

PRODUCTION OF FUEL CELL SYSTEMS

2nd edition



RWTHAACHEN
UNIVERSITY





The chair "Production Engineering of E-Mobility Components" (PEM) of RWTH Aachen University deals with the production engineering of fuel cells. Within the mechanical engineering sector, the activities range from the cost-efficient production of hydrogen-powered drivetrain components to innovative mobility solutions and overall emission reduction. Through national and international projects in companies at various stages of the value chain as well as participation in numerous research projects, PEM offers extensive expertise.



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Fuel Cells

The VDMA Fuel Cells Working Group supports manufacturers of fuel cell components and systems in Germany in expanding their industry network. It currently offers more than 80 leading, nationally and internationally active manufacturers and suppliers a communication platform for networking and joint representation of interests. Technical solutions for optimizing and reducing the costs of fuel cell systems and their respective components as well as for setting up series production are developed in project groups.



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Do you have any questions?

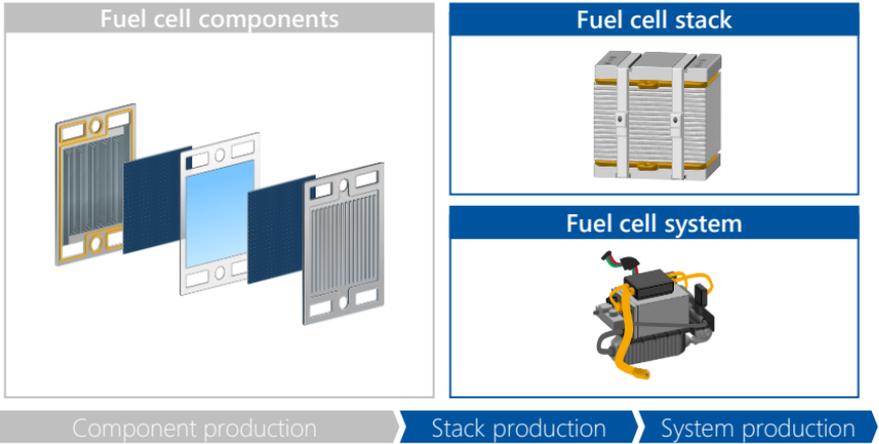
Talk to us!



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Overview

of a PEM fuel cell



In this guide, the production process of a polymer electrolyte membrane (PEM) fuel cell system is illustrated schematically based on the individual production steps for stack and system production, including the assembly.

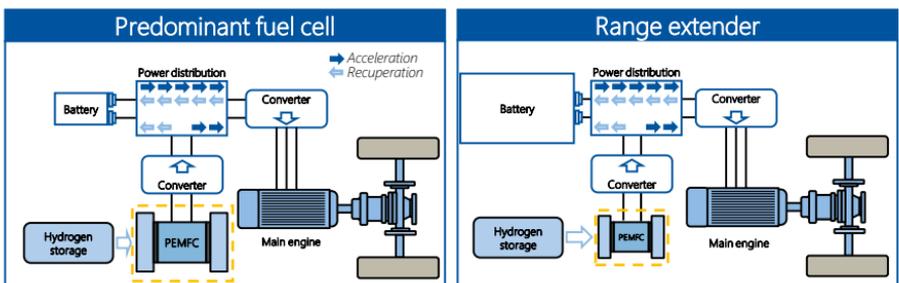
The individual PEM fuel cells are connected in series in a **fuel cell stack**. The stack and other electrical, mechanical and thermal components are assembled to form the **fuel cell system**.

Depending on the system design, the number and the dimension of inter-connected fuel cells within a stack varies. The design of the peripheral components is adjusted correspondingly to the performance data of the fuel cell stack. Due to the large number of different product and process variants, comprehensive information on the process parameters is only possible to a limited extent and can be specified in more detail in joint discussions with the PEM chair or the VDMA.

Automotive applications

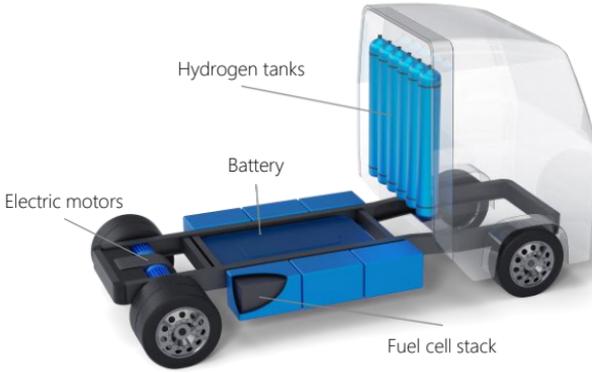
of the PEM fuel cell

For automotive applications, two different drive strategies based for PEM fuel cells can be distinguished. If the vehicle has a drive system dominated by the fuel cell, the driving power requirement is primarily covered by the fuel cell. An additional lithium-ion battery is installed to handle short-term power peaks. Alternatively, the fuel cell can be used as a so-called range extender. In this case, the fuel cell functions as an "onboard charging system" for the vehicle's lithium-ion battery, which is the main energy supply.



Vehicle architecture

of a PEM fuel cell system



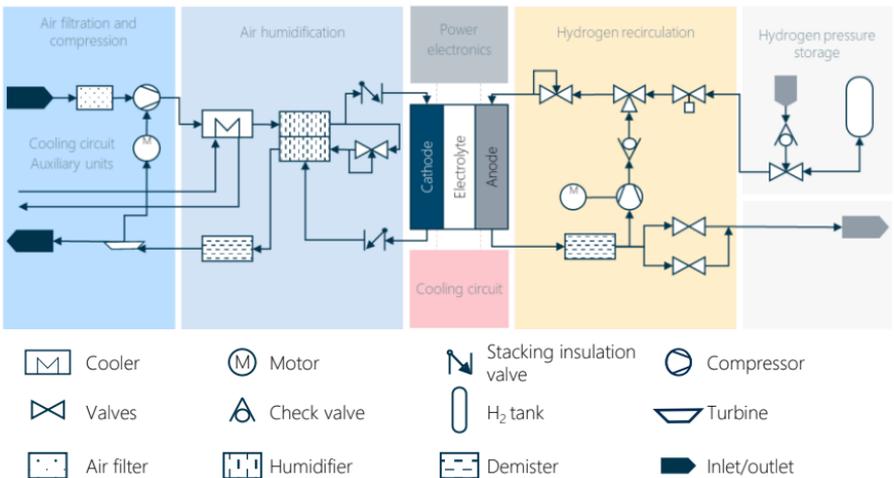
The architecture of the drive train of a fuel cell electric vehicle (FCEV) consists of the main components fuel cell system, hydrogen tanks, lithium-ion battery, electric motor and power electronics. While the battery, electric motor and power electronics are also part of a battery-powered vehicle, fuel cell system and hydrogen tanks are unique to a FCEV.

While the hydrogen tank is usually made of carbon fiber-wrapped plastic, the fuel cell system consists of air, hydrogen and cooling circuits: In the **air circuit**, ambient air is first compressed and then humidified before being fed to the cathode side of the fuel cell. The hydrogen is supplied by the pressure storage and the recirculated and compressed hydrogen from the stack outlet.

The **cooling circuit** ensures that the reaction heat is dissipated. It is necessary for the cold start capability at temperatures below freezing point.

System architecture

The architecture of a fuel cell system including functional peripheral components is structured as follows:



Balance-of-Plant components

as part of the system architecture

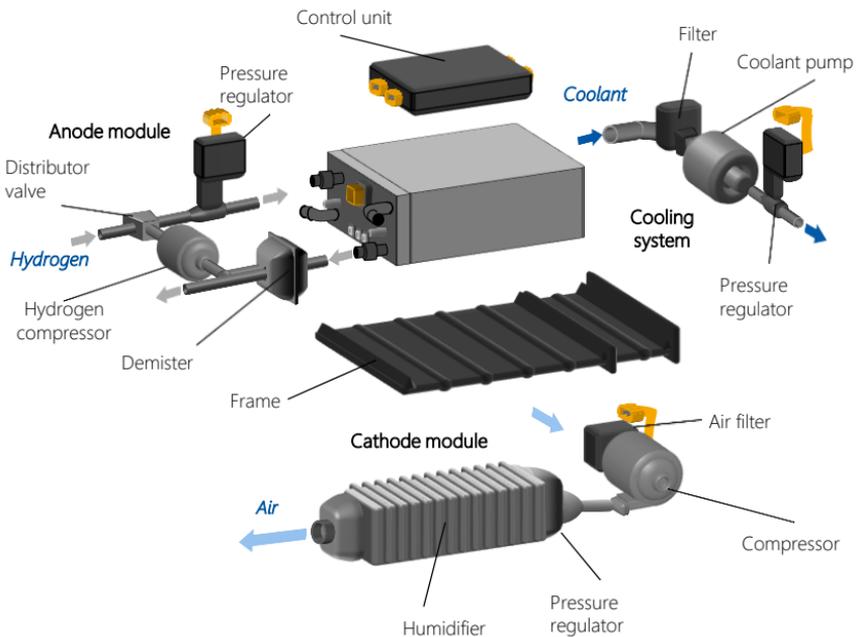
The components of a fuel cell system are holistically referred to as "Balance-of-Plant" (BoP). The individual components can be subdivided into three super-ordinate subsystems: anode module, cathode module and cooling system. They ensure the functionality of the media circuits and are exemplarily illustrated below. The hydrogen storage is not part of the illustration.

Anode module:

- Closed hydrogen circuit including pressure-temperature control
- Anode module as dosing unit for supplying the anode and hydrogen recirculation
- Assurance of the operating pressure and hydrogen purity

Cooling system:

- Temperature control of the fuel cell by de-ionized coolant
- Consists of coolant pump, coolant filters and pressure regulator
- Cooling power requirement of the stack up to 150% of the nominal stack capacity



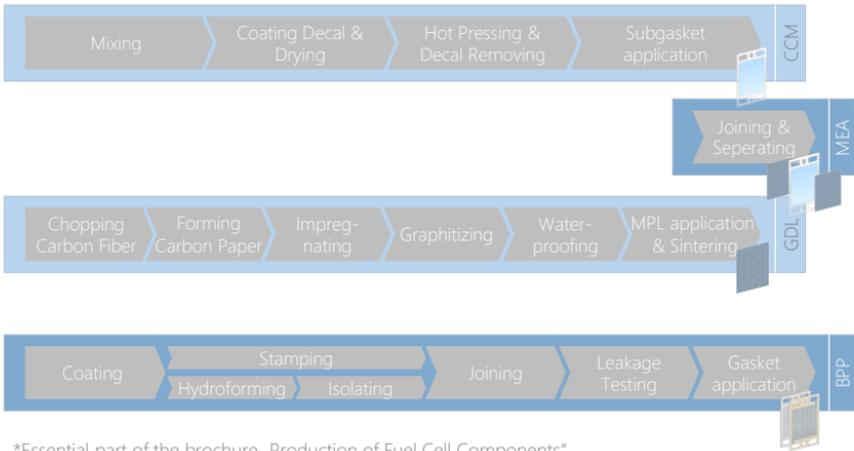
Cathode module:

- Supply and treatment of the reactant oxygen by means of air filter, electrically operated compressor and air humidifier
- Oil-free turbocharger as air compressor, supported by reaction exhaust air, to increase efficiency
- Humidifier made of bundled or stacked separating membranes

Production process of a PEM fuel cell system

- The process chain for the series production of PEM fuel cell systems differs depending on the application and the number of units produced annually. Uniform standards are not yet available due to the manual nature of fuel cell production.
- The production of a PEM fuel cell system can be divided into the three superordinate steps of component production, stack production, and system production.
- This guide presents the process steps that make up the current state of the art in the production of PEM fuel cell stacks and systems.
- The production of the individual fuel cell components is explained in more detail in a separate guide ("Production of Fuel Cell Components").

Component production*:

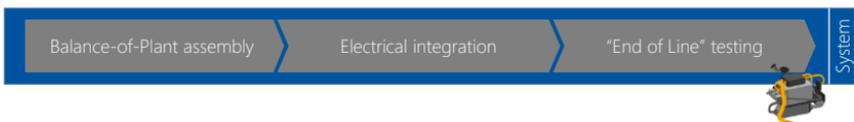


*Essential part of the brochure „Production of Fuel Cell Components“

Stack production:



System production:



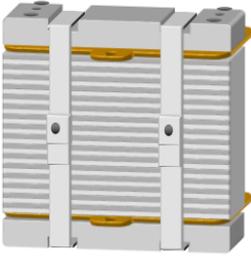
Process step
 Intermediate product
 Final product

Overview

PEM fuel cell stack and system



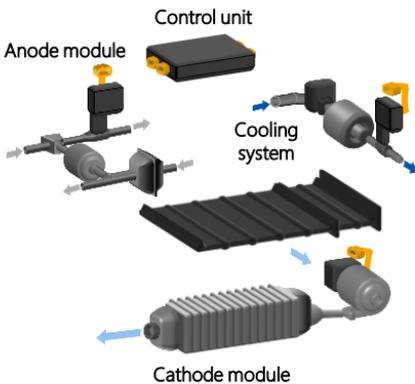
Fuel cell stack



- The fuel cell stack consists of any number of individual fuel cells connected in series which enables scalable power ranges.
- In addition to the individual cells, a functional stack consists of end plates, current collectors, a distribution plate and a monitoring unit.
- In practice, there are several ways to apply a clamping force to the fuel cell stack components. For example, tension bands (see figure) or tension rods.



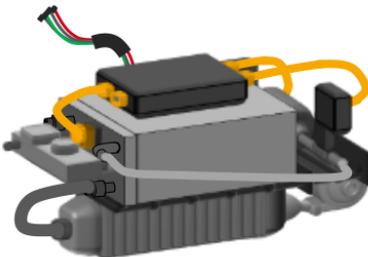
BoP components



- The Balance-of-Plant (BoP) consists of an air circuit (cathode module), a hydrogen circuit (anode module), and a high-temperature and low-temperature cooling system.
- In the air circuit, the ambient air is filtered, compressed and fed to the fuel cell in a specified condition.
- In the air circuit, the ambient air is filtered, compressed and supplied to the fuel cell in a controlled proportion.



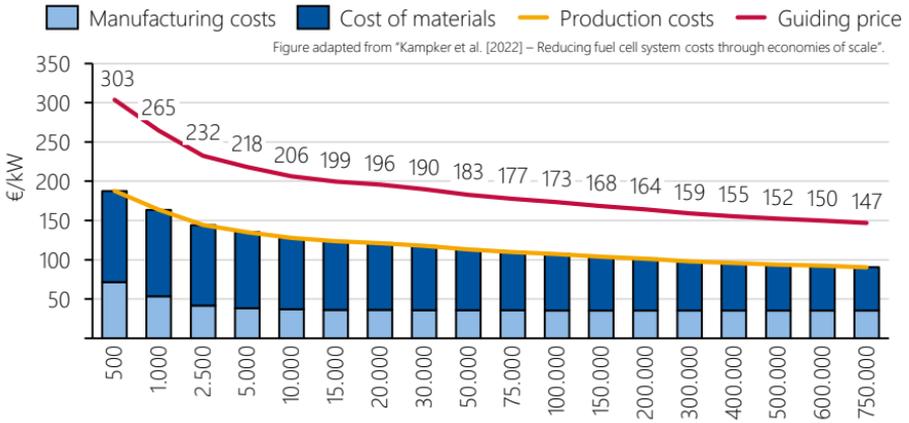
Fuel cell system



- The fuel cell stack, the Balance-of-Plant (BoP) and the tank system make up the fuel cell (FC) system.
- The two cooling systems are used to cool the fuel cell stack (high temperature) and to temper the compressed air (low temperature) as well as auxiliary units.

Scaling the production

Cost degression through economies of scale



The costs were calculated using the example of a fuel cell system specified by the PEM chair of RWTH Aachen University and its production steps. The modelling of production technology currently established on the market shows that the production costs are almost constant from a production volume of approximately 2,500 fuel cell systems per year. This is due to the underlying system technology, which has not yet been designed for large quantities. This makes it difficult to achieve economies of scale and the associated cost reductions. At this point, mechanical and plant engineering can make a considerable contribution to making economies of scale usable at an early stage through innovative production technology. The following explanations in this guide refer to a production scenario of 10,000 FC systems per year.

Cost structure

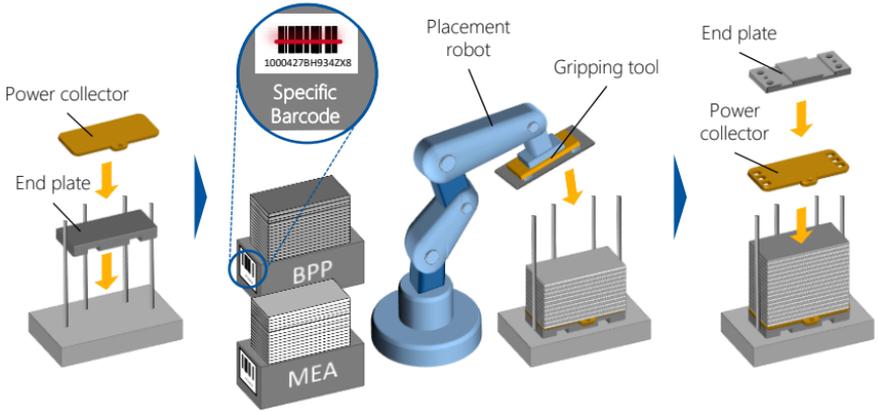
of the FC system



The expenses modelled by the RWTH chair PEM are based on a cost structure that defines the "target price" as the selling price of the product when all costs, taxes and calculated profit of the company are covered. The "total costs" are made up of expenses for sales, administration, research, and development as well as manufacturing costs. The "manufacturing costs" are the sum of production and material costs. The "production costs" consist of "direct production costs" and "production overheads", while the "material costs" comprise the "direct material costs" and the "material overheads". Direct costs refer to expenses incurred per product produced. Overhead costs include expenses that are only indirectly allocated to individual products. In the following, the investment costs per plant are shown for each production step.

Stacking and pre-assembly

Stack production



Component production

Stack production

System production

- At the beginning of fuel cell stack production, the lower end plate and the lower current collector are pre-assembled.
- An optional scanning step of product labels of the MEA (membrane electrode assembly) and the BPP (Bipolar Plate) in the incoming goods department facilitates later component traceability of the product.
- MEA (here: 5-layer MEA), BPP and gaskets are stacked on top of each other in a defined order: (1) BPP, (2) gasket, (3) MEA, (4) gasket, (5) BPP.
- Finally, the upper current collector and the upper end plate with media accesses are added.
- The exact alignment of the individual components of the stack can be ensured by guiding elements.

Process parameters & requirements

- Number of fuel cells: 2 - 10 cells per kW
- Stacking speed: < 2.3 seconds per component
- Component positioning accuracy: 0.1 mm/100 μ m

Technology alternatives

- Pick-and-place robot for stacking process
- Fully automatic stacking by feeding systems
- Semi-automatic stacking by carousel devices
- Manual stacking

Quality influences

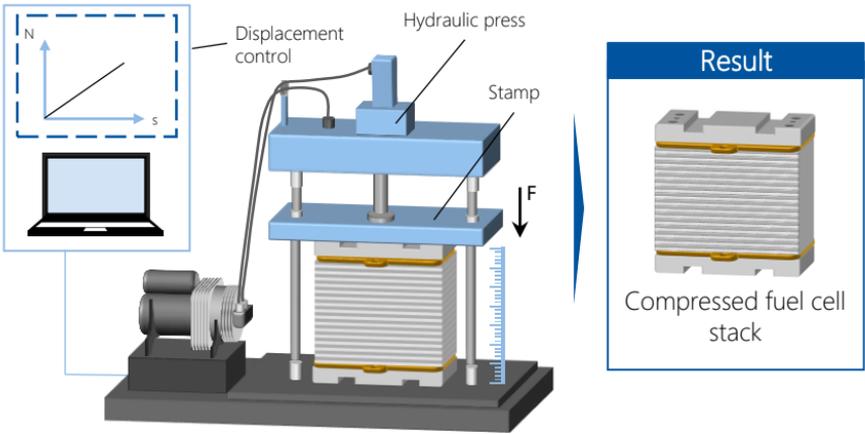
- Accuracy of component thickness: < 10 μ m
- Cleanroom classification: ISO 8

Quality criteria

- Stack height 1 - 2 mm per cell (depending on performance level)
- Accuracy of cell positioning
- Non-destructive

Compression

Stack production



Component production

Stack production

System production

- Compression takes place within a pressing device, for example a hydraulic press.
- By pressing the individual components, the fuel cell seals are compressed and the stack is thus sealed.
- The contact resistances between the components are lowered by the compression.
- A regulation of the pressing force and the pressing path ensures sufficient compression and avoids damage to the components due to overloading.
- Uniform pressing has a significant influence on the subsequent power density as well as the service life of the stack.

Process parameters & requirements

- Press force (product-dependent): max. 160 kN for metallic bipolar plates
- Uniform contact pressure
- Pressing path (depending on product)
- Process time: 150 seconds to 30 minutes per stack

Technology alternatives

- Spindle press
- Hydraulic press
- Pneumatic press
- Servo-hydraulic press

Quality influences

- Pressing force and displacement accuracy: +/- 2%
- Cleanroom classification: ISO 8
- Traversing speed
- Positioning accuracy

Quality criteria

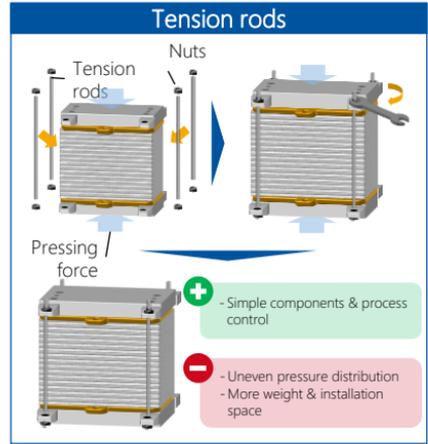
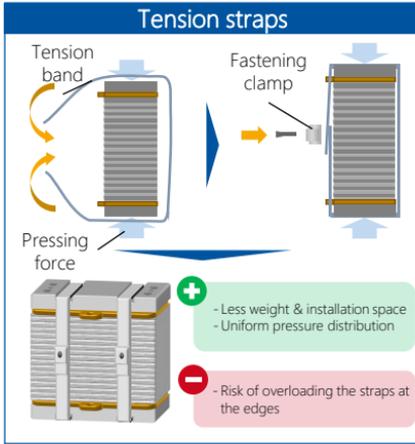
- Stack height: 1 - 2 mm per cell (depending on power class)
- Tightness
- Non-destructive
- Even pressure distribution

Production costs [excerpt]

Investment for equipment: € 0.2 - 0.4 million

Tensioning

Stack production



Component production

Stack production

System production

- The permanent compression of the stack is guaranteed by suitable tensioning devices, usually tension bands or tension rods.
- The tensioning devices are fastened in the press while the force is still applied.
- The bands, usually metallic or carbon fiber-reinforced, are placed around the stack and overlapped.
- The ends of the belts are joined by means of clamps, sometimes also with a material joint (e.g. by welding) or with a form fit (e.g. by crimping).
- Tension rods are alternatively guided through the openings provided on the end plates and fastened against the end plates by means of nuts.

Process parameters & requirements

- Contact pressure: approx. 0.5 - 1 MPa
- Tightening torque: approx. 11 Nm (single cells)
- Rotation of the device up to 180° in cross-sectional area

Technology alternatives

- Tension rods
- Clamping plates
- Clamping straps
- Sheathing

Quality influences

- Screwing order
- Tightening torque
- Uneven tensioning due to deformation of the end plate

Quality criteria

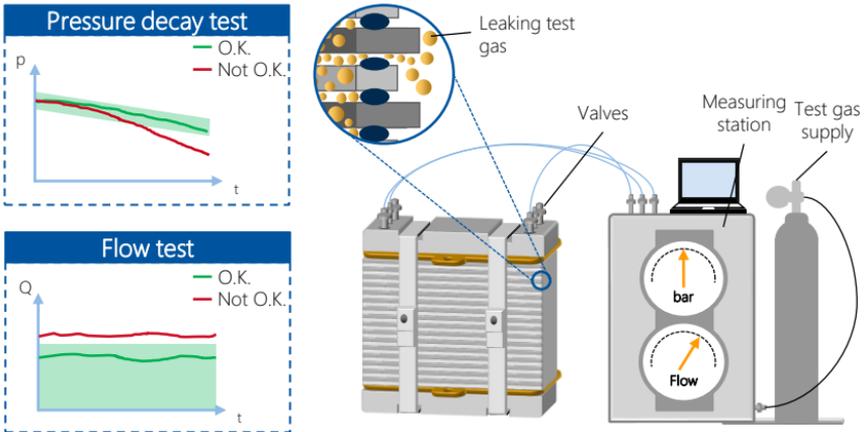
- Destruction-free tensioning belts
- No fractures or cracks in the cells or endplates
- Uniform pressure distribution

Production costs [excerpt]

Investment for equipment: € 0.1 - 0.2 million

Check tightness

Stack production



Component production

Stack production

System production

- To check the tightness of the compressed stack, a pressure drop, or flow test is carried out.
- A measuring station including test gas supply is connected to the media inputs of the stack.
- In the pressure drop test, the outputs of the stack are closed, and the pressure drop is measured over time after filling with test gas.
- During the flow test, the outputs of the stack are opened, and the test gas flow is measured.
- The overall tightness of the stack, but also that of the individual circuits can be determined.

Process parameters & requirements

- H₂ leak rate: max. 1×10^{-1} mbar l/s (according to IEC 62282-2)
- O₂ leak rate: max. 4 times leakage rate of H₂
- Operating load: depending on stack power
- Test medium: helium or nitrogen

Technology alternatives

- Nitrogen as test gas
- Helium as test gas
- Flow test
- Pressure drop test

Quality influences

- Tightness of the supply lines and media connections
- Destruction-free components
- Uneven tensioning
- Ambient pressure and temperature
- Dust protection

Quality criteria

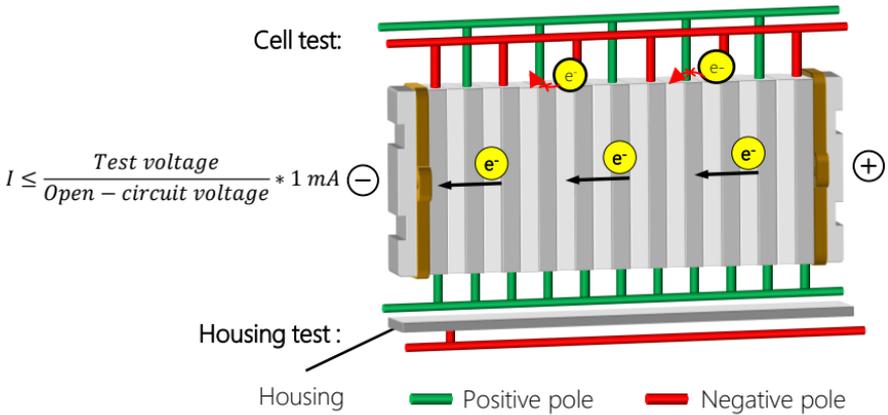
- Leak rate
- Definition of acceptable rework

Production costs [excerpt]

Investment for equipment: € 0.3 - 0.4 million

Check insulation

Stack production



Component production

Stack production

System production

- The insulation test ensures that the clearances and solid insulation of the components have sufficient dielectric strength to withstand a temporary overvoltage.
- Insulation testing takes place between a touchable conductive component and the circuit and is intended as a fully automatic procedure.
- The test is considered to have been passed if no electrical breakthroughs have occurred within the cells and between the stack and the housing (summarized figure above).
- The leakage current must not exceed 1 mA multiplied by the ratio of the test voltage to the open-circuit voltage.
- Since individual fuel cells act like capacitors, the cause of short circuits cannot always be clearly determined.

Process parameters & requirements

- Test duration type test: min. 60 sec. (according to DIN EN 62477-1)
- Test duration unit test: >5 sec. (according to DIN EN 62282-2-100)
- Frequency of the test voltage: 38 - 62 Hz
- Test voltage: 2 to 6 kV
- Test medium: coolant

Technology alternatives

- None available

Quality influences

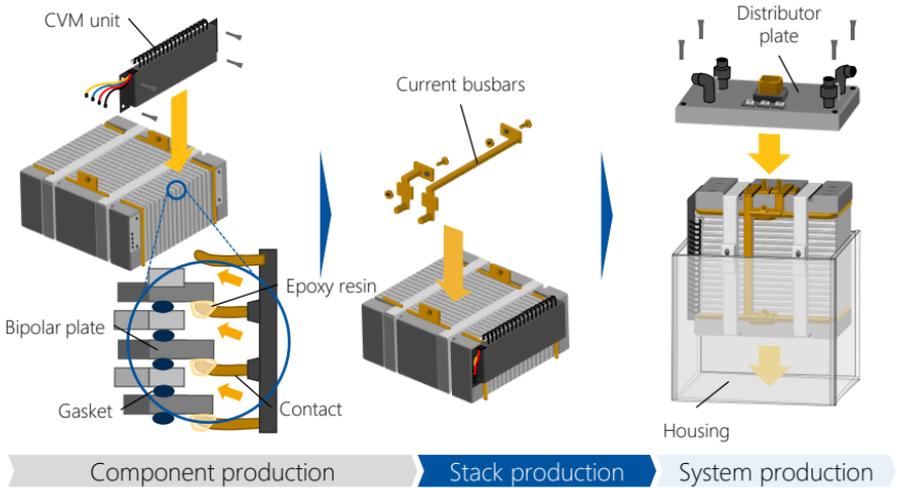
- Individual fuel cells act like capacitors → Source of power failures difficult to identify
- A lot of manual operations

Quality criteria

- Prevention of electrical breakthroughs

Finalization

Stack production



- The CVM (cell voltage monitoring) unit is attached to the side of the stack to monitor the voltage of the individual cells.
- The individual contacts of the CVM unit are attached to the bipolar plates of the fuel cells using epoxy resins.
- The current busbars for the later HV output wiring of the stack are screwed to the current collectors.
- The stack is inserted into a housing and the housing cover is mounted.
- The cover of the enclosure is also the distribution plate and contains all inputs and outputs for media as well as connections for sensors and HV cabling.

Process parameters & requirements

- Dosing quantity of the epoxy resin
- Ensuring transport safety
- Positioning accuracy of the conductor ends

Technology alternatives

- Semi-automated assembly
- Measurement of the total stack voltage instead of individual cell voltages

Quality influences

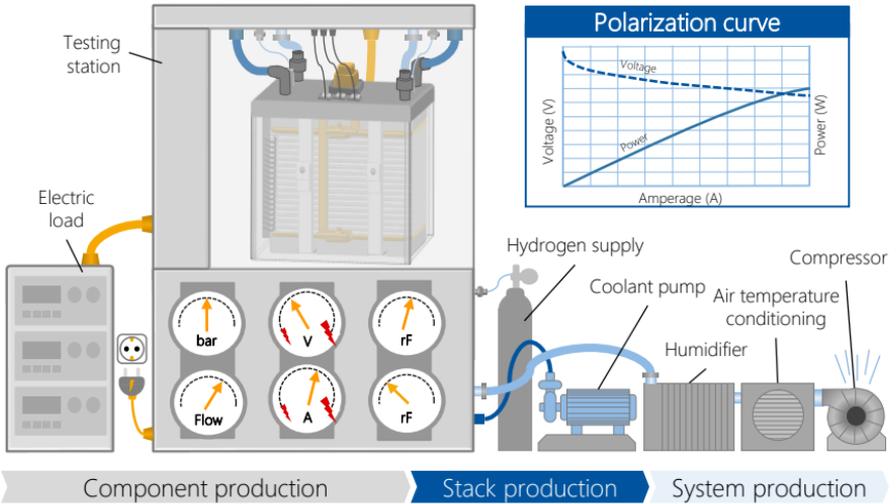
- Wetting and quality of the epoxy resin
- Handling and safety regulations for employee inspection

Quality criteria

- Conductivity and correct reception of the individual cell voltages
- Serviceability with the possibility of opening the housing

Break-in and testing

Stack production



- The assembled fuel cell stacks are activated in a test stand to ensure performance.
- During activation, impurities and solvent residues are removed, the pores are opened, and the membrane and ionomers are moistened.
- During the break-in process, different combinations of flow rate, media pressure, air temperature, and humidity are run through.
- The performance of the stack increases steadily at the beginning and then asymptotically approaches an optimum, resulting in a trade-off between activation time and performance.
- Different protocols exist that cause different activation times and cell degradation.
- In some cases, a new leak test is necessary following the activation process.

Process parameters & requirements

- Process time: approx. 10 min for 90% power and approx. 120 to 480 min for 100% power
- Operating load: 0.3 to 0.6 V (sometimes 0.9 V)
- Operating temperature: 55 to 95°C
- Operating pressure: 3.4 to 5 bar

Technology alternatives

- Discontinuous load cycles
- Discontinuous media supply
- Discontinuous temperature curve

Quality influences

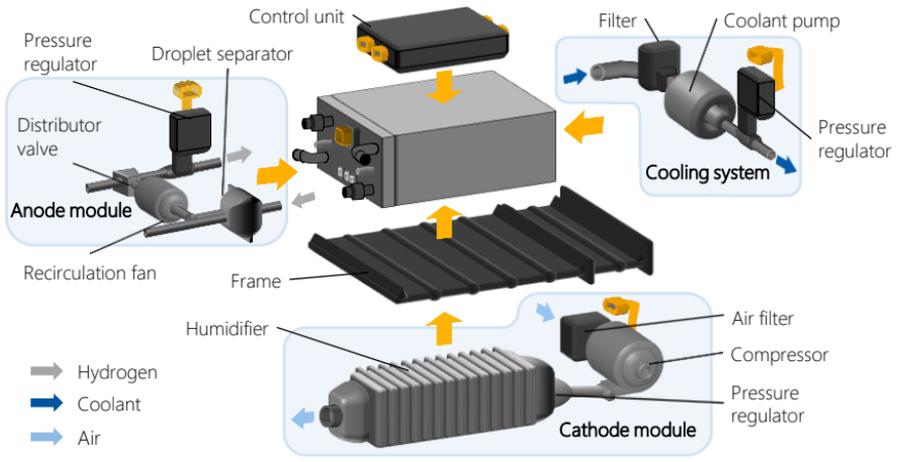
- Media purity (i.e. grade 7 hydrogen for mobile applications)
- Media supply and cooling capacity
- Tightness of the supply lines and media connections
- Operating pressure and temperature

Quality criteria

- Cell voltage and efficiency
- Influence on cell degradation
- Tightness

Balance-of-Plant Assembly

System production



Component production

Stack production

System production

- The Balance-of-Plant (BoP) components are connected to the fuel cell stack, for example with the aid of a mounting frame.
- To supply the entire system with hydrogen, the anode module (consisting of hydrogen recirculation blower, pressure regulator, distributor valve, droplet separator, and lines) is attached.
- To ensure the necessary system cooling, the cooling system (consisting of filters, coolant pump, pressure regulator, and pipes) is installed.
- The cathode module (consisting of compressor, air filter, humidifier, pressure regulator and pipes) is mounted to supply the entire system with air.
- The control unit is mounted to control the media supply and thermal management.

Process parameters & requirements

- Assembly instructions including division into subassemblies
- Component design suitable for assembly (e.g. hole pattern in the frame)
- Ensuring transport safety (cables, connections, protective flaps, etc.)

Technology alternatives

- Partial automation of assembly possible
- Plug-in and screw connections

Quality influences

- Handling and safety regulations for control by employees
- Inline measurement and testing technology of assembly
- Poka-Yoke design to protect against incorrect assembly
- Accessibility of the connection points

Quality criteria

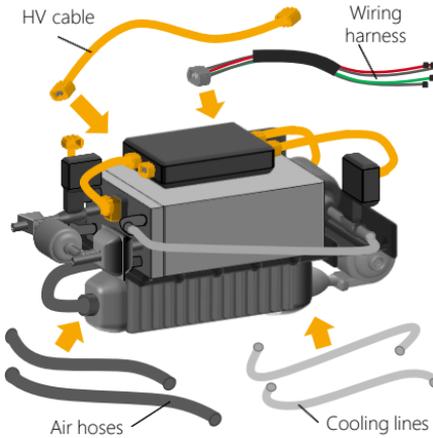
- External integrity and technical cleanliness
- Firmly seated joints
- Correct positioning and wiring of the peripheral devices
- Dismountability

Production costs [excerpt]

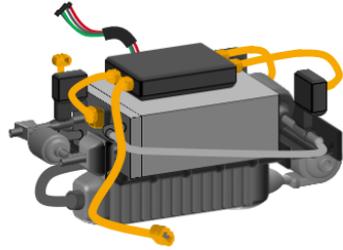
Investment for equipment: € 0.05 - 0.1 million

Electrical integration

System production



Assembled fuel cell system



Component production

Stack production

System production

- The previously mounted BoP components are connected to the media openings of the stack via lines.
- The control unit is connected to the individual BoP components.
- The HV output wiring is attached.
- In the last assembly step, the wiring harness is mounted for later vehicle integration.

Process parameters & requirements

- Qualification of employees for the installation of flexible cables
- Qualification of employees for assembly under high-voltage safety (> 60 V)
- Ensuring transport safety (cables, connections, protective flaps, etc.)

Technology alternatives

- Plug-in and screw connections
- Pressing on the hoses and lines

Quality influences

- Handling and safety regulations for control by employees
- Accessibility of the connection points
- Poka-Yoke design for protection against faulty contacting

Quality criteria

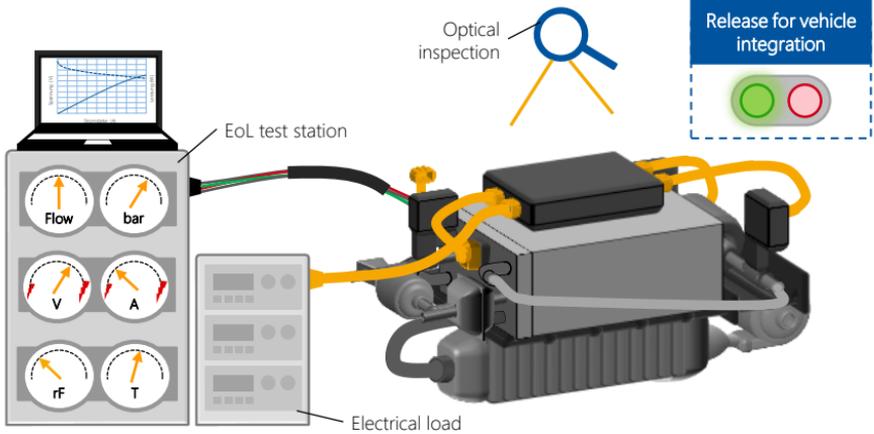
- External integrity and technical cleanliness
- Firmly seated joints
- Correct positioning and wiring of the peripherals
- Dismountability

Production costs [excerpt]

Investment for equipment: approx. € 0.05 million

End-of-Line testing

System production



Component production

Stack production

System production

- The entire fuel cell system, including all connected media lines and aggregates, is tested on an End-of-Line (EoL) test bench.
- The system runs through a test program in which different operating states are triggered through by varying the input parameters.
- The EoL testing ensures the functionality of the system consisting of the individual components (incl. software) and their correct connection to each other.
- In the process, the system undergoes a function and safety test for flawless performance as well as flow of gases and liquids. If the EoL test is completed without a fault signal and the optical test is passed, the fuel cell system is released for the vehicle integration.

Process parameters & requirements

- Process know-how
- List of criteria for comprehensive testing (no uniform regulation)
- Defined delivery status in coordination with vehicle assembly
- Qualification of employees for high-voltage safety (> 60 V)

Technology alternatives

- Upstream testing of the individual peripheral components → safety test not included
- Statistical testing with increasing production numbers
- Possibly combine EoL with commissioning

Quality influences

- None

Quality criteria

- Factory acceptance test (FAT) as final product release
- Definition of permitted rework
- Internal characteristics of manufacturer and customer

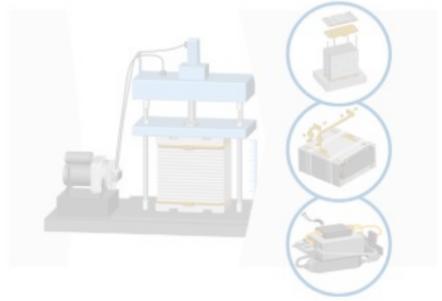
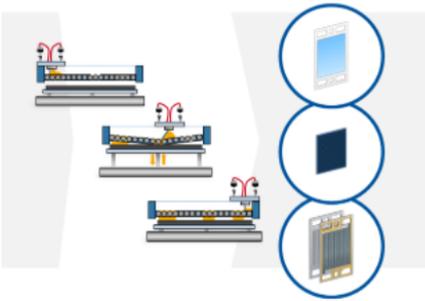
Production costs [excerpt]

Investment for equipment: approx. € 0.55 million

Further Information

on fuel cells and H₂ components

The production chain of a fuel cell system explained in this guide is based on the production of individual fuel cells. For more information on this, please refer to the guide listed below. It further details the production steps for manufacturing the individual cell components and the associated total costs.



PRODUCTION OF FUEL CELL COMPONENTS

2nd edition



PRODUCTION OF FUEL CELL SYSTEMS

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