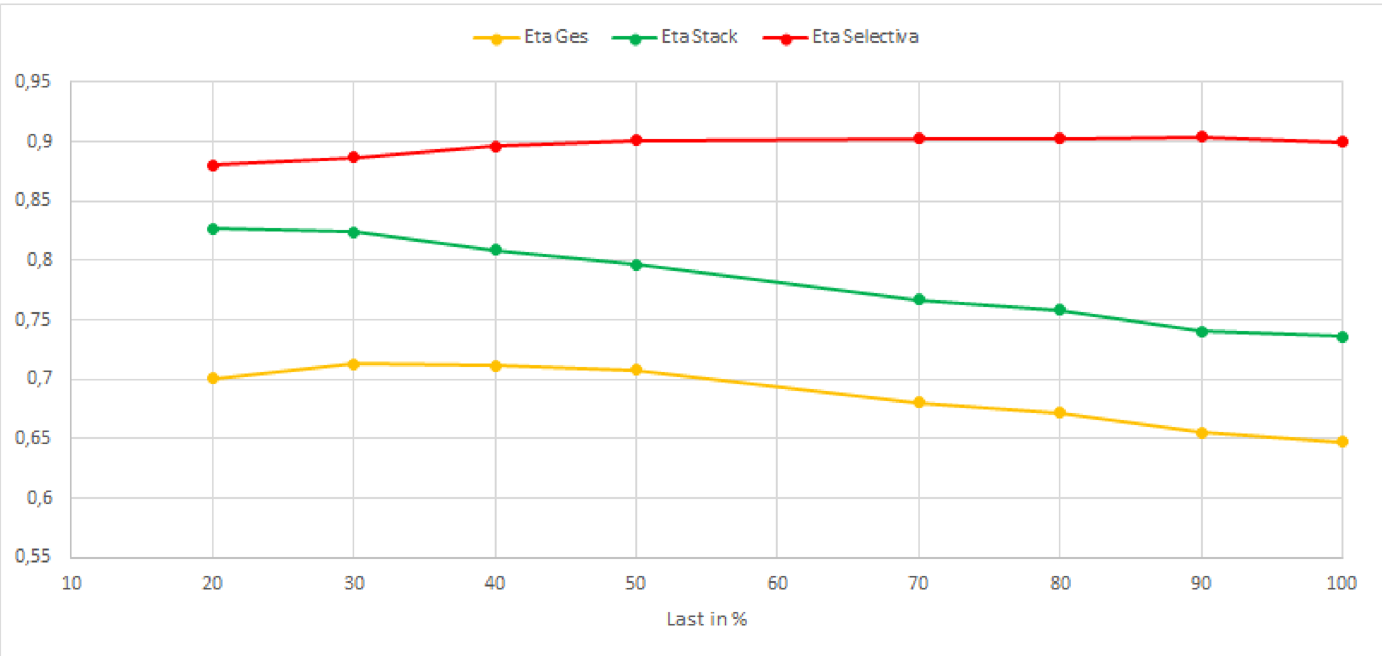


Figure 3-24: Efficiencies of electrolysis system

For the current supply of the electrolysis stack, Fronius Selectiva battery charging systems were used. At low loads, the efficiency of this devices is at around 88%. Above 40% load the efficiency is above 90%. For the electrolysis stack, the efficiency is between 83% at low power and 74% at full power. The efficiency of the whole system is above 70% at low and partial load and 65% at full load.

4 Development and industrialisation of PEM Fuel Cells

4.1 Content presentation

As for the electrolyser system, a modular approach was also chosen for the fuel cell system. The development concentrated on a stationary system with a 10kW PEM fuel cell stack from an external supplier. For a higher power demand, several modules can be combined.

Main features of the stationary fuel cell system (Figure 4-1):

- 10 kW PEM fuel cell
- Atmospheric pressure operation
- In-house developed hydrogen recirculation
- Heat extraction up to 40°C possible
- Water cooled condensate separator for exhaust air and product water
- In-house developed cell voltage monitoring unit
- Nitrogen connection for inerting
- System control via PLC in combination with LabView software interface

Figure 4-1: CAD drawing and ready assembled prototype of PEM fuel cell system

DCAC converter

For a cost-effective DC/AC converter, a design with a self-developed DC/DC and a next generation Fronius Symo GEN24 Plus 10.0 inverter was chosen. The combination with a mass-produced solar inverter ensures the best price / performance ratio. In order to ensure a longer lifetime and to avoid derating situations caused by over temperature, a water-cooled platform was chosen. This also improved the overall efficiency of the fuel cell system.

In order to be able to cover the full voltage range of 60 to 113V in combination with the current range from 30 to 165A, a topology called NPC LLC resonant converter was chosen. This also promised a high efficiency of above 95% over the full power range of the fuel cell stack (Figure 4-2).

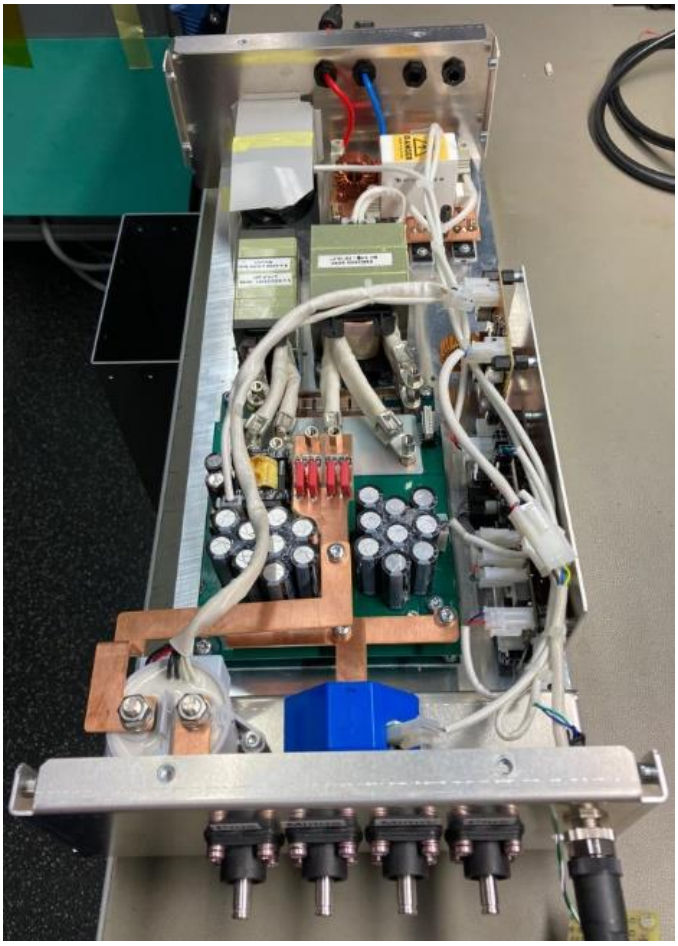


Figure 4-2: DCDC converter

4.2 Results and conclusions

The stationary fuel cell system was tested on the testbed at HyCentA with regard to optimization potential, see Figure 4-3. The hydrogen consumption during the testing period was approximately 15 kg.

Figure 4-3: Set up of fuel cell system on the fuel cell system testbed Schönbein at HyCentA

The test plan included several test cycles to uncover optimization potential in the individual paths for anode, cathode and coolant as well as for the overall system. Figure 4-4 shows the short conditioning and standard polarisation curve used for comparison tests.

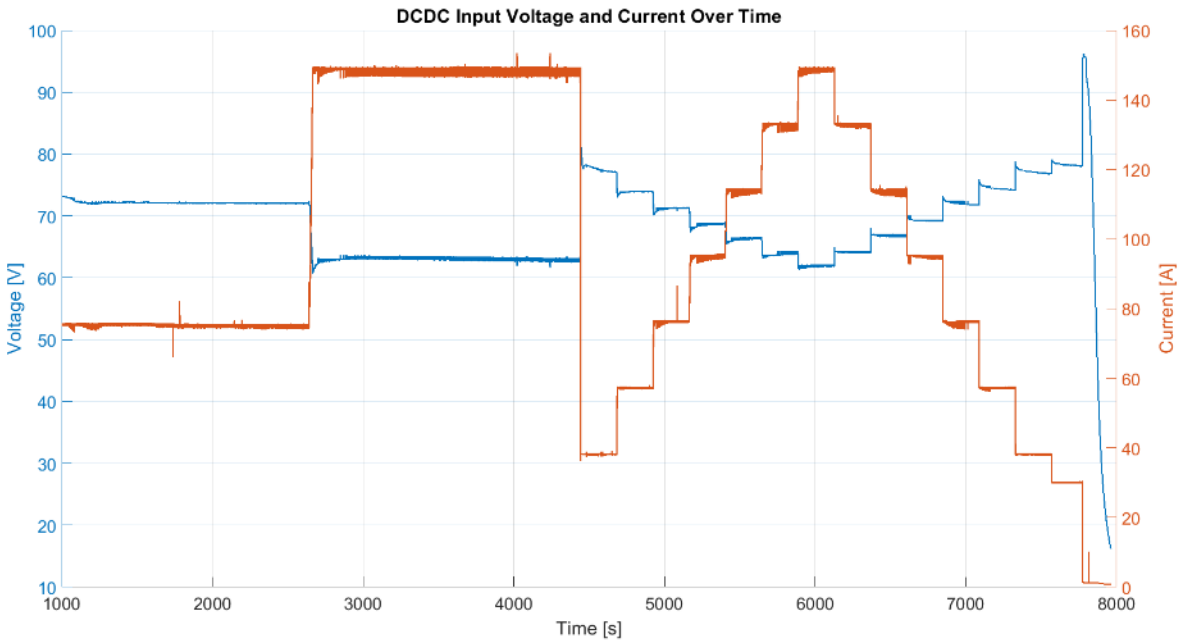


Figure 4-4: Conditioning and polarisation curve

Lambda-Min-Evaluation

This test procedure was done to find out the minimum cathode stoichiometry necessary to decrease the fan power but concurrently guarantee a stable cell voltage and subsequently a reliable water removal. Therefore, all operating points of the polarization curve were investigated. All points were stabilized and then the lambda was minimized. As soon as stochastic flickers of the cell voltage could be observed and/or a decrease in the stack voltage occurred, the minimum lambda could be determined.

After determination of the minimum lambda, four polarization curves were carried out with the reference lambda, the minimum lambda and two lambda values in between see Figure 4-5.

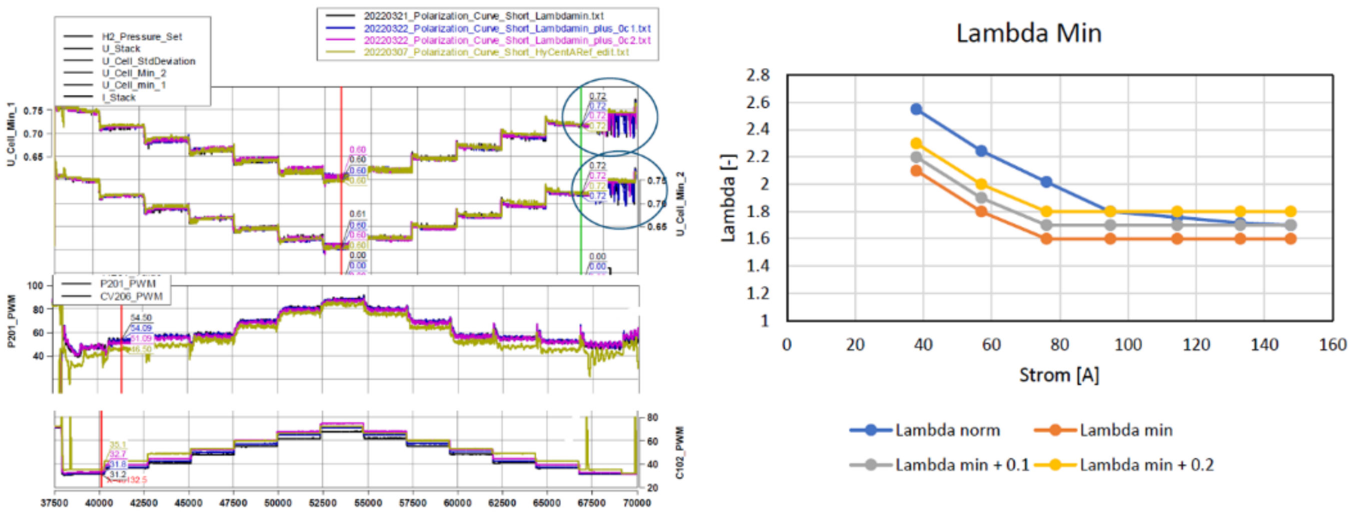


Figure 4-5: Polarization curves with minimum lambda and variations

The following findings could be observed:

- A lower lambda leads to a lower fan power consumption with a reduction possible up to 11%
- Lower stack voltage in various operation points
- Flickering of cell voltages in the last operating point visible. Significantly less flickering at lambda min +0.2 and the base calibration.
- No significant influence on anode path

Efficiency measurements

The efficiency of the whole system was between 43% at full load and 55% at partial load. Figure 4-6 shows the system efficiency of the fuel cell system, including all balance of plant components depending on the AC output power.

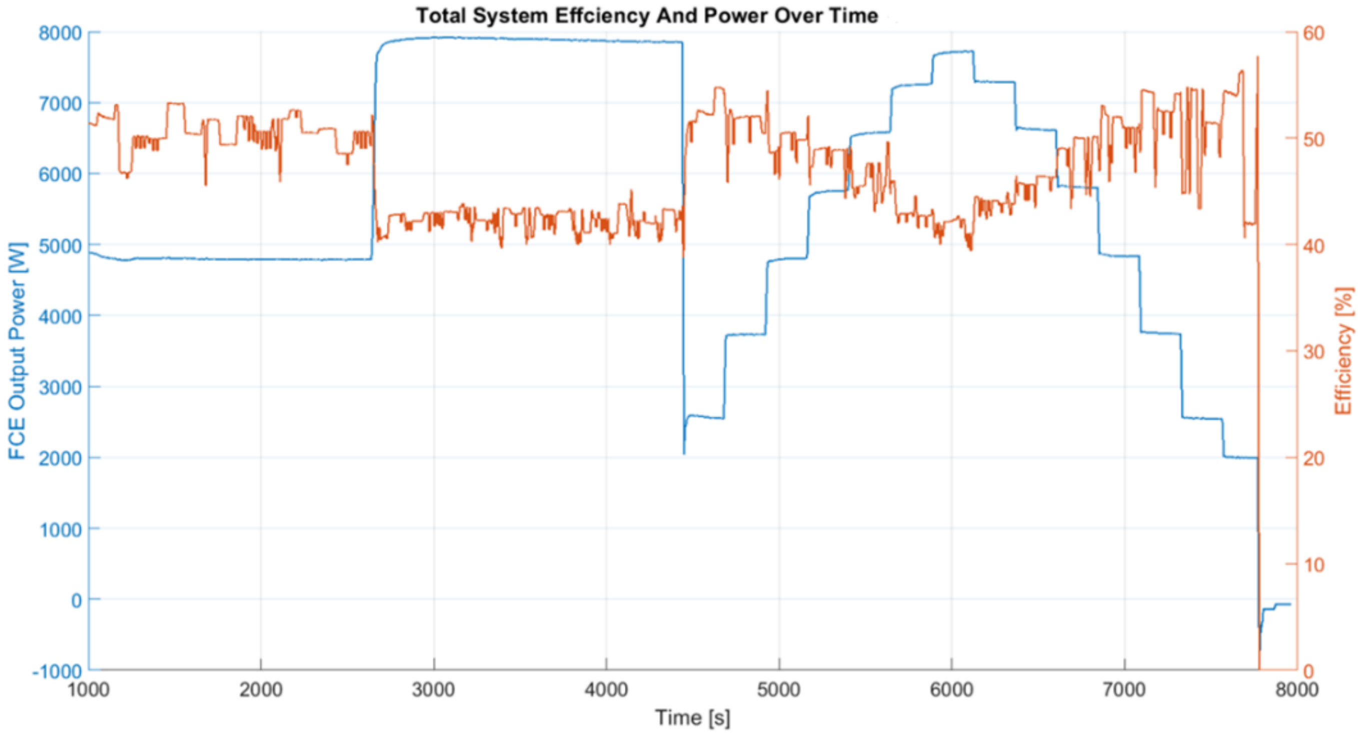


Figure 4-6: Efficiency of complete fuel cell system

As already described, the DCDC converter was newly developed within this project for the fuel cell system. The simulations showed an efficiency of above 95% for the whole load range. The measurements validated this prediction, as can be seen in Figure 4-7.

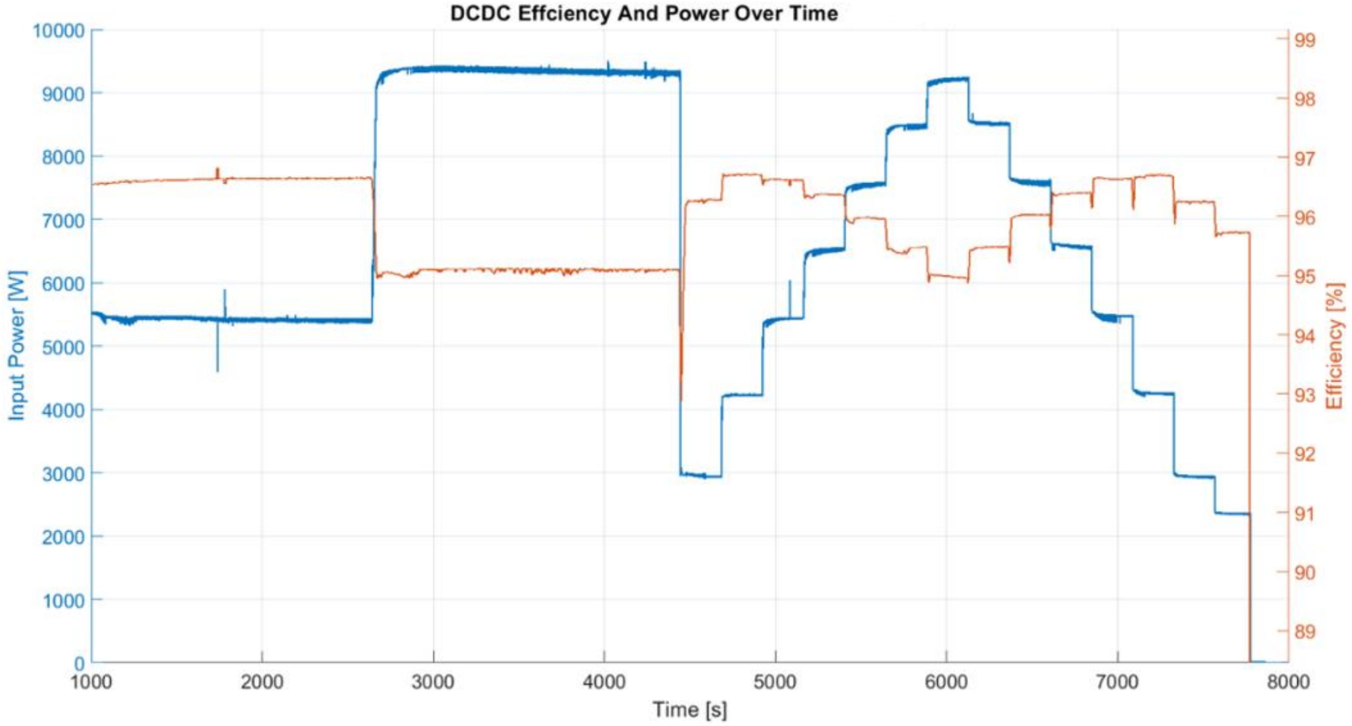


Figure 4-7: Efficiency of DCDC converter

A commercially available photovoltaic inverter from Fronius was used to convert the direct current from the fuel cell stack into alternating current for the electric grid. This solar inverter is already highly sophisticated, as the efficiency between 97.5 and 98.5% shows (Figure 4-8).

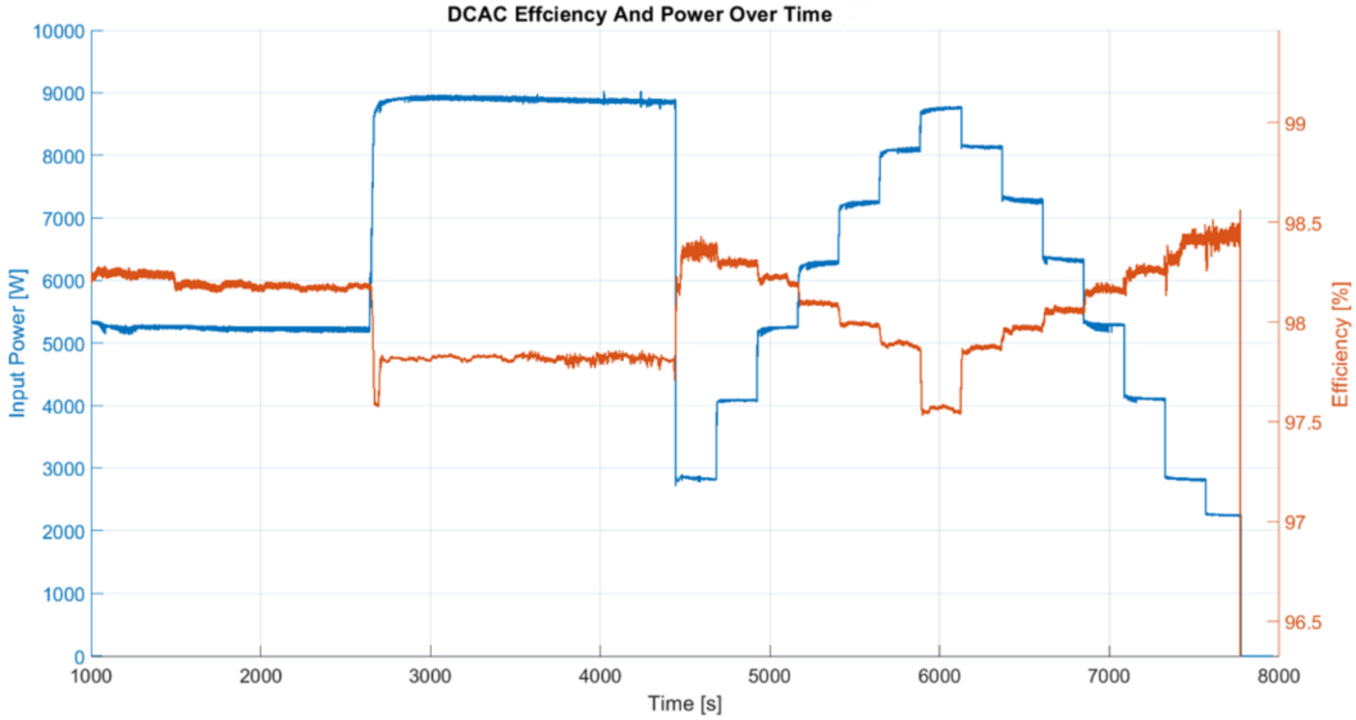


Figure 4-8: Efficiency of DCAC converter

5 Accompanying technical, ecologic and economic simulations

The accompanying impact assessment includes the analysis of socio-technical, ecological and economic implications that may arise from a future roll-out of the electrolysis and fuel cell technologies in respective applications.

5.1 Applied methods

The following sections briefly describe the methods used within the accompanying impact assessment. Further details on the individual model parameters and boundary conditions are further elaborated in the corresponding sections.

5.1.1 Analysis of future cost development and reduction potentials

To make projections of potential future costs of the main technologies developed within the project, technology costs were analyzed using learning curve and scaling methods. Therefore, the calculation model *CoLLeCT* was utilized. *CoLLeCT* represents a tool to calculate and analyze overall learning curves for variable assemblies by observance of the learning rates of its sub-components and their properties. Thus, it allows a detailed analysis of the cost structure as well as the comprehension of components from comparable and well-known technologies. Consequently, it is possible to determine the cost development of complex structures on at an early technology state according to future production volumes. Additionally, the modular approach allows for a consideration of spill-over effects from concurrent usages of technologies and components and a more detailed analysis of individual scalability and corresponding cost effects.

5.1.2 Macroeconomic assessment

The project included an analysis of macroeconomic effects at the Austrian level through the implementation of *SOLHUB* applications developed within HyTechbasis. In comparison to individual technology costs, the focus was not on the micro level (end consumer, companies), but on the entire economy of Austria. Within the analyses, concrete macroeconomic effects for a small, open economy (here: Austria) were quantified. In particular, effects of investment impulses due to roll-outs of selected *SOLHUB* applications - *SOLHUB as hydrogen refueling station* and *SOLHUB as electricity storage* - and domestic trade balance effects resulting from the substitution of imported fossil fuels and electricity were examined and quantified.
In view of the current developments - the economic recession caused by Covid-19 pandemic and current developments in the context of the Ukraine crisis - Austria is faced with the challenge of taking effective and efficient measures to create jobs and increase economic growth in the short, mid- and long-term. At the same time, the expansion of the production, storage and usage of renewable energy (green electricity and green hydrogen) will be essential for Austria to achieve its climate and energy policy goals. Herein, it was investigated whether selected *SOLHUB* applications can contribute to creating macroeconomic dividends on the path to climate neutrality.

5.1.3 Life Cycle Assessment

Within the project a Life Cycle Assessment (LCA) was performed considering a hydrogen production pathway via PEM electrolysis, where three different electricity sources are used as feed-in stock and various combinations of PEM capacities and daily production rates. The goal of this study was to determine the environmental impacts inferred by the production of green and grey hydrogen applying ISO 14040/44 LCA methodology. The first step of each LCA is to determine the system boundary and goal and scope of the assessment.

A “cradle-to-gate” assessment was carried out for the production of hydrogen through electrolysis, comprising the manufacturing phase of the PEM electrolysis plant at various capacities, the compression of the H_2 from 26- to 450 bar and the storage. Furthermore, a “cradle-to-use” assessment was made for the different use cases (mobility and), expanding the H_2 pathway with energy required for dispensing the hydrogen (mobility use case) and manufacturing of the PEM fuel cell (H_2 reconversion pathway). The LCA was based on GaBi ts 10.6 software and database as well as Ecoinvent 3.8 database.

5.1.4 Socio-technical assessment

The socio-technical assessment with model SAMBA was used for the analysis of the social and public acceptance of **HyTechbasis** respectively the application of the developed technologies in the Fronius **SOLHUB**, an integrated solution for the production, storage, distribution as well as re-conversion of solar hydrogen. The analysis focuses on the identification of opportunities as well as barriers and the generation of potentials for the future development. Based on significant effects on the Austrian economy, society and environment, targeted strategies and recommendations are derived.
The model SAMBA (Socio- and Multicriteria Model for reducing Barriers Analysis) is a tool for qualitative socio-technical assessments that has been developed at the Energieinstitut an der Johannes Kepler Universität Linz. It provides a qualitative empirical based analysis in order to find out more about the impacts of emerging technologies, processes, products or services. SAMBA combines two existing and acknowledged methodologies: stakeholder analysis and STEEP analysis, a qualitative assessment of sociological, technological, environmental, economic and political dimensions. The overall aim is to derive recommendations how to obviate emerging technologies, processes, products or services from obstacles and facilitate their successful implementation. Other comparable models or studies also combine stakeholder analysis and the qualitative assessment of different dimensions as the influence of relevant stakeholders on the developed indicators can be seen as strategically important [1, 2, 3].
As shown in Figure 5-1, the SAMBA model consists of four different modules: Module 1 – Starting Point, Module 2 – Stakeholder Analysis, Module 3 – STEEP Analysis and Module 4 – Comprehensive Analysis. Module 2 to 4 further consist of sub-modules, which split up the working steps within the modules into more details.

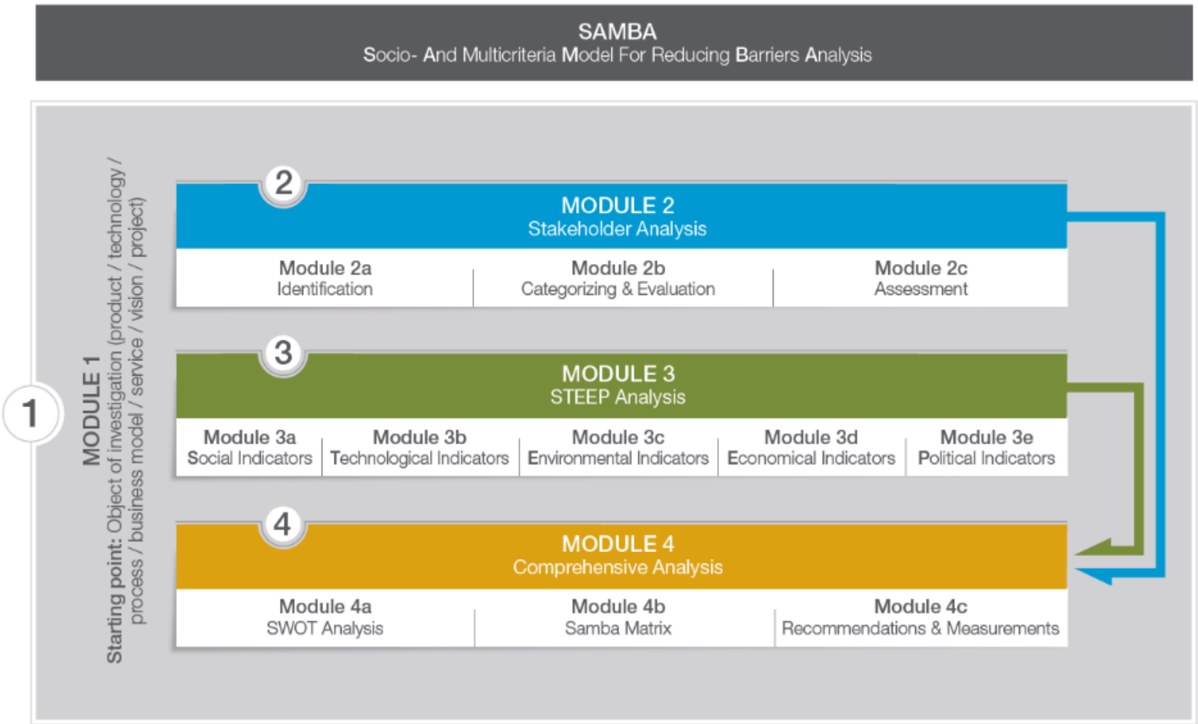


Figure 5-1: SAMBA Model. Source: Energieinstitut an der JKU Linz

5.2 Assessment of technological learning and scaling effects

To project future cost development for the HyTechbasis technologies the calculation model CoLLeCT was used. It allows for a determination of overall learning curves for technologies at early technology stages or low market uptake. The assessment of technological learning effects is therefore based on the consideration of individual learning rates and properties of included components. This disaggregation enables a comparison of learning rates between different technologies with similar subcomponents, materials, and manufacturing processes. Hence, it reduces the requirement of high amounts of cumulative productions to assess technological learning processes. Additionally, the modular approach allows to integrate common peripheral components in the analysis because direct and indirect learning effects, which result from spillover effects from concurrent usages, can be decoupled from the main (novel) technology. Consequently, also changes in the costs structure can be analyzed, allowing to identify potential leverages for cost reductions at early technology stages.
Even though this kind of learning curve assessment requires a certain knowledge, depending on the level of modularization, of the corresponding component and cost structure, as well as individual learning rates, the amount of technology-specific components is usually minor. Thus, a determination of component learning rates can also be derived from established technologies. This simplifies the generation of a found data basis and thus extends the range of assessable technologies.
In general, economies of scale subsume the different effects of cost reductions that come with increasing scales of product or technology deployment. Herein, two different scaling effects are differentiated: (i) cost changes resulting from increasing cumulative production volumes, also referred to as economies of number scale, and (ii) nonlinear increases in costs for implementations of larger scales, referred to as

economies of unit scale. Both effects are described in more detail below based on previously published literature [4, 5, 6]. For further details please refer to the corresponding publications.

5.2.1 Component and cost structure

The initial costs and their distribution to the individual components determines the starting point for the future cost analysis. The cost models were defined separately for electrolysis and fuel cell. For both technologies literature-based cost assumptions were compared to actual system costs evaluated for the testbeds configurations used in the project.

5.2.1.1 Electrolysis system cost structure

The literature-based cost model used for the electrolysis system was reused from previous analyses (cf. [4, 5]), which were performed on large-scale implementations of the three main electrolysis technologies. The corresponding model for the PEM electrolysis system was downscaled from 1 MW_{el} to 120 kW_{el} to fit the project targets and considers four modules: (i) PEM electrolysis stack, (ii) power electronics, (iii) gas conditioning, and (iv) balance of plant (BoP). Furthermore, the stack module is subdivided in 12 components. The corresponding cost structure is shown in Figure 5-2 at initial system costs of 2240 €/kW_{el}.

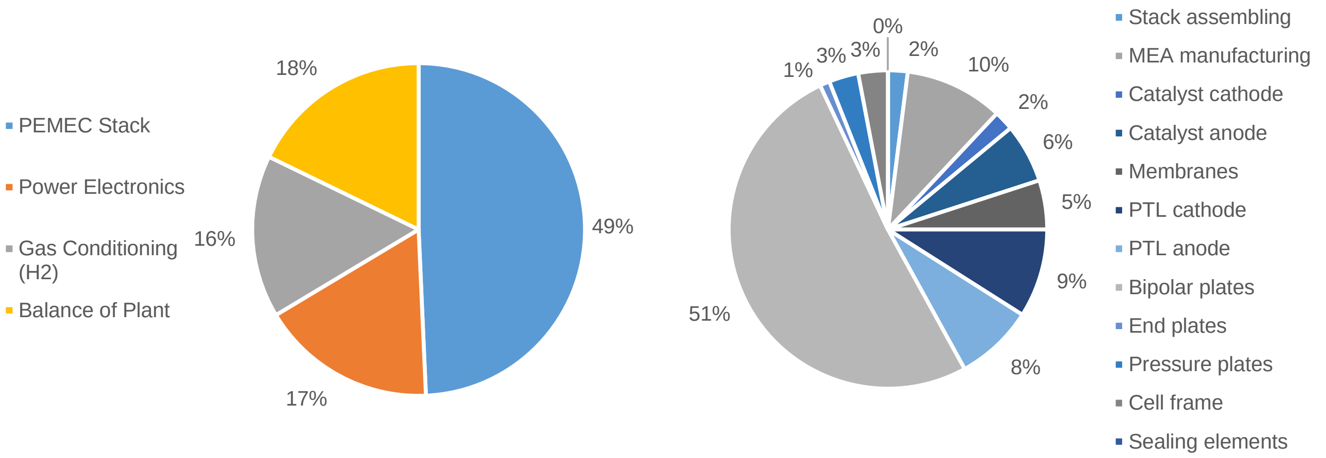


Figure 5-2: Literature-based cost structure for the PEM electrolysis system (left) and stack (right). Adapted from [4].

For the testbed system costs the cost structure was found to be different, particularly regarding stack and power electronics cost shares (see Figure 5-4). However, overall system costs were found to lower compared to the literature-based model at 1770 €/kW_{el}.

5.2.1.2 Fuel cell system cost structure

The initial costs for the fuel cell system were defined for a 5 kW system according to available literature data [7, 8]. The component structure was slightly adapted to be comparable to the distribution and nomenclature of the electrolysis model; thus, the fuel cell stack model also considers 12 components. The system also includes four modules: (i) PEM fuel cell stack, (ii) power electronics & control, (iii) fuel &

air conditioning, and (iv) balance of plant (BoP). The presumed costs for the literature-based model relate to 8000 €/kW. The corresponding cost structure is shown in .

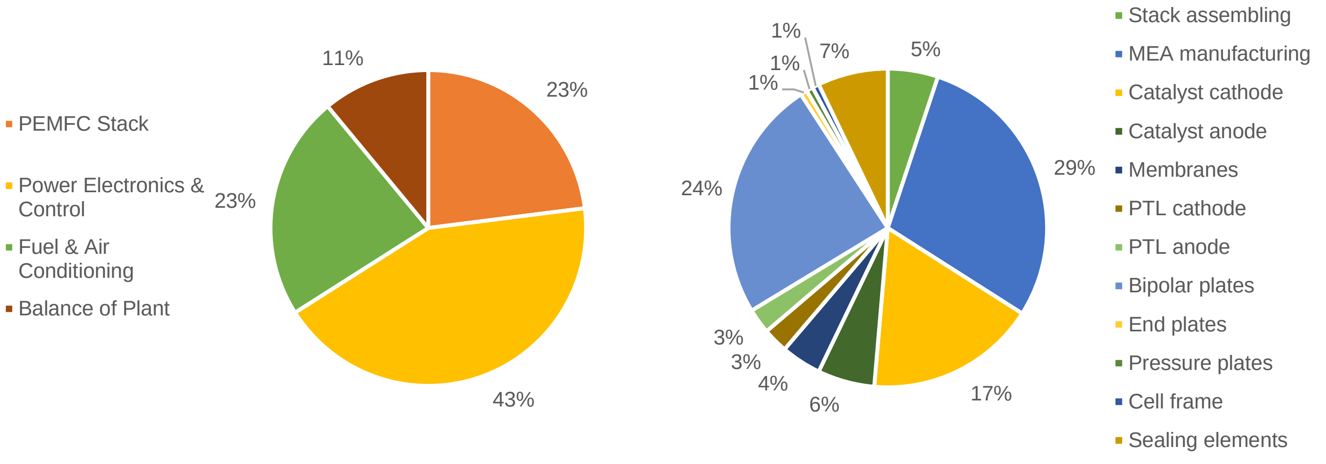


Figure 5-3: Literature-based cost structure for the PEM fuel cell system (left) and stack (right). Based on [7, 8].

The costs evaluated for the testbed system showed significant differences compared to the literature data (see Figure 5-4). In particular, the cost share of the stack on the overall system costs was found to be twice as high, while the cost share of power electronics was only a third. However, overall system costs were also found to be significantly lower for the testbed system at 5070 €/kW.

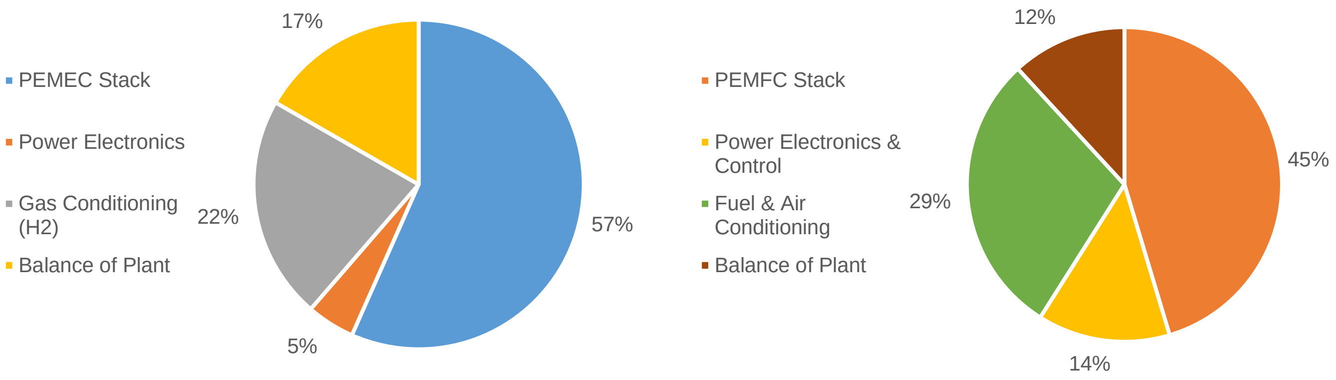


Figure 5-4: Cost structures evaluated for the testbed electrolysis (left) and fuel cell (right) system.

5.2.2 Market development and potential spillover effects

To evaluate future cost effects from technological learning the development of cumulative technology productions from current values is substantial (besides the learning rate). For the electrolysis system the presumptions made in previous studies [5, 6] were used, which consider the global industrial demand for renewable hydrogen along with potential demands for energy storage by 2050 in three deployment scenarios (see Table 5-1). As these scenarios consider electrolysis capacities of all technologies, technology shares of PEM systems were considered as defined in [5]. This also accounts for concurrent usages of peripheral system modules in other electrolysis and non-electrolysis technologies.[1]

Table 5-1: Global demand scenarios for electrolysis. Based on [5].

Scenario	Electrolysis capacity in GW_{el}	Notes
Low	1,310	• PtH_2 for chemical industry (ammonia, refinery, methanol synthesis) only • No storage
Moderate	2,170	• PtH_2 for chemical industry • PtH_2 for storage
High	4,530	• PtH_2 for chemical & steel industry • PtH_2 for storage

The assessment of technological learning effects for the fuel cell system relates to the general stationary application of PEM fuel cells. However, due to close similarities to other applications of PEM fuel cells as well as concurrent usages of peripheral components in other stationary and non-stationary systems, corresponding applications were appropriately considered to account for potential spillover learning effects. The analysis considered different international studies and roadmaps on current and future deployment of fuel cells in (mainly) mobile and stationary applications [9, 10, 11, 12]. Furthermore, annual reviews of the fuel cell industry were used to determine market developments and distribution of fuel cell technologies from 2011–2020 [13, 14]. Evaluated current and future market potentials for all fuel cell applications and stationary applications in particular are shown in Figure 5-5, along with expected shares of PEM technology for the respective applications. It can clearly be seen that stationary applications for PEM fuel cells are expected to stay at minor relevance (~18% market share), while the other markets, particularly driven by mobile applications, are seen with significantly increasing demands for PEM fuel cells. The impact of potential spillover effects from these markets was particularly addressed in the learning curve analysis.

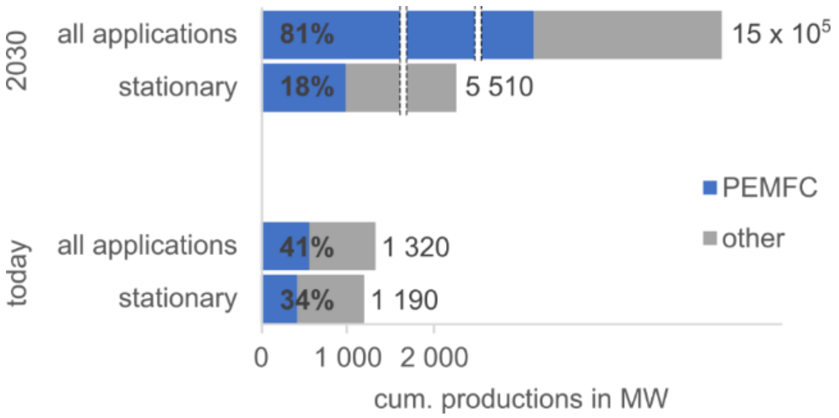


Figure 5-5: Evaluated market development for PEM and other fuel cells in relevant applications

[1] For a detailed description of model dependencies please refer to [4, 5].

5.2.3 Resulting cost reduction potentials induced by economies of scale

5.2.3.1 Effects of technological learning

The cost development for PEM electrolysis systems was evaluated according to the three defined industrial electrolysis deployment scenarios (low, moderate, high). The respective results for both, the literature-based and the testbed-related model, are shown in Figure 5-6. Despite an initially higher overall learning rate, owing to the higher share of the stack module, both models show similar cost reduction potentials and reach a comparable cost level in the long term, due to higher learning rates in literature-based model at lower cost levels. It also shows, that the additional impact of considered storage capacities (high vs. moderate scenario) is minor compared to the effects resulting from the more certain demands in industrial applications. Consequently, costs of PEM electrolysis systems in small-scale applications, such as for refueling or local energy storage, are expected to be mainly driven by spillover effects from industrial technology usages at larger scales.

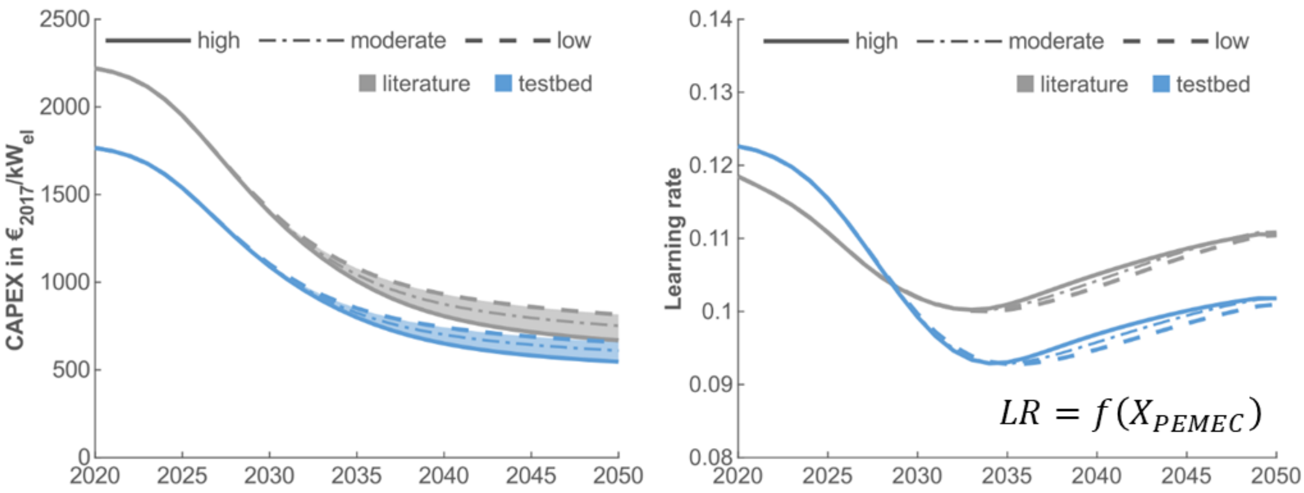


Figure 5-6: Calculated specific cost development (left) and corresponding system learning rates (right) for the PEM electrolysis system

For the fuel cell system, the focus of the learning curve analysis was on the impact of spillovers from concurrent technology uses. Therefore, the dependency of learning effects to the cumulative production of stationary PEM fuel cells was investigated in four configurations of model dependencies. These four scenarios basically represent a stepwise changing of system module dependencies from *'direct'* (=learning effects of the module are only driven by the cumulative production of stationary PEM fuel cells) to *'independent'* (=learning effects of the module only driven by the cumulative production of stationary PEM fuel cells and relevant productions concurrent applications)[2]. The corresponding scenarios are listed in Table 5-2.

Table 5-2: Module dependency configurations of the fuel cell learning curve model

	Stack	**Power Electronics**	**Fuel & Air Cond.**	**BoP**

[2] For a detailed description of module dependencies on cumulative productions in the learning curve model please refer to the corresponding literature [4, 5, 6].

all independent	**independent** (all PEM systems)	**independent** (stat. systems)	**independent** (stat. systems)	**independent** (stat. systems)
direct: Gas Cond.	**independent** (all PEM systems)	**independent** (stat. systems)	**direct** (stat. PEM systems)	**independent** (stat. systems)
direct: Gas Cond. & BoP	**independent** (all PEM systems)	**independent** (stat. systems)	**direct** (stat. PEM systems)	**direct** (stat. PEM systems)
direct: Gas Cond., BoP & Stack	**direct** (stat. PEM systems)	**independent** (stat. systems)	**direct** (stat. PEM systems)	**direct** (stat. PEM systems)

The results shown in Figure 5-7 indicate that cost reductions through technological learning are low for stationary PEM fuel cells if they are only driven by the cumulative production of this specific application (*direct* dependency) and, thus, being not affected of similar usages of components in other applications. However, considering spillover effects for the PEM stack module from usages in other applications – mainly transport/mobile – (cumulative productions mostly *independent* from stationary fuel cells) expectable learning effects increase significantly. Spillover effects from concurrent usages for the other system modules (gas conditioning, BoP) are comparably low. This means, that a close consideration of potential spillover effects is of major relevance for future cost estimations related to stationary PEM fuel cells to not disregard these impacts.

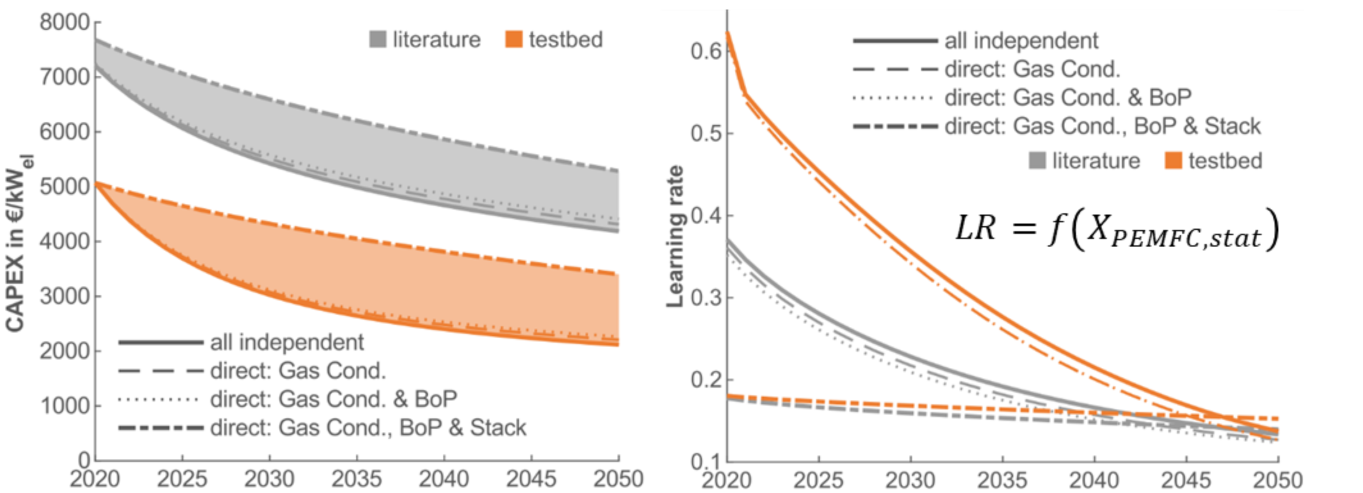


Figure 5-7: Calculated specific cost development (left) and corresponding system learning rates (right) for the PEM fuel cell system

Figure 5-7 also shows that the learning curve for the testbed model is steeper compared to the literature-based model. This is caused by the higher overall learning rate of the system, which is mainly caused by the higher cost share for the stack module. However, the highest difference is still related to the initial costs evaluated for the system, which indicates that a close reevaluation is required for an appropriate technology cost assessment.

5.2.3.2 Effects of unit scaling

Besides the effects of technological learning, the impacts of unit scaling on the system costs were considered as well. Therefore, the component structure of the learning curve models was used to apply per-component scaling factor. Then the impact of up- and downscaling from the reference system size – within project relevant system capacities – on the specific system costs was evaluated. The results are shown in Figure 5-8 in relation to the previously calculated learning curves. Based on these, unit-scaling effects from up-scaling are found to be more significant for the electrolysis system than for the fuel cell system (considering a scale-up of the system capacity by a factor of 5 for both).

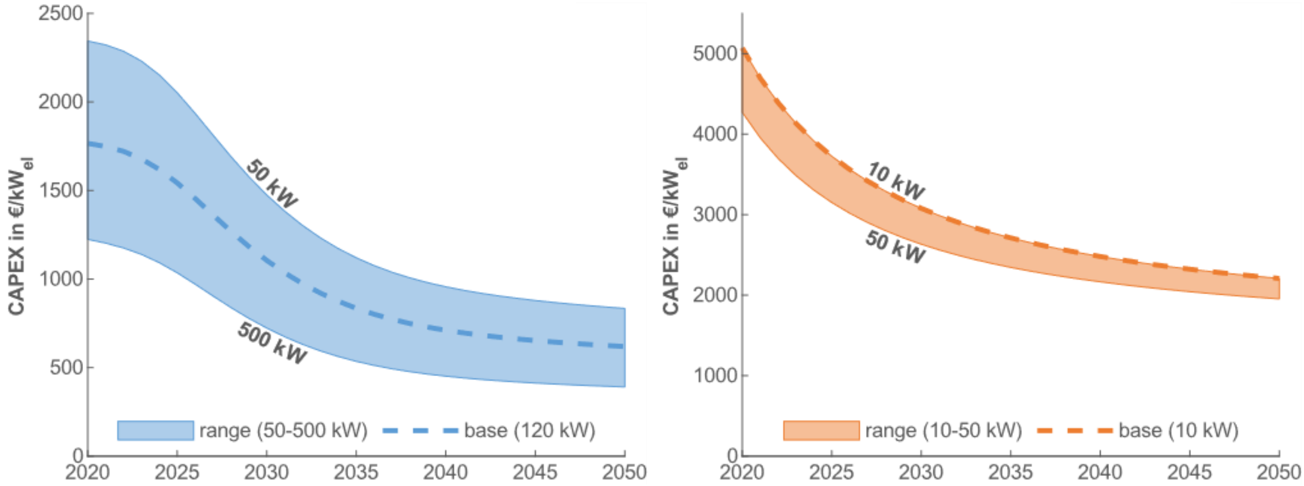


Figure 5-8: Representation of unit-scaling effects related to the calculated learning curve for the PEM electrolysis (left) and fuel cell (right) system

5.2.4 Conclusions and optimization potentials

The evaluation of scaling effects for the technologies developed in HyTechbasis indicates a significant cost reduction potential for both, electrolysis and fuel cell system. With relation to the technological investigations elaborated within the project, a significant cost reduction potential is expected according to the stack components. As the literature-based cost structure for the electrolysis cell in Figure 5-9 shows, approx. 80% of the stack costs are represented by catalysts, membrane, PTLs, and bipolar plates. Furthermore, these components commonly show high learning rates, either from material savings or manufacturing improvements. Therefore, alternative manufacturing techniques as investigated within the project may leverage additional learning effects. However, a reasonable assessment of the dedicated impacts requires an establishment of production processes at a (early) commercial state. Therefore, a reconsideration of respective learning effects at a later stage will be required for quantitative results.

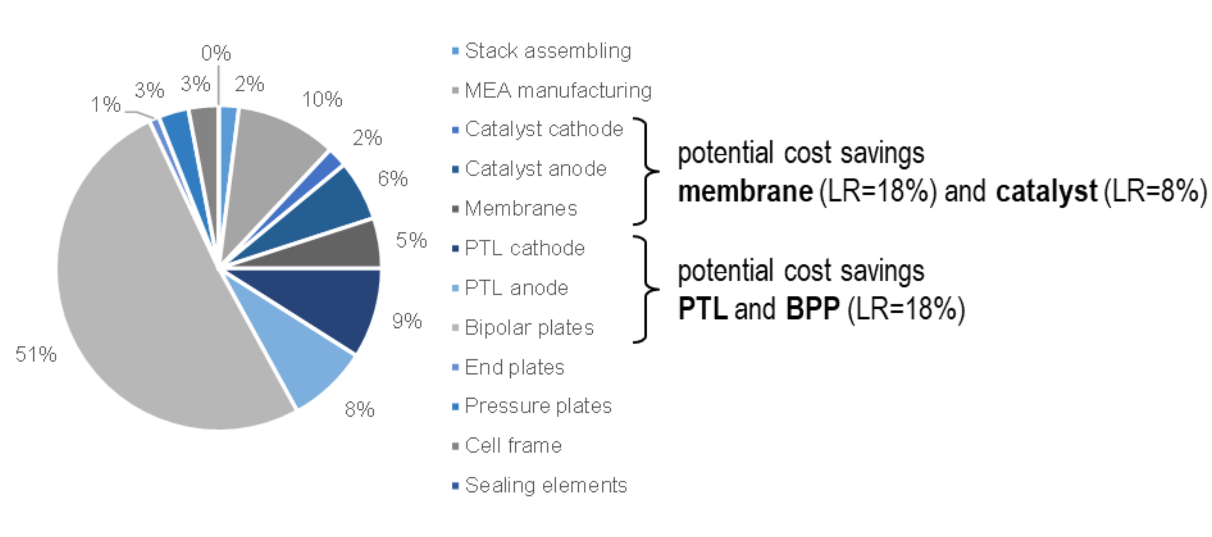


Figure 5-9: Cost optimization potentials related to economies of scale

5.3 Macroeconometric simulation

The macroeconomic effects in Austria due to roll-outs of selected *SOLHUB* applications are quantified through using the multi-sectoral model MOVE2. The time series-based simulation model MOVE[3] and its successor MOVE2[4] were developed at the Energieinstitut an der Johannes Kepler Universität Linz. These models allow the estimation of various economic and structural changes within Austria and the analysis of economic, environmental and energy-related effects based on different political and/or investment decisions. MOVE2 focuses on energy-related issues, which enables comprehensive and complex studies of all aspects of the national energy market. All endogenous variables are explained by stochastic equations, and the economic relationships are revealed through the use of time series. Therefore, the model draws on the economic structures of the past to simulate certain changes in future scenarios. The model is well suited to the purpose as already shown in former macroeconomic analyses for Austria (Goers and Schneider, 2019[5]; Bointner et al., 2013[6]).
The model is based on the expenditure concept of the gross domestic product (GDP) [7] which defines that *GDP* at point of time *t* equals the sum of investments *I*, private consumption *C*, government spending *G* and exports minus imports *NX:*

[3] Tichler, R. (2009): Optimale Energiepreise und Auswirkungen von Energiepreisveränderungen auf die oö. Volkswirtschaft - Analyse unter Verwendung des neu entwickelten Simulationsmodells MOVE (Linz: Energiewissenschaftliche Studien).

[4] Baresch, M., Goers, S.. Tichler, R., Schneider, F. (2014): MOVE2 - Modell zur Simulation der (ober-) österreichischen Volkswirtschaft mit einem speziellen Schwerpunkt auf Energie. Update des Modells MOVE (Linz: Energieinstitut an der Johannes Kepler Universität).

[5] Goers S, Schneider F (2019) Austria's Path to a Climate-Friendly Society and Economy-Contributions of an Environmental Tax Reform. Modern Economy 10: 1369–1384.

[6] Bointner R, Biermayr P, Goers S, et al. (2013) Wirtschaftskraft Erneuerbarer Energie in Österreich und Erneuerbare Energie in Zahlen. Blue Globe Report #1/2013. Vienna: Austrian Climate and Energy Fund

[7] See for example the explanations of the U.S. Bureau of Economic Analysis and International Monetary Fund: https://www.bea.gov/data/gdp/gross-domestic-product

$$GDP_t = I_t + C_t + G_t + NX_t$$

In particular, the development and interactions of those central macroeconomic variables, i.e., GDP, investments, employment, net exports and private consumption are displayed via the simulation analyses' results.

The different modules of MOVE2 are presented in Figure 5-10. The economic module covers 13 economic sectors (including the aggregate of private households). In addition to economic activities (investment, production, etc.) consumptions for different energy sources are considered at the sectoral level, so that the interaction of economy and energy is captured (energy module). Since the use of energy implicates the generation of pollutant emissions (incl. greenhouse gas emissions), MOVE2 also contains an emissions tool, which calculates the changes in emissions due to the energy consumption.[8] Within the module MOVE2social, the effects on unemployment or employment can be divided in economic sectors, income, gender and age.

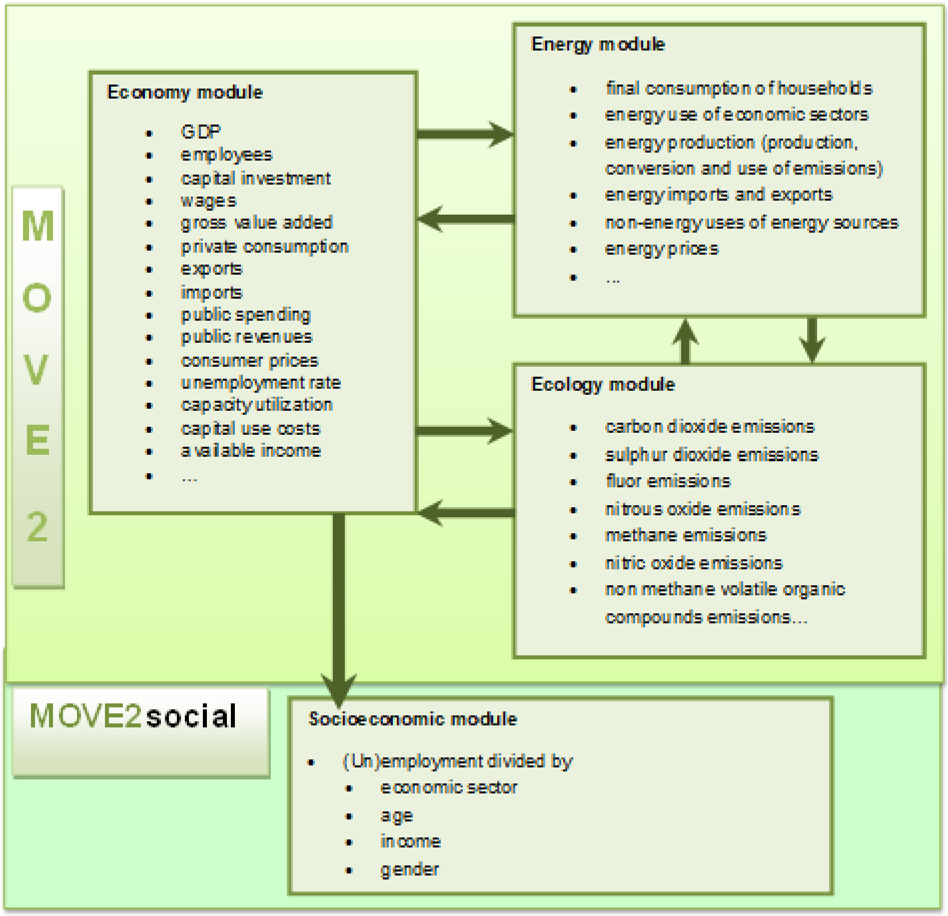


Figure 5-10: Overview of the tool MOVE2's modules (incl. MOVE2social). Source: Baresch et al. (2015)

https://www.imf.org/external/pubs/ft/fandd/basics/gdp.htm#:~:text=GDP%20measures%20the%20monetary%20value,the%20borders%20of%20a%20country

[8] In HYTECHBASIS 4 WIVA, the ecological impact is evaluated within the framework of a life cycle analysis.

5.3.1 Simulation design

In order to display the detailed effects of policy measures and investment decisions, two scenarios are set up in the MOVE2 model for simulations. First, a baseline scenario of developments in the Austrian economy is calibrated by historical data. This baseline scenario is based on key assumptions on economic growth, population growth, energy production and demand and energy prices. Secondly, scenarios are modelled, which basically involve a projection of what will happen because of the roll-outs of selected *SOLHUB* applications. By subtracting the simulation results of the 'what if the roll-outs of selected *SOLHUB* applications' from the baseline scenario it becomes possible to quantify and characterize the macroeconomic impacts.

The general assumptions for the simulations are the following:

- Geographical scope:
  The simulations evaluate the macroeconomic impacts stemming from the roll-outs of selected *SOLHUB* applications developed in the project HyTechbasis - *as hydrogen refueling station* and *SOLHUB as electricity storage* - in Austria.
- Timeframe:
  The simulation analyses consider a period of 10 years from 2024 to 2033.
- Business-as-usual scenario:
  The simulations display the effects compared to the business-as-usual scenario, in which there are no roll-outs of selected *SOLHUB* applications.
- Energy prices and taxes:
  The diesel prices are based on average levels (2021)[9] and take into account the future crude oil price developments forecasted by EIA[10] so that current increases are taken into account to a certain extent. Furthermore, the mineral oil taxation and CO_2 pricing starting in Austria in 2022 within the framework of the eco-social tax reform[11] was taken into account. By 2050, the CO_2 price in the non-emissions trading sector is assumed to increase to 300 €/tCO_2. The assumed electricity price amounts to 150 €/MWh.

The next generation electrolysis and fuel cell technologies developed in the HyTechbasis project are aimed to serve as base technologies implemented in the SOLHUB. It represents a system solution for local production, storage and use of renewable hydrogen. The scenarios with regard to rolling-out selected *SOLHUB* applications for the macroeconomic simulations are "*SOLHUB as hydrogen refueling station roll-out"* and *"SOLHUB as electricity storage roll-out*". For each of these two roll-outs, the same expansion path (additional newly installed systems per year and additional cumulative installed systems) is assumed (see Figure 5-11).

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[9] See information provided by Statistik Austria: http://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/energie_und_umwelt/energie/preise_steuern/index.html
[10] See information provided by the U.S. Energy information Administration: https://www.eia.gov/outlooks/steo/
[11] Details of the tax reform Act con be found via https://www.parlament.gv.at/PAKT/VHG/XXVII/ME/ME_00158/

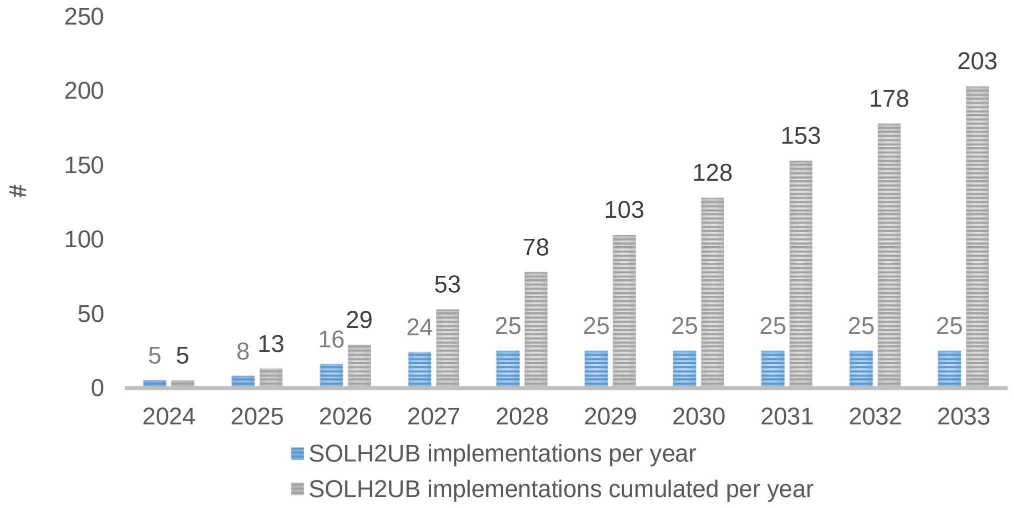

Figure 5-11: Expansion paths in the roll-out scenarios

5.3.1.1 Roll-out of SOLHUB as hydrogen refueling station

For this application roll-out, the following technical assumptions were made, representing the reference implementation:

- H_2 production: 48kg/d, single electrolyzer with two stacks (120-150kW BOL-EOL), approx. 220kW total connected load (incl. auxiliaries, compressor, refueling cooling, air conditioning...)
- Incl. container and all auxiliaries, no heat extraction, 700bar fuel dispenser with pre-cooling
- Medium and high-pressure storage systems with 450 (28kg) and 900bar (60kg) storage banks

The investment costs for an implementation in this configuration, which are effective in the sectors energy, production of material goods (manufacturing), construction and services, were presumed with 1.450.000 € excl. VAT (in consultation with Fronius). It should be noted that import quotas for the necessary technologies, materials and services were taken into account. Thus, for the electrolyzer and the refueling station infrastructure, the share produced abroad was taken into account.[12] The service and maintenance costs amount to 4% of the investment costs per year.

The production of H_2 and its use as fuel in road transport can substitute diesel consumption and resulting diesel imports. Per plant, 17.5 t H_2 are produced per year, resulting in the substitution of approx. 97,000 l diesel, as displayed in Figure 5-12 and Figure 5-13.

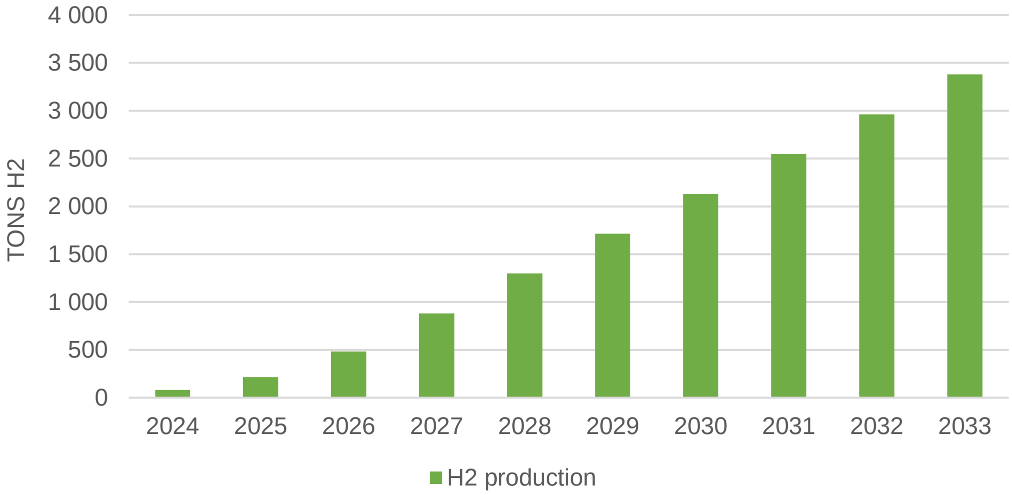

Figure 5-12: H_2 produced in the SOLHUB as hydrogen refueling station roll-out

[12] For the electrolyzer, a constant import quota of 70% was assumed, for the fueling station infrastructure a constant import quota of 30% was assumed.

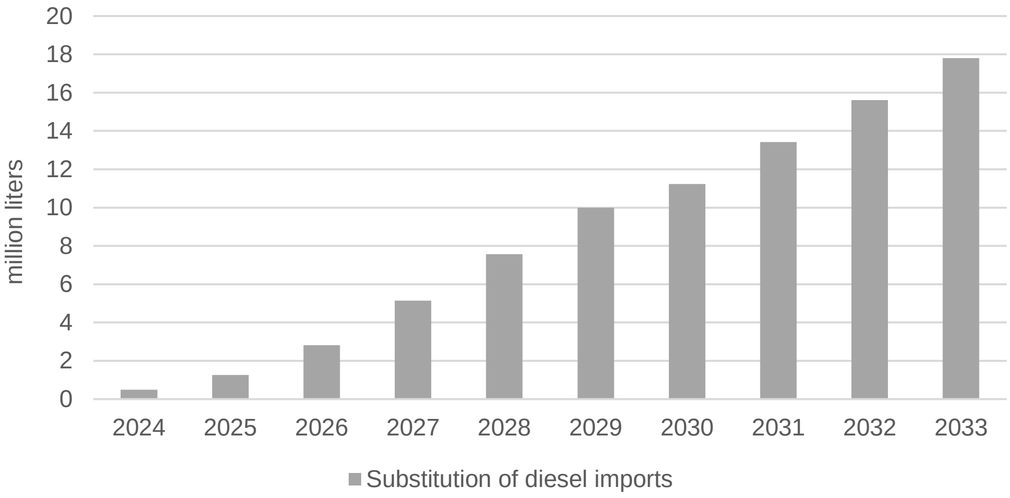

Figure 5-13: Diesel imports substituted in the SOLHUB as hydrogen refueling station roll-out

5.3.1.2 Roll-out of SOLHHUB as electricity storage:

For this application roll-out, the following technical assumptions were made:

- H_2 production: 48kg/d, single electrolyzer with two stacks, approx. 180kW total connected load
- Fuel cell with 40kW
- Incl. container and all auxiliary aggregates, incl. heat extraction
- Medium pressure storage system 450bar with 56kg
- Commercial PV system (costs: 1,150 €/kW)

The investment costs for an implementation in this configuration, which are effective in the sectors energy, production of material goods (manufacturing), construction and services, were presumed with 1.315.000 € excl. VAT (in consultation with Fronius; incl. PV a capacity of 100 kWp). It should be noted that import quotas for the necessary technologies, materials and services were taken into account. Thus, for the electrolyzer, the fuel cell, and the PV system, the share produced abroad was taken into account[13]. The service and maintenance costs amount to 4% of the investment costs per year.

The production and storage of electricity and its feeding into the grid when there is demand can substitute electricity imports. Per plant, 0.4 TJ electricity are produced and stored per year, resulting in the substitution of approx. 74 TJ electricity in 2033, as displayed in Figure 5-14.

[13] For the electrolyzer and the fuel cell, a constant import quota of 70% was assumed, for the PV system a constant import quota of 40 % was assumed.

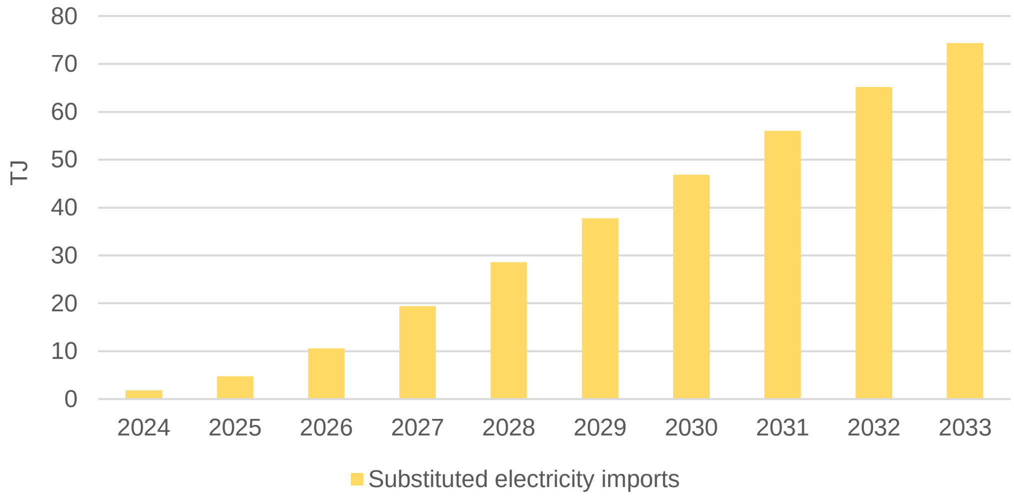

Figure 5-14: Electricity imports substituted in the *SOLHUB as electricity storage* roll-out

5.3.2 Derived macroeconomic impact

Based on the results of the ex-ante simulation analyses, positive effects on the Austrian economy through rolling-out the selected *SOLHUB* applications - *SOLHUB as hydrogen refueling station* and *SOLHUB as electricity storage* - can be identified (see Table 5-3).

Table 5-3: Average GDP and employment effects of *SOLHUB* applications

SOLHUB hydrogen refueling station roll-out		***SOLHUB electricity storage roll-out***	
∆ GDP$_{Ø2024-2033}$	**∆ employment$_{Ø2024-2033}$**	**∆ GDP$_{Ø2024-2033}$**	**∆ employment$_{Ø2024-2033}$**
+64 m €p.a.	+ 800 employees	+10 m €p.a.	+ 200 employees

Notes: Nominal and net values. Results include direct and induced effects compared to the business-as-usual scenario. Assumptions on the scenarios can be found in Section 5.3.1.
Source: Own calculation based on MOVE2, January – March 2022, Energieinstitut an der JKU Linz.

In both scenarios, there are positive investment impulses and effects on the trade balance. The latter results in scenario *SOLHUB as hydrogen refueling station* from the substitution of imported diesel by domestically produced H_2, and in scenario *SOLHUB as electricity storage* from the provision of renewable electricity, which substitutes electricity imports. In the case of the *SOLHUB as hydrogen refueling station,* these effects outweigh the import costs for implementing the technologies. As a result of increased employment, there are also induced effects. A higher wage level leads to higher consumption. Economic growth also once again boosts corporate investment activities in various sectors of the economy.
In the roll-outs, an average additional economic value of 0.7 m € per plant is created in the scenario *SOLHUB as hydrogen refueling station*, and an additional economic value of 0.1 m € per plant is created in the scenario *SOLHUB as electricity storage*.
It should be noted that the two roll-out scenarios are not comparable with each other, since different energy sources are produced or different imports (diesel, electricity) with different future price paths are substituted in the applications considered. However, the simulation results clearly show that a double dividend is created in both scenarios. On the one hand, there is additional economic growth (economic

dividend), on the other hand, there is an ecological benefit (ecological dividend - see also the results of the LCA in Section 5.4.3). Against the background of current developments in the context of a possible security of supply crisis due to the war in Ukraine, both implementations also show that domestic security of supply can be created.

5.3.2.1 Roll-out of *SOLHUB* as hydrogen refueling station: Detailed results

The additional economic growth leads to an additional GDP of 155 m € in 2033. The main drivers are investments due to implementing the *SOLHUB* hydrogen refueling stations, which, including multiplier effects, amount to 40 m € in 2033. Domestic production of H_2 and substitution of diesel imports generate positive effects on the current account. The continuous expansion pushes investment activities of domestic enterprises and amplifies trade balance effects annually. Investments in hydrogen refueling station infrastructure have strong effects on economic growth and employment (due to a low import ratio). In addition, consumers of fuel have more financial resources available due to the substitution of diesel by H_2. These are partly used for reinvestment, which in turn boosts the economy. In 2033, additional employment of 2,200 employees is achieved. It should be noted that these are net effects, so additional employment in other sectors of the economy is also captured as a result of general economic growth. The higher employment leads to a higher wage level, so that private household consumption also increases.

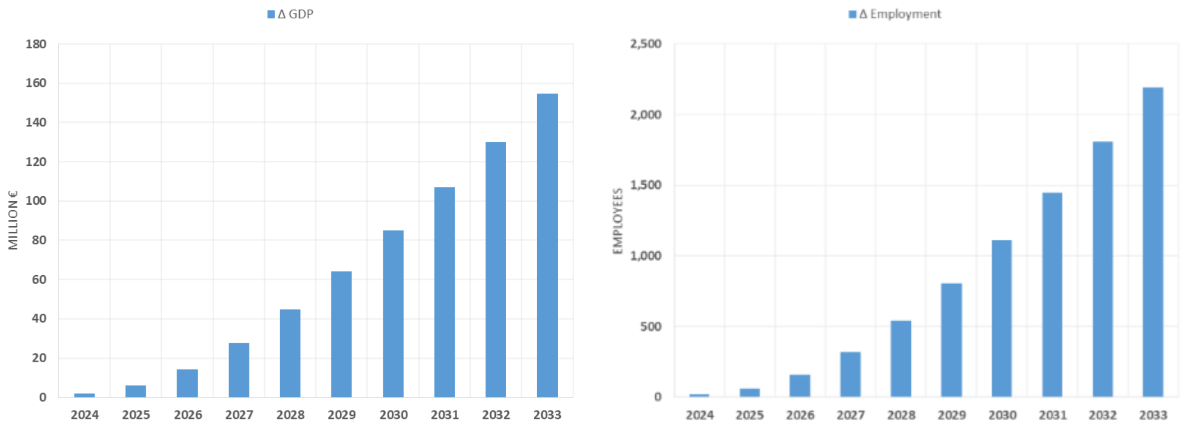

Figure 5-15: GDP and employment effects through the *SOLHUB as hydrogen refueling station roll-out*
Notes: Nominal and net values. Results include direct and induced effects compared to the business-as-usual scenario. Assumptions on the scenarios can be in Section 5.3.1.
Source: Own calculation based on MOVE2, January – March 2022, Energieinstitut an der JKU Linz.

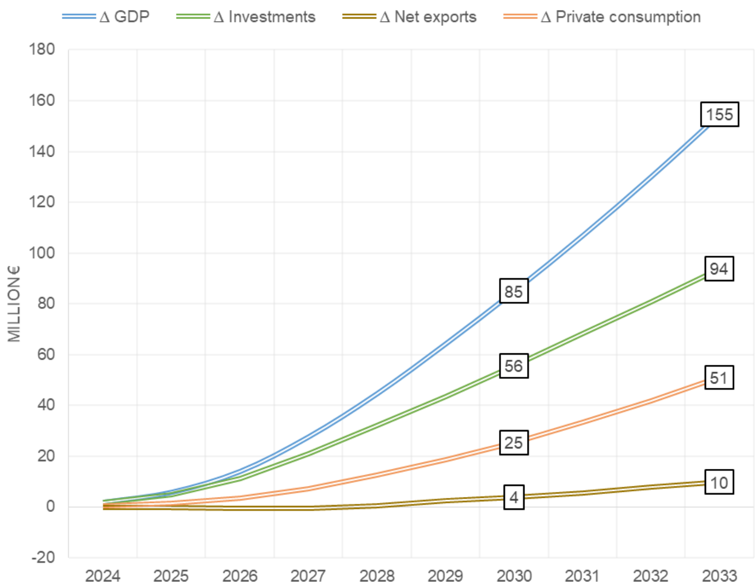

Figure 5-16: Effects on key macroeconomic variables and their interaction through the *SOLHUB as hydrogen refueling station* roll-out

Notes: Nominal and net values. Results include direct and induced effects compared to the business-as-usual scenario. Assumptions on the scenarios can be in Section 5.3.1.

Source: Own calculation based on MOVE2, January – March 2022, Energieinstitut an der JKU Linz.

Table 5-4: Macroeconomic effects through the *SOLHUB as hydrogen refueling station roll-out*

	Δ GDP [m €]	**Δ Investments [m €]**	**Δ Net exports [m €]**	**Δ Consumption [m €]**	**Δ Employment [# employees]**
2024	+2	+2	-0.3	+0.4	+20
2025	+6	+5	-0.3	+1	+60
2026	+14	+11	-0.5	+4	+160
2027	+28	+21	-0.5	+7	+320
2028	+45	+32	+0.5	+12	+540
2029	+64	+43	+3	+19	+810
2030	+85	+56	+4	+25	+1,110
2031	+107	+68	+5	+33	+1,450
2032	+130	+81	+8	+42	+1,810
2033	+155	+94	+10	+51	+2,190
Ø	+64	+41	+3	+19	800

Notes: Nominal and net values. Results include direct and induced effects compared to the business-as-usual scenario. Assumptions on the scenarios can be in Section 5.3.1.

Source: Own calculation based on MOVE2, January – March 2022, Energieinstitut an der JKU Linz.

5.3.2.2 Roll-out of *SOLHUB as electricity storage*: Detailed results

The additional economic growth leads to an additional GDP of 17 m € in 2033. The main drivers are investments due to implementing the *SOLHUB* electricity storage (incl. PV systems), which, including multiplier effects, amount to 13 m € in 2033. Domestic production of electricity generates positive effects on the trade balance which, however, are outweighed by imports of the required technologies. In 2033, additional employment of 390 employees is achieved. Analogously to Section 5.3.2.1, it should be noted that these are net effects, so additional employment in other sectors of the economy is also captured as a result of general economic growth. The higher employment leads to a higher wage level, so that private household consumption also increases.

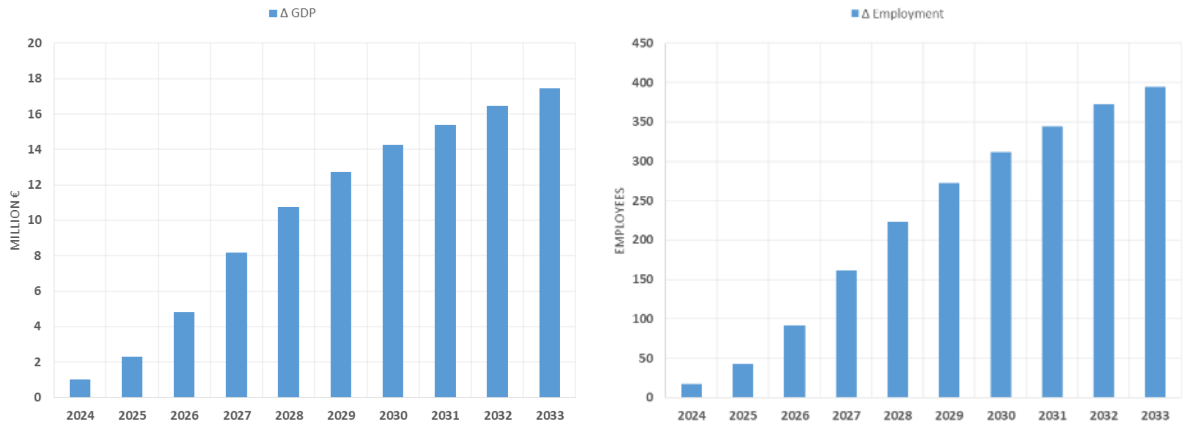

Figure 5-17: GDP and employment effects through the *SOLHUB as electricity storage (incl. PV systems) roll-out*

Notes: Nominal and net values. Results include direct and induced effects compared to the business-as-usual scenario. Assumptions on the scenarios can be in Section 5.3.1.

Source: Own calculation based on MOVE2, January – March 2022, Energieinstitut an der JKU Linz.

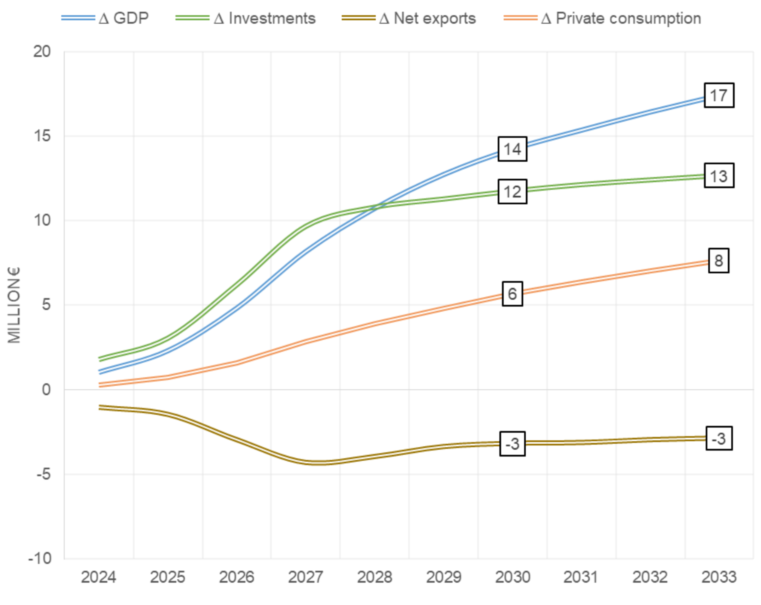

Figure 5-18: Effects on key macroeconomic variables and their interaction through the SOLHUB as electricity storage (incl. PV systems) roll-out

Notes: Nominal and net values. Results include direct and induced effects compared to the business-as-usual scenario. Assumptions on the scenarios can be in Section 5.3.1.

Source: Own calculation based on MOVE2, January – March 2022, Energieinstitut an der JKU Linz.

Table 5-5: Macroeconomic effects through the *SOLHUB as electricity storage (incl. PV systems) roll-out*

	Δ GDP [m €]	Δ Investments [m €]	Δ Net exports [m €]	Δ Consumption [m €]	Δ Employment [# employees]

2024	+1	+2	-1	+0.3	+20
2025	+2	+3	-1	+1	+40
2026	+5	+6	-3	+2	+90
2027	+8	+10	-4	+3	+160
2028	+11	+11	-4	+4	+220
2029	+13	+11	-3	+5	+270
2030	+14	+12	-3	+6	+310
2031	+15	+12	-3	+6	+340
2032	+16	+12	-3	+7	+370
2033	+17	+13	-3	+8	+390
Ø	+10	+9	-3	+4	+200

Notes: Nominal and net values. Results include direct and induced effects compared to the business-as-usual scenario. Assumptions on the scenarios can be in Section 5.3.1.
Source: Own calculation based on MOVE2, January – March 2022, Energieinstitut an der JKU Linz.

5.3.2.3 Socio-economic evaluation of additional employment

in addition to the economic efficiency and environmental effectiveness, socioeconomically preferred or non-regressive distributional effects also have to be taken into account. On the basis of the module MOVE2social, the effects of energy and climate policies for Austria can be displayed from a socioeconomic point of view (Baresch et al., 2014) [14]. With regard to the additional employment, MOVE2social defines the following subdivisions and socio-economic parameters: (i) income class, (ii) gender and (iii) age. The results show that within the average additional employment per year, about three quarters of the additional employees receive an income between 30,000 and 60,000 €, gender neutrality is almost achieved and more than half of the additional employees are between 36 and 55 years old.

Table 5-6: Socio-economic distribution of additional employment (average values)

Average values ($Ø_{2024-2033}$) for *SOLHUB as hydrogen refueling station* and *SOLHUB as electricity storage roll-out scenarios*	
Distribution of additional employment via	
Income class	
0 – 30,000 €	20%
30,000-60,000 €	75%
> 60,000 €	5%
Gender	
female	48%
male	52%
Age	
16-25 years	16%
26-35 years	20%

[14] Baresch, M., Goers, S.. Tichler, R., Schneider, F. (2014): MOVE2 - Modell zur Simulation der (ober-) österreichischen Volkswirtschaft mit einem speziellen Schwerpunkt auf Energie. Update des Modells MOVE (Linz: Energieinstitut an der Johannes Kepler Universität).

36-45 years	31%
46-55 years	26%
56-65 years	8%

Notes: Results include direct and induced effects compared to the business-as-usual scenario. Assumptions on the scenarios can be in Section 5.3.1.
Source: Own calculation based on MOVE2social, March 2022, Energieinstitut an der JKU Linz.

5.4 Life Cycle Assessment

5.4.1 Methodology

In general, the applied LCA methodology has been described extensively in literature [15, 16]; thus this section is meant to give an overview over the most important aspects pertaining to this study. LCA is a powerful decision support tool, complementing other methods, which are equally necessary to help effectively and efficiently make consumption and production more sustainable. The 14044 standard provides the indispensable framework for LCA, as summarized in Figure 5-19. Its individual steps and iterative approach are briefly introduced in the following paragraphs.

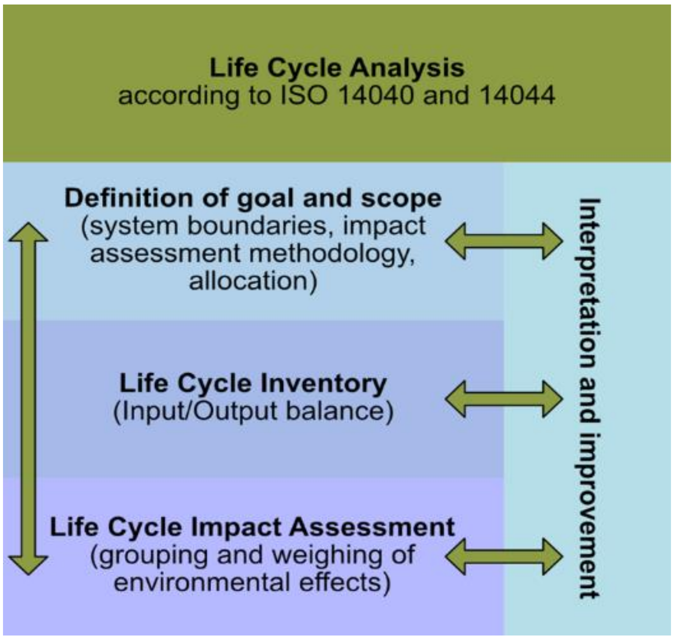

Figure 5-19: General methodology of LCA according to ISO 14040 and 14044. Source: Energieinstitut an der JKU Linz based on [17]

The first step to an LCA should be the definition of goal and scope. Due to the reason that LCA is an iterative process, these definitions are likely to be revised in case a better-suited case is found. The collection of data, the creation of the life cycle inventory (LCI) is followed by the impact of the latter (LCIA, life cycle impact assessment) which should be performed iteratively and may also induce a change of goal, scope or functional unit [18].

5.4.1.1 Definition of goal and scope

The system boundary defines where the investigated process ends and where the system starts. First the boundaries between the technical system (biorefinery) and nature are determined. A typical LCA starts with the extraction of raw materials, the processing thereof and an End-of-life (EoL) phase in which the product is either recycled, disposed of or thermally valorised. Although this is a prominent approach, another widely used option is cradle-to-gate in which the system ends at the production of the analysed good. This concept is useful for comparing a new manufacturing process to an established one.

5.4.1.2 Life Cycle Inventory analysis

The inventory analysis is done on the basis of unit processes. It is a quantitative assessment of the inputs going in the unit process and outputs of unit processes in terms of material and energy flows. Inputs are mostly energy and substances, whereas outputs are intermediates, final products as well as emissions.
A major issue in Life Cycle Inventory (LCI) compilation is data collection and generation. For every unit process within the process system the inputs and outputs have to be quantified. [18], [19]. Usually the mass- and energy balances are related to the functional unit, in this case 1kg of H_2 produced These balances are crucial for an LCA, as the results can only be as good as the provided data [20]. The ensure the quality of data only background processes of the GaBi & Ecoinvent will be used.

5.4.1.3 Life Cycle Impact Assessment

On the basis of the inventory resulting environmental burdens are aggregated to a number of impact categories. Life Cycle Impact Assessment (LCIA) is the stage during LCA where results of inventory analysis are transformed to environmental impacts. The material and energy flows of the LCI are matched to impact categories in a step called classification and in the following step of characterization category indicator results are calculated [21]. These steps require the LCA practitioner to choose from the variety of impact categories, indicators and characterization models [22]. A comprehensive example is the midpoint category of climate change, constating of the amount of greenhouse gases like CO_2 and CH_4 emitted during a process. These are life cycle inventory results which are attributed to impact category of climate change. The following category indicator is the quantification of the intensification of infrared radiation oriented on a reference substance. As a result, the impact of CO_2 and CH_4 on environment is subsumed as kg CO_2-equivalents which is the measure for the Global Warming Potential (GWP). Methane is also a good example how an LCI on its own can mislead, as one kg of methane is equivalent to 25 kg CO_2 and sulphur hexafluoride even to 25,000 kg when it comes to the global warming midpoint category [23].
One of those methods which covers scope definition, life cycle inventory and the impact assessment and therefore confirms the norm ISO 14044 is the CML-norm (Centrum voor Milieukunde). In general, the CML method is a problem-oriented classification of material and energy flows for impact assessment and categorizes results in so-called midpoint categories [24]. The method is internationally accepted amongst LCA practitioners and thus will be used for this work. Table 5-7 shows the impact categories within the CML method which are investigated here.

Table 5-7: Impact categories and units within the CML method

Impact categories within the CML method	Unit
Global warming potential (GWP 100 years)	[kg CO_2-Equiv.)

Ozone layer depletion potential (ODP, steady state)	[kg R11-Equiv.]
Acidification potential (AP)	[kg SO_2-Equiv.]
Eutrophication potential (EP)	[kg Phosphate-Equiv.]
Photochemical ozone creation potential (POCP)	[kg Ethene-Equiv.]
Human toxicity potential (HTTP inf.), Terrestric ecotoxicity potential (TETP inf.)	[kg DCB-Equiv.]
Freshwater aquatic ecotoxicity potential (FAETP inf.), Marine aquatic ecotoxicity potential (MAETP inf.)	[kg DCB-Equiv.]
Abiotic depletion (ADP)	[kg Sb-Equiv.]

Source: Energieinstitut an der JKU Linz based on [25]

The impacts of every substance monitored in the LCI is attributed to one of the CML impact categories shown above. This is done by converting the substances of the LCI to the units which describe the particular impact categories by using characterization factors. The result is a complete LCIA [25]. The LCIA is done purely descriptive, there is no weighing of results in order to keep the analysis scientifically objective. Weighing the environmental impacts against each other is deemed unscientifically and therefore omitted.

5.4.1.4 Life Cycle Interpretation

Interpretation of LCA has to contain the identification of significant issues, an evaluation considering completeness, sensitivity and consistency checks, conclusions, limitations, and recommendations. This means ensuring the system, its boundaries and the functional unit were chosen adequately. Even if those are found acceptable a sensitivity analysis should be performed nevertheless. Part of Life Cycle Interpretation will be a sensitivity analysis. Normally important mass or energy flows with considerable contributions are further investigated. Moreover, values derived from literature with a high uncertainty are a good candidate for a sensitivity analysis too.

5.4.2 Study design

5.4.2.1 Scenarios and system boundary

The goal and scope of this LCA study is to examine the environmental impacts associated with the production of hydrogen from three main pathways and various technology mixes, and three use cases comprising of dispensed hydrogen towards a fuel cell truck and bus; and hydrogen reconversion with a use of a PEM fuel cell. The study is aimed at analysing the environmental soundness of using different electricity combinations and comparing them throughout various implementations.
Figure 5-21 displays the two system boundaries specified, with system boundary 1 (SB1) being a cradle-to-gate and system boundary 2 (SB2) being a cradle-to-use scope, the latter extending the SB1 with additional use case processes. SB1 consists of the manufacturing of the PEM electrolyzer, the electrolysis process, compression and storage; while SB2 adds additional electricity requirements for the dispensing of the bus and truck, and the fuel cell manufacturing processes for the FC pathway.
Excluded from the system are the end of life (EoL), waste and recycling processes; as well as the manufacturing processes of the compressor, hydrogen refuelling station (HRS) and the transport means (bus & truck).

Functional units:

- The reference system (FU) for SB1 is 1kg H2 produced.
- The reference system (FU) for SB2 is 1km transport by a bus/truck and 1kWh electricity output from the fuel cell.

	50kW PEM (13 kg H2)			100kW PEM (20 kg H2)			200kW PEM (50 kg H2)			500kW PEM (100 kg H2)			500kW PEM (200 kg H2)		
	AT Grid	RES	PV+ AT Grid	AT Grid	RES	PV+ AT Grid	AT Grid	RES	PV+ AT Grid	AT Grid	RES	PV+ AT Grid	AT Grid	RES	PV+ AT Grid
SB.1, H2 prod. (FU = 1kgH2)	Sc.1	Sc.2	Sc.3	Sc.4	Sc.5	Sc.6	Sc.7	Sc.8	Sc.9	Sc.10	Sc.11	Sc.12	Sc.13	Sc.14	Sc.15
SB.2, Bus (FU = 1km)	Sc.16	Sc.17	Sc.18							Sc.19	Sc.20	Sc.21	Sc.22	Sc.23	Sc.24
SB.2, Truck (FU = 1km)	Sc.25	Sc.26	Sc.27							Sc.28	Sc.29	Sc.30	Sc.31	Sc.32	Sc.33
SB.2, Fuel cell (FU = 1kWh)	Sc.34	Sc.35	Sc.36	Sc.37	Sc.38	Sc.39	Sc.40	Sc.41	Sc.42						
	10kW PEM-FC			20kW PEM-FC			50kW PEM-FC								

Figure 5-20: List of the analyzed scenarios in the study. Source: Energieinstitut an der JKU

Figure 5-20 shows the scenarios integrated into this LCA study based on the input parameter configurations from Fronius, where the different PEM-EC capacities had been coupled with different daily H_2 production rates in SB1. SB2 builds on the scenarios from SB1, including 9 additional scenarios for the truck use case (Sc. 16-24) and 9 additional scenarios for the bus use-case (Sc. 25-33) For the PEM-FC only 6 scenarios are considered (Sc. 34-42) due to the constraints of the fuel cell sizes (10-,20- and 50kW FC). In general, the scenarios for SB2 are based on the SB1 scenarios that had shown the largest variations in the impact assessment, deeming the inclusion of further scenarios unnecessary and repetitive.

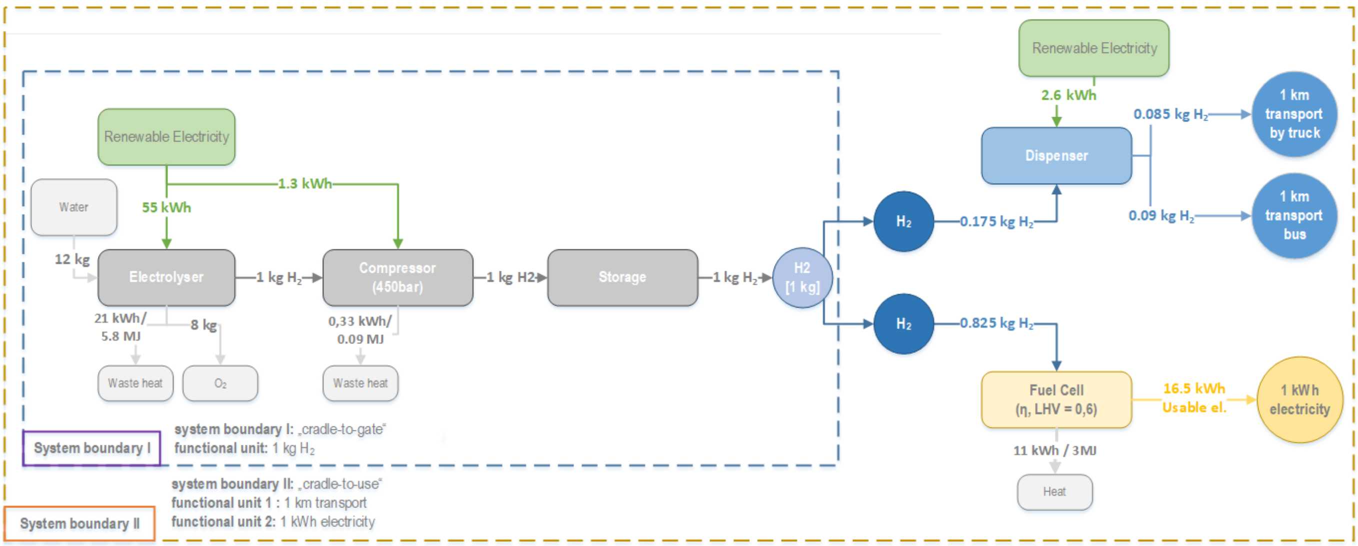

Figure 5-21: A schematic overview of the system boundary used in LCA study.

5.4.2.2 Assumptions

The main assumptions are summarized in Table 5-8, followed by a more detailed description of each system component in the following order: electrolyzer (a), compressor (b), storage (c), dispenser (d), truck (e), bus (f) & fuel cell (g).

Table 5-8: Summary of the main assumptions for the input parameters.

System boundary	Assumptions		Unit	Value
(I) H_2 **production:**				
	PEM-EC Stack (a)	Efficiency (η)	% (LHV)	61 [-]
		Production rate per kW	kg H_2 / hr	0.0183 [-]
		Electricity demand	kWh/kgH_2	55 [-]
		H_2O consumption	kg H_2O/kgH_2	12 [-]
(I) H_2 **Compression**				
Isothermal compression (b):	26 bar → 450 bar	Electricity demand	kWh/kg H_2	1.32 [26]
	compression	Efficiency (η)	η %	75 [3]
(I) H_2 **Storage**				
		Capacity	kg H_2	27 / 50 [-]
	Storage tank	Type	-	IV [27]
(II) Bus & Truck:				
	Dispenser (d)	Electricity demand	kWh/kg H_2	2.57 [28]
	Truck operation (e)	H_2 consumption	kg H_2 /km	0.0845 [29]
	Bus operation (f)	H_2 consumption	kg H_2 /km	0.09 [30]
(II) Fuel Cell:				
	PEM-FC Stack (g)	Efficiency	% (LHV)	60 [31]

Note: Where no reference is provided, the data comes from the project partners Fronius.

5.4.2.3 Life Cycle Inventory compilation & data demand

As mentioned before, an LCA can only be as good as its input or data inventory (LCI). For the compilation of the LCI second-hand data has been used from several literature sources.

5.4.2.3.1 LCI for the PEM-EC, PEM-FC and storage tank.

The Life Cycle Inventory (LCI) is attained from literature sources for the PEM electrolyzer (PEM-EC), fuel cell (PEM-FC) and storage vessel processes.
For the PEM electrolyzer the bipolar plates made of titanium were found to have the highest weight share among the components with roughly 89% weight share of the total stack. The environmental hotspot materials include platinum and iridium, which only have a minor fracture of the weight share (0.01 & 0.13%). The LCI for a 1 kW PEM-EC stack is based on [32] [33]. The LCI for a PEM-EC balance of plant (BoP) is literature based as well [32], [34]. The LCI for a 1 kW PEM-FC and the balance of plant is based on [35].

The materials for the storage vessel are taken from the Argonne National Library's publication [27], where materials for a Type IV tanks had been gathered for a 350- and 700-bar pressure. The scaling of the weight of the individual materials had been done linearly between the 350- and 700-bar pressure tanks in order to aim for a close estimate for a 450-bar storage tank.

5.4.2.3.2 Electricity sources

Considering that the PEM electrolyser requires 55 kWh electricity in order to produce a kg of hydrogen in a gaseous state, the intensities of the different electricity sources must be carefully analyzed and understood in order to assess their life cycle impacts. The electricity demand for the operation phase of the electrolyzer has been identified to have the largest impact in multiple LCA studies [32] [33].
The Austrian grid mix in the GaBi database, used for this study, is referenced to the year of 2018 [36]. Apart from the grid mix, electricity from photovoltaics and an Austrian green electricity mix based on renewable energy sources (RES) are used as feed-in stock for the electrolysers. The latter source had been based on future estimation by the Austrian Federal Environment Agency (Umweltbundesamt), where a grid mix composition for the year of 2050 had been estimated. This mix consists of appox. 47 % hydro power, 24 % PV, 22% wind, 5 % biomass, 1 % biogas and 1 % waste.

5.4.2.3.3 Benchmark processes for comparison of the LCIA result

Benchmark processes used to compare the results with alternative H_2 production pathways. The processes used for steam methane reforming (SMR) differ between natural gas and heavy fuel oil (HFO) sources. It is important to note that the SMR and SR processes are only included as a cradle-to-gate processes, thus the additional impact by compression and storage for SB1 are not added to these processes. Benchmark processes are extracted from GaBi ts 10.6 Professional database.

5.4.2.4 Real implementation scenario – PV

For the purpose of analyzing the life cycle impacts of green hydrogen production solely from photovoltaics (PV), a real implementation scenario of a 100 kW PEM coupled with a 200 kW PV is assessed separately. This configuration, meaning twice the capacity of PVs compared to the PEM-EC results in roughly a 2'200 full load hour operation per year. This estimate is based on the nature of the photovoltaic load curve for which a sample visualized for one week (01.06.2019 – 08.06.2019) can be seen in Figure 5-22.
PV production that exceeds the electrolyzer capacity cannot be directly utilized for hydrogen production. Therefore, storage capacities - to increase annual full-load hours of hydrogen production - or other usages for the excess power (e.g,, grid feed-in) have to be considered to maximise the overall plant efficiency.

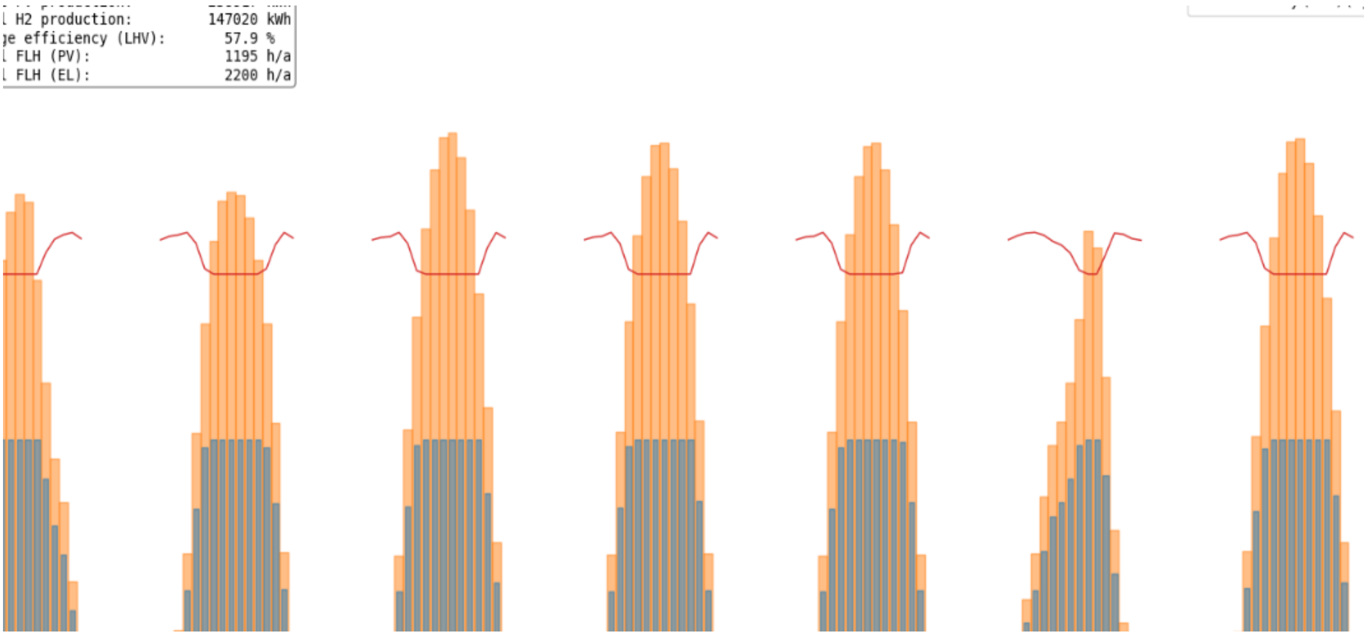

Figure 5-22: Load curve for one week of electricity generation from a 200 kW PV plant and hydrogen production for a 100 kW electrolysis capacity

5.4.3 Environmental impact assessment

The following sections show the results for the impact assessment phase of the LCA study through the CML 2001 method where all impact categories are included with the addition of the Primary Energy Demand (PED), including both the non-renewable and renewable energy sources in a net calorific value (see Table 5-7).

5.4.3.1 GHG-emissions, PEM-EC & FC

In this subsection the GWP impact category is assessed, showcasing the results for the PEM-EC & FC components and the SB1 & SB2.

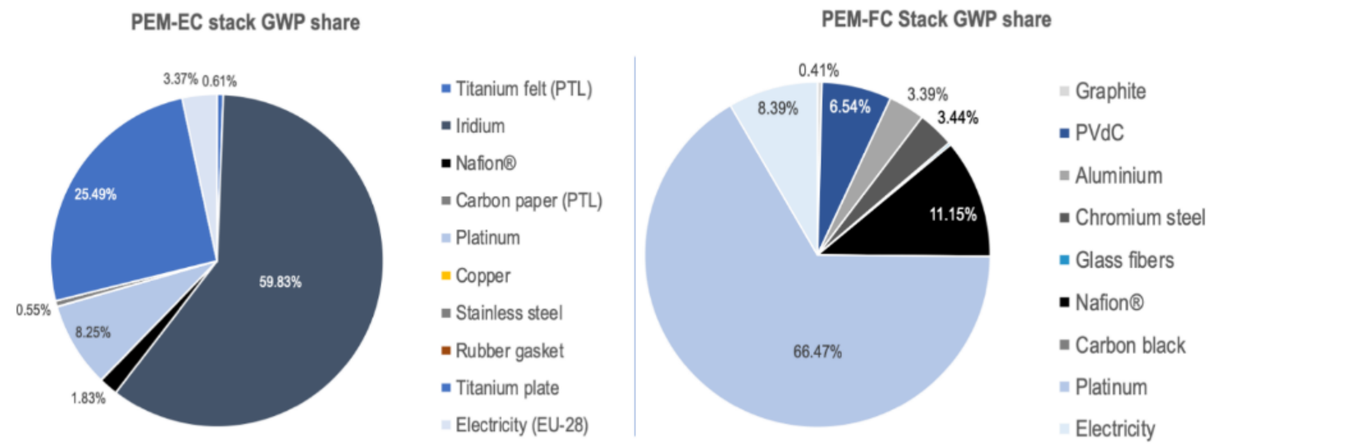

Figure 5-23 - GWP share between the materials of a PEM-EC and PEM-FC stack's manufacturing phase (not incl. assembly). Source: Energieinstitut an der JKU based on GaBi ts 10.6

Out of the PEM stack manufacturing, iridium, platinum and titanium alone were responsible for respectively 62.7%, 8.8% and 22.4% of the total stack manufacturing impact (Figure 5-27). The BoP components for the PEM-EC were responsible for between 31-48% of the total manufacturing impact (depending on the scenario) out of which steel, copper and aluminium amounted to respectively 38%, 31.5% and 17.6% of the PED for the BoP components.

5.4.3.1.1 GHG-emissions, scenarios (SB1 & 2)

5.4.3.1.1.1 SB1 – H_2 production

Figure 5-24 shows the Global Warming Potential (GWP) results of SB1, where the H2 production scenarios are compared with the benchmark processes for steam reforming pathway from HFO and NG from GaBi ts 10.6. The carbon footprint mainly stems from the electricity consumption, with the PEM manufacturing responsible for an average of 0.7%, 6.7% and 1.2% of the total GWP for the respective scenario groups of 'AT Grid', 'AT RES' and 'PV+AT Grid', respectively.
For the scenarios based on the combination of the Austrian grid mix and electricity from PV ('PV+AT Grid'), the PV share was responsible for 12.7%, 19.4%, 13.5%, 19.4% and 7% of the total carbon footprint respectively, for scenarios 3, 6, 9, 12 & 15. The decrease in the PV driven carbon footprint is due to the limit of 2'200 full load hours of PV power generation, resulting in a smaller share of the impact where the overall full load hours are higher (e.g., Sc. 15, 500kW PEM combined with 200kg H_2 output).
Comparing the results to the benchmark processes reveal that the steam methane reforming (SMR) pathway is less carbon intensive than the 'AT Grid' scenarios and for Sc. 15, the SMR results in a lower carbon footprint by 1.6 kg CO_2-eq. The SMR benchmark process emits 6.9 kg **less** CO_2-eq to the 'AT Grid', while the SMR H_2 production pathway emits over 6 times **more** carbon dioxide compared to the 'AT RES' scenarios. Similarly, the steam reforming heavy fuel oil (HFO) pathway has a 2.7 kg CO_2-eq smaller CO_2 footprint compared to the 'AT Grid', however, the SR HFO benchmark has over 7.5 times **higher** carbon footprint than 'AT RES' scenarios.

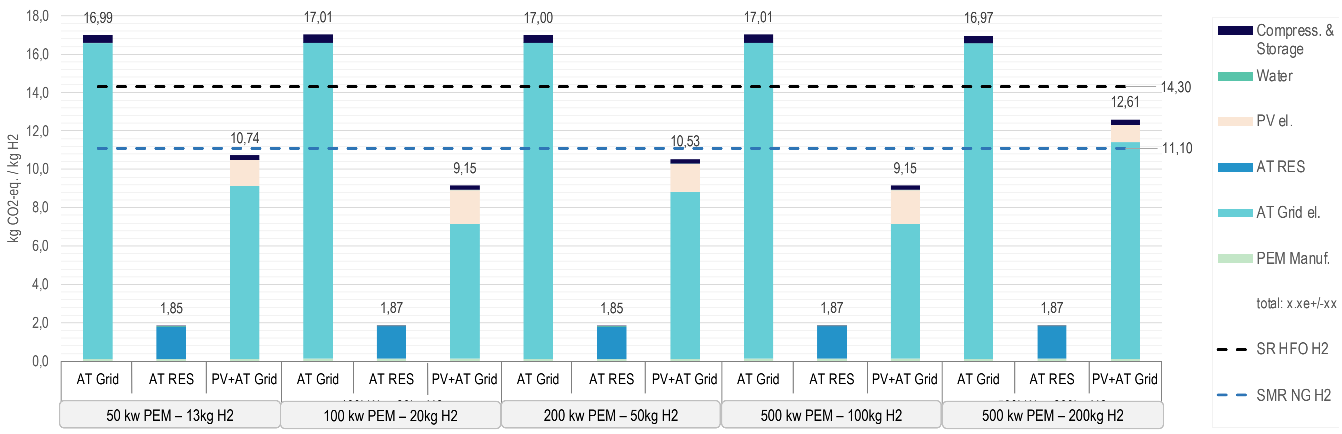

Figure 5-24: Global warming potential (GWP) per kg H_2 produced compared with the benchmark processes. Source: Energieinstitut an der JKU based on GaBi ts 10.6

5.4.3.1.1.2 SB2 – FC Bus & Truck application

Figure 5-25 shows the SB2 GWP results for a diesel-fuelled bus & truck, compared to the benchmark processes (steam reforming pathway from HFO and NG) and literature-based results for a WTW diesel bus & truck. The ratio between the benchmark processes and the scenario results remain the same as

for SB1 (Figure 5-24) as only the amount of hydrogen required per km driven distance changes, which is constant for all scenarios. The results for the FC bus indicate a carbon saving of 0.17- and 1.59 kg CO2-eq. / km compared to the diesel bus benchmark for the ‘AT Grid’ and ‘AT RES’ scenarios, respectively. Similarly, the FC truck scenarios result in a carbon saving of 0.07- and 1.4 kg CO2-eq. / km compared to the diesel truck benchmark for the ‘AT Grid’ and ‘AT RES’ scenarios, respectively. These results validate the importance of using green electricity for hydrogen production as opposed to using the grid.
The results for the ‘PV+AT Grid’ scenarios vary between the scenarios due to the amount of full load hours (FLH) being fixed at 2’200 h/yr from the PV source, meaning that the higher the overall FLH are for the given scenario, the more FLHs are required from the Austrian grid which has a more than 10 times higher carbon intensity (kg CO_2-eq. / kWh).

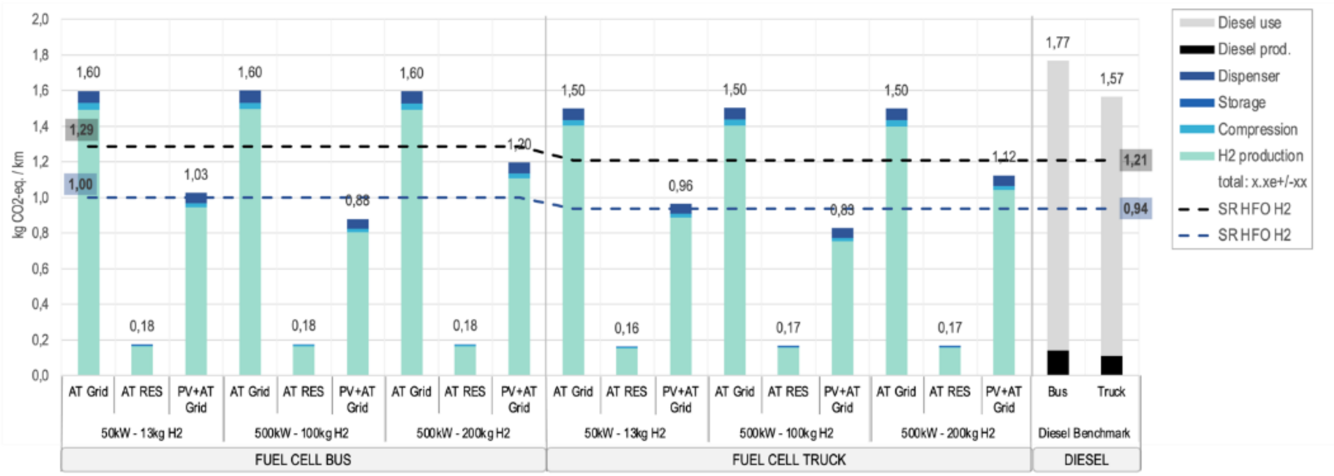

Figure 5-25: GWP per km driven distance for a FC Bus & Truck, compared with diesel alternatives (WTW). Source: Energieinstitut an der JKU based on GaBi ts 10.6

5.4.3.1.1.3 SB2 – PEM-FC H_2 reconversion

Figure 5-26 shows the SB2 fuel cell GWP results compared with the benchmark processes for various electricity sources, including Austrian electricity from natural gas, the Austrian grid, photovoltaics and from the European Union’s average grid mix.
The results show that the Austrian grid electricity is less carbon intensive than the ‘AT Grid’ scenarios, by 0.65 kg CO_2-eq. / kWh, indicating that it is not environmentally feasible to reconvert hydrogen from this pathway as opposed to using the grid, unless excess power is being used with zero footprint allocation. Furthermore, the PV electricity has a lower carbon footprint by at least 0.06 kg CO_2-eq. / kWh compared to the ‘AT RES’ scenarios.

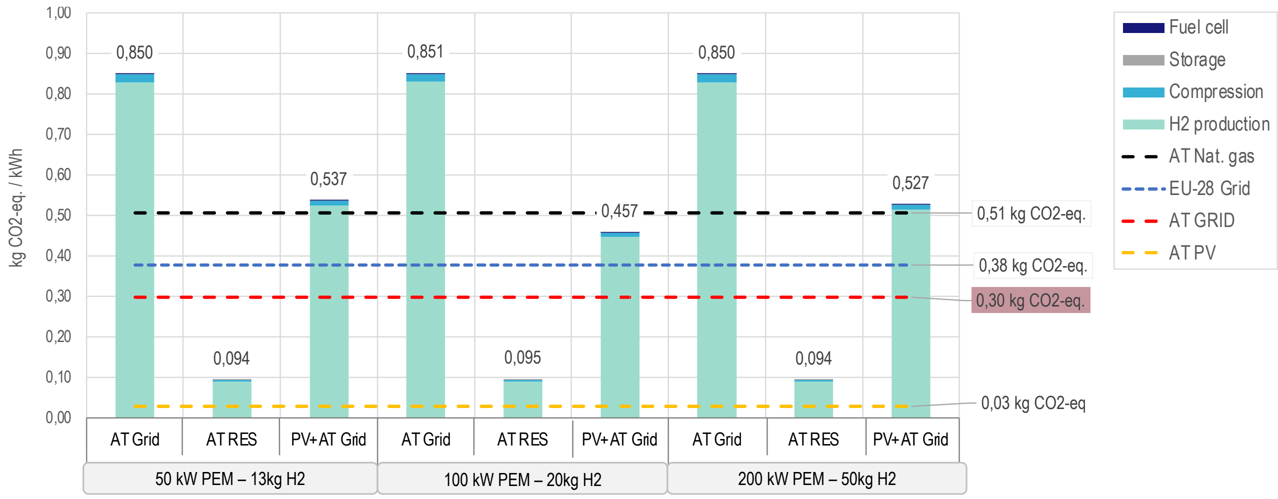

Figure 5-26: Greenhouse Gas emissions per kWh reconverted, compared with benchmark processes. Source: Energieinstitut an der JKU based on GaBi ts 10.6

5.4.3.2 Primary Energy Demand, PEM EC & FC

Figure 5-27 shows the Primary Energy Demand (PED) share between the different components used for the PEM-EC & FC stacks. It is visible that the catalysts (iridium and platinum) have the highest share of the PED for the PEM-EC stack with 63% and 8.8%, while for bipolar plates (titanium) had the second-largest share with 22.4%. The BoP components for the PEM-EC were responsible for between 31-48% of the total manufacturing impact (depending on the scenario) out of which steel, copper and aluminium amounted to respectively 38%, 31.5% and 17.6% of the PED for the BoP components**.**
As for the PEM-FC, the largest share of the PED is stemming from the Platinum loading of the stack, with 73.5%.

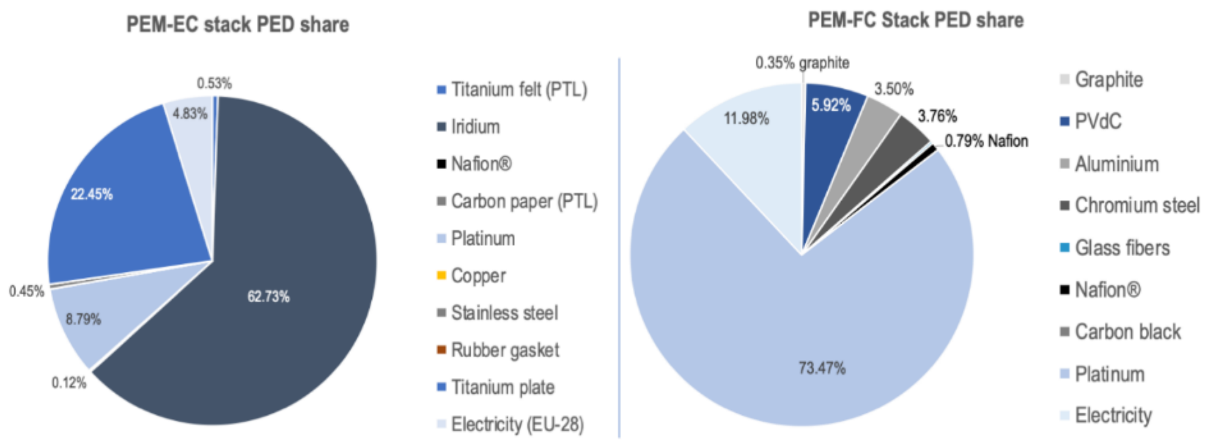

Figure 5-27: PED share between the materials of a PEM-EC and PEM-FC stack's manufacturing phase (incl. electricity for assembly). Source: Energieinstitut an der JKU based on GaBi ts 10.6

5.4.3.2.1 Primary Energy Demand, scenarios (SB1 & 2)

5.4.3.2.1.1 SB1 – H_2 production

As with the GWP, the Primary Energy Demand (PED) also mainly stems from the electricity consumption (Figure 5-28), with the PEM manufacturing responsible for an average of 0.4%, 0.3% and 0.2% of the total PED between the scenario groups of 'AT Grid', 'AT RES and 'PV+AT Grid', respectively. For the green 'PV+AT Grid' Scenarios the primary energy deriving from the photovoltaic manufacturing amounted to 63.5%, 73.8%, 65%, 73.8%, and 47.9% respectively for Sc. 3,6,9,12 & 15; while between 23.6 – 49.5% was due to the 'AT Grid' electricity consumption for these scenarios. The PED for the renewable electricity sources solely stems from the manufacturing of the generators, as their operation is emission-free.

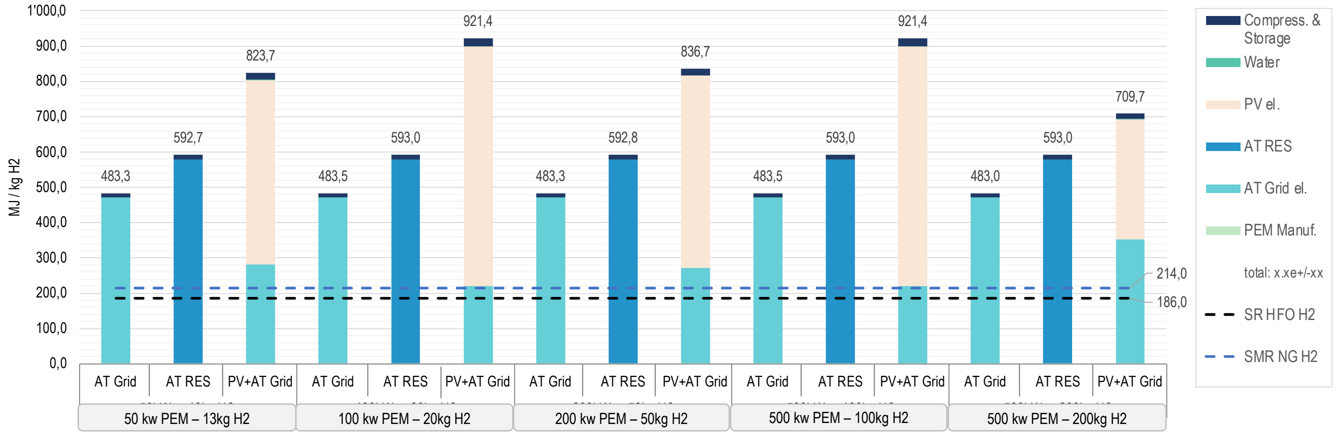

Figure 5-28: Renewable and non-renewable primary energy demand per kg H_2 produced. Source: Energieinstitut an der JKU based on GaBi ts 10.6

The PV source had been identified as the most energy intensive process, which is underlined by the fact that the PV full load hours only amount to 2'200 h /yr, although for the 'PV+AT Grid' scenarios their energy intensiveness is the most visible. The AT RES scenarios have the second highest PED, with a roughly 110 MJ higher energy demand than the AT RES scenarios, which likely stems from the high PV share (24.3%) in the RES mix.
The high share of PED for the renewable energy sources can be explained by their low conversion efficiency [37], [38]. However, Figure 5-29 indicates that most of the primary energy derives from renewables for the 'AT RES' scenarios, while the opposite is true for the 'AT Grid' scenarios.

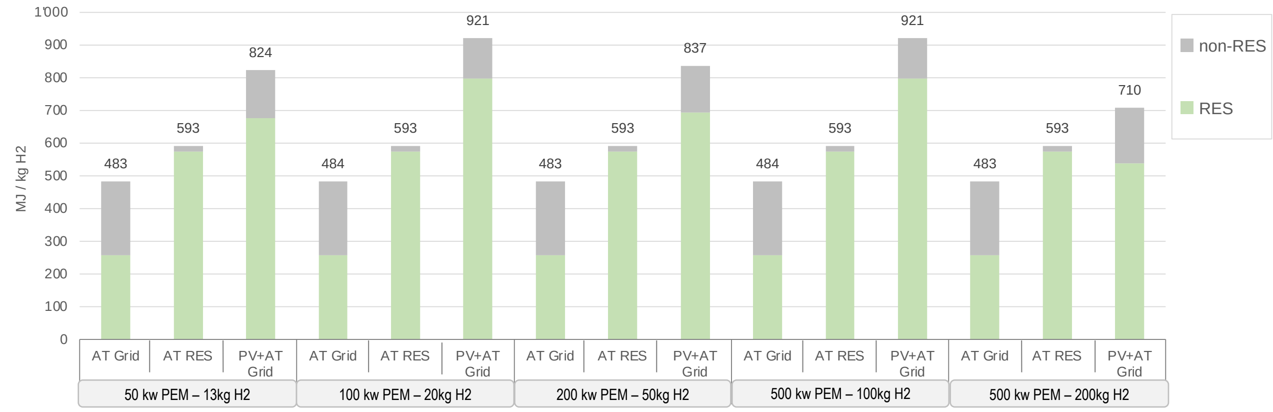

Figure 5-29 - Renewable vs. non-renewable primary energy demand per kg H_2 produced. Source: Energieinstitut an der JKU based on GaBi ts 10.6

5.4.3.2.1.2 SB2 – FC Bus & Truck application

Figure 5-30 shows the SB2 fuel cell truck & Bus PED results compared to the benchmark processes and literature-based results for a well-to-wheel (WTW) diesel-fuelled bus & truck; as well as the steam reforming pathway from heavy fuel oil (HFO) and SMR natural gas. The results indicate that the steam methane reforming (SMR NG) pathway is less energy intensive than all of the scenarios analysed. The 'AT Grid', 'AT RES and 'PV+AT Grid' scenarios have a 2.4-, 4- and 3-times larger PED compared to the SMR natural gas pathway, respectively.

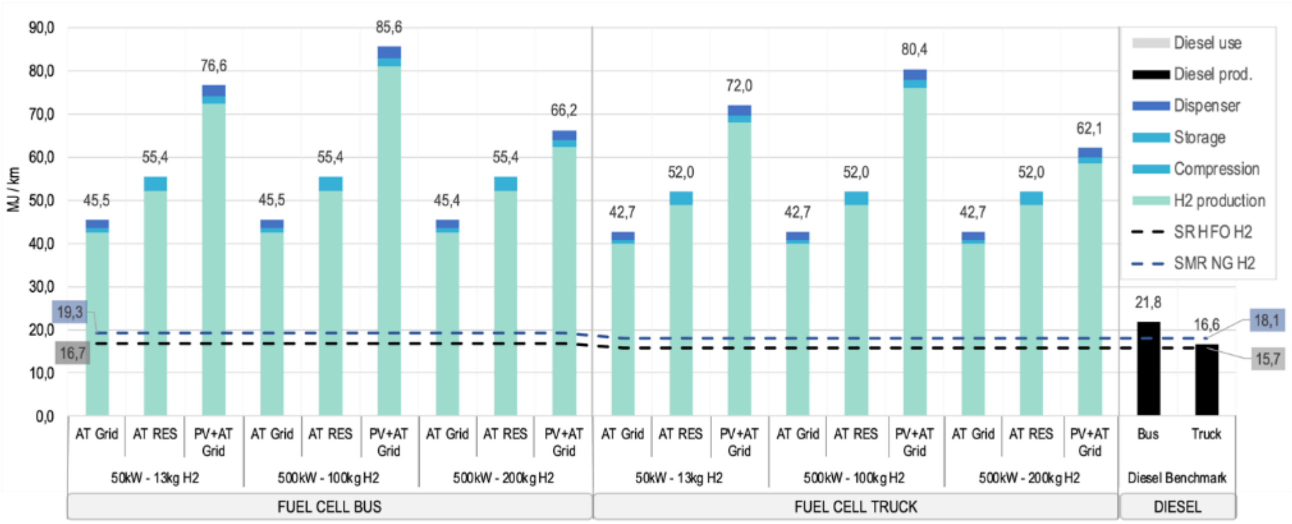

Figure 5-30: Renewable and non-renewable primary energy demand per km driven distance. Source: Energieinstitut an der JKU based on GaBi ts 10.6

SMR requires only 0.49 MJ (1.76 kWh) electricity to produce 1kg H_2, besides requiring 16.3 litres of H_2O and 3.04 kg natural gas [39]; thus, being far less carbon intensive from the electrolysis production pathway, which requires 55 kWh electricity to produce 1 kg H_2.
The bus and truck benchmark processes require similar amounts of primary energy to the steam reforming benchmark values, consisting of the PED from diesel production, which results in 21.8 MJ and 16.6 MJ per km driven respectively for the diesel bus and truck.
The diesel bus & truck PED does however not include the energy required for dispensing the fuel into the tank, which is assumed to be far less energy intensive than the refuelling of the FC vehicles. The green 'AT RES' scenarios (Sc.17, 20, 23, 26, 29 & 32) have a high PED due to the energy intensive manufacturing process of the wind turbines[15] and PV solar panels[16], which together make up 46% of the electricity mix used for these scenarios (see section 5.4.2.3.2').

5.4.3.2.1.3 SB2 – PEM-FC H_2 reconversion

Figure 5-31 shows the PED required for 1kWh electricity output from a PEM fuel cell, along with the benchmark electricity processes directly taken from the GaBi ts. 10.6 database [36], where the energy

[15] Building wind turbines is a very energy-intensive process, especially the production of the steel towers and the concrete foundations. According to the German Environment Agency (Umweltbundesamt, UBA), wind power plants generate 40 times more energy compared to the energy required for the production, operation and the disposal of a wind power plant [33].
[16] The production of the raw material, polysilicon, is fairly energy intensive. For 1 kW of PV power, approximately 6 kg of polysilicon are needed. To produce 6 kg of polysilicon, 480 kWh of electricity is required using technology that is dominant in the market today [34].

intensiveness of 1 kWh worth of reconverted hydrogen through the PEM fuel cell is compared with 1 kWh electricity use by photovoltaics, the Austrian- and the EU-28 average grid mix.

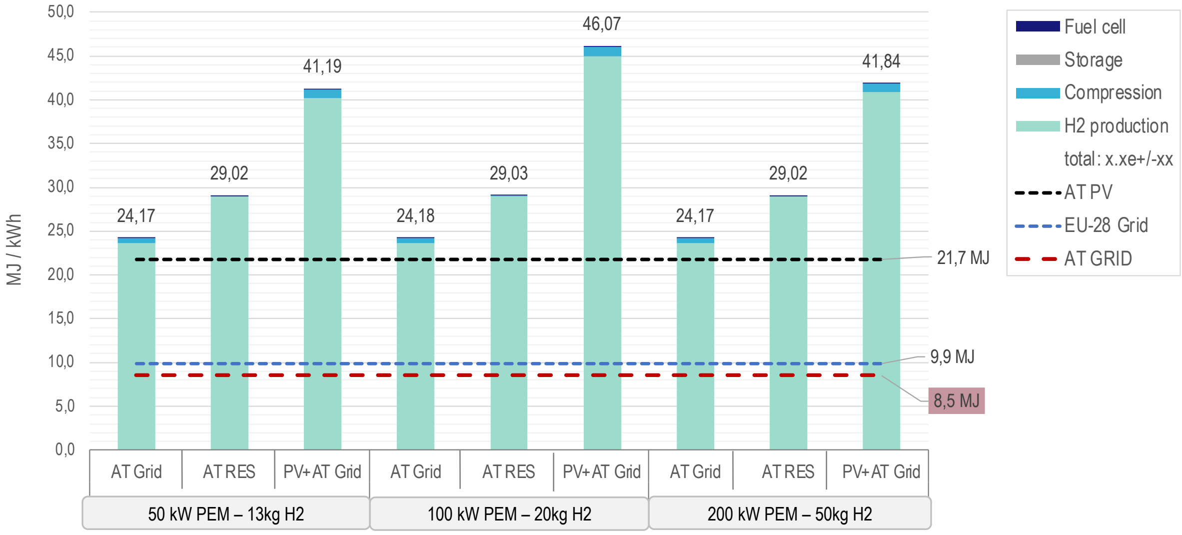

Figure 5-31: Renewable and non-renewable primary energy demand per kWh electricity output. Source: Energieinstitut an der JKU based on GaBi ts 10.6

The results show that the primary energy can almost exclusively be associated with the hydrogen production (SB1), while a more detailed explanation has already been provided for the PED results for SB1 (see section 5.4.3.1.1)

5.4.3.3 Other environmental impacts of H_2 production

In this subsection the life cycle emissions of H_2 production for SB1 (Sc.1-15) are analysed. The results show that for most of the impact categories (apart from the FAETP and ODP) the impacts are mostly associated with the electricity source for the electrolysis rather than the manufacturing of the stack, water consumption and energy required for H_2 compression.
Out of the scenarios analysed, the green 'AT RES' H_2 pathway scenarios (Sc. 3,6,9,12 & 15) proved to be the most environmentally friendly options for H_2 production, with the exclusion of the human toxicity potential (HTP) impact category.

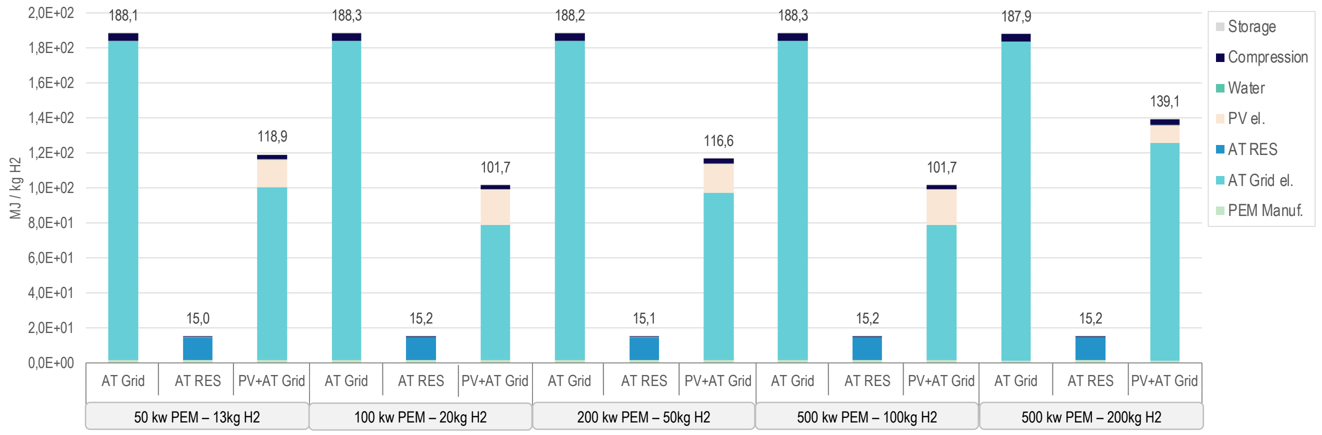

Figure 5-32: Abiotic Depletion Potential (ADP fossil) for SB1 for 1kg H_2 produced, expressed in MJ. Source: Energieinstitut an der JKU based on GaBi ts 10.6

The abiotic depletion potential of non-renewable fossil sources (ADP foss.) shows that the majority of the impact stems from the Austrian grid mix usage (Figure 5-32). However, for the scenarios based on the Austrian RES input, the impact is mainly caused by the PV input of the electrolysis phase, which has a higher ADP intensity than wind and hydro by 3.5- and 14 times, respectively.

Out of the PEM stack manufacturing, iridium, titanium and platinum alone were responsible for respectively 67%, 21% and 9% of the total stack manufacturing ADP. The BoP components for the PEM-EC were responsible for between 30-47% of the total manufacturing impact (depending on the scenario) out of which steel and copper amounted to respectively 44% and 30% of the BoP ADP-fossil.

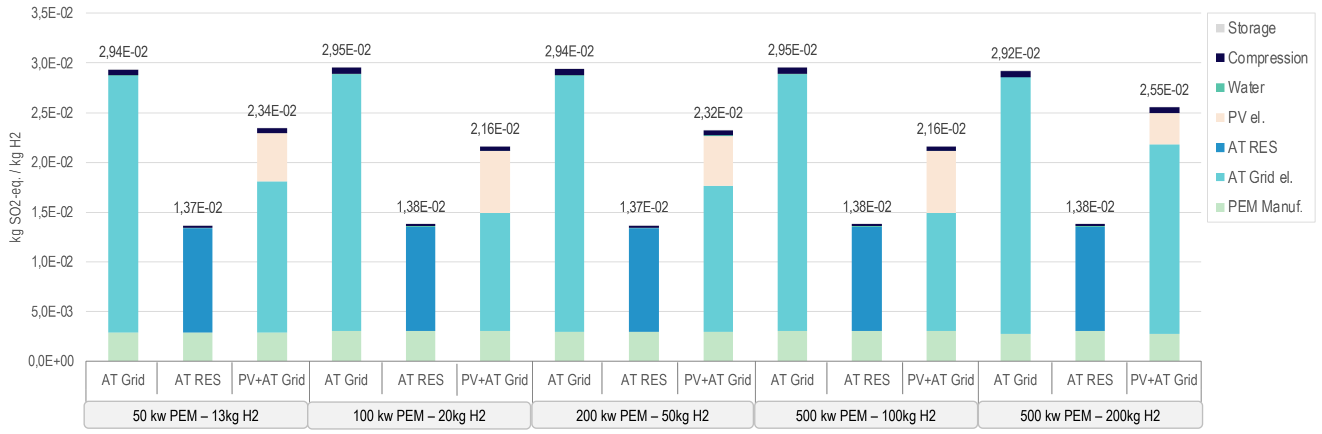

Figure 5-33: Acidification Potential (AP) for SB1 for 1kg H_2 produced, expressed in kg Sb eq. Source: Energieinstitut an der JKU based on GaBi ts 10.6

The Acidification Potential (AP) is impacted significantly by the PEM manufacturing, especially in the green H_2 scenarios, where its impact is close to 22% of the total on average, due to the lower impact of the electricity source (Figure 5-33).

Out of the PEM stack manufacturing, Iridium and Platinum alone were responsible for respectively 85% and 12% of the total stack manufacturing AP. The BoP components for the PEM-EC were responsible for between 12-21% of the total manufacturing AP (depending on the scenario) out of which copper use was accountable for 71% of the BoP AP.

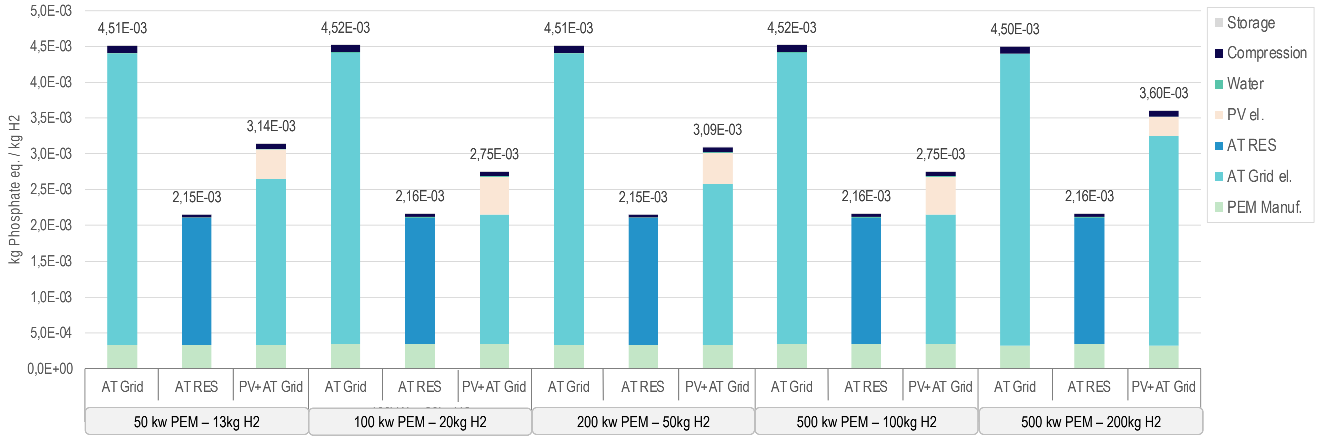

Figure 5-34: Eutrophication potential (EP for SB1 for 1kg H_2 produced), expressed in kg Phosphate eq. Source: Energieinstitut an der JKU based on GaBi ts 10.6

Figure 5-34 shows the Eutrophication Potential for H2 production, where again the Austrian grid mix contributed the most to the impact category. The manufacturing phase has a significant impact for the green electricity scenarios with 15.6% of the EP on average between the scenarios. For the ‘AT Grid’ and ‘AT Grid + PV’ scenarios, the manufacturing phase makes up 7.4% and 11% of the total EP, respectively. The PV share adds up to 13%, 19.3%,13.7%, 19.3% and 7.4%, respectively for scenarios 3, 6, 9, 12,& 15.

Out of the PEM stack manufacturing, iridium, titanium, and platinum alone were responsible for respectively 76%, 13% and 10% of the total stack manufacturing EP. The BoP components for the PEM-EC were responsible for between 5-9% of the total manufacturing impact (depending on the scenario) out of which copper, steel and LCD display were accountable for respectively 40%, 22% and 21% of the BoP EP.

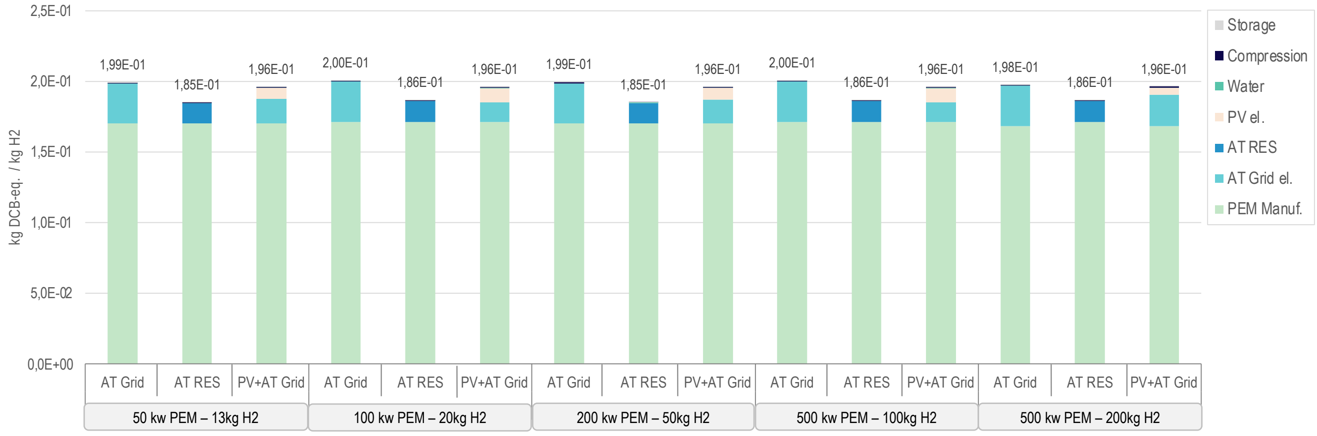

Figure 5-35: Freshwater Aquatic Ecotoxicity Potential (FAETP) for SB1 for 1kg H_2 produced, expressed in kg DCB eq. Source: Energieinstitut an der JKU based on GaBi ts 10.6

The FAETP is largely contributed to by the manufacturing of the PEM electrolyzer (Figure 5-35), out of which the PEM stack manufacturing stems largely from the Iridium and Platinum loadings, responsible for respectively 84% and 11.5% of the total stack manufacturing impact. The BoP components for the PEM-EC were responsible for between 2-4% of the total manufacturing impact, out of which the LCD display and copper amounted to 71% & 17% of the FAETP for the BoP components.

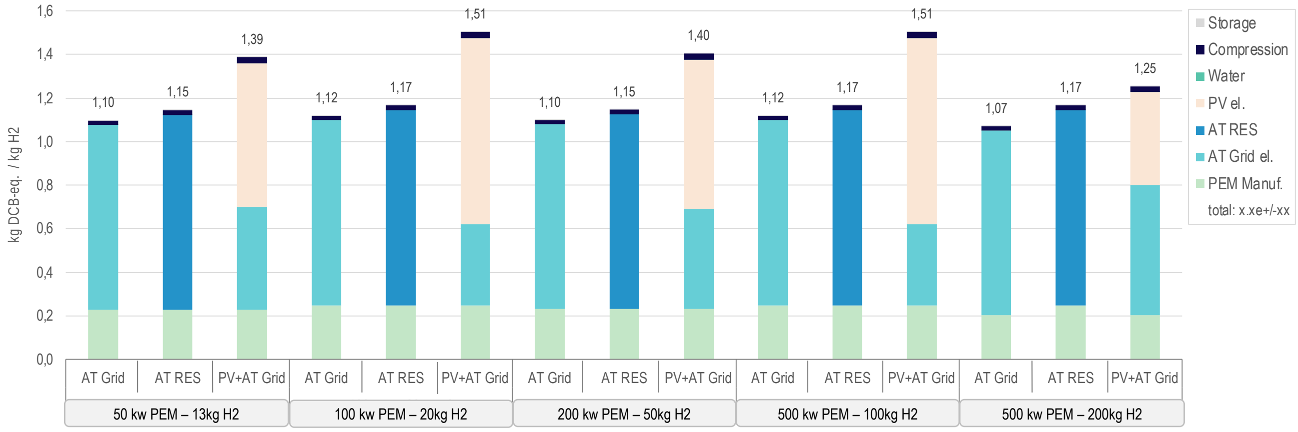

Figure 5-36: Human Ecotoxicity Potential (HTP), for SB1 for 1kg H_2 produced expressed in kg DCB eq. Source: Energieinstitut an der JKU based on GaBi ts 10.6

The Human Toxicity Potential (HTP) can be largely accounted towards the electricity consumption (Figure 5-36), with the PEM manufacturing responsible for an average of 21%, 20.8% and 16.4% of the total HTP between the scenarios for ‘AT Grid’, ‘AT RES’ and PV+AT Grid’, respectively.
Out of the PEM stack manufacturing, iridium, platinum and titanium alone were responsible for respectively 78%, 10.5% and 6% of the total stack manufacturing impact. The BoP components for the PEM-EC were responsible for between 23-38% of the total manufacturing impact (depending on the scenario) out of which copper and aluminium constituted respectively 56% and 20% of the HTP for the BoP components.

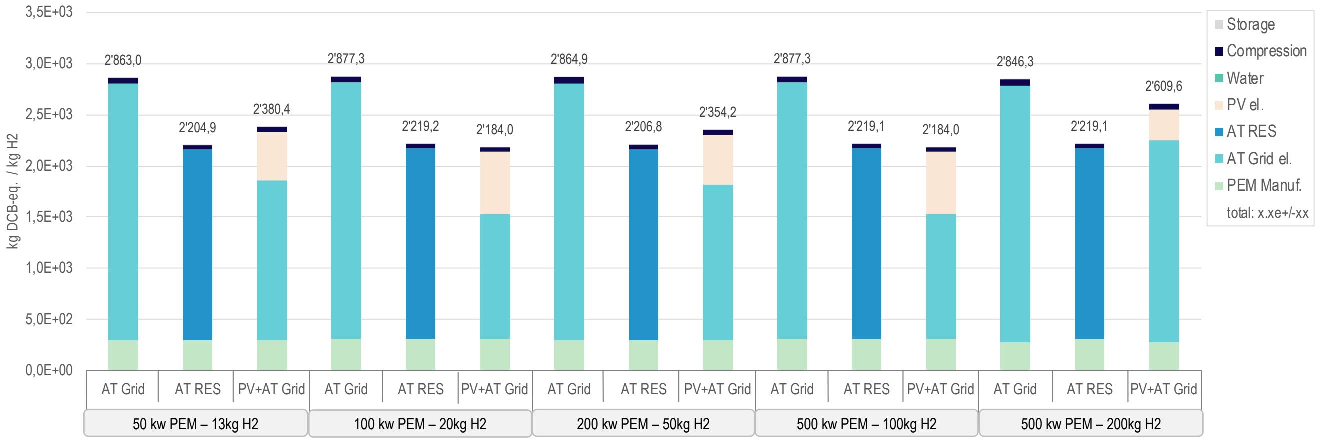

Figure 5-37: Marine Aquatic Ecotoxicity Potential (MAETP) for SB1 for 1kg H_2 produced, expressed in kg DCB eq. Source: Energieinstitut an der JKU based on GaBi ts 10.6

The Marine Aquatic Ecotoxicity Potential (MAETP) stems mainly from the electricity consumption (Figure 5-37), with the PEM manufacturing responsible for an average of 10.3%, 13.7% and 12.7% of the total MAETP between the scenarios for ‘AT Grid’, ‘AT RES’ and PV+AT Grid’, respectively. For the green ‘AT RES’ scenarios (Sc 2,5,8,11 & 14), the PV source has the most significant impact of the electricity mix due to its MAETP intensity being 13- and 76 times higher than that of wind and hydro power source. The ‘PV+AT Grid scenarios had 19.7%, 27.9%, 20.7%, 27.9% & 11.7% stemming from the PV use,

respectively for Sc. 3,6,9,12 & 15.; while between 87.2-88.1% of the MAETP was due to the AT Grid electricity consumption between these scenarios.
Out of the PEM stack manufacturing, iridium, platinum and titanium alone were responsible for respectively 79%, 11% and 9% of the total stack manufacturing impact. The BoP components for the PEM-EC were responsible for between 11-20% of the total manufacturing impact (depending on the scenario) out of which the aluminium, copper and LCD use constituted respectively 36%, 32%, and 24% of the MAETP for the BoP components.

The Ozone layer Depletion Potential (ODP) is mainly due to the PEM manufacturing (Figure 5-38) for a near 100% rate for all scenarios, mainly due to the Nafion material use of the PEM stack, to which the closest alternative tetrafluoroethylene had been used. TFE is polymerized from chlorodifluoromethane (R22) which contributes greatly to ODP as the unit of measure for the impact category is trichlorofluoromethane (R11).

Figure 5-38: Ozone layer Depletion Potential (ODP) for SB1 for 1kg H_2 produced, expressed in kg R11 eq. Note that only the top of the column charts is displayed. Source: Energieinstitut an der JKU based on GaBi ts 10.6

Out of the PEM stack manufacturing, Nafion (TFE), iridium and titanium were responsible for respectively 99.1%, 5% and 3.5% of the total stack manufacturing impact. The BoP components for the PEM-EC were responsible for between 0.1-0.2% of the total manufacturing impact (depending on the scenario) out of which the LCD display was solely responsible for the ODP of the BoP components.

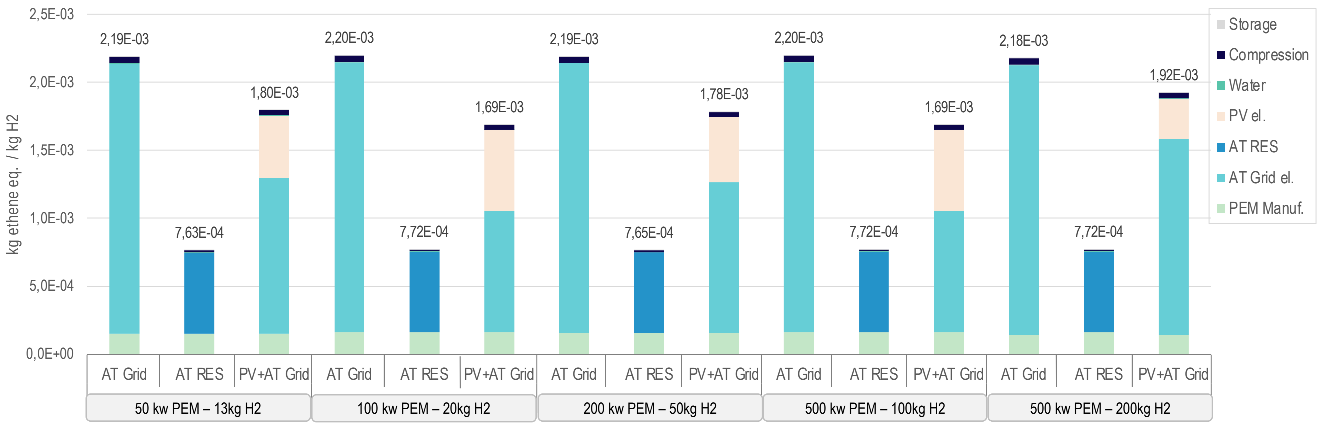

Figure 5-39: Photochemical Ozone Creation Potential (POCP) for SB1 for 1kg H_2 produced, expressed in kg Ethene eq. Source: Energieinstitut an der JKU based on GaBi ts 10.6

The Photochemical Ozone Creation Potential (POCP) is mainly impacted by the electricity consumption (Figure 5-39), with the PEM manufacturing responsible for an average of 7.1%, 20.8% and 8.8% of the total POCP between the scenarios for ‘AT Grid’, ‘AT RES’ and PV+AT Grid’, respectively (Figure 5-39).

The 'PV+AT Grid scenarios had 25.5%, 35.3%, 26.7%, 35.3% and 15.5% stemming from the PV use, respectively for Sc. 3,6,9,12 & 15.
Out of the PEM stack manufacturing, iridium, platinum and titanium alone were responsible for respectively 80%, 11% and 8% of the total stack manufacturing impact. The BoP components for the PEM-EC were responsible for between 13-24% of the total manufacturing impact (depending on the scenario) out of which copper and steel amounted to respectively 49% and 36% of the POCP for the BoP components.

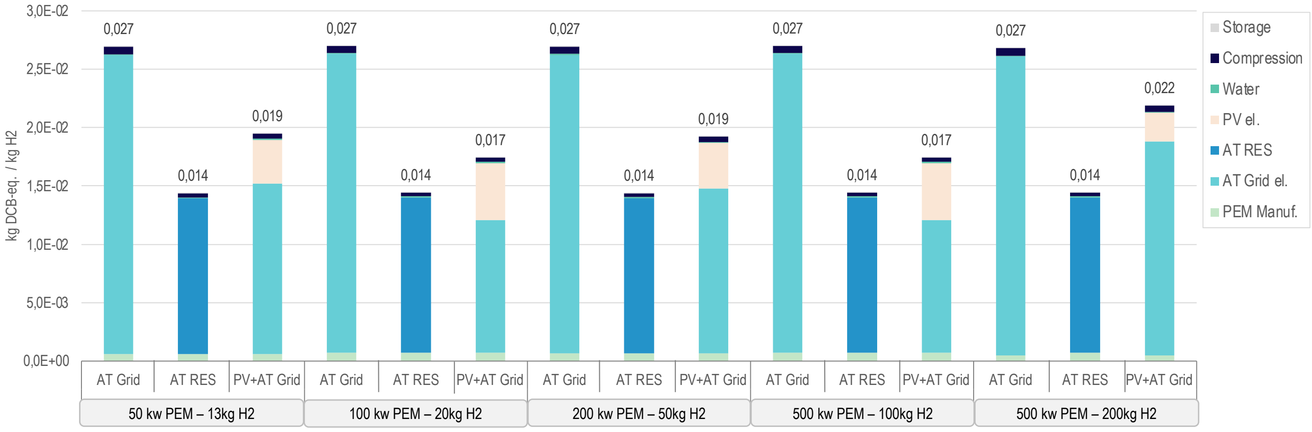

Figure 5-40: Terrestric Ecotoxicity Potential (TETP) for SB1 for 1kg H_2 produced, expressed in kg DCB eq. Source: Energieinstitut an der JKU based on GaBi ts 10.6

The Terrestric Ecotoxicity Potential (TETP) is mainly impacted by the electricity consumption (Figure 5-40), with the PEM manufacturing responsible for an average of 2.5%, 5% and 3.6% of the total TETP between the scenarios for 'AT Grid', 'AT RES' and PV+AT Grid', respectively. The 'PV+AT Grid scenarios had 19.2%, 27.8%, 20.2%, 27.8% and 11.1% stemming from the PV use, respectively for Sc. 3,6,9,12 & 15.
Out of the PEM stack manufacturing, iridium, platinum and titanium alone were responsible for respectively 72%, 8.6% and 17% of the total stack manufacturing impact. The BoP components for the PEM-EC were responsible for between 43-61% of the total manufacturing impact (depending on the scenario) out of which copper and stainless steel amounted to respectively 66% and 19% of the TETP for the BoP components

5.4.3.4 PV real implementation scenario results

The 'AT PV' forms the real implementation scenario, where a 100 kW PEM electrolyzer is coupled with a 200 kW PV plant (see section 5.4.2.4). In Figure 5-41, the other scenarios that are based on a 100 kW PEM capacity are shown as references to the 'AT PV' result. The biggest difference between the 'AT PV' and the rest of the 100 kW PEM scenarios, is the full load hours (FLH), as the former scenario results in 2'200 FLH opposed to the almost 4'000 FLH for the other three scenarios (Sc. 4-6).

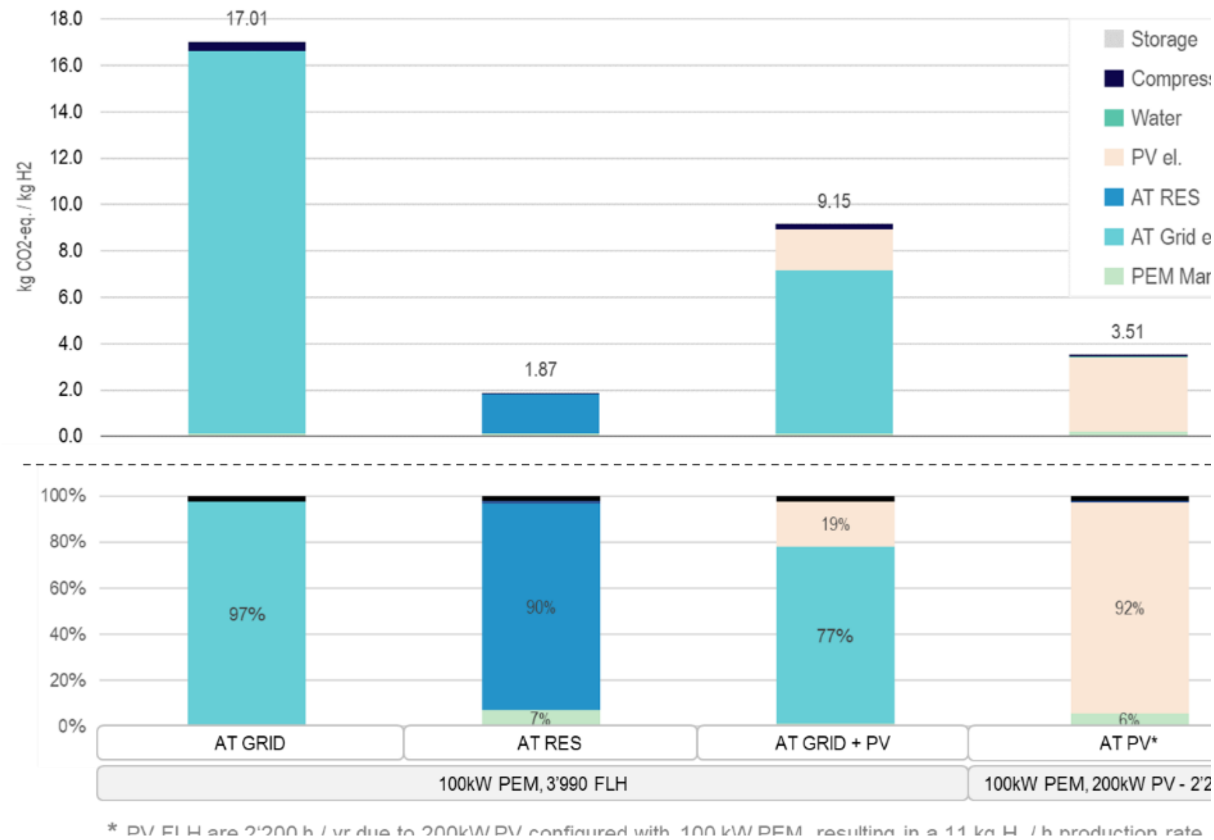

Figure 5-41 - GWP result for the real implementation scenario (AT PV), compared with other 100kW PEM scenarios. Source: Energieinstitut an der JKU based on GaBi ts 10.6

The GWP results indicate that when comparing the carbon footprint of the ‘AT RES’ and the ‘AT PV’, the latter scenario resulted in an almost 1.9 times larger footprint. The most notable difference stems from the electricity source, due the PV electricity source having twice the carbon intensity of the ‘AT RES’ electricity mix (0.058- vs 0.03 kg CO_2-eq./kWh.

5.4.3.5 Sensitivity Analysis

Due to the range of efficiency provided by Fronius (58-64% LHV), the outcome of the impact assessment is significantly affected by the electricity consumption of the stack and thus, make it necessary to implement a sensitivity analysis to assess its influence on the results. For the results, the average value of this range (61% LHV eff.) had been used throughout the life cycle impact assessment (LCIA) and only in this chapter is the sensitivity assessed for two of the most widely regarded impact categories, i.e., GWP and PED.

5.4.3.5.1 Full load hours sensitivity

Due to the efficiency range, the amount of full load hours[17] (FLH) vary greatly between the scenarios based on a 50 kW PEM-EC with 13 kg H_2/day and a 500 kW PEM-EC with a 200 kg H_2/day production

[17] Full load hours are a benchmark for the utilisation rate of a facility. A full load hour is defined as the equivalent of one operation hour at nominal load. Consequently, 1,000 full load hours are achieved with 1,000 operating hours at nominal load, or 2,000 operating hours at 50 per cent of the nominal load. The nominal load refers to the maximum output a facility can permanently produce at normal intended operating conditions. The full load hours are usually indicated in reference to one year. Accordingly, 1,000 full load hours per year signify that the plant generates 11.4 per cent of the power it could generate were it operated at nominal load for the entire 8,760 hours of the year [44]

rate. Consequentially, the amount of full load hours provided by the AT Grid varies for the 'PV+AT Grid' scenarios, as the PV FLH had been fixed at 2'200 FLH for these scenarios (Sc 3,6,9,12,15). Subsequently, the lower the efficiency gets, the higher the Austrian grid mix share, as more FLH are required to supply the same amount of hydrogen as with higher efficiencies. Considering that the AT Grid had a higher carbon intensity per kWh electricity (0.299 for AT Grid vs 0.058 kg for PV source).

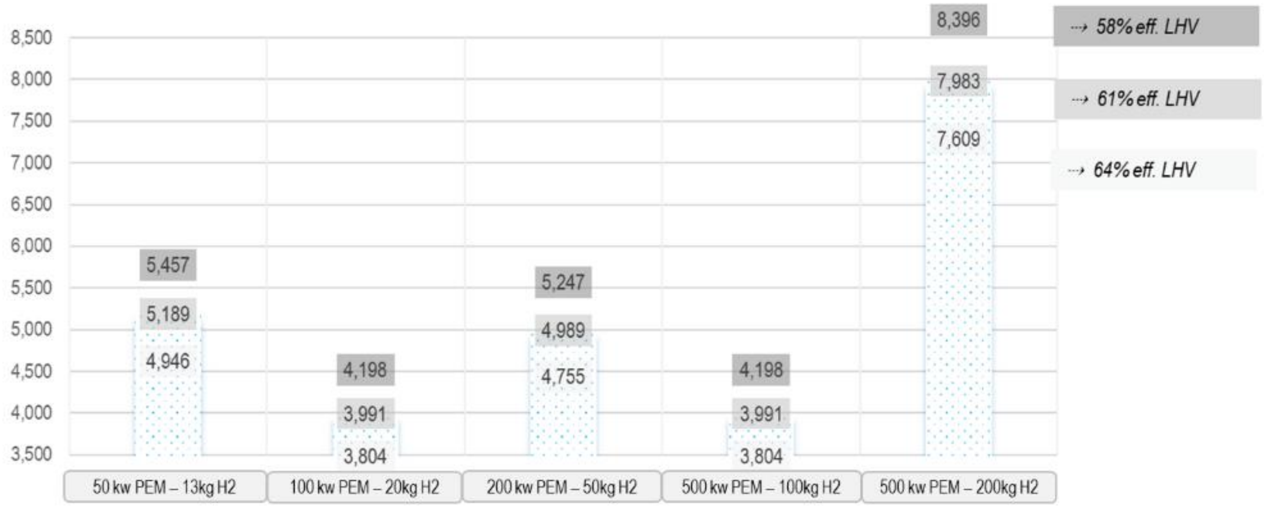

Figure 5-42: Sensitivity of the efficiency range and its implications on the full load hours (hr/yr) for the PEM-EC

However, it is also noticeable from Figure 5-42 that some of the scenarios have unreasonably high FLHs to implement intermittent RES, such as wind and PV only. The best example for this is the configuration of a 500kW PEM with a 200 kg daily hydrogen output, which – even by using the highest efficiency at 64% - results in 7'600 FLH. It also becomes evident that the real implementation scenario, being limited to only using electricity from PV, will have less FLHs then the scenarios analyzed due to limited solar availability in Austria. According to Acatech's report [40], PtG and PtL facilities need to achieve 3,000 to 4,000 full load hours annually in order to be operated in an economically efficient manner. Some countries are able to produce these figures based on RES availability. indicates that the Middle East and North Africa utilizing wind and PV could achieve more than 4'000 FLHs. Another example for an extensive yearly green electricity utilization is Iceland, where 8'000 FLH are achievable by coupling the PtG plant with geothermal and hydro, which are both baseload power generators [41] [42].
It is unclear how a mix of PV and baseload AT Grid operation would affect the FLHs and if such an operation would increase the need for down-times caused by increased frequency of maintenance.

5.4.3.5.2 GWP sensitivity, SB1

Figure 5-43 provides an overview of the sensitivity analysis for the SB.1 scenarios, indicating the min-max range of the GWP impact based on the efficiency range. Panel 'a' shows an enlarged portion between the 90-110% range of panel 'b', where the min and max range of GWP is shown compared to the 61% efficiency use (100% benchmark). The results show that by using the highest efficiency (64% LHV) an average GWP reduction of 4.6%, 4.4% and 4.5% can be reached respectively for the 'AT Grid', 'AT RES' and 'PV+AT Grid' scenarios. Similarly, by using the lowest efficiency (58% LHV), an average total GWP increase of 5%, 4.8% and 5% is reached for the same scenario groups, respectively. This suggests that the efficiency of the electrolyzer plays a significant role in carbon savings.
Out of the phases analysed for H_2 production, the electricity consumption and the PEM manufacturing per FU are impacted the most by the efficiency parameter variations. The electricity consumption for 58% efficiency increases by 2.84 kWh (5.2%), while the 64% efficiency decreases the consumption by 2.58 kWh (4.7%) compared to the 55kWh consumption at 61% LHV efficiency.

Figure 5-43: Sensitivity analysis for the SB1 scenarios, indicating the effect of the efficiency range on the GWP.

5.4.3.6 Conclusion from the Life Cycle Assessment

This study had assessed the environmental impacts and primary energy demand of hydrogen production for a PEM electrolyzer, using various capacities, production rates and electricity inputs. Through the life cycle impact assessment (LCIA) using the CML 2001 method, it was found that the main environmental footprint was associated with the electricity source for electrolysis, where the Austrian grid mix scenarios had the highest footprint apart from the FAETP and ODP categories, where the biggest footprint was due to the PEM manufacturing. It was also found that the 'PV+AT Grid' combination served as a mitigation of the GWP impact compared to the 'AT Grid' scenario group, with an average decrease in the GWP by 39% on average.

The **hydrogen production scope** (SB1), including the PEM manufacturing, electrolysis, compression and storage processes, had the largest influence over the environmental footprint of the use cases. On average, the manufacturing phase in SB1 was responsible for 0.7%, 6.7% and 1.2% of the respective GWP of the 'AT Grid', 'AT RES' and 'PV+AT Grid' scenarios; indicating that the greener the pathway, the more noticeable the PEM stack manufacturing impacts are. The SB2 results for the fuel cell bus & truck mirrored the ratio of the results from the SB1, as only the fraction of H_2 required had to be adjusted to suit the given FU. The same can be stated for the fuel cell reconversion, with an exemption made for the inclusion of the fuel cell manufacturing, which resulted in a minor (under 0.1%) of the GWP for all scenarios.

For the **mobility use case** (SB2), where a FC bus and truck km transport had been assessed, it was found that the most environmentally viable option compared to the diesel fuel alternative was the use of green H_2 (based on the 2050 AT grid mix projection by the Umweltbundesamt), which was found to have an over 10- and 9.5 times lower CO_2-eq. footprint than the diesel alternative vehicle, respectively for the FC bus & truck.

Through the **sensitivity analysis** it was found that the efficiency parameter range of 58-64% LHV affected the GHG emissions of the scenarios significantly, with a -4.5 / +5.0% average deviation for all scenarios in SB1; compared with the 61% average LHV efficiency operation.

A real implementation scenario 'AT PV' had been included in this study in form of a 100kW PEM capacity coupled with a 200kW PV plant and directly compared with the other scenarios based on a 100kW PEM size. It was found that the 'AT PV' scenarios result in an average yearly full load hours of 2'200, opposed to almost 4'000 full load hours for the other scenarios (Sc. 4,5 & 6) operating at a 61% LHV efficiency. Due to this vast operational difference and the higher carbon intensity of the PV source compared to the renewable electricity source, using only the PV source results in a 1.9 times higher carbon footprint per functional unit compared to the scenario based on Austrian renewable energy sources (3.51- vs 1.87 kg CO_2-eq). However, the 'AT PV' scenario resulted in an almost 5 times lower carbon footprint than the corresponding 'AT Grid' scenario and over 2.5 times lower than that of the 'PV+AT Grid' scenario.

Future analysis could be made by including different electrolyzer types to enable cross-referencing between the manufacturing impacts and electricity consumption rates of the different technologies as well as by adding transportation processes between various locations in Austria where the hydrogen will be produced, stored and used.

5.5 Socio-technical assessment

The following sections show the results for the socio-technical assessment derived from the SAMBA model.

5.5.1 MODULE 2 - Stakeholder Analysis

The identification of the various stakeholders and their corresponding evaluation in connection with the developed **SOLHUB** is of particular importance. It is known, which stakeholders can be supportive but also obstructive and therefore possibly represent a barrier to be overcome. The identification process of stakeholders considered relevant delivered a list of in total 96 different stakeholders. In the subsequent process of stakeholder evaluation, 14 persons from the consortium partners contributed with their individual evaluations, which are anonymized and jointly summarized. Data collection for the stakeholder analysis was done by a questionnaire where participants, were asked to evaluate every stakeholder individually with the criteria “influence”, “importance” and “attitude”:

5.5.1.1 Attitude of the stakeholders

Based on the evaluation of the general attitude of the stakeholders (Support, Neutral, Ambivalent, Opponent), the following overview can be derived:

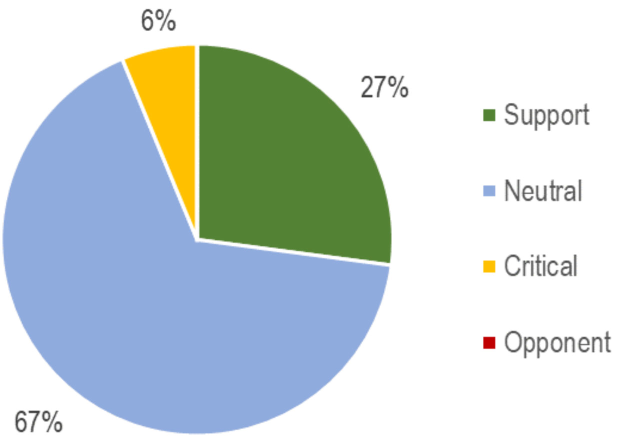

Figure 5-44: Attitude of the stakeholders. Source: Energieinstitut an der JKU Linz

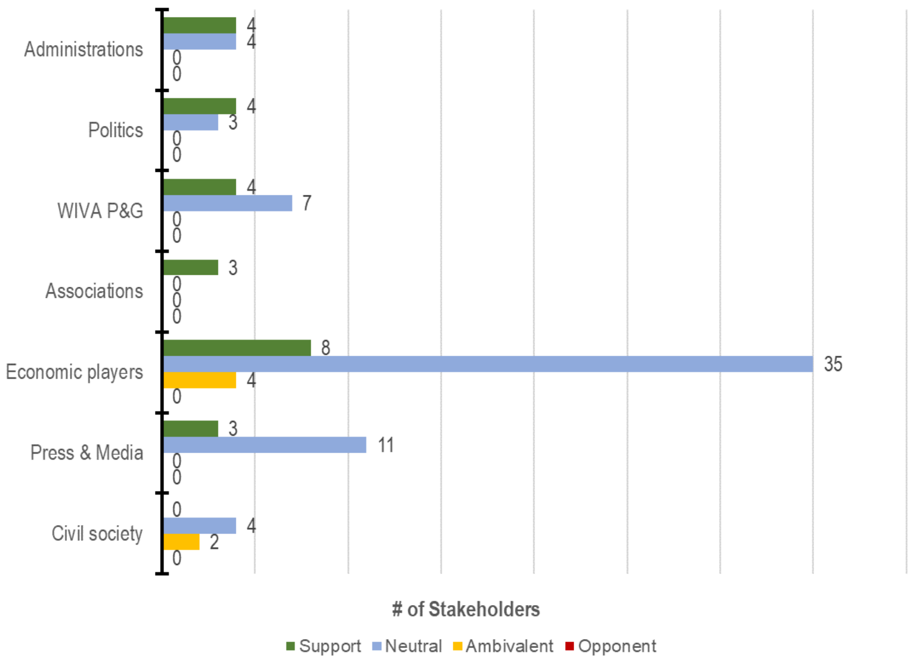

Figure 5-45: Attitude of the stakeholders per category. Source: Energieinstitut an der JKU Linz

As shown in Figure 5-44 and Figure 5-45 most of the stakeholders are expected to have an (on average) “neutral” attitude concerning the **SOLHUB**. In the category “Economic Players”, four stakeholders as well as in the category “Civil Society”, two stakeholders can be found which are (on average) expected to be “ambivalent”.

5.5.1.2 General result of the stakeholder analysis

The identification process of stakeholders that are relevant to the project **HyTechbasis** delivered a list of 96 different stakeholders. In the subsequent process of stakeholder evaluation, 14 persons from the consortium partners contributed with their individual evaluations.

- Most of the stakeholders are expected to have a “neutral” attitude on the **SOLHUB**. However, there are many stakeholders, implying the need to manage these in case of implementation and to guarantee the support of those expected to be supporters.
- It is assumed, that no stakeholders or stakeholder groups are expected to be “opponents”, what means, that there are no direct problems expected to emerge from stakeholders. Six stakeholders, four of the category “Economic players” and two belonging to “Civil society”, may have an ambivalent attitude. Especially the stakeholders “Residents of cities and municipalities” and “Neighbours” require special attention due to their estimated influence and importance in case of a construction of the **SOLHUB** in their neighbourhood. A recommendation for action can be a good and well-prepared information-policy to solve possible future problems in an early stage. In contrast, the other four ambivalent stakeholders only have to be monitored and represent competitors with a different electrolysis or fuel cell technology.
- The “Funding Organization”, the “Research Promotion Agency” and the “Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology” have to be managed closely and collaboration with them is of great value for the project and the development of the **SOLHUB**.
- It can be concluded, that respondents expect the general attitude of stakeholders and stakeholder groups towards the further development of the **SOLHUB** for the energy model region WIVA P&G to be very positive and no significant resistance is expected.

It is important to mention that a stakeholder analysis can only be a snapshot and has to be repeated throughout the timeline of technology development as it steps into market, is rolled out, increases market penetration, becomes visible in the public etc. The results of evaluation may change with the maturity and stage of technology development. Accordingly, more stakeholders become directly affected and their today´s mainly neutral attitude may change to being supporters or even opponents. As hydrogen technologies e.g., for the fuelling of vehicles are rolled-out more strongly it is also likely that groups of stakeholders which have to be managed closely, increases. This current stakeholder analysis should be considered preliminary giving the picture for an early-stage technology development without showing a broader roll-out.

5.5.2 MODULE 3 - STEEP Analysis

Parallel to the stakeholder analysis, which focuses on the immediate environment in the form of relevant stakeholders, the project also examines the embedding of the **SOLHUB** in the wider environment in order to identify potential problems, challenges, obstacles and also opportunities for the technology. These are described in the STEEP analysis along five different dimensions using various indicators and analyzed on the basis of the evaluated expert interviews in specific relevance to the project. A set of suitable indicators for each of the five dimensions of society, technology, economy, environment and politics of the STEEP analysis was developed and qualitatively assessed. Therefore, every dimension started with a brief overview and discussion of the used indicators in a compact table format. After a

general qualitative description, a project-specific analysis based on literature, expert interviews and different assessment models of the Energieinstitut an der JKU Linz was carried out.
The results of the STEEP analysis respectively the strengths, weaknesses, opportunities and threats concerning the **SOLHUB** are summarized directly in the following section of the report, Module 4.

5.5.3 MODULE 4 - Comprehensive Analysis

The final comprehensive analysis merges the results of Modules 2 and 3 in the SAMBA matrix and derives recommendations and measures for how to overcome existing barriers to technology implementation. In this matrix, identified opportunities and threats are contextualised with the strengths and weaknesses of the **SOLHUB**. The aim is to identify measures that are necessary to minimise the risks and increase the opportunities for the implementation of the system.
First, the SWOT analysis defines all the necessary criteria for the subsequent SAMBA matrix and the various strategies and recommendations derived from it.

5.5.3.1 SWOT analysis

The SWOT analysis identifies and lists the various strengths, weaknesses, opportunities and threats regarding the introduction of the SOLHUB compared to the situation without the system. For the SWOT analysis, the data from stakeholder analysis and STEEP analysis were processed into a corresponding overall statement.

5.5.3.1.1 Strengths

- The concept or the use case of a hydrogen refuelling station can be rated with a TRL of 8-9 as they are already commercially available.
- Secure, decentralised power and backup power supply in the event of a failure in the overall power grid.
- General working conditions can be changed by on-site production and availability of hydrogen to increase independence, e.g., from power-grid respectively other sources of renewable energy or hydrogen refuelling stations.
- Integration requirements are limited to a power grid or other renewable electricity resources and therefore the potential problems causing an inefficient integration are very limited.
- Decentralised one-stop-shop solution for decarbonisation to solve and circumvent the current challenges and bottlenecks due to lack of infrastructure for transport, storage and distribution. Therefore, no supply-chain infrastructure for hydrogen production as well as transports for final product needed (on-site production and usage of hydrogen).
- High supply security through the combination of solar power and other renewable energy resources and the decentralised production and storage of hydrogen.
- High modularity of the system due to the range of produced hydrogen (between 24 and 100 kilogram) and feedstock (PV, power grid, other renewable resources).
- Competitive advantage as it supports the transformation of the energy system towards decarbonization targets.
- Changes in land-use are limited to size of the **SOLHUB** as hydrogen is produced and consumed on-site.

- Refuelling process for hydrogen was already proved to be safe and therefore stations can be classified as safe facilities.
- Significant economies-of-scale effects can be expected through technological learning and upscaling.
- Integrated solution for hydrogen production from renewable energy and the use for different use cases from refuelling of hydrogen vehicles, over backup power to seasonal storage.
- High replicability due to the fact that only power grid or access to a renewable electricity production plant is needed for production.

5.5.3.1.2 Weaknesses

- A major share of the production costs for hydrogen are caused by the electricity needed for electrolysis.
- Hydrogen technologies are still much more expensive than fossil counterparts and so not yet competitive for all sectors.
- Extended effort for capacity adaptation due to dependency on number of electrolyzers.
- Key challenges of high investment combined with an initial low rate of utilization, long period for capital recovery and high risk regarding the expected number of vehicles that are potentially supplied.
- Usage of internal PV can depend on regional solar irradiation and be a limiting factor.
- Levelized generation costs are still highly dependent on the annual full load hours of operation owing to still high CAPEX; thus, limitation to local renewable electricity supply may lead to high production costs.
- Component lifetimes are still limited, and thus increasing replacement costs.

5.5.3.1.3 Opportunities

- The stakeholder-analysis resulted in neutral to positive evaluations on a general level.
- Hydrogen can be used safely but training, initiatives and tutorials for employees due to special features and unrivalled characteristics for understanding are required.
- Public acceptance of hydrogen technologies has strong supporters at international level including Japan, South Korea, USA and at the EU level Germany, UK, France and the Nordic countries. In recent times, stakeholders from others countries also became interested.
- High political acceptance of hydrogen in general, hydrogen refuelling infrastructure and electricity storage on European and national level.
- Decentralized hydrogen production facilities combined with refuelling stations have the potential to overcome the frequently mentioned “chicken-egg-problem”.
- Contributes to the societal trends in transport sector concerning zero-emission solutions as well as in on-demand electricity supply. According to research, especially the construction of a renewable on-site hydrogen production station has become a trend.
- A mobility use case for the **SOLHUB**, including the hydrogen use in a fuel cell bus and truck, had been assessed, which reports, that the use of green hydrogen, has an 11- to 12 times lower CO_2-eq. footprint than the diesel alternative.

- Cost reductions driven by increasing overall global productions are presumed to be independent of individual system scales and are expected to decrease, solely under consideration of industrial demands for renewable hydrogen.
- Supports the sustainable development on community level as it appropriately promotes the local respectively regional level due to its decentralised concept.
- “Clean Vehicle Directive” to purchase clean vehicles by public institutions as a chance as the system is among others especially designed for municipalities.
- Special funding for the purchase of hydrogen vehicles as well as the needed infrastructure is essential and already exists on national level.
- Exemption from the system admission as well as the system provision charge for facilities converting electricity into hydrogen or synthetic natural gas and further, the exemption from the renewable flat-rate subsidy as well as the renewable funding contribution (ElWOG 2010).
- Several alliances on national, international and global level exist for hydrogen technologies.
- Use case of electricity storage can play a key-role due to the future activities for the further construction and integration of fluctuating renewable energy sources.
- Contributes to a higher resource efficiency due to usage of waste heat for heating or hot water production.
- Economic feasibility depends especially on costs of electricity and hydrogen technologies which are likely to decrease in the future.
- Improves domestic supply of hydrogen and therefore may contribute to reduce future hydrogen imports as hydrogen can be produced directly on-site.
- Flexibility in location as the **SOLHUB** can be installed nearly everywhere in urban, suburban as well as in rural areas and contributes to the local usage of hydrogen.

5.5.3.1.4 Threats

- Level of acceptance is decreasing when it comes to infrastructure implementation in the own neighbourhood, while participants’ knowledge of, and familiarity and experience with these technologies can be rated as low.
- Social and public acceptance depends on distance to installed systems and safety standards as well as knowledge and familiarity with the respective technology.
- The group of civilians and here the ambivalent attitude of neighbours next to an installed system as well as residents of cities and municipalities are important as their concern raises especially due to a lack of sufficient understand of hydrogen technology.
- The stakeholder evaluation at the early technology development stage may provide a potentially distorted result as some stakeholders evaluated with a “neutral” attitude may become “supporters” or in the worst case “opponents” as the technology is rolled-out.
- The integration of hydrogen into the existing energy systems is rated as a complex process in the absence of (governmental) steering mechanisms, it potentially will not be realised at the required pace to meet climate ambitions.
- Some issues may arise due to noise from compressors, light emissions at night as well as increased traffic, which potentially disturb residents nearby.

- Changes in land use can also arise due to the decentral solution and, e.g., the needed additional PV or wind power plants.
- The general question if hydrogen will become established as a renewable fuel e.g. compared to e-mobility.
- Manufacturing of electrolyzer and fuel cell is likely to increase raw material demand from overseas and therefore an increase in transports can happen.
- Several raw materials as main components of electrolysis and fuel cells are critical concerning demand and supply. Therefore, import dependency on South Africa (Iridium, Platinum) due to low domestic production, exists.
- Electricity costs have a significant impact as they strongly depend on the energy source and the higher the full-load hours of the system, the lower is the share of CAPEX.
- Austrian hydrogen strategy is still in the formulation process and issuing could be among others advantageous to add additional planning securities for technology deployment. In general, partly missing consistency of policies and strategies are important aspects to achieve planning security for industry and companies.
- Renewable electricity as an input to the system may be scarce in the future.
- Well developed countries have an easier access to new technologies due to their better economic conditions and therefore the opportunities depend on the geographical region.

5.5.3.2 SAMBA Matrix

From the respective strengths, weaknesses, opportunities and threats identified in the SWOT analysis in connection with fuel cell trucks, the following SAMBA matrix is developed, which is the basis for the corresponding basic strategies and recommendations for action.

	STRENGTHS	**WEAKNESSES**
SAMBA Matrix	▪ Use case of a H2 refuelling station can be rated with a TRL of 8-9. ▪ Safe, decentral power & back-up supply. ▪ General working conditions & independency can be changed by on-site H_2 production. ▪ Integration requirements are limited to a power grid & renew. electricity resources. ▪ Decentral solution to solve challenges & bottleneck of missing H_2 infrastructure. ▪ High security of supply ▪ High flexibility of the system due to the range of produced H_2 & feedstock ▪ Competitive advantage as it supports the transformation of the overall energy system. ▪ Changes in land-use limited to size of system ▪ Refuelling process for H_2 at a refuelling station was already proved to be safe. ▪ Direct learning effects would attribute for cost reductions.	▪ H_2 leakage is reported as the main concern and cause for explosion and fire. ▪ Major shares of production costs for H_2 are caused by electricity needed for electrolysis. ▪ H_2 technologies are still much more expensive than fossil counterparts & so not affordable for everyone. ▪ Extended effort for capacity adaptation needed due to, e.g., number of electrolyzers. ▪ Key challenges of high investment combined with an initial low rate of utilization, long period for capital recovery & high risk regarding the expected number of vehicles. ▪ Usage of internal PV can depend on regional solar irradiation & can be a limiting factor. ▪ Levelized generation costs are still highly dependent on the annual full load hours of operation owing to still high CAPEX; thus,

	▪ No transports for final product needed due to one-stop-shop solution. ▪ Integrated solution for H_2 production & usage for different use cases. ▪ High replicability due to limited preconditions	limitation to local renewable electricity supply may lead to high production costs. ▪ Component lifetimes are still limited, and thus increasing replacement costs.
OPPORTUNITIES	**STRENGHTS / OPPORTUNITIES**	**WEAKNESSES / OPPORTUNITIES**
▪ General acceptance of H_2 technologies resulted in neutral to positive evaluations. ▪ H_2 can be used safely but training, initiatives and tutorials for employees are required. ▪ H_2 has strong international supporters. ▪ Decentralized H_2 production with potential to overcome the "chicken-egg-problem". ▪ Contributes to societal trends in transport sector & in on-demand electricity supply. ▪ Green H_2 per bus & truck km, has an 11–12 times lower CO_2 footprint than diesel. ▪ Costs are calculated to decrease. By upscaling to 500 kW, they could be further reduced. ▪ High political national & internat. acceptance of H_2, H_2 refuelling infrastructure & storage. ▪ Supports the sustainable development on regional, local & community level. ▪ "Clean Vehicle Directive" as chance as the system is specifically designed for municipalities. ▪ Funding for the purchase of H_2 vehicles & infrastructure exists on national level. ▪ Exemption from system admission & provision charge & renew. flat-rate subsidy ▪ Several alliances on national, international and global level exist for H2 technologies. ▪ Integration of renewable energy sources. ▪ Contributes to closed loop. ▪ Feasibility depends on costs of electricity & electrolyzers which are likely to decrease. ▪ Doesn't exclude people from use. ▪ Independency of future H_2 imports. ▪ Able to be located everywhere & contributes to local usage of hydrogen.	**Preparation of good materials and guidance (presentations, folders, etc.) for the targeted training of the various users of the SOLHUB to be able to ensure their full safety.** **Targeted information to possible customers about the different advantages of the SOLHUB (supply security, flexibility, limited integration requirements, exemption from admissions & charges, integration of the access head to other processes etc.) to generate additional sales-potential and to support sustainable development.** **Presenting the SOLHUB as an innovative, decentralised solution for hydrogen production and use for different use cases in the various existing hydrogen alliances at national, international and global level to raise awareness and drive solutions for future decarbonisation.** **Formation of a special sales partnership with manufacturers of hydrogen vehicles in order to be able to overcome the existing "chicken-and-egg problem" between vehicles and necessary infrastructure. The acquisition of the vehicles will also be promoted and financially supported at the national level.** **Special outreach and information campaigns with municipalities, as the SOLHUB was a.o. specifically developed for them and the "Clean Vehicles Directive" obliges them to purchase clean and energy-efficient road vehicles.**	**Implementation of strategies for targeted cost reduction of the individual components as well as the entire SOLHUB, as hydrogen technologies are usually significantly more expensive than fossil counterparts, e.g., by using other funding programmes for further functional simplification.** **Simplification of capacity adjustment to generate a secure investment for a given consumer over years, as the load factor should be high and the period for capital recovery is long. The higher the full load hours of the system, the lower the levelized share of CAPEX. The solution is part of a social trend and currently poses a high risk, e.g., due to the expected number of vehicles.** **Communication of the facts, that production costs for hydrogen in the SOLHUB depend mainly on costs of renewable electricity and electrolyzer which are both likely to decrease in the future. Therefore, it represents, among other, the perfect solution for companies already using renewables.** **Active research concerning the prevention of hydrogen leakage as cause for explosions and fire in any cases as it is reported as a major concern with huge implications for overall high and positive acceptance at national, international and global levels.**
THREATS	**STRENGTHS / THREATS**	**WEAKNESSES / THREATS**
▪ Acceptance is decreasing when it comes to implementation in the own neighbourhood. ▪ General knowledge familiarity & experience with these technologies can be rated as low. ▪ Civilians, neighbours & residents are important as their concern raises due to a lack of understanding of H_2 technology. ▪ Social & public acceptance depends on distance to systems and safety standards.	**A clear communication strategy for the general public, but also for companies, to familiarise them with hydrogen technologies and the safe process as well as the high TRL value of e.g., hydrogen refuelling stations to further increase general acceptance.** **Targeted information to future neighbours of a SOLHUB about the functionality of the system, nature of hydrogen, different benefits and safety**	**The integration of other renewable electricity sources into the SOLHUB should be as simple as possible, as the internal PV system is of limited size and renewable electricity can be a future bottleneck, source of competition and dependent on imports.** **Develop strategies to make the SOLHUB affordable for non-developed countries, as current hydrogen technologies are primarily designed for countries with better economic conditions and**

▪ Integration of H_2 into the existing energy system will not be realised at the required pace without government intervention. ▪ Some issues may arise due to noise from compr., light emissions & increased traffic. ▪ Changes in land-use can arise due to the needed additional PV or wind power plants. ▪ The general question if hydrogen will become established as a renewable fuel. ▪ Manufacturing of electrolyzer & fuel cell will increase transports due to required raw materials from overseas. ▪ Several raw materials of electrolysis and fuel cells are critical concerning demand and supply. Therefore, import dependency of the European Union on South Africa and Congo. ▪ Electricity costs have a significant impact as they strongly depend on the energy source & full-load hours ▪ Austrian hydrogen strategy is still in the formulation process. ▪ Partly missing consistency of policies are important aspects to achieve planning security for industry and companies. ▪ Present and future competition for renewable electricity as input for the system. ▪ Well developed countries have an easier access to new technologies due to their better economic conditions & opportunities.	**before construction measures as acceptance depends on distance.** **Reduction and substitution of raw materials (Iridium, Platinum) that are critical concerning demand and supply. Import dependency on South Africa and Congo can be an issue in the future. For this case, also the development and implementation of recycling strategies can be a solution.** **Reduction and substitution of raw materials from overseas in the electrolyzer as well as the fuel cell to decrease overall total transport operations and their emissions.** **Consideration of possible noise from compressors, light emissions and increased traffic from the SOLHUB before determining a specific location to avoid problems.**	**opportunities. A modified design of the technologies including different cost schemes for diverse regions and purchase groups could be useful in this case.** **The size of the internal PV system should be adapted to the target region, as its use depends on the solar radiation of the region and can therefore be a limiting factor.** **Austrian hydrogen strategy is still in the formulation process and issuing could be among others advantageous to add additional planning securities for technology deployment. In general, partly missing consistency of policies and strategies are important aspects to achieve planning security for industry and companies.**

5.5.4 Strategies and recommendations

From the SAMBA matrix the following strategies and recommendations for the project **HyTechbasis** and the development of the **SOLHUB** are derived.

Communication & Stakeholder Engagement

- Targeted information to possible customers via various communication channels about the different advantages of the **SOLHUB** (supply security, flexibility, limited integration requirements, exemption from admissions & charges, integration of the access head to other processes etc.) to generate additional sales-potential and to support the entire sustainable development.
- Preparation of good information materials and guidance (presentations, folders, flow-charts, etc.) for the targeted training of the various users of the **SOLHUB** to be able to ensure their full safety. In general, hydrogen can be used safely but excellent initiatives and tutorials for employees are required.
- Special outreach and information campaigns to municipalities, as the **SOLHUB** is, among others, specifically developed for them as potential users and further, the "Clean Vehicles Directive" obliges them to purchase clean and energy-efficient road vehicles till 2030 respectively 2035.
- Presenting the **SOLHUB** as an innovative, decentralised solution for hydrogen production and use for different use cases in the various existing hydrogen alliances at national, international and

global level to raise awareness and drive solutions for future decarbonisation represented in the strategies and programs.

Acceptance

- A clear communication strategy for the general public, but also for companies, to familiarise them with hydrogen technologies and the safe processes as well as the high TRL value of, e.g., hydrogen refuelling stations to further increase general acceptance. Due to the lack of sufficient understanding of hydrogen energy, it has long been regarded as dangerous. Therefore, safety and knowledge of the technology can be seen as one of the key facts of social and public acceptance.
- Trough international cooperation and harmonisation, the setting of high safety standards must be achieved in order to generate public acceptance of this technology.
- Targeted information to potential future neighbours of a **SOLHUB** about the functionality of the system, general nature of hydrogen, different benefits and safety before construction measures as acceptance depends on distance. Special strategies and opportunities for direct stakeholder feedback are a solution to inform neighbours as well as residents of cities and municipalities before it is built at a particular site.
- Consideration of possible noise from compressors, light emissions and increased traffic, e.g., for the refuelling of vehicles from the **SOLHUB** before determining a specific location to avoid problems in advance.

Technological development

- Simplification of the **SOLHUB** concerning capacity adjustment to generate a secure investment for consumers over years, as the load factor should be high and the period for capital recovery is long. The higher the full load hours of the system, the lower the levelized share of CAPEX. The solution is part of a social trend and currently poses a high risk, e.g., due to the expected number of vehicles which is currently on a low level.
- Reduction and substitution of raw materials (Iridium, Platinum, Cobalt) that are critical concerning demand and supply because import dependency on countries like South Africa or Congo can be an issue in the future. For this case, also the development and implementation of recycling strategies can be a solution.
- The integration of other renewable electricity sources into the **SOLHUB** should be as simple as possible, as the internal PV system is of limited size and renewable electricity can be a future bottleneck, source of competition and dependent on imports.
- The size of the internal PV system should be adapted to the target region of the construction, as its use depends on the solar radiation and can therefore be a limiting factor.
- To decrease overall total transport operations and their emissions, the reduction and substitution of specific raw materials from overseas in the electrolyzer as well as the fuel-cell of the **SOLHUB** should be realised. An effective measure also could be establishing recycling technologies for material recovery and application of secondary materials.

Economics

- Implementation of strategies for targeted cost reduction of the individual components as well as the entire **SOLHUB**, as hydrogen technologies are usually significantly more expensive than fossil counterparts, e.g., by using other funding programmes for further functional simplification.
- Communication of the facts, that production costs for hydrogen in the **SOLHUB** depend mainly on costs of renewable electricity and the electrolyzer which are both likely to decrease in the future [43] and therefore, the **SOLHUB** is an interesting investment-case. The main production costs for hydrogen are caused by the electricity needed and therefore, it represents, among others, a good solution for companies already using renewables energy resources.
- Develop "standard use case" for the **SOLHUB** to show potential customers the applicability and economic feasibility.
- Development of strategies to make the **SOLHUB** affordable for non-developed countries, as current hydrogen technologies are primarily designed for countries with better economic conditions and opportunities. A modified design of the technologies including different cost schemes for diverse regions and purchase groups could be useful in this case.

Infrastructure

- Development of special sales partnership with manufacturers of hydrogen vehicles in order to be able to overcome the existing "chicken-egg problem" between vehicles and necessary infrastructure. The acquisition of hydrogen vehicles will also be promoted and financially supported at the national level and therefore, a win-win-situation could be realised in the end.

Future Roll-Out

- Austrian hydrogen strategy is still in the formulation process and issuing could be among others advantageous to add additional planning securities for technology deployment. Therefore, active lobbying that consistency of policies and strategies are important aspects to achieve planning security for industry and companies concerning the target of climate neutrality.

6 Regulatory and legal aspects of electrolysis units and hydrogen production[18]

The Austrian legal framework for hydrogen and Power-to-X was screened and a position paper[19] was prepared in a coordination process lasting several months with the relevant stakeholders and distributed to the relevant policy makers. In this position paper proposals for amending and specifying the Austrian legal framework on hydrogen and Power-to-X in the areas of levies and tariffs, certification, plant construction, infrastructure and refueling were elaborated. Particularly important aspects were:

- Definition and synchronisation of specific terms like renewable hydrogen and gas

[18] Parts of this report are derived from or build on results of the projects HyTruck (project number 868790) and UpHy I (project number 868835).

[19] *WIVA P&G*, Positionspapier: Vorschläge zur Änderung und Präzisierung des österreichischen Rechtsrahmens zu Wasserstoff und Power-to-X (2020), [Online] Available at: https://www.wiva.at/v2/postionspapier_recht2020/.

- Guideline for the implementation of Power-to-Gas plants to achieve an easy and fast process (see also DVGW[20])
- Differentiation of permission process considering the application (commercial or private).

In addition, a working group on "Authority Procedures" was initiated. Within this working group, problems and approaches to solutions that exist in connection with these procedures were identified and discussed.

Furthermore, specific regulatory and legal aspects of electrolysis units and hydrogen production were analysed. In this regard, especially the Renewable Energy Expansion legislative package brings several new provisions for Power-to-Gas plants and renewable gases. The Renewable Energy Expansion legislative package was enacted in July 2021 and, on the one hand, newly introduced the Renewable Energy Expansion Act (F.L.G. I No. 150/2021 as amended by F.L.G. I No. 13/2022, hereafter REEA) and amended nine existing laws, including the Natural Gas Sector Act 2011 (F.L.G. I No. 107/2011 as amended by F.L.G. I No. 67/2022, hereafter NGSA 2011) and Electricity Act 2010 (F.L.G. I No. 110/2010 as amended by F.L.G. I No. 7/2022, hereafter EA 2010), in which the aforementioned new provisions are found. These relate in particular to investment aid, tariffs and charges, operation of Power-to-Gas plants, permissible percentage of hydrogen in the natural gas pipelines, guarantees of origin and renewable gas badge as well as certificates. In addition, renewable hydrogen, renewable gas, and synthetic gas were defined in the NGSA 2011 and are as follows:

- Renewable hydrogen is hydrogen produced exclusively from energy from renewable energy sources[21],
- Renewable gas is renewable hydrogen or gas from biological or thermochemical conversion produced exclusively from energy from renewable energy sources, or synthetic gas produced on the basis of renewable hydrogen[22] and
- Synthetic gas is gas produced on the basis of hydrogen.[23]

Investment aids for Power-to-Gas plants: § 62 of the REEA provides for annual subsidies of 40 million € for Power-to-Gas plants.[24] This is to ensure the effective implementation of the transformation from sector coupling and integration, to a purely renewable energy system as fast as possible.[25] Power-to-Gas plants with a minimum capacity of at least 1 MW are eligible for investment grants, provided that they are used exclusively for the production of renewable gases and purchase exclusively renewable electricity. Plants that are constructed and operated by system operators in accordance with the provisions of § 22a EA 2010 are not eligible for subsidies. Plants that blend hydrogen to fossil gas in the public gas grid are also excluded from the possibility of receiving funding.[26] An investment subsidy shall be established by ordinance of the Federal Minister for Climate Action, Environment, Energy, Mobility, Innovation and Technology in agreement with the Federal Minister for Agriculture, Regions and Tourism in subsidy rates of up to 45% of the investment volume directly required for the construction of the plant

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[20] https://www.dvgw.de/themen/energiewende/power-to-gas/portal-green.
[21] Cf. § 7 (1) (16a) NGSA 2011.
[22] Cf. § 7 (1) (16b) NGSA 2011.
[23] Cf. § 7 (1) (61a) NGSA 2011.
[24] Cf. § 62 (2) REEA.
[25] Cf. Explanatory notes on the government bill for the Renewable Energy Expansion Package (ErläutRV 733 BlgNR 27. GP 16).
[26] Cf. § 62 (1) REEA.

(excluding land costs). A special investment subsidy may be granted in the ordinance for plants that contribute to operational security of the network.[27]

If a Power-to-Gas plant only has a minimum capacity of 0.5 MW and a maximum capacity of less than one MW, subsidies of up to 20% of the investment volume directly required for the construction of the plant (excluding land) are possible. If a support contract is concluded, the plant must be put into operation within 36 months of this date.[28]

Network tariffs and charges: As far as the network tariffs for the purchase of electricity by the Power-to-Gas plant are concerned, some facilitations can be found in the EA 2010. Power-to-Gas plants with a minimum capacity of 1 MW do not have to pay the system admission charge up to a grid connection quotient[29] of 200 rm/MWel of agreed capacity if they exclusively purchase renewable electrical energy and do not feed into the gas grid.[30] If the Power-to-Gas plant only uses renewable electrical energy, has a minimum capacity of 1 MW and does not feed into the gas grid, the system provision charge is also exempt from payment.[31] In addition, Power-to-Gas plants, if they have a minimum capacity of 1 MW, do not have to pay any of the system utilization charge and charge for system losses imposed for the purchase of renewable electrical energy for 15 years from the date of commissioning.[32]

Since hydrogen may not be fed directly into the public gas grid in Austria, if methanation does not follow and hydrogen is planned to be fed into the gas grid, natural gas must first be obtained from the gas grid, mixed with the renewable hydrogen produced, and then the natural gas-hydrogen mixture must be fed into the public gas grid. Under the old provisions, the gas-side system utilization charge had to be paid for natural gas taken for the purpose of blending and reinjection. Now, section 73 (8) NGSA 2011 stipulates that no grid usage charge is payable for gas withdrawn for the purpose of blending with hydrogen and subsequently re-injected.

Furthermore, it has to be examined whether the renewable electricity contribution and the renewable electricity flat rate have to be paid. They both serve to raise a share of the subsidies pursuant to § 71 of the REEA.[33] The renewable electricity contribution is to be paid by all end consumers connected to the public electricity grid, with the exception of pumped storage power plants and low-income households[34], in proportion to the respective system utilization charges and charges for system losses.[35] The amount of the renewable electricity contribution is determined annually in advance by ordinance of the Federal Minister for Climate Action, Environment, Energy, Mobility, Innovation and Technology in agreement with the Federal Minister for Digital and Economic Affairs. For the calendar year 2022, no renewable electricity contribution will be levied, as it was set in the renewable electricity contribution ordinance 2022 (F.L.G. II No. 600/2021) at 0% of the Austrian-wide average system utilization charge and charge for system losses payable per grid level pursuant to the system charges ordinance 2018 (F.L.G. II No. 398/2017 as amended by F.L.G. II No. 558/2021). The renewable electricity flat rate refers to the

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[27] Cf. § 62 (4) REEA.
[28] Cf. § 62 (9) REEA.
[29] The grid connection quotient indicates the running meters of electrical line in relation to the electrical connected capacity of the plant (MWel) (cf. explanatory notes on the government bill for the Renewable Energy Expansion Package; ErläutRV 733 BlgNR 27. GP 32).
[30] Cf. § 54 (6) EA 2010.
[31] Cf. § 55 (10) EA 2010.
[32] Cf. § 111 Abs. 3 EA 2010.
[33] Cf. § 5 (1) (15), (16) REEA.
[34] Cf. § 72 REEA.
[35] Cf. § 5 (1) (15), § 75 (1) REEA.

contribution in € per metering point to be paid by all end consumers connected to the public electricity grid, with the exception of end consumers providing balancing services pursuant to sections 23b to 23d EA 2010, as well as pumped storage power plants and low-income households.[36] However, it is set at zero for 2022, and is not to be paid until 2023.[37] If a Power-to-Gas plant has a minimum capacity of 1 MW, exclusively obtains renewable electricity and does not feed into the gas grid, exemptions from the obligation to pay the renewable electricity flat rate and the renewable electricity contribution may be specified in the ordinances pursuant to sections 73 (7) and 75 (2) of the REEA in accordance with EU state aid regulations, where applicable. As long as this is not the case, these exceptions can be granted as de minimis aid under the conditions of Regulation (EU) 1407/2013 (as amended by 2020 L215/3).[38].

Operation by transmission and distribution system operators: The Electricity market directive (Directive 2019/944 as amended by 2019 L158/125, hereafter ED 2019) introduces the concept of energy storage and issues specific provisions in this regard. Accordingly energy storage in the electricity system means "deferring the final use of electricity to a moment later than when it was generated, or the conversion of electrical energy into a form of energy which can be stored, the storing of such energy, and the subsequent reconversion of such energy into electrical energy or use as another energy carrier;".[39] In the electricity system, a facility in which energy storage occurs, is an energy storage facility.[40] The Directive stipulates that Member States may allow distribution system operators and transmission system operators to own or construct energy storage facilities under certain conditions, in derogation from the general prohibition.[41] Austria has made use of this and has issued provisions for the exceptionally possible operation of Power-to-Gas plants (which therefore apparently qualify as energy storage facilities) by distribution and transmission system operators.[42]

Determination of the permissible hydrogen content in the gas network: Up to now, the permissible proportion of hydrogen admixture has been specified in the ÖVGW norms. Accordingly, the permissible proportion is currently set at 10% in the ÖVGW norm G B2010. Now, however, the Federal Minister for Climate Action, Environment, Energy, Mobility, Innovation and Technology, in agreement with the Federal Minister for Digital and Economic Affairs, has the right to set a maximum value for the technically permissible proportion of hydrogen in natural gas pipeline systems by ordinance.[43]

Guarantees of origin and certification: With regard to guarantees of origin in connection with plants that produce renewable gas on the basis of renewable electricity, it is stipulated that the plant operator must transfer guarantees of origin and environmental impacts of electricity production to gas production. The guarantees of origin and environmental impacts on which electricity generation is based must be reduced by the conversion losses incurred during gas production and classified in the electricity verification system as energy input for gas labeling, whereby the conversion losses must be classified as consumption in the energy sector.[44]

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[36] Cf. § 5 (1) (16) REEA.
[37] Cf. § 73 (1) REEA.
[38] Cf. §§ 73 (1a) and 75 (1a) REEA.
[39] Art. 2 (59) ED 2019.
[40] Art. 2 (60) ED 2019.
[41] Cf. Art. 36 (1) and Art. 54 (1) ED 2019.
[42] Cf. § 22a EA 2010.
[43] Cf. § 133a NGSA 2011.
[44] Cf. § 83 (6) REEA.

Furthermore, it is essential to certify hydrogen produced via green electricity. CertifHy®[45] has developed high-quality hydrogen certification schemes across Europe, CertifHy® Guarantees of Origin (GOs), that will support hydrogen’s market growth as they are a reliable tool for consumers to track hydrogen’s origin and environmental attributes. In Austria and Germany, the TÜV Süd has developed a certification for Green Hydrogen, TÜV SÜD Standard CMS 70, version 01/2020 "Production of green hydrogen”[46], which enables to prove that the produced hydrogen has significantly lower greenhouse gas emissions than conventionally produced hydrogen or fossil fuels. These certified Green Hydrogen quantities can be registered in the European Union-supported guarantee of origin system for hydrogen from renewable energies.

Renewable gas certificate and renewable gas badge: With the newly introduced renewable gas certificates, the production of renewable gas that is not fed into the public grid and is used in end consumption or is used as a material can be verified.[47] They are generated and listed in the regulatory authority's guarantee of origin database in accordance with section 86 (2) of the REEA. The issuance of a green certificate for gas, excludes the issuance of a guarantee of origin according to §§ 81-84 REEA.[48] A renewable gas certificate is valid for 1 MWh[49] by default and has a validity period of twelve months from the generation of this energy unit. After use, the certificate must be cancelled.[50]

A Renewable gas badge is „a record of renewable energy that counts towards Austria’s national contribution under Article 3 (2)” RED II[51] and “towards suppliers’ renewable gas quota;“.[52, 53] Therefore, if a renewable gas certificate has a renewable gas badge, it can count toward the green gas quota.[54] The renewable gas quota is an obligation to suppliers to substitute a certain percentage of fossil gas volumes sold with renewable gas.[55] The relevant provisions apply when a renewable gas quota is established.

Natural Gas Tax: The supply of natural gas in the tax territory[56] is subject to the natural gas tax pursuant to § 1 (1) (1) Natural Gas Tax Act (F.L.G. No. 201/1996 as amended by F.L.G. I. No. 63/2022).[57] Among other things, hydrogen is listed as natural gas within the meaning of the Natural Gas Tax Act. The natural gas tax for hydrogen is in principle 0.021€/m^3. [58] However, for operations after April 30, 2022 and before July 1, 2023, the levy will be 0.0038 € instead of 0.021 € per m^3.[59] A tax exemption is provided for hydrogen that can be shown to meet the sustainability criteria of the Fuel Ordinance 2012 or other standards implementing the RED II and that has been produced exclusively from renewable energy sources.[60] It should be noted, however, that the applicability of Section 3 (2) (3) of the Natural

45 https://www.certifhy.eu/
46 https://www.tuvsud.com/de-at/presse-und-medien/2020/februar/tuev-sued-zertifiziert-gruenen-wasserstoff.
47 Cf. § 5 (1) (29) and § 86 (1) REEA.
48 Cf. § 86 (2) REEA.
49 Cf. § 86 (4) REEA.
50 Cf. § 86 (5) REEA.
51 If gas is produced from energy in the form of biomass fuels, sustainability requirements and greenhouse gas savings criteria (cf. § 6 (2) and (3) REEA) must also be met.
52 Cf. § 5 (1) (27) REEA.
53 Cf. § 5 (1) (27) REEA and § 85 (1) REEA.
54 Cf. § 86 (3) REEA.
55 Cf. § 87 (1) REEA.
56 The tax territory within the meaning of the Natural Gas Tax Act is the territory of the Federal Republic pursuant to § 1 (3) of the Natural Gas Tax Act, with the exception of the territory of the local municipalities of Jungholz and Mittelberg.
57 Pursuant to § 1 (1) of the Natural Gas Levy Act, deliveries to natural gas undertakings within the meaning of § 6 (14) NGSA 2011 and to other resellers shall be exempt from this requirement if the natural gas is intended for onward delivery.
58 Cf. § 5 (4) Natural Tax Act.
59 Cf. § 8 (6) Natural Tax Act.
60 Cf. § 3 (2) (3) (b) Natural Tax Act.

Gas Tax Act, which implements this tax exemption, has been postponed until EU legal obligations, in particular obligations under state aid law, have been fulfilled.[61]

Unification of permission and admission processes within the whole process chain: For commercial purposes, a plant licence according to the Trade Regulation Act 1994 (F.L.G 194/1994 as amended by F.L.G. I No. 65/2020) must be obtained. Process plants for the production of hydrogen by chemical conversion are listed in the Trade Regulation Act 1994 in Annex 3 under point 4.2a. These are large plants with special hazard potential (IPPC plants) for which special and thus more complex procedural regulations apply. No clear threshold values are quantified for electrolysis plants. It is recommended that clear threshold values should be established for electrolysis plants. Emissions from electrolysis plants are limited to O_2, minor amounts of H_2, noise and waste water. Plant waste water from electrolysis plants can usually be discharged into the existing public sewer system, as the limit values listed in Annex A of the Ordinance of the Federal Minister of Agriculture and Forestry on the limitation of wastewater emissions from the production of technical gases (F.L.G. 670/1996 as amended by F.L.G. II No. 389/2021) are complied with.

The operator obligations regarding the "control of major-accident hazards involving dangerous substances" regulated in Section 8a are applied to establishments with dangerous substances exceeding the quantity thresholds specified in Annex 5 Trade Regulation Act 1994 ("SEVESO establishments"). According to Annex 5 Part 2 No. 15 Trade Regulation Act 1994, an establishment in which hydrogen is present in a quantity of 5 to less than 50 tonnes is a lower-tier establishment and an establishment in which hydrogen is present in a quantity of 50 tonnes or more is an upper-tier establishment.

It is recommended to establish a uniform interpretation in which non-stationary storage facilities that are only temporarily located on the premises (such as vehicle tanks or ADR shipping containers) are not to be included in the calculation of the stored quantity of hazardous substances.

However, for private applications, the federal-state laws have to be taken into account. Thus, all gas installations in a private use environment fall within the scope. This also includes gas installations that cannot be assigned to any federal law due to a lack of legal material. The different definitions in the provincial legal norms for combustible gases are also valid for hydrogen. The exception is the Upper Austrian Gas Ordinance (S.L.G. 98/2015). Here, an explicit integration of the term hydrogen is required. The minimum safety requirements for hydrogen systems in the private environment must be defined and integrated into the gas safety laws. This applies in particular to home refuelling systems and hydrogen systems for energy-autonomous single-family homes.

[61] Cf. § 8 (5) Natural Tax Act and BGBl. II No. 440/2019 (Announcement of the Federal Minister of Finance on the date of applicability of § 2 (1) and § 3 (2) (3) Natural Tax Act, § 1 (3) (2) and § 2 (2) (2) (b) Energy Tax Rebate Act (F.L.G No. 201/1996 as amended by F.L.G. I No. 46/2022) as well as § 2 (1) (1) and § 4 (1) (10) Mineral Oil Tax Law (F.L.G. No. 630/1994 as amended by F.L.G. 63/2022), F.L.G. II. No. 440/2019).

7 Outlook and recommendations

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