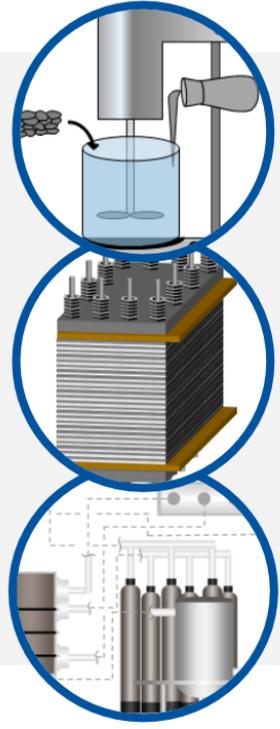
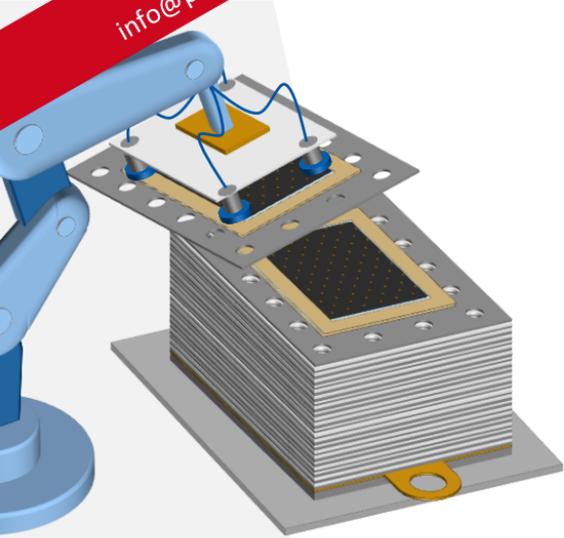


Also available as  
a free brochure

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# PRODUCTION OF ELECTROLYZER SYSTEMS



Power-to-X  
for Applications



Fuel Cells



**RWTH AACHEN  
UNIVERSITY**

The chair of “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University conducts research on various aspects of production technology for fuel cells. The activities reach across the mechanical engineering sector, ranging from cost-efficient production of components for hydrogen-powered drivetrains and innovative mobility solutions to overall emissions reduction. Through national and international projects involving renowned companies at various stages of the value chain as well as through participation in numerous research initiatives, PEM offers profound expertise.



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The VDMA Fuel Cells Working Group pursues the goal of establishing fuel technologies in Germany and positioning them on global markets. To this end, the working group represents the political interests of more than 90 leading producers and suppliers in Germany and abroad.

VDMA “Power-to-X for Applications” is a cross-industry platform for information, communication, and collaboration within the P2X community, engaging all key stakeholders and actors, from the development of manufacturing processes to the production of synthetic fuels and raw materials all the way to the end consumer.



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Do you have any questions?

Contact us!

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# Motivation

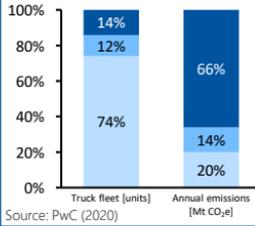
for the use of hydrogen in mobility

**i** A primary contributor to road-related European emissions is **freight transport within the classes N1, N2, and N3**, accounting for approximately **40%**.

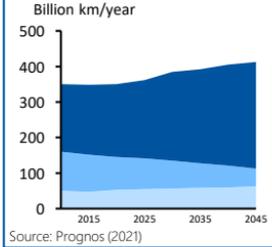
Commercial Vehicle Classes (CV)

- N1: light CV with a GVW <3.5t
  - N2: medium-duty CV with a GVW of 3.5 - 12 t
  - N3: heavy-duty CV with a GVW >12 t
- GVW: Gross Vehicle Weight

## Truck Fleet & Emissions in Germany



## Forecast of European Driving Distances

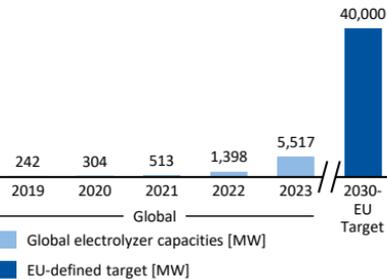


Light and heavy commercial vehicles play a significant role in carbon dioxide (CO<sub>2</sub>) emissions within the mobility sector. To reduce emissions and achieve climate protection goals in mobility, fuel cells can be utilized to electrochemically convert hydrogen into electrical energy. Since this reaction produces only water, fuel cells serve as a clean conversion unit within an electric drive. To contribute to the reduction of climate-damaging CO<sub>2</sub> emissions in transportation using "green hydrogen", the deployment of electrolyzers becomes necessary to provide the required green hydrogen. It can be injected into a hydrogen refueling station through a distribution system, making it available to end users.

Next to mobility, further sectors such as the chemical industry, steel production, and energy supply for buildings can represent significant markets for hydrogen. However, all these markets share the common requirement of establishing not only the necessary electrolyzer capacities but also to build plants powered by renewable energy and distribution systems to replace "gray hydrogen" with the green alternative.

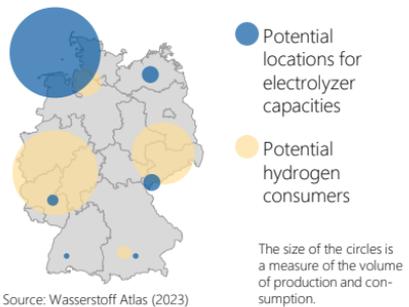
## Installed and planned electrolyzer capacities<sup>1</sup>

Over the next years, an expansion of electrolyzer capacities is necessary to meet the demand and achieve climate protection goals.



## Qualitative comparison of hydrogen producers and consumers

The spatial decoupling of hydrogen production and utilization across all sectors necessitates the use of transport pipelines.



## Conclusion: Expansion of the hydrogen infrastructure is a necessity



Substitution of gray hydrogen with green hydrogen



Expansion of electrolyzer and RE capacities by a multiple

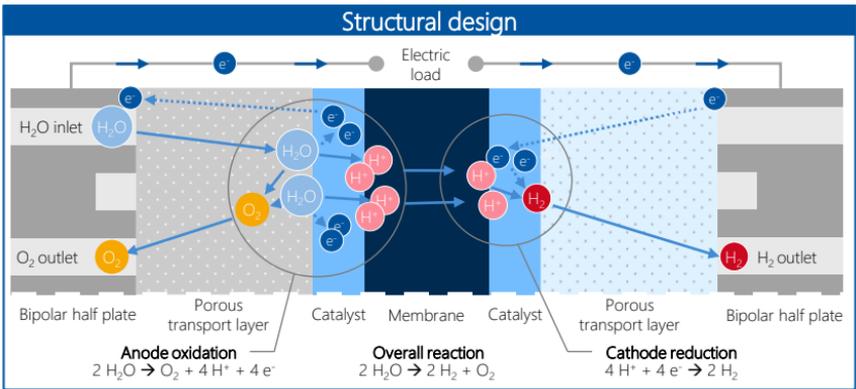


Establishment of hydrogen distribution infrastructure

<sup>1</sup> Electrolyzer capacities for 2023 also consider planned capacities for the 2023 financial year.

\*RE = Renewable Energy

# Operating Principle of a PEM electrolyzer



The principle of converting water into hydrogen and oxygen using electrical energy is based on the following operating principle:

- Water is supplied to the anode side through the flow channels of the **bipolar half plates** (BPHP).
- Water diffuses through the **porous transport layer** (PTL) to the anode side of the **catalyst-coated membrane** (CCM).
- Water is catalytically oxidized, generating protons (H<sup>+</sup> ions) which are conducted through the humidified membrane to the cathode side.
- Electrons are conducted to the cathode side through an external circuit where they react with the protons to form hydrogen.
- The produced gases, hydrogen and oxygen, are purified and stored for further use.

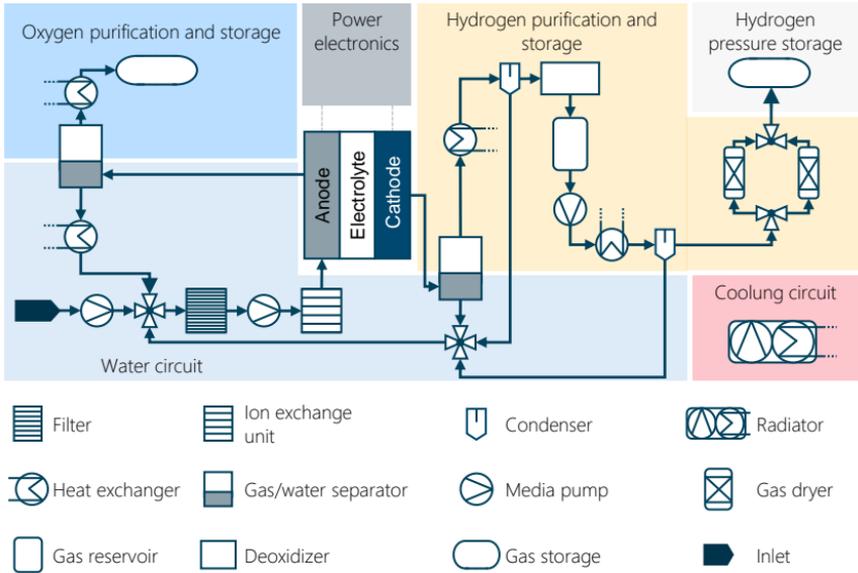
## Electrolyzer Types in comparison

The following overview presents the currently available electrolyzer types in industry and research, their reaction media, and common operating temperatures. While SOEL and AEMEL are less prevalent in the market, PEMEL and AEL represent more established technologies. Accounting for around 60 to 70% of globally installed capacity, AEL is currently the most widely adopted technology. However, PEMEL is the technology for which there are the most offered products on the market. Due to its strong market representation, the following discussion focuses on PEMEL. Nevertheless, a comprehensive comparison among all four technologies will be provided at the end.

Electrolyzer types	Anode in/out	Ion transport	Cathode in/out	Temp. [°C]
SOEL Solid Oxide Electrolyzer	Air → O <sub>2</sub>	← O <sub>2</sub> <sup>-</sup>	H <sub>2</sub> → H <sub>2</sub> O	800
AEL Alkaline Electrolyzer	KOH → O <sub>2</sub>	← OH <sup>-</sup>	H <sub>2</sub> → KOH	90
PEMEL Polymer Electrolyte Membrane Electrolyzer	H <sub>2</sub> O → O <sub>2</sub>	→ H <sup>+</sup>	H <sub>2</sub>	60
AEMEL Anion Exchange Membrane Electrolyzer	H <sub>2</sub> O → O <sub>2</sub>	← OH <sup>-</sup>	H <sub>2</sub>	

# System Architecture

## of a PEM electrolyzer system



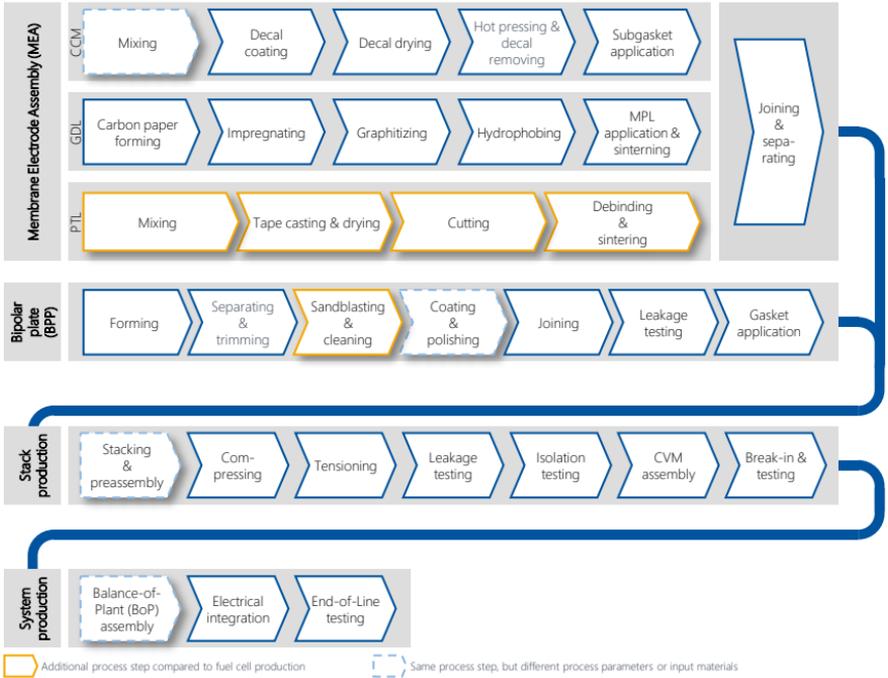
The system architecture of a PEM electrolyzer can be divided into six typical areas, with practical implementation varying depending on the system.

- Water cycle:** The water cycle is primarily fed from the water supply with deionized water. Since the reaction in the cell is not proceeded completely, the reaction products – oxygen and hydrogen – also contain water. This is separated by separators and condensers and returned to the electrolyzer. Before entering the cell, the water filter and ion exchanger ensure the necessary water quality.
- Hydrogen purification and storage:** On the cathode side, a fraction of water and oxygen is also present along with the desired hydrogen. The purity level is increased by the gas/water separator, two condensers, a deoxidizer, and finally by Pressure Swing Adsorption (PSA). With compression pumps and heat exchangers, hydrogen is stored at high pressure and as low temperature as possible.
- Oxygen purification and storage:** The electrolyzer reaction produces high-purity oxygen, which is separated from the water cycle using the gas/water separator. If process heat is removed, it can be stored and sold as a raw material, e.g., for industrial manufacturing processes.
- Cooling circuit:** The cooling circuit extracts the heat generated by the electrolyzer process, mainly from the stack but also from the compression pumps, using appropriate heat exchangers. The water in the cooling circuit circulates through a pump and releases the absorbed heat to an external heat exchanger.
- Power electronics:** The power electronics supply the required DC voltage to the stack. Initially, a high current is set in the transformer, and then the alternating current is rectified.

# Production Process

## of a PEM electrolyzer system

In the illustrated production process, the production of a PEM electrolyzer system is compared to that of a PEM fuel cell system. Distinctions are made between additional and divergent production steps:



# Process Chain Comparison

## between PEM fuel cell systems and PEM electrolyzer systems\*

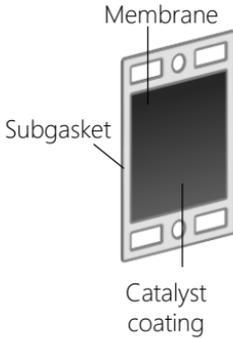
- Component level:** In comparison to the PEM fuel cell, a PEM electrolyzer uses an iridium catalyst on the anode side. This requires adjustments in the mixing process. Additionally, due to high electrical potentials on the anode side of a PEM electrolyzer, a porous transport layer (PTL) needs to be applied. On the cathode side, a carbon-based gas diffusion layer (GDL) similar to the PEM fuel cell can be used. Both components are abbreviated as „PTL“ in the following.
- Stack level:** In contrast to the PEM fuel cell, the PEM electrolyzer has a larger cell area, making its stacking process more challenging in terms of part handling.
- System level:** Assembling a PEM fuel cell involves a classic assembly process according to the automotive industry, where individual system elements are assembled at successive stations. In contrast, assembling a PEM electrolyzer system, particularly in the case of large electrolyzer systems, is akin to assembling large process engineering plants. Additionally, container solutions are frequently applied in the case of electrolyzers.

\* This brochure presents the production processes that differ from PEM fuel cell production. The production processes that are nearly identical in both technologies are described in the brochures "Production of Fuel Cell Components" and "Production of Fuel Cell Systems" by PEM of RWTH Aachen University and VDMA.

# Overview

## of PEM electrolyzer cell components

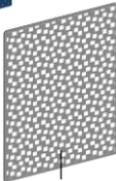
### Catalyst-coated membrane



- The polymer membrane coated with the catalysts is called a “catalyst coated membrane” (CCM).
- At the cathode, platinum, and at the anode, iridium is used as the catalyst material.
- The catalyst layers have distinct loadings, facilitating the electrochemical reactions.
- The semipermeable membrane facilitates the transportation of protons and additionally serves to separate the reaction gases.

### Porous transport layer

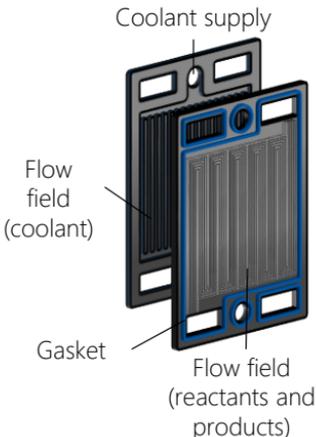
Carbon paper or carbon cloth



Sintered titanium powder, for example

- On the hydrogen side, a carbon- or titanium-based PTL can be placed between BPP and catalyst layer.
- At the anode, a titanium-based PTL is used.
- The PTLs conduct electrons, assist in thermal management, and facilitate efficient transport of reaction water and feed gases.
- Due to their mechanical stability, the PTLs enhance handling during the assembly process and ensure that the membrane is not damaged during the pressurized operation of the electrolyzer.

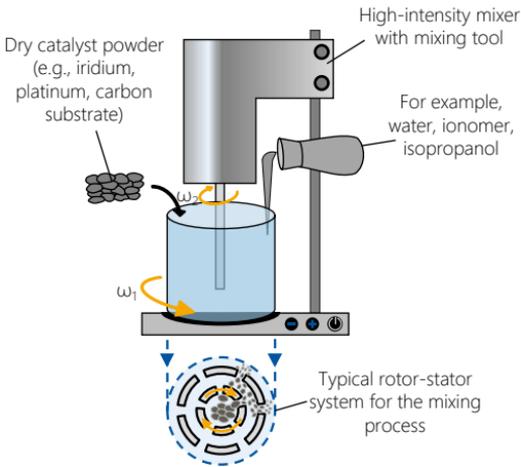
### Bipolar plate



- The Bipolar Plate (BPP) consists of two formed and joined half plates, ensuring the transport of reactants and products within the electrolyzer cell.
- Through the cavity formed by joining the two half plates, the electrolyzer system can be cooled if this is not accomplished through process water.
- Typically, in a PEM electrolyzer, titanium materials or stainless steel are used for the BPP, with coatings such as titanium-silver, ruthenium oxide, platinum, or gold being applied.

# Mixing

## CCM production



### Anode formula (example)

**Catalyst powder:**

Iridium Oxid  $\text{IrO}_2$  (approx. 8 wt.-%)

**Solvent:**

Isopropanol (approx. 42 wt.-%) and Propylene Glycol (approx. 42 wt.-%)

**Binder:**

Ionomer Solution (approx. 8 wt.-%)

### Cathode formula (example)

**Catalyst powder:**

Carbon-supported Platinum Pt/C (approx. 4 wt.-%)

**Solvent:**

Isopropanol (approx. 33 wt.-%) and Propylene Glycol (approx. 33 wt.-%)

**Binder:**

Ionomer Solution (approx. 30 wt.-%)

### Component production

### Stack production

### System production

- The catalyst ink for the cathode primarily consists of carbon substrate (e.g., carbon black) and catalyst material (such as platinum).
- On the anode, iridium oxide is used due to higher potentials.
- In general, both catalyst inks are finalized by the help of additives.
  - The solvents generally contribute to the homogenization and liquefaction of the ink.
  - The binder enables the transport of protons within the catalyst layer to the membrane.
- Catalyst ink mixing for the CCM's anode and cathode layers is done separately.
- Mixing is typically done using agitators, which allow for achieving a homogeneous viscosity of the ink.

### Process parameters & requirements

- Catalyst loading:
  - 1 - 2.5  $\text{mg}/\text{cm}^2$  (anode)
  - 0.3  $\text{mg}/\text{cm}^2$  (cathode)
- Mixing duration: 5 mins.
- Temperature: 20 - 25°C
- Mixing speed: approx. 20,000 rpm

### Alternative technologies

- Ultrasonic bath
- Paddle mixer
- Rotary ball mixer

### Quality influences

- Mixing duration, intensity, and temperature
- Wear of mixing tool
- Atmosphere during mixing process (e.g., nitrogen instead of air)
- Solvent evaporation behavior

### Quality characteristics

- Homogeneous dispersion
- Viscosity
- Low particle agglomeration

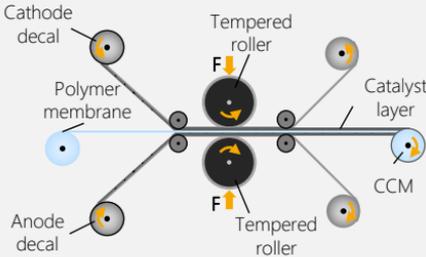
# Manufacturing CCM

## Coating concepts and research approaches

There are various approaches for producing CCMs, which can be divided into indirect and direct methods.

- Indirect methods: In the decal and transfer tape methods, the catalyst ink is first applied and dried onto another material in an intermediate step.
- Direct methods: In direct methods, the catalyst ink is applied directly onto one of the functional layers, either the membrane or the PTL.

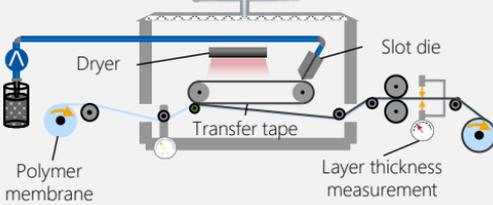
### Decal method



In the **decal method**, the catalyst ink is coated onto a polymer transfer tape which is then dried and transferred onto the membrane through a hot-pressing process.

- + Stable manufacturing process that is commonly used in the industry
- The used decal is considered a waste product.

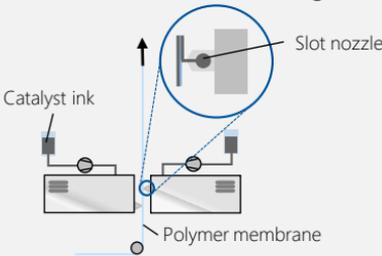
### Transfer tape



The **coating of a reusable intermediate element** (in this case, transfer tape) with the catalyst ink and subsequent (partial) drying takes place. The transfer is carried out using a hot-pressing process.

- + There is no membrane swelling due to contact with water.
- The intermediate element needs to be cleaned after the transfer.

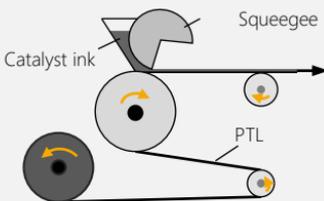
### Membrane direct coating



In the **direct coating of the membrane**, it can be coated directly using a slot die in a roll-to-roll process.

- + The value chain can be reduced and simplified by one process step.
- The membrane is sensitive to moisture and swells due to the water in the catalyst ink, making it difficult to achieve a homogeneous catalyst layer.

### GDE approach

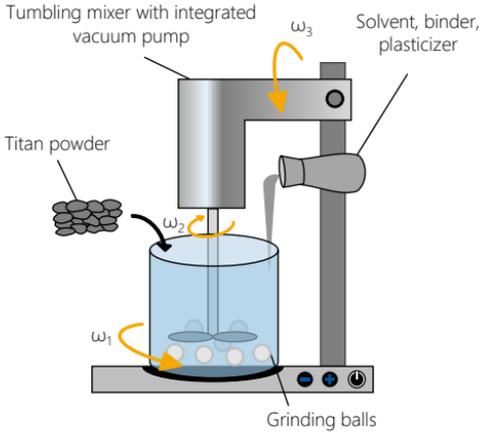


In the **GDE approach**, the PTL is directly coated, creating a Gas Diffusion Electrode (GDE).

- + The PTL or GDE represents an advantageous substrate in terms of handling.
- The liquid catalyst ink can penetrate the pores of the PTL and reduce porosity by clogging.

# Mixing

## PTL production



### Ink formula (example)

#### Sinter powder:

Ti-HDH (Hydride-Dehydride), 69 wt.%

#### Solvent:

Ethanol, 28 wt.%

#### Binder and Plasticizer:

PVB Resin, Triethylene Glycol, and Polyethylene Glycol, 3 wt.%

#### Optional:

Addition of a pore-forming agent to increase porosity

### Component production

### Stack production

### System production

- The mixing process for the titanium ink involves the use of a mixing tool, such as a tumbling mixer.
- Initially, the binder and plasticizer are processed with the solvent in the mixer until a homogeneous dispersion is achieved.
- Subsequently, the metal powder is added, and grinding balls can be used to aid the mixing process.
- An integrated vacuum pump prevents the formation of air bubbles in the created dispersion.

### Process parameters & requirements

- Titanium powder particle size:  $<45\mu\text{m}$
- Mixing duration: approx. 24 hrs.
- Pressure: ambient pressure
- Temperature: room temperature, typically around  $22^\circ\text{C}$

### Alternative technologies

- Sintering powder: spherical titanium powder (Ti-GA)
- Solvent: methyl ethyl ketone, deionized water
- Binder: polyvinyl alcohol
- Plasticizer: benzyl butyl phthalate

### Quality influences

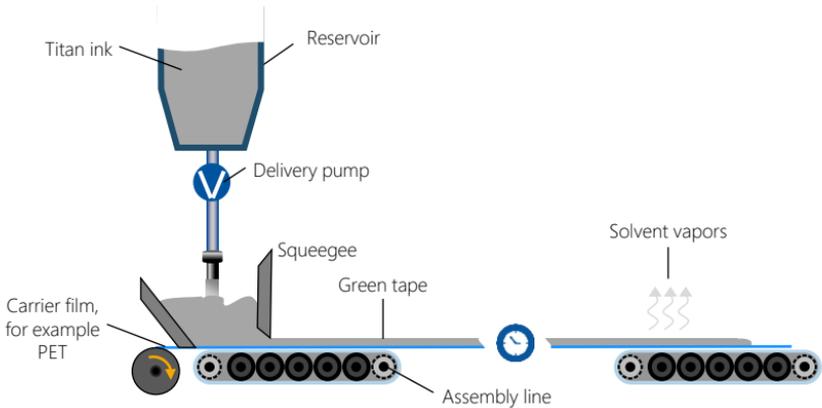
- Ambient atmosphere
- Mixing ratio of components
- Particle size of titanium powder
- Duration of mixing process

### Quality characteristics

- Homogeneity of the ink
- Viscosity
- Absence of bubbles

# Tape Casting & Drying

PTL production



## Component production

## Stack production

## System production

- The aim of tape casting is to uniformly apply the prepared titanium ink onto a flat carrier film.
- To achieve this, the titanium ink is pumped from a reservoir behind a squeegee whose horizontal distance from the carrier film sets the layer thickness.
- As the conveyor belt moves, a thin layer of the titanium ink forms on the carrier film, also known as the „green tape“.
- The resulting green tape dries on the conveyor belt under ambient environmental conditions until most of the solvent evaporates.

## Process parameters & requirements

- Wet layer thickness:  $300 \pm 30 \mu\text{m}$
- Feed rate: 250 mm/min.
- Typical pore size: 15 - 20  $\mu\text{m}$
- Drying time depends on drying intensity, e.g., using a heated conveyor belt or heating elements: 15 mins.

## Alternative technologies

- Additive manufacturing processes

## Quality influences

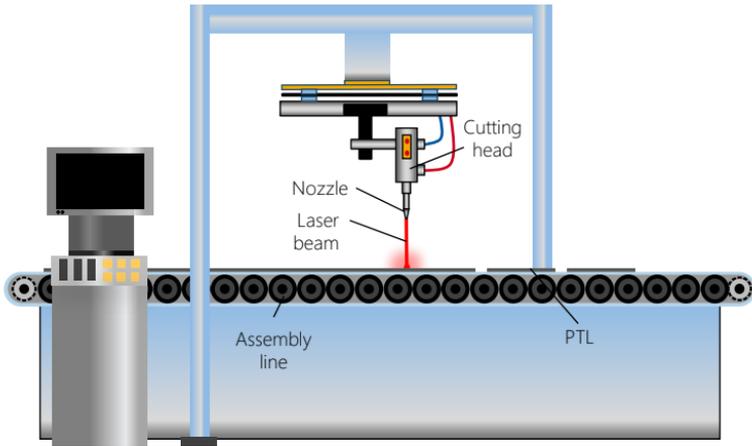
- Viscosity of the ink
- Height accuracy of the squeegee
- Material of the carrier foil
- Feed rate
- Environmental conditions
- Drying time

## Quality characteristics

- Tolerance of wet layer thickness
- Degree of drying of the green tape
- Homogeneity of the surface

# Cutting

## PTL production



### Component production

### Stack production

### System production

- Inside the cutting head, the laser beam is focused through a lens and projected onto the dried tape.
- The cutting optics are mounted on a so-called XY gantry which enables precise movement of the cutting head within a predefined area.
- The high energy input results in the separation of the material along the predefined PTL geometry.

### Process parameters & requirements

- PTL area:  $>1,400 \text{ cm}^2$
- Laser output power: 500 - 2,000 W
- Feed rate: 20 to max. 300 m/min. at 0.2 mm thickness
- Accuracy: 10 - 50  $\mu\text{m}$

### Alternative technologies

- Shear cutting
- Waterjet cutting

### Quality influences

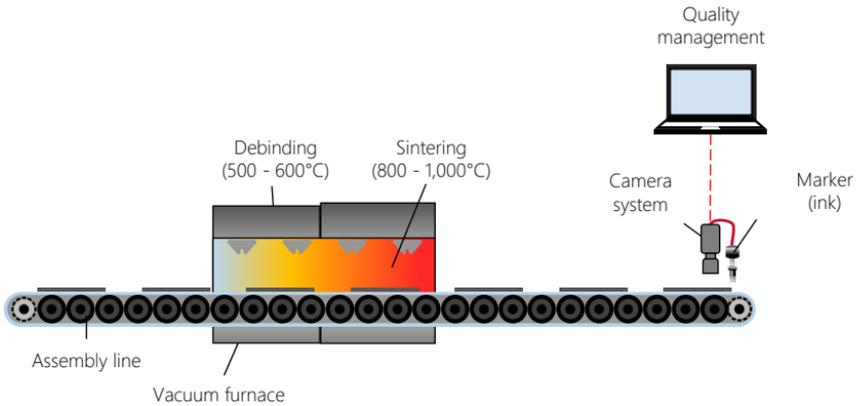
- Type of laser
- Cutting speed
- Focusing
- Process-induced contaminants

### Quality characteristics

- Burr-free edges
- No impairment of material porosity
- Trimming without distortion

# Debinding & Sintering

PTL production



Component production

Stack production

System production

- To remove the additives introduced into the titanium ink for the casting process, a debinding step is conducted.
- This involves gradually increasing the temperature until the target temperature is reached.
- Following debinding, the actual sintering process occurs, during which the porous structure of the PTL is established.
- Shrinkage of the PTL may occur during this process, and depending on the resulting PTL size, a subsequent laser cutting process might be performed to ensure dimensional accuracy.

## Process parameters & requirements

- Debinding temperature: 500 - 600°C
- Sintering temperature: 800 - 1,000°C
- Total process duration: 2.5 - 10 hrs.

## Alternative technologies

- Variation of sintering temperature and duration

## Quality influences

- Drying duration
- Residual solvent content
- Accuracy of debinding and sintering temperature
- Duration of debinding and sintering processes

## Quality characteristics

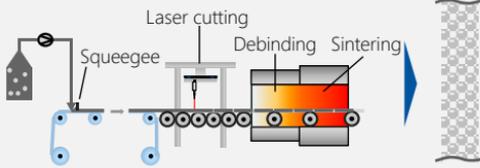
- Dimensional accuracy after heat input
- Homogeneous surface quality
- Planarity of the PTL

# Manufacturing PTL

## Summary of key production methods

In the electrolyzer, a titanium-based porous transport layer (PTL) is used on the anode side (and optionally on the cathode side) to facilitate the transport of reactants and ensure electrical conductivity within the cell. In the industry, various manufacturing methods for the titanium-based PTL are established, especially concerning the processing of the used titanium.

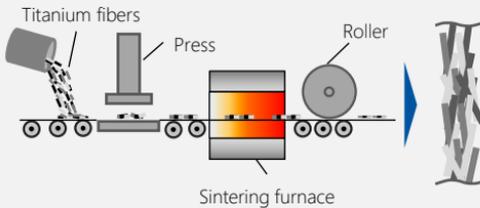
### Sintered from titanium powder



A flowable mixture of titanium particles, solvents, binders, and plasticizers is evenly applied onto a **film**, then **air-dried, cut to size, preheated, and sintered**.

- + Porosity and pore size can be controlled through the selection of specific titanium particles and sintering parameters.
- Comparatively cost-intensive manufacturing

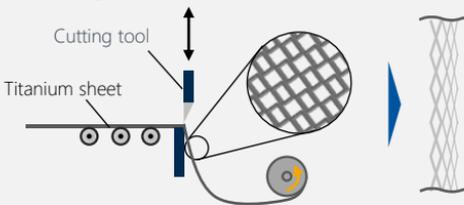
### Titanium fleece



Titan fibers are **evenly distributed, compressed, and then bonded through sintering** into an irregular porous web, which is eventually smoothed to achieve the desired thickness and uniformity using **roller smoothing**.

- + Comparatively thick titanium fleeces exhibit increased electrical conductivity.
- Porosity (50%) below the optimum range (70 - 80%)

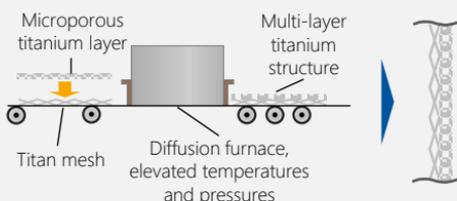
### Expanded metal sheets



From a titanium sheet, **successive staggered cuts create an expanded metal mesh**. Expanded metal meshes of various mesh sizes are then welded together to form a PTL.

- + Cost-effective manufacturing
- Irregular surface can damage the membrane during com-compression.

### Multi-layer titanium structures

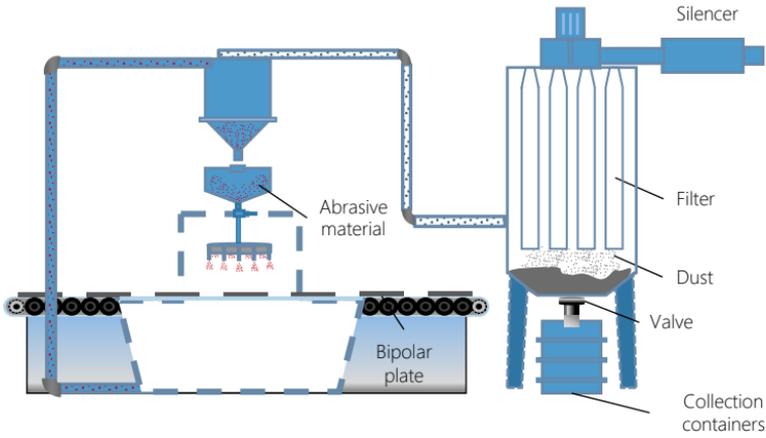


A microporous layer of sintered titanium or titanium fleece is applied to a titanium mesh using **diffusion welding**. This arrangement allows the use of bipolar plates without flow fields.

- + Enhanced efficiency through increased current density, temperature, and operating pressure
- Still in transition from research to industrialization

# Sandblasting

## BPP production



### Component production

### Stack production

### System production

- Sandblasting can be seen as a preparatory process step for the surface of the bipolar plates.
- The aim is to increase surface roughness, thereby enhancing the adhesion of the coating materials.
- This production step can generally be considered as optional.

#### Process parameters & requirements

- Blasting abrasive:  $\text{SiO}_2$  powder
- Mesh size: up to 0.2 mm

#### Alternative technologies

- Laser structuring
- Ceramic or corundum blasting media

#### Quality influences

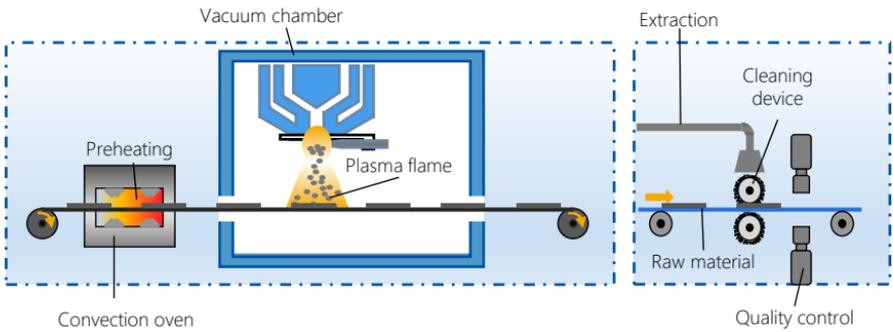
- Pressure of the blasting media application

#### Quality characteristics

- Uniform surface roughness
- Surface free from contaminants

# Coating

## BPP production



### Component production

### Stack production

### System production

- The bipolar plates are coated to enhance corrosion resistance.
- Vacuum Plasma Spraying is suitable for automated process design while achieving low manufacturing costs.
- Initially, the plates are heated to improve adhesion in the coating process.
- Subsequently, in a vacuum chamber, a plasma of argon, nitrogen, and hydrogen is used to deposit the coating metal, such as niobium, onto the BPP.
- The chamber's reduced pressure of 50 mbar prevents oxidation of the niobium particles before they are applied to the BPP.
- Directly after coating, the BPPs are polished.

### Process parameters & requirements

- Plasma enthalpy: 21.3 MJ/kg
- Chamber pressure: 50 mbar
- 1 - 3 nozzle heads; speed: 350 mm/sec.
- Coating materials: Nb, Ti, Pt, Ag
- Number of layers: 32; layer thickness: 0.1  $\mu\text{m}$
- Production volume: up to 168 units/hr.

### Alternative technologies

- Physical Vapor Deposition (PVD)
- Arc Ion Plating (AIP)
- Chemical Vapor Deposition (CVD)
- Electrophoretic Deposition (EPD)
- Electrolytic Deposition (ELD)
- Sputtering

### Quality influences

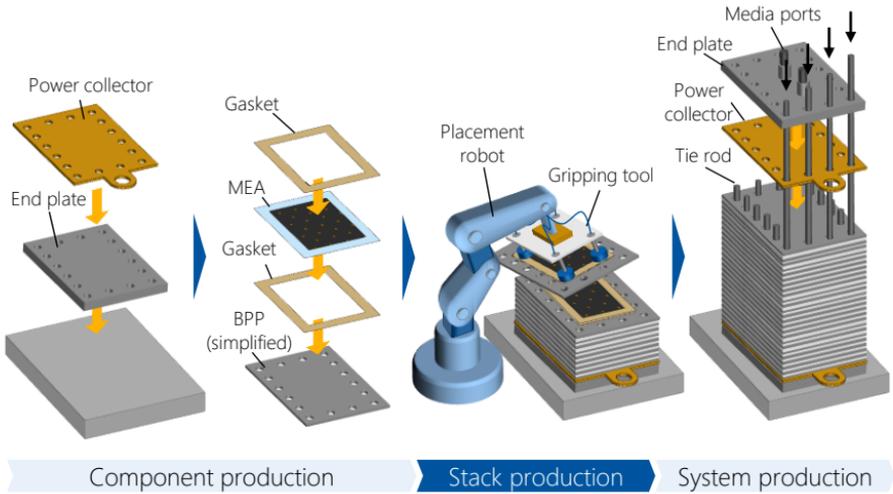
- Coating material
- Morphology of the coating powder: ideally, a spherical shape
- Plasma composition

### Quality characteristics

- Uniform acceleration and temperature of the plasma flame
- Coating homogeneity
- Corrosion resistance
- Electrical conductivity

# Stacking and Pre-assembly

## Stack production



- At the beginning of the electrolyzer stack manufacturing process, the lower end plate and lower current collector are preassembled.
- The MEA (here: 5-layer MEA\*), BPP, and two gaskets are stacked in a predefined sequence.
- By subsequently stacking these packages into a stack, functional individual cells are formed, each bounded by two bipolar plates.
- Finally, the upper current collector and upper end plate, along with media connections, are added to the stack.
- The precise alignment of the stack's individual components can be ensured through external and internal guiding elements.

### Process parameters & requirements

- Number of electrolyzer cells: Depending on the stack size, several hundred individual cells are stacked.
- Stack speed: approx. 3 - 5 secs. per component
- Precise component handling with a positional accuracy of about 0.1 mm

### Alternative technologies

- Manual stacking in the R&D segment (<100k MEAs/yr.)
- Semi-automated stacking using a conveyor system with manual handling (100k - 700k MEAs/yr.)
- Fully automated stacking through conveyor or feeding systems (>700k MEAs/yr.)

### Quality influences

- Tolerance accuracy of component thickness: <10  $\mu\text{m}$
- Positioning accuracy:  $\pm 0.1$  mm
- Cleanroom environment class: ISO 8
- Relative position of repeat components to the robot

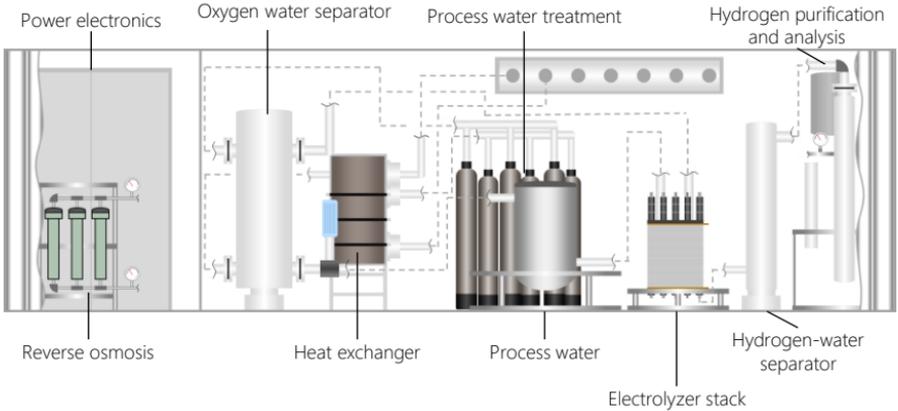
### Quality influences

- Relative positioning of cells to each other
- Non-destructiveness

\* The Membrane Electrode Assembly (MEA) consists of the Catalyst Coated Membrane (CCM), also known as "MEA 3", along with the subgaskets and the Porous Transport Layer (PTL). The combination of MEA 3 and subgaskets is usually called "MEA 5". Including the PTL, the composite is labeled as "MEA 7".

# Balance-of-Plant Assembly

## System production



### Component production

### Stack production

### System production

- The electrolyzer stack constitutes the core of an electrolyzer system which is interconnected with all other peripheral components during system assembly.
- Depending on the size of the electrolyzer, the assembly can take place in a 40-foot (approximately 12-meter) shipping container, for example.
- Due to the size of the components to be installed, they are initially positioned at the installation site, with crane systems possibly being used for this purpose.
- Once all components are in place at the installation site, they are connected by applying pipes.
- Eventually, the components are electrically integrated, and an end-of-line testing is conducted.

### Process parameters & requirements

- Assembly instructions along with subdivision into sub-assemblies
- Assembly-friendly component design
- Ensuring transport safety

### Alternative technologies

- Currently only manual assembly

### Quality influences

- System design and materials
- Assembly environment

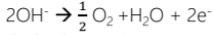
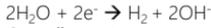
### Quality influences

- Dismantling
- Accessibility of components and systems
- External integrity

# Technology Comparison

## Alkaline electrolyzer

### Reaction equations

**Anode reaction:****Cathode reaction:****Overall reaction:**

### Materials

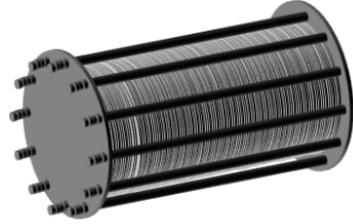
**Catalyst:**

Anode and cathode: nickel-plated stainless-steel plates

**Electrolyte:**

Potassium hydroxide (KOH) 20 - 40 wt.% or sodium hydroxide solution

### Typical stack design



AEL

PEMEL

SOEL

AEMEL

- In alkaline electrolysis, the anode and cathode are immersed in a liquid electrolyte (potassium hydroxide solution).
- The anode and cathode will be separated by a diaphragm.
- Oxidation takes place on the cathode side, resulting in hydrogen hydroxide ions (OH<sup>-</sup>).
- While the hydroxide ions can diffuse through the diaphragm, the hydrogen is retained and discharged from the cell.
- On the anode side, the hydroxide ions oxidize to water and oxygen.

### Operating parameters

- Pressure: 1 - 30 bar
- Temperature: 40 - 90°C
- pH: 12 - 14
- Design variants: mono or bipolar plate design
- Hydrogen purity: >99.8%

### Advantages

- Service life of up to 90,000 operating hours
- Highly mature technology
- Precious-metal-free catalysts (cost-effective)

### Trends

- Zero-gap cell architecture
- Increase in current density to 2 - 3 A/cm<sup>2</sup>
- Reduction of the resistance of individual cell components

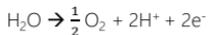
### Applications

- Industrial hydrogen production
- Energy storage
- Hydrogen refueling stations

# Technology Comparison

## PEM electrolyzer

### Reaction equations

**Anode reaction:****Cathode reaction:****Overall reaction:**

### Materials

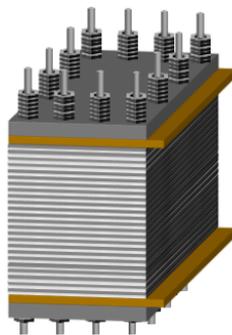
**Catalyst:**

Anode: Iridium ( $\text{IrO}_2$ ); Cathode: Platinum (Pt)

**Electrolyte:**

Polymer electrolyte membrane

### Typical stack design



AEL

PEMEL

SOEL

AEMEL

- In the PEM electrolyzer, the anode and cathode are separated from each other by a polymer electrolyte membrane.
- The membrane is permeable to protons ( $\text{H}^+$ ), which are produced at the anode.
- Protons, oxygen, and electrons are formed by oxidation of deionized water.
- The protons diffuse through the membrane where they are reduced to hydrogen on the cathode side together with electrons and transported out of the cell dissolved in water.

### Operating parameters

- Pressure: <70 bar
- Temperature: 20 - 80°C
- pH: 2
- Design variants: planar design
- Hydrogen purity: up to 99.999%

### Advantages

- Compact cell design
- Dynamic operation
- Cold start time: <15 mins.
- Operation under differential pressure

### Trends

- Reduction of precious metal loads by approx. 40 to 60%
- Improvement of service life up to 80,000 operating hours
- Scaling production

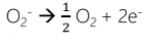
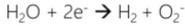
### Applications

- In combination with renewable energy or hydrogen refueling stations
- Industrial hydrogen production
- Mobile power supply systems
- Power-to-gas systems

# Technology Comparison

## Solid oxide electrolyzer

### Reaction equations

**Anode reaction:****Cathode reaction:****Overall reaction:**

### Materials

**Catalyst:**

Anode: Lanthanum strontium manganate;

Cathode: Nickel (Ni/GDC or Ni/8YSZ)

**Electrolyte:**

$\text{Y}_2\text{O}_3$  (YSZ)- or  $\text{Sc}_2\text{O}_3$  (ScSZ)-stabilized zirconium dioxide ( $\text{ZrO}_2$ )

### Typical stack design



AEL

PEMEL

SOEL

AEMEL

- In the solid oxide electrolyzer, the anode and the cathode are separated from each other by a ceramic electrolyte.
- The electrolyte is permeable to oxygen ions ( $\text{O}_2^-$ ), which are formed at the cathode by the reduction of water vapor.
- In this reaction, hydrogen is also formed which is then discharged from the system.
- On the anode side, the oxygen ions oxidize to oxygen and electrons.
- The high operating temperatures of up to 1,000°C place high demands on the materials and seals used and lead to long start-up times of the system.

### Operating parameters

- Pressure: 1 bar
- Temperature: 600 - 1,000°C
- Operation: Co-electrolysis (simultaneous production of two different gases), reversible electrolysis fuel cell operation
- Design variants: Stack level (planar, tubular), cell level (electrolyte, electrode-based)

### Advantages

- High reaction rates
- Use of precious-metal-free catalysts
- High efficiency in CHP applications
- Some of the electricity required can be replaced by process heat, which increases efficiency.

### Trends

- Reduction of process temperature
- Improvement of the electrode and electrolyte materials' process stability
- Increasing the service life
- Reduction of manufacturing costs

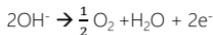
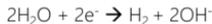
### Applications

- In CHP applications (use of high-quality process heat from industrial processes)
- Chemical industry
- Energy storage
- Power-to-gas systems

# Technology Comparison

## AEM electrolyzer

### Reaction equations

**Anode reaction:****Cathode reaction:****Overall reaction:**

### Materials

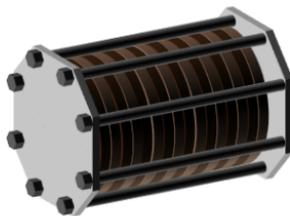
**Catalyst:**

Anode and cathode: Nickel-based compounds

**Electrolyte:**

Alkaline anion exchange membrane

### Typical stack design



AEL

PEMEL

SOEL

AEMEL

- The system and the cell design of the AEM electrolyzer are like those of a PEM electrolyzer, whereas here, more cost-effective materials are used.
- Some of these materials are known from alkaline electrolysis, which is why the AEM electrolyzer is often referred to as a combination of AEL and PEMEL.
- At the cathode of the AEM electrolyzer, water is reduced to hydrogen and hydroxide ions.
- The hydroxide ions diffuse through the anion exchange membrane and oxidize at the anode to water and oxygen.

### Operating parameters

- Pressure: <35 bar
- Temperature: 40 - 60°C
- pH: 9 - 11
- Modes: pressure mode
- Design variants: planar design

### Advantages

- Precious-metal-free catalysts and titanium-free components (cost-effective)
- Operation under differential pressure
- Low ohmic losses

### Trends

- Scaling of individual stack modules
- Increasing the chemical and mechanical resistance of the membrane
- Development of further suitable catalysts
- Further industrialization

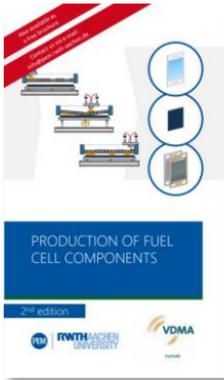
### Applications

- Industrial hydrogen production
- Energy storage
- Power-to-gas systems
- Carbon capture and utilization

# Guides

## to electrolyzer and fuel cell production

In the "Production of Electrolyzer Systems" and "Fuel Cell Production" guides, the Chair of Production Engineering of E-Mobility Components (PEM) of RWTH Aachen University, together with VDMA, presents the process chains in the production of electrolyzers as well as fuel cells at component and system level.



### Production of Fuel Cell Components

The "Production of Fuel Cell Components" guide reflects the state of the art in the manufacturing of the membrane, bipolar plate, and gas diffusion layer. One focus is on the commercially available process alternatives that contribute to cost reduction through scaled production.

2<sup>nd</sup> edition  
ISBN 978-3-947920-31-0

*Editors*  
PEM of RWTH Aachen University & VDMA

Available online



### Production of Fuel Cell Systems

The "Production of Fuel Cell Systems" guide describes in detail how fuel cell systems can be utilized in mobile applications. Building upon the "Production of Fuel Cell Components" guide, it explains how these components are processed into a fuel cell stack and ultimately into a complete system.

2<sup>nd</sup> edition  
ISBN 978-3-947920-30-3

*Editors*  
PEM of RWTH Aachen University & VDMA

Available online



### Production of Electrolyzer Systems

Fuel cells and electrolyzers exhibit similarities both at component and process level which are elaborated upon in the "Production of Electrolyzer Systems" guide. The comprehensive overview concludes with a holistic comparison of the electrolyzer technologies available on the market.

1<sup>st</sup> edition  
ISBN 978-3-947920-42-6

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Available online

