MANUFACTURING TECHNOLOGIES FOR EQUIPMENT ALONG THE H_2 VALUE CHAIN

Contributions of selected members of the VDMA network Power-to-X for Applications

A cooperation between VDMA Roland Berger

Foreword

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The energy transition has been advancing relentlessly for some time now and is currently being further accelerated by Russia's invasion of Ukraine. There is widespread agreement that the future belongs to green energies. And something else is certain: hydrogen will play a decisive role.

Hydrogen will be a key enabler in reducing greenhouse gas emissions as it can be applied directly in industrial applications like the production of green steel with hydrogen direct reduction. It can also help with energy storage. Renewables such as wind or solar power are often generated asynchronously to consumption, making storage crucial to the success of the energy transition. With the help of electrolysis, energy, in the form of hydrogen or its derivatives, can be stored for almost any period, transported to its destination and converted again as needed. If green energy is used for electrolysis, the hydrogen produced is climate-neutral.

But for this to happen, the entire hydrogen economy must first develop on an industrial scale, from production to storage and transport. This requires, among other things, the widespread availability of manufacturing technologies and equipment. This joint study by the VDMA and Roland Berger explores the challenges that still need to be solved to achieve this, particularly in the technologies used to manufacture these machines and equipment.

The study presents selected examples of contributions to the innovation and scaling of manufacturing technologies, based on more than 20 interviews with VDMA member companies. Most of the necessary solutions are already well known. Companies must now seize the opportunity to secure a strong long-term position in the emerging hydrogen economy by participating in the upcoming industrialization and manufacturing scale-up.

BERNHARD LANGEFELD
Senior Partner Operations, Roland Berger

At Roland Berger, we are convinced that hydrogen will be an important part of successful climate action on a path to net-zero greenhouse gas emissions. Moreover, like a number of other clean technologies, it will be part of a new competitive paradigm that prioritizes sustainable growth. This is particularly true for sectors that are hard to decarbonize such as heavy industry or heavy-duty mobility.

There are already many studies analyzing the hydrogen economy. What sets this one apart is its focus on manufacturing technologies as well as innovations from mid-sized German companies. We spoke with industry representatives about their assessment of the technology readiness and quickly determined that there is little left to do in this area in terms of pure innovation. The main task over the coming years will be to industrialize manufacturing by maturing and scaling known technologies.

This is where Next Generation Manufacturing (NGM) comes into play. NGM provides a range of levers, from new manufacturing technologies and increased efficiency to digitalization and the reorganization of manufacturing footprints. As we describe below, partnerships can help accelerate innovation. And digital technologies can help reduce lead times, as the example of hydrogen compressors shows.

The study was conducted in cooperation with VDMA, whose members were invited to provide insights into their solutions. Our aim is to showcase innovative manufacturing technologies or innovatively manufactured components to players in the hydrogen value chain and investors looking for the right entry into a new industry. In addition, the study proposes three important actions that will help the hydrogen economy achieve a much-needed breakthrough.

Contents

1 **Introduction** 4

2 **Methodology and key findings** 8

3 **Manufacturing technology examples** 11

4 **Call for action** 23

Cover: Broetje-Automation; Photo caption: Robot head able to lay up to 16 individual tows simultaneously **Photo left:** VDMA, Roland Berger GmbH

1. Introduction

Why the new hydrogen economy matters

As the backbone of many industries, manufacturers face continuous pressure to improve performance and efficiency. This now coincides with several global megatrends approaching tipping points, which broadens the criteria for manufacturing competitiveness. Taking these criteria into account, companies now can use six levers (individualization, sustainability, industry disruption, populism, digitalization and location matters) to reposition their manufacturing and turn it from a liability into a value driver. This is what we at Roland Berger call "Next Generation Manufacturing."

Two of these levers, sustainability and industry disruption, are especially important for the rise of clean hydrogen as a key pillar in the energy transition efforts of companies, industries and economies alike. On the one hand, clean hydrogen is important for decarbonization; on the other, it will only become more widespread through a greater push toward sustainability and continued development of disruptive technologies – which it also reinforces, creating a symbiotic relationship. → A

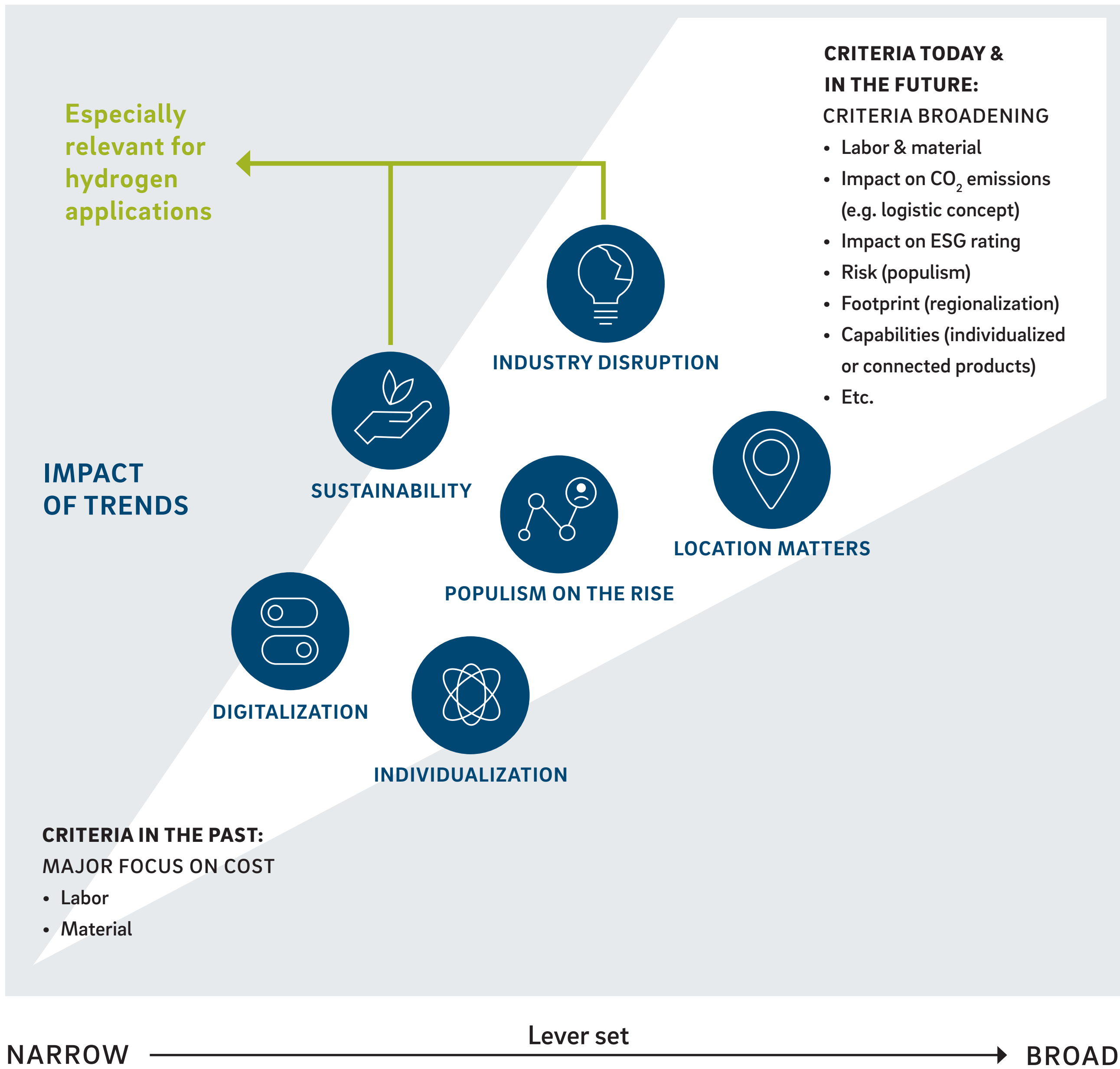
Hydrogen will be an important part of successful climate action on a path to net-zero greenhouse gas emissions. However, this will require the emergence of industrial supply chains for the new hydrogen economy.

Clean hydrogen has become a significant talking point for the decarbonization of industrial processes, mobility and energy sectors. It will be a powerful lever to meet the goal of the Paris Agreement and limit global greenhouse gas emissions to well below 2°C compared with pre-industrial levels. Thanks to its versatility, hydrogen can contribute to the decarbonization of a wide range of sectors, including heavy industry, long-haul and heavy-duty transport, and energy. These are sectors that are generally considered "hard to decarbonize" and which are yet to achieve meaningful reductions in greenhouse gas emissions. What's more, hydrogen's storability and transportability would enable the necessary coupling between various sectors and end uses.

Today, Europe is a global frontrunner in pushing hydrogen as a decarbonization enabler, with ambitious political targets as well as strong policies and regulations to support market development. At the same time, producers and offtakers are pressing ahead with major projects to get the market going. As a result, we expect hydrogen consumption in Europe to double from approximately 10 Mt today to around 20 Mt by the end of the decade. While most of these volumes will continue to be used as feedstock in industrial processes,

A A new competitive paradigm

Impact of NGM trends on manufacturing "competitiveness" criteria today and in the future



Source: Roland Berger

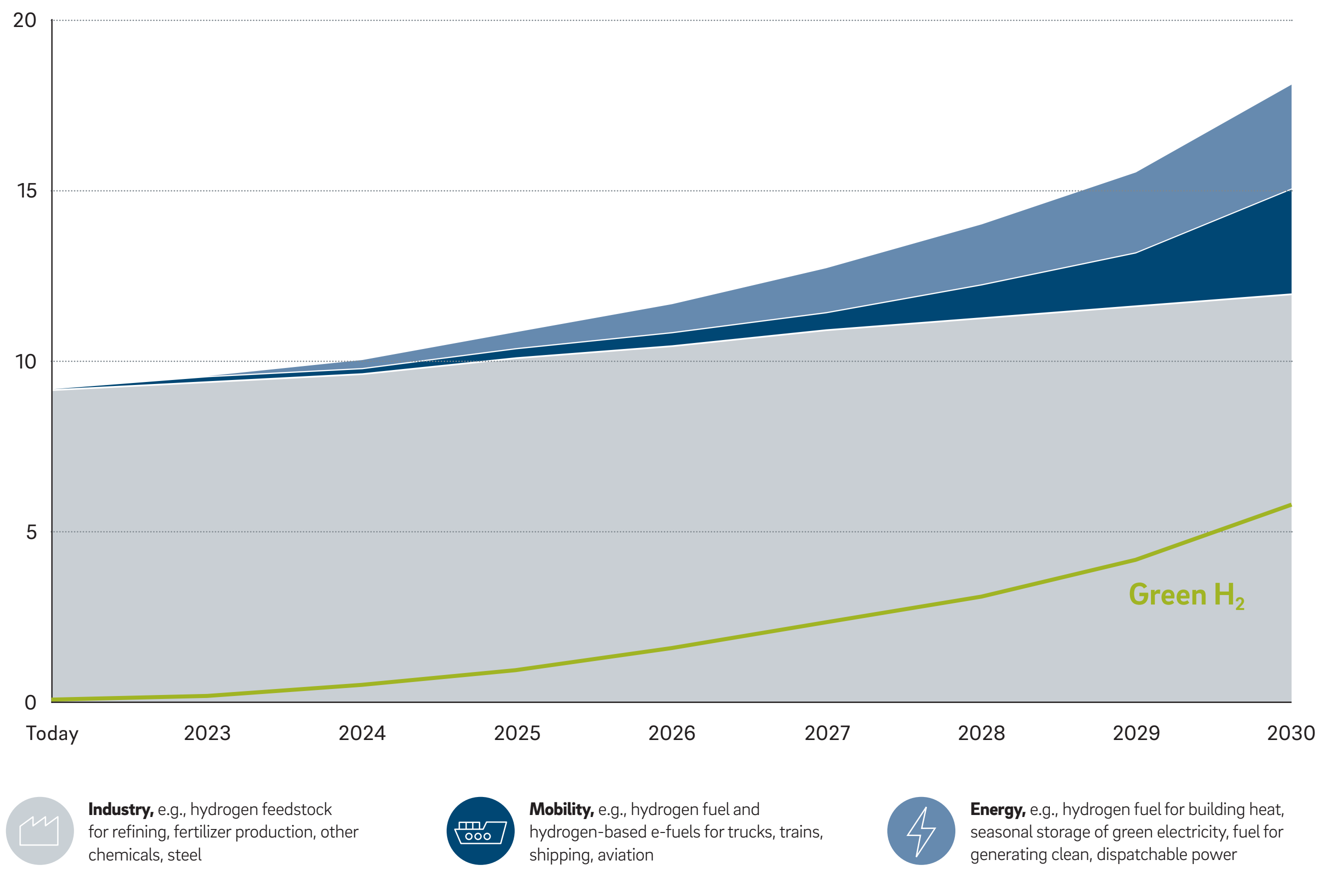
applications in the mobility and energy sector will expand. → B

Low- or zero-carbon hydrogen from electrolysis as well as carbon capture, utilization and storage (CCUS) makes up only a fraction of production volume today. However, we estimate that green hydrogen's share in European supply (from domestic production and imports) will increase to approximately one-third by 2030. Therefore, we expect investments in the necessary equipment to grow significantly in the coming years – with the market for electrolyzer equipment in Europe reaching EUR 6–10 bn in 2030, depending on actual cost degression and project realizations.

In addition to the European efforts, many countries around the world have already passed dedicated national hydrogen strategies, emphasizing the importance of hydrogen for decarbonizing their economies in the coming decades. Recent geopolitical events and structural increases in energy prices are accelerating matters further. European countries that have historically relied

B Hydrogen consumption outlook in Europe, 2022–2030

European hydrogen demand forecast by end use, green hydrogen supply [Mt]

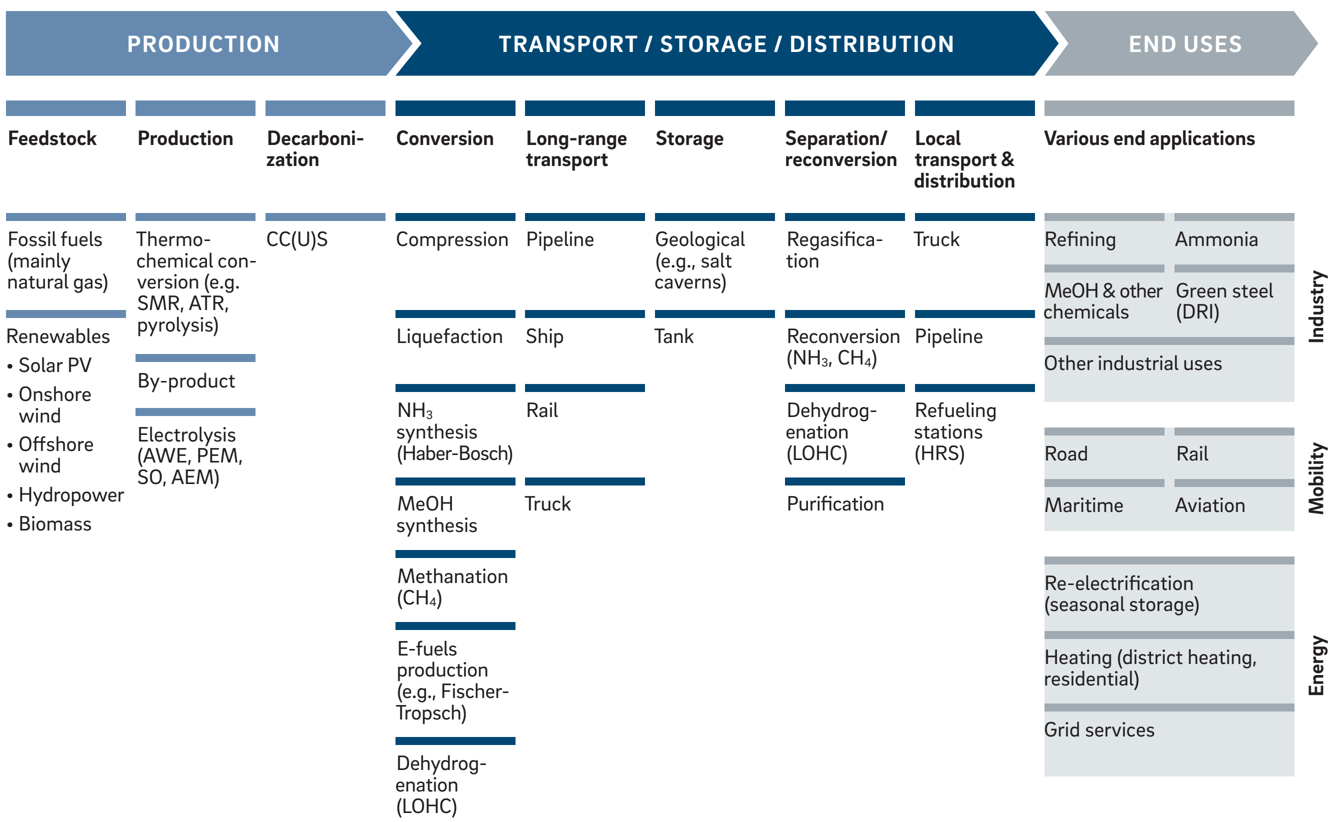


Source: Roland Berger

on Russian gas imports for decades are now quickly seeking to gain energy independence by not only looking for alternative suppliers, but in particular by even more aggressively pushing domestic renewable energy production – including green hydrogen.

The new hydrogen economy also presents significant growth opportunities in the emerging industrial supply chains. This study presents examples of manufacturing technologies from the mid-sized German companies that can contribute to the maturing and scaling of hydrogen equipment supply: enabling sufficient volumes, increasing efficiencies in manufacturing, innovating new components and alternative materials, etc. It also provides an understanding of how these technologies and equipment are expected to evolve, identifying essential developments in efficiency, technological scalability and cost reduction. Thus, the scope of this study includes various use cases along the hydrogen value chain. → C

C Key technologies along the hydrogen value chain (non-exhaustive)
Hydrogen value chain with its three main process steps of Production, Transport/Storage/Distribution and End Uses



Source: Roland Berger

2. Methodology and key findings

Gaining detailed insights into the hydrogen economy

This study is based on more than 20 interviews with representatives from member companies of the VDMA network Power-to-X for Applications. The aim was to understand the key technologies, before screening them for their significance in the hydrogen economy and any improvements they may offer over existing technologies. We divided the manufacturing technologies into three archetypes:

1. **Innovation:** Completely new technologies developed to meet the special needs of hydrogen applications (major R&D effort)

2. **Enhancement:** Existing technologies that can be used by enhancing technological boundaries to meet the needs of hydrogen applications (intermediate R&D effort)

3. **Transfer:** Application of existing technologies – often well-known in other industries – to different areas of the hydrogen value chain (minor or no R&D effort)

Based on this work, we identified a set of related themes.

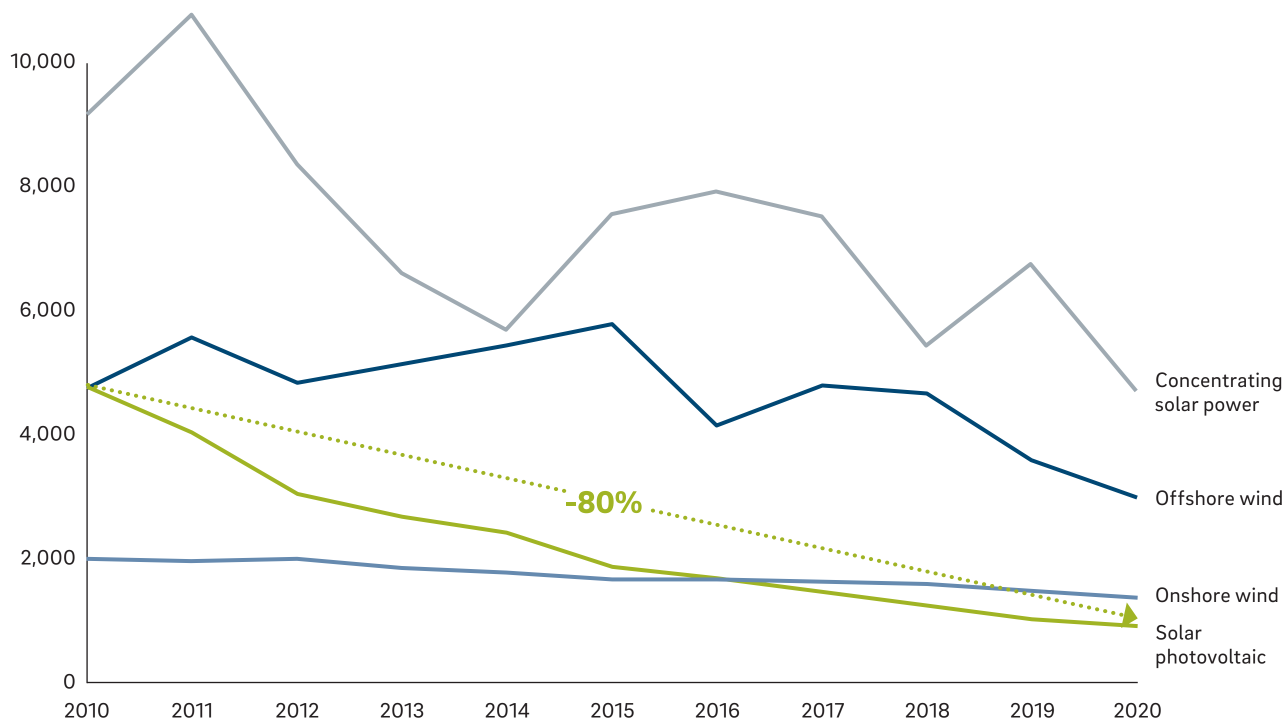
KEY FINDING 1:
Industrial supply chains are on the verge of industrialization

The new hydrogen economy is still a nascent market. While volumes have remained low, equipment manufacturers have mostly relied on small-scale production solutions with a low share of automation. Only a few companies are prepared for mass production, and manufacturing costs are high, mainly due to the high degree of customization and the associated technical effort. Industrialization is the next step. All interviewees saw the need to achieve scalability and increased efficiency to enable economically viable industrialization. Above all, this requires a higher degree of standardization, automation and, in some parts, innovation. However, most of the necessary production technologies for the hydrogen economy already exist, with the majority falling under the "Transfer" archetype mentioned above. As a result, the need for innovation is relatively modest.

KEY FINDING 2:
Cost-efficient manufacturing solutions can significantly contribute to market uptake

The cost of clean hydrogen solutions must come down significantly to compete with incumbent fossil-fuel technologies – even on a level playing field with tougher regulation. As an example, the photovoltaic industry has reduced costs by more than 80% over the past decade. → D

D Installation cost decrease in renewable energies over the past decade
Weighted average total installed cost [USD/kW]



Source: IRENA Power Generation Cost Report 2020

E Market growth as perceived by interview participants
Highest perceived market growth currently upstream in the hydrogen value chain

Source: Roland Berger

A similar development is yet to arrive in the hydrogen economy and cannot be achieved by one single manufacturing technology. For hydrogen, several factors need to contribute, such as innovation in next-generation products, substitution of high-cost materials, as well as standardization and simplification at component and system levels. However, the key lever lies in scaling up manufacturing to achieve economies of scale and accentuate the learning curve.

KEY FINDING 3:
Clean hydrogen production manufacturing needs (and is getting) the most attention

Increased innovation and industrialization are critical in the manufacturing of clean hydrogen production technologies. They require the most attention for the successful ramp-up of the new hydrogen economy, especially electrolyzer production. OEMs and suppliers see demand increasing soon, with stack manufacturing investments already experiencing significant growth over the past year. In general, growth outlooks become more modest further downstream. A lack of capacity in the preceding process steps still hinders sufficient market growth for certain applications. Clean hydrogen will remain a supply-constrained market in the short and medium term. → E

As outlined in a recent Roland Berger study on hydrogen transport, midstream technologies for hydrogen distribution will also be important. These could make hydrogen a successful energy carrier in end-use applications and their industrial scale-up must be initiated as soon as possible to avoid creating a bottleneck.

KEY FINDING 4:
Many companies for whom hydrogen is a niche business today are ready to scale up production

There are currently very few manufacturers that are fully dedicated to developing hydrogen solutions. Those venturing into the sector are typically already well positioned in related industries like chemicals, which enables some cross-financing to develop and ramp up hydrogen solutions. As the mid-sized German companies in this study illustrate, businesses are ready to take the next step and invest in large-scale and advanced manufacturing capacities. Entrepreneurial spirit, often found in mid-sized German companies, and a strong drive for innovation based on sound technical expertise motivate these companies and, together with the availability of public funding, enable them to take this important next step.

KEY FINDING 5:
Significant public funding and rising demand will help the industry to kickstart industrialization

The momentum for a major leap forward in manufacturing hydrogen technologies is growing. Governments around the world, particularly in Europe, Asia and North America, have significantly upped public support schemes to boost demand for clean hydrogen via financial support for project investments. As a result, green hydrogen project announcements have more than quadrupled over the past 18 months. The European Union and key member states have also created large-scale funding schemes to support the growth of European industrial supply chains – along the entire hydrogen value chain. The most significant framework is Important Projects of Common European Interest (IPCEI), which enables national governments to give direct state aid to companies investing in manufacturing capacities for hydrogen technologies.

3.

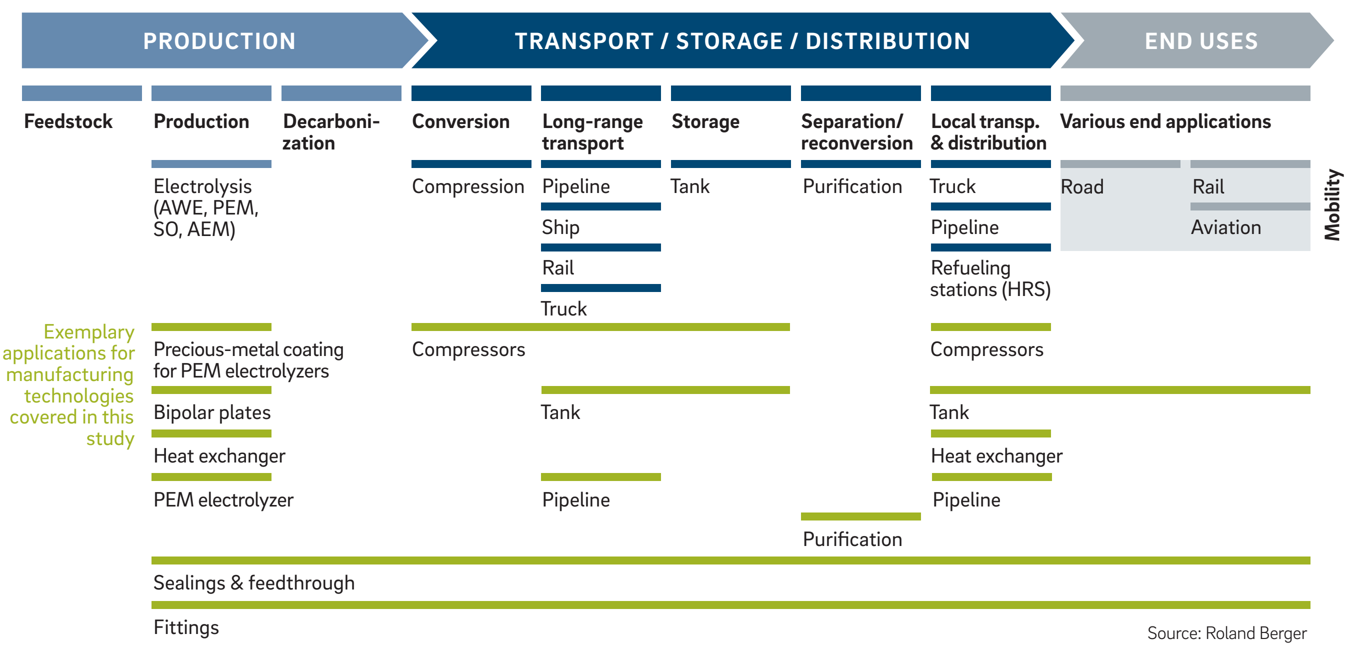
Manufacturing technology examples

Selected insights into manufacturing technologies for the hydrogen economy

Based on our interviews, we took an in-depth look at a selection of key applications along the hydrogen value chain. → F

Each analysis below focuses on the manufacturing technologies needed and the scale-up potential for each application.

F Technological deep dives along the hydrogen value chain
Exploring applications for manufacturing technologies in the hydrogen value chain



Source: Roland Berger

PRECIOUS-METAL MATERIALS

Value stream process supported:
Production
Key contribution:
Material supply for PEM electrolyzer membrane coatings
Manufacturing technology:
Material preparation of precious metals
Technology archetypes:
Enhancement; innovation

Both electrolyzer membranes and fuel cell membranes are coated with materials containing precious metals like iridium and platinum, which promote the electrocatalytic reactions with water or oxygen and hydrogen, respectively. Due to slightly different process parameters and cell designs, these coating materials are highly optimized for their respective applications. The limited availability of the precious metals used also makes end-of-life recycling an important topic.

For PEM electrolysis, cathodes are typically made of platinum black while the anode conventionally is made of iridium black. The limited availability of iridium compared with platinum makes the anode the limiting factor in terms of future scale-up and pricing risks for PEM electrolysis.

One interesting recent technological development comes from the company Heraeus, enabling a significant reduction in the amount of iridium needed. This is achieved by substituting bulk iridium with supported iridium oxide. This new material enables cost reduction by reducing iridium weight concentrations from over 98% to around 10% in the catalyst. To enable the production of this material, the newly introduced manufacturing process ensures sufficient surface area of the catalyst as well as material stability for further processing such as membrane coating. Overall, the described material and its unique manufacturing technology reduce investment levels for electrolyzer OEMs significantly.

In general, adequate technologies for the material preparation are already in place here. There is potential for improvement by further substituting precious metals in the coating material as well as increasing the efficiency of recycling. From a technological point of view, a scale-up to larger production volumes is certainly possible. However, the scarcity of precious metals is a major cost driver, and rising demand will increase raw material prices as well as supply chain difficulties due to limited sourcing opportunities. Given that precious metals already represent a significant share of the cost of the electrodes, this will be a major economic challenge and could be solved by this new material.

BIPOLAR PLATES

Value stream process supported:
Production
Key contribution:
Component supply for electrolyzers
Manufacturing technology:
Hydroforming; cutting; welding
Technology archetypes:
Transfer

Bipolar plates are essential components in every electrolyzer and fuel cell. They serve as carrier plates for both poles of the cells, connect different cells in the electrolyzer and discharge gases from the reaction zone. Made of either graphite or metal, bipolar plates are individual components that must be adapted to each type of electrolyzer. Although their profile design is different, the plates are also required in fuel cell stacks. Any synergies in terms of manufacturing technologies should be exploited.

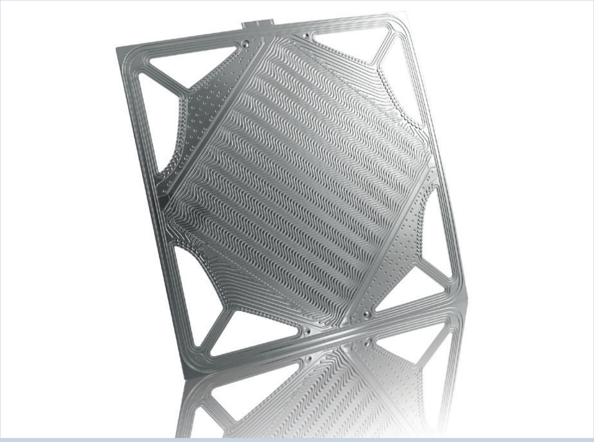
Traditionally, bipolar plates are manufactured using mechanical forming processes. A critical step here is the application of the flow profile to the plate. This is usually either milled from the solid into the plate using mechanical milling tools on CNC machines or stamped into sheet metal. The milling process typically involves a lot of material waste. In addition, tool changes and complex clamping of work pieces make automation difficult. Some of these disadvantages can be overcome with a stamping press. Cycle times are shorter but there is still material waste, and the equipment is expensive due to at least two dies required.

An alternative manufacturing technology is available from Graebener® Bipolar Plate Technologies. By using hydroforming, which applies a high-pressure hydraulic fluid, Graebener® can produce very delicate structures using only one die. The process produces much less material waste and there are no chips to be treated. What's more, automation is less complex than in milling, and changeover times are shorter. Another advantage of hydroforming is the avoidance of tool wear, which enables higher equipment availability. There is a downside, however, as cycle times are slower than conventional processes, especially stamping.

Hydroforming is currently unique on the market for bipolar plate production and could establish itself as an effective alternative manufacturing technology. In our view, all manufacturing processes will be used in equal manner at the beginning of the hydrogen economy until the necessary experience is available and a superior technology emerges.

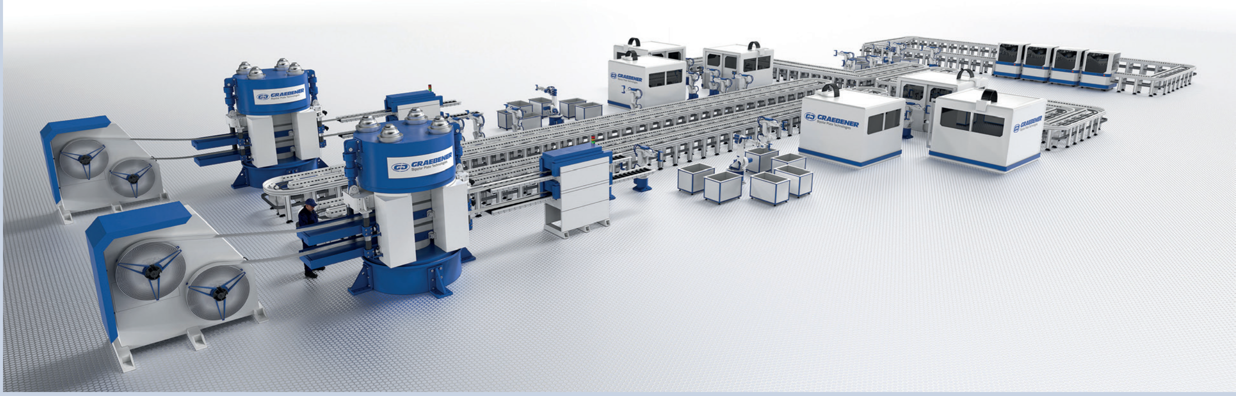
The biggest hurdle to scalability, regardless of the manufacturing technology applied for forming, is a lack of standardization as it takes considerable effort to adapt a production line to individual plate designs. After forming, bipolar plates need to be joined by welding processes that are complex and take high effort as well. Welding can easily become the bottleneck in the production line, and therefore an appropriate welding process such as laser welding is key for scale-up in addition to the technology used for plate forming.

Production line modularization would enable a gradual transition to series manufacturing, which can be scaled from small, manually operated systems up to larger, fully automated setups. Due to a lack of demand, these ideas are currently only in a conceptual phase and their practicality is unproven.



1 Bipolar plate

2 Hydroforming press



3 Production line from the coil to the finished bipolar plate

Photos: 1, 2 and 3: Graebener® Bipolar Plate Technologies

ELECTROLYZER STACK MANUFACTURING

Value stream process supported:
Production
Key contribution:
Stack assembly
Manufacturing technology:
Automated stack production
Technology archetypes:
Transfer

An electrolysis cell is made from two electrodes – a positively charged bipolar plate (anode) and a negatively charged one (cathode) – as well as a separator, such as a proton exchange membrane. An electrolyzer usually contains several electrolysis cells, which are connected in series to boost performance and provide sufficient voltage. This basic concept is similar in all relevant electrolyzer types, although materials and operating conditions vary.

The interconnection of the components of each cell is called stacking. Today, the stacking process is largely manual due to low volumes and frequently changing cell designs. Scaling up manufacturing for more widespread use of electrolyzers in the hydrogen economy would require robotic automation of the stack assembly process. Here, the interaction with upstream and downstream steps in electrolyzer production is important. This would represent a transfer of technological know-how that already exists in the fuel cell sector. In particular, the manufacturing of the bipolar plates is currently detached from the stacking of the cell, with membrane coating only partially handled by the OEM. Because the stacking is highly performance relevant, it will be carried out by OEMs themselves in the future.

The emerging electrolyzer industry features a growing numer of players, many of which are technological pioneers and strong innovators in their field. In Germany, OEMs include companies such as thyssenkrupp nucera, Siemens Energy, ITM Linde Electrolysis, Sunfire and H-TEC, a subsidiary of MAN Energy Solutions. All of them – independently or with partners – are working on the design of production lines for electrolyzers that will help automate stacking, as part of their investments in the first "gigafactories." The main objective here is to increase production volume and reduce manufacturing cost while maintaining the quality of the process.

Existing manufacturing technologies for stacking are sufficient to reach required technical specifications. Building a fully automated stacking line requires both the necessary technology and system integration expertise, which is not yet widespread. A further challenge for scale-up lies in supplier availability and component costs such as membranes. There are currently very few component suppliers available, and those that exist do not yet produce at scale.

Today's electrolyzers typically have a capacity of several megawatts. Many electrolyzer suppliers are pursuing a modular approach that theoretically enables systems to be scaled up to several gigawatts. All these approaches significantly increase the number of stacks required as well as the number of identical components, making highly efficient production lines a key capability in the hydrogen economy.

HEAT EXCHANGER

Value stream process supported:
Production; local transport and distribution
Key contribution:
Component of electrolyzers and fueling stations
Manufacturing technology:
Additive manufacturing or subtractive machining/welding
Technology archetypes:
Enhancement; transfer

During electrolysis, electrolytes, hydrogen and oxygen are cooled via heat exchangers, which must meet different pressure and temperature range requirements depending on the electrolysis technology. Heat exchangers for local hydrogen fueling stations, such as those for cars or trucks, must withstand pressures of up to 1,000 bar design pressure, with operating pressures around 700 bar for the current H70 fuel dispenser systems. This need for high operating pressures is to shorten vehicle fill times from greater than 30 minutes down to something acceptable to consumers of 3–5 minutes.

Safety is extremely important for all heat exchanger applications in the hydrogen economy. Sealing plays an important role in this due to the reactivity of hydrogen with atmospheric oxygen. Other important factors include compact, thermally responsive size and the ability to operate continuously that enables back-to-back filling with no wait times, simplified maintenance that maximizes uptime, and small size, eliminating the need for costly, time-consuming underground installation, which allows use in urban or limited-space areas – something that other, less compact technologies cannot do.

Conventional models, known as "shell-and-tube" or "plate-and-shell" heat exchangers, are primarily manufactured using subtractive manufacturing processes followed by welding. In the printed circuit heat exchanger (PCHE), the metal is removed from the heat transfer plates by chemical milling, as is done in the manufacture of printed circuit boards for IT equipment. At the current early stage of the hydrogen life cycle, the early introduction of technologies with the right level of technological maturity for commercial use is desired. Additive manufacturing will come, but later in the hydrogen application life cycle. An innovative solution has been developed in this area by Alfa Laval, which says its HyBloc is 85% smaller and lighter than traditional heat exchangers, making them easier to integrate into dispenser housings due to their relatively small channels requiring less metal to support high operating pressure and subsequent high heat transfer coefficients. It can also operate in a temperature range of -196°C to 800°C and at pressures of up to 1,250 bar – both well beyond the specifications of traditional solutions. The design allows for highly efficient cooling, which, unlike conventionally manufactured heat exchangers, also allows for continuous operation under demanding conditions like at high-capacity refueling stations, which reduces the wait times between vehicle fillings. The HyBloc is made up of four different standard models servicing different fill rates.

Additive manufacturing is a manufacturing technology for heat exchangers with considerable potential for widespread use in the hydrogen economy. Apart from manufacturing issues, the biggest challenge still lies in the scalability of manufacturing: a lack of standardization necessitates significant engineering effort to adapt each heat exchanger to its specific application. Both this and the technological limitations of 3D printing cycle times are significant cost drivers. Scaling up manufacturing is feasible but more difficult than for well-known conventional subtractive solutions. Any efforts toward this must be justified by a clear technological benefit compared with conventionally produced heat exchangers.

1 Printed circuit heat exchanger produced using chemical milling

Photo: Alfa Laval

GAS DRYING AND PURIFICATION

Value stream process supported:
Production; separation/reconversion

Key contribution:
Equipment for drying and purification of hydrogen

Manufacturing technology:
Milling; turning; welding

Technology archetypes:
Transfer

After hydrogen has been generated or stored, it must be dried and purified to avoid clogging the fuel cell during the application phase. There are various physical and chemical processes for the purification process, although not all of them are suitable for scaling up from the laboratory environment to an industrial scale. Catalytic purification is one of the processes that seem best suited to the hydrogen economy.

Purification equipment today is tailored according to specific requirements of the final application in terms of pressure, flow rate, target purity and so on. For series production, standardization will therefore be decisive, but it must be closely coordinated with future standardized electrolyzers.

Gas drying and purification equipment manufacturing uses classic manufacturing processes such as milling or turning and welding. The expertise lies in the knowledge of the purification process, equipment design and correct systems assembly.

→ Drying-process innovation

The Berlin-based company Silica Verfahrenstechnik GmbH has developed a special process for the regeneration of hydrogen-drying granulate without any losses of hydrogen. First, the impurities of the produced hydrogen are removed via catalytic cleaning before the hydrogen gas is dried in a second process step. To allow a continuous operation, at least two drying columns are necessary. While one column is in operation mode, the drying granulate of the other column must be regenerated. For this procedure Silica developed a lossless, closed-loop regeneration process, which can be operated independently from the incoming hydrogen stream. Silica Verfahrenstechnik GmbH is thus able to produce hydrogen purification systems that are immediately ready for use even if there is a lack of renewable energy (no solar power, no wind). In addition, this system can also deliver the full hydrogen product quality in the lower partial load operation.

1 Innovative hydrogen purification system by Silica Verfahrenstechnik GmbH

PIPELINES

Value stream process supported:
Long-range transport
Key contribution:
Pipelines for hydrogen transportation
Manufacturing technology:
Forming and welding; coating
Technology archetypes:
Transfer

Pipelines can be used to transport hydrogen gas over long distances. The pipeline technologies currently used in the oil and gas industry can also be used for most requirements of 100% hydrogen concentrations. There are currently few pure hydrogen pipelines in operation today.

Pipelines are made of steel by forming tubes and welding them together. Internal flow coatings like epoxy are applied to the pipe to improve flow properties and external coating to facilitate installation and protect against corrosion (in addition to a sacrificial anode). Generally speaking, pipeline manufacturing technologies are transferred from other industrial applications, which large players like EUROPIPE are well capable of.

We assume the scalability of pipeline manufacturing is a given as the technology is already available for other gaseous applications. The biggest difference between conventional and hydrogen pipelines is the compressors that need to be integrated due to the different physical properties of the gas.

HYDROGEN COMPRESSORS

Value stream process supported:
Conversion; long-range transport; local transport & distribution
Key contribution:
Increase of volumetric energy density via hydrogen compression
Manufacturing technology:
Milling; turning; welding
Technology archetypes:
Transfer

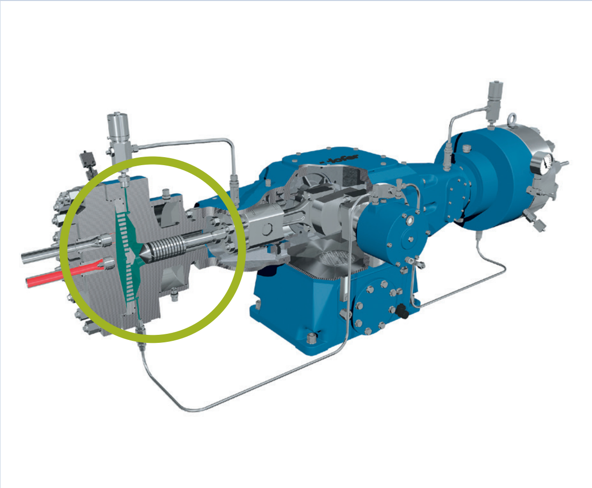
Hydrogen is characterized by a very high gravimetric energy density and a very low volumetric energy density. This means that although hydrogen is lighter with the same energy content, it also takes up significantly more space than other energy carriers. For efficient storage and transport it is therefore essential that hydrogen is compressed.

Piston compressors are typically used for hydrogen pipelines as well as storage in caverns at up to 250 bar. Diaphragm compressors, on the other hand, can be used to compress hydrogen for applications like refueling stations at high pressures of 1,000 bar or more.

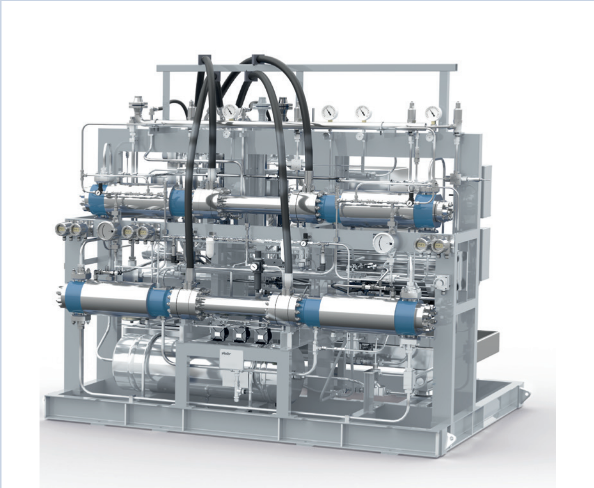
Well-established manufacturing technologies are applied in the hydrogen compressor production process: Turning, milling and welding are the basis to produce the main components. Know-how transfer from other industrial applications helps in creating best-fit solutions for the hydrogen economy. Natural gas systems, for example, can be converted by using more piston rings and different valves.

Hydrogen compressors are currently manufactured in very low volumes or even in individual production setups with long lead times. This is where NEUMAN & ESSER, an experienced manufacturer of hydrogen compressors, has used digitalization to optimize some processes for series production. The company has reduced delivery times for fuel station compressors, for example, from more than 15 to nine months. It uses digital tools in various areas of compressor manufacturing, from digital costing for faster offers to complete connectivity of production, including algorithmic planning and seamless shop-floor management.

Scaling up to mass production is a challenge as both cost reductions and improved delivery times must be realized through efficient processes. Standardized product portfolios could also increase efficiency and ease integration of compressors into hydrogen systems.



1 Hydrogen compressor with several piston rings to improve tightness



2 Hydraulic hydrogen piston compressor as an exemplary application for the compressor

VALVE TECHNOLOGY

Value stream process supported:
All value stream steps from generation to distribution
Key contribution:
Control and shut-off valves, including special valves for pressure-swing absorption, low temperatures and/or high pressures, as well as for challenging process conditions
Manufacturing technology:
Casting; milling; turning; welding
Technology archetypes:
Transfer

Valves are needed along the entire value chain of the hydrogen economy. They must be maintenance-free and guarantee years of reliable service. In addition to the brittling properties of hydrogen, they must also be able to withstand extreme conditions such as temperatures of -253°C during the liquefaction of the hydrogen. Valve technologies for hydrogen are already used in a wide range of industrial applications in the oil and gas, chemical, and food and beverage sectors. As such, there is already plenty of know-how at specialized companies such as SAMSON.

1 Valve housings clamped for further processing

For the hydrogen economy, SAMSON assumes that the products required are very similar to those used in other sectors. Only certain properties need to be adapted, which can be covered by a mix of new and existing solutions. Manufacturing technologies require just a few minor adjustments, primarily due to the use of different materials for hydrogen applications. Low-temperature materials without hydrogen embrittlement are a good example, which are currently in low demand but are likely to be very important for the hydrogen economy.

In valve manufacturing, then, there are many existing solutions that can be transferred to hydrogen. The challenge lies in scaling them up to series production, although compared with other areas of the hydrogen economy, this is a comparatively low hurdle.

Photo: SAMSON AKTIENGESELLSCHAFT 2022

FEEDTHROUGHS AND SEALS

Value stream process supported:
Production; local transport & distribution
Key contribution:
Seals and feedthroughs for extreme conditions
Manufacturing technology:
Glass manufacturing; glass-to-metal sealing; plating
Technology archetypes:
Transfer

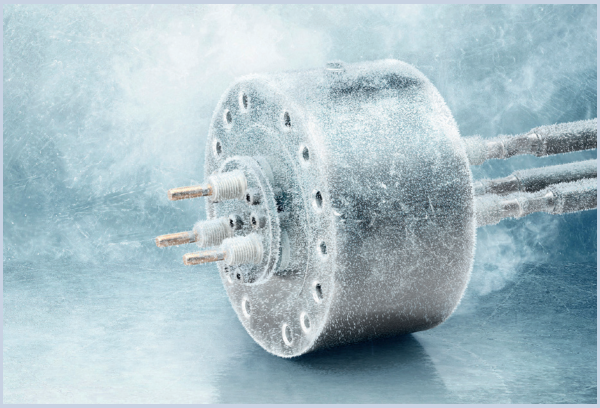
Hydrogen is the lightest element in the periodic table and, as a gas, could easily escape from many types of equipment. For safety reasons, this must be avoided at all costs, which is why seals have to be highly reliable and wear-free. The same goes for feedthroughs, which allow access to the hydrogen-filled system while remaining leak-proof. Feedthroughs are used for the safe passage of sensors or for feeding electrical energy or signals into closed systems like hydrogen tanks or cryogenic submersible pumps.

Hermetic glass feedthroughs and seals can be used across all steps of the hydrogen economy. They are resistant to high pressure, temperature and corrosion, while offering minimized risk of leakages. In addition, they are also explosion-proof and can be used safely for many years without maintenance for most applications.

Hydrogen production via solid oxide electrolyzer cells can involve temperatures of up to 1,000°C, posing a serious challenge for the materials in feedthroughs and seals. The opposite extreme is found in hydrogen transport and storage, where seals must withstand pressures of up to 1,000 bar and/or temperatures as low as -253°C (liquefied hydrogen). In both extremes, glass seals and feedthroughs are used because of their extreme robustness. Compared with conventional solutions, glass-to-metal seals offer reduced total cost of ownership due to the use of non-aging materials.

One of the world's leading suppliers of hermetic feedthroughs and components is SCHOTT. The company has decades of experience in manufacturing special types of glass for industrial applications and offers solutions relevant to the hydrogen economy. These include hermetic glass-to-metal seals as well as fully explosion-proof electrical equipment, which are extremely challenging to produce and must be precisely tailored to each application in terms of materials and design, which SCHOTT validates and optimizes with the customer.

Today's manufacturing technologies for glass seals and feedthroughs can be transferred to the hydrogen economy with little effort. The biggest challenges in terms of scalability are the adaption of current processes to future volumes and the reduction of validation and engineering effort, as cost pressure is high. Technological improvements and standardization appear key to successful (and economical) series production for the hydrogen economy.



1 Glass feedthrough at low temperatures

2 Quality control of an industrial sensor feedthrough with glass sealing inside the flange

HYDROGEN TANKS

Value stream process supported:
Local transport & distribution; end applications
Key contribution:
(High-)pressure hydrogen tanks for ambient or cryogenic temperatures
Manufacturing technology:
Composite filament winding/towpreg handling; autoclave; metal or plastics processing
Technology archetypes:
Transfer; enhancement

There are five types of pressure vessels for storing compressed hydrogen. They differ primarily in their weight and pressure levels due to their mechanical design concepts. Type 1 pressure vessels are made of steel, can be used up to around 200 bar and are widely used in the chemical industry. For higher pressures up to 1,000 bar, the metallic wall in the cylindrical area is strengthened with a resin-impregnated glass or carbon fiber structure to produce a type 2 pressure vessel, which is primarily used for stationary applications like refueling stations. Type 3 is a metallic liner, usually made of aluminum, which is completely encased in carbon-fiber-reinforced plastic and can withstand pressures of between 350 and 700 bar. Due to its lighter weight, it is primarily used in mobile applications such as fuel cell vehicles. Type 4 pressure vessels use a polymeric liner instead of metal and are encased with carbon-fiber-reinforced polymers (CFRP), reducing weight further and making the tank even more attractive for mobile applications. Type 5 tanks are fully composite pressure vessels without the usage of an additional liner, to further reduce structural weight.

In the hydrogen economy, all types of pressure vessels are used for hydrogen storage. However, types 2 to 5 are more recent developments and therefore technologically more challenging. Manufacturing expertise of composite structures is particularly relevant. Some existing product knowledge can be used and transferred to the hydrogen environment, but technological optimization is still required to scale up manufacturing, particularly with regard to increasing efficiency and reducing costs.

Below, we go into further detail on three use cases for hydrogen tanks in different modes of transport.

→ USE CASE 1: Heavy-duty commercial vehicles with tanks (type 4)

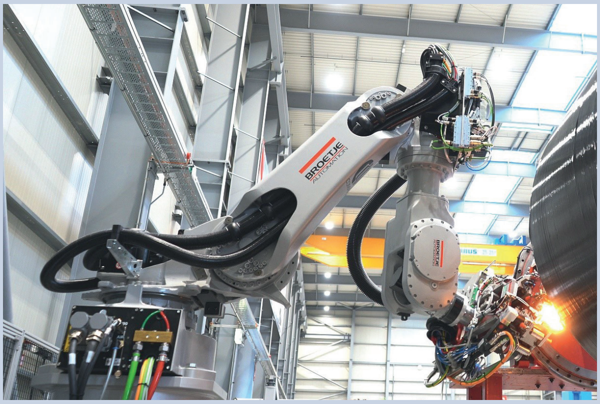
High-pressure tanks are a standard product yet with smaller production volumes. Differentiation between competitors is through efficient, advanced manufacturing technologies and varying product designs, e.g. sealing concepts and differences in the layer design, thus ensuring technological advantages in terms of gravimetric storage density. This is why Voith is currently working to scale up more-efficient manufacturing processes for 700 bar type 4 hydrogen pressure tanks and complete Plug & Drive storage systems. Among other things, the company replaces the previous wet winding process with pre-impregnation of the carbon fiber, which enables higher process speeds. By increasing material efficiency and quality as well as automation and reducing non-productive time, Voith increases its production output significantly and provides processes optimized for high-volume production. It will also use existing technological know-how from other industrial applications – such as high-volume serial automotive manufacturing for composite structural parts – to further increase competitiveness via additional cost reductions.

→ USE CASE 2: Aircraft with high-volume tanks (type 4 and 5)

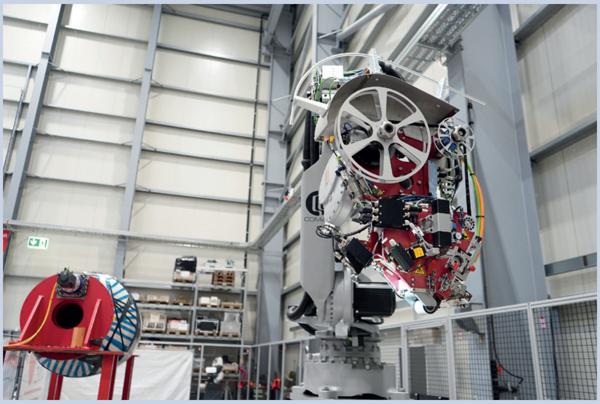
Weight and capacity are vital factors for the storage of hydrogen in aircraft. This indicates that type 4 or type 5 pressure vessels with large volumes need to be used in future applications. Aviation's stringent safety and certification requirements represent an additional hurdle, with a particular impact on development time.

Large-volume type 4 and 5 tanks for the aviation industry are currently still in the development phase. One industrial consortium, comprising two OEMS, the German Aerospace Center (DLR) in Stade, and Broetje-Automation, among others, is looking at various design and manufacturing aspects of a cryogenic hydrogen tank as part of a three-year development project. The group's current approach is to develop and improve technologies and processes for a hydrogen tank on a real aerospace geometrical scale. To meet safety requirements, the consortium is working in parallel on manufacturing and structure-integrated sensor systems for quality assurance and structural health monitoring. The entry-into-service target is 2035 and envisages the manufacturing of five tanks per day per facility.

In terms of manufacturing technologies, GroFi®, a multi-robot research facility, will be used at DLR to validate the manufacturing of cryogenic, composite tanks. GroFi® was co-developed and delivered by Broetje-Automation using technology from other applications and can efficiently produce composite structures up to 5.5 meters in diameter. The laying accuracy and tension of the fibers in such large dimensions are decisive for the product's quality. A new single-fiber approach for dome area manufacturing could have an impact here, enabling a lightweight and flexible solution.



1 Large-scale tank production for the aviation industry



2 Automated robot head for various materials and part configuration during manufacturing

Photos: 1 and 2: Broetje-Automation

→ USE CASE 3: Heavy-duty commercial vehicles with cryogenic hydrogen tanks (type 3)

As an alternative to high-pressure storage at around 700 bar, or storage in liquid form in vacuum-superinsulated low-pressure containers, hydrogen can also be stored under cryogenic conditions. This is a hybrid of the other two forms, in which hydrogen is stored as a cryogenic gas at up to 350 bar and between -240°C and -100°C. As with the storage of hydrogen at high pressure, the storage of cryogenic gas takes place in pressure vessels with an inner liner of aluminum and a wrapping made of CFRP.

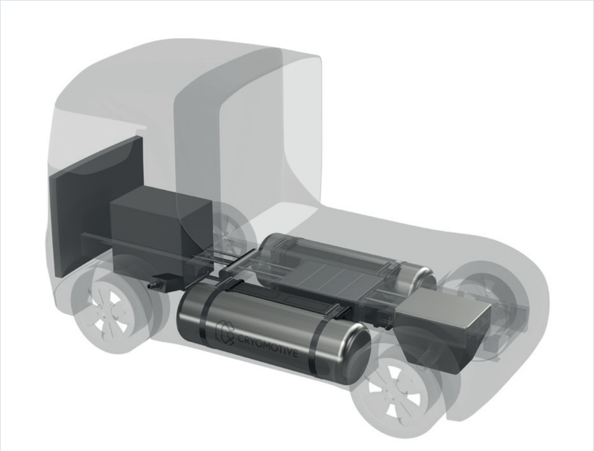
This type of hydrogen storage is currently in the development phase and is particularly relevant for long-distance heavy vehicles under continuous operation. The initial focus is on trucks, but this is expected to expand to rail vehicles. The technology, originally developed by BMW for passenger cars, is currently being further developed by Cryomotive and validated and optimized by an industrial consortium (Cryomotive, MAN Truck & Bus, Clean Logistics, IABG and TU Munich) with the aim of starting series production in 2025/26. According to Cryomotive, the storage of cryogenic hydrogen offers numerous advantages, such as a very high physical density (twice that of 700 bar hydrogen gas), rapid refueling and comparatively low costs.

The manufacturing technologies for cryogenic tanks are analogous to high-pressure tanks for hydrogen. As a result, scaling up manufacturing faces similar challenges. Automation is the biggest lever here due to the high volume of process costs – only 20% to 30% of a tank's costs are materials. There is also currently very little manufacturing know-how for the aluminum liner in Europe, so it is currently produced mainly in North America and Asia.

The race for the most efficient industrialized solution for hydrogen tank production is very much on. We believe the winning technologies will become apparent as soon as the expected demand for higher production volumes appears.

1 Cryogenic tank system for mobility applications

2 Cryogenic refueling station



3 Cryogenic tank system for truck applications

Photos: 1, 2 and 3: Cryomotive GmbH 2022

4.

Call for action

Three action areas to support critical hydrogen technology manufacturing solutions

The new hydrogen economy is on the verge of its first real wave of industrialization. Many of the key technologies are ready to move from niche application to widespread use in the energy transition – and so are the necessary manufacturing technologies. For the first time, the sector has a chance to break the traditional chicken-and-egg problem – where equipment manufacturers look for reasons to invest in "gigafactories" and users wait for more mature and cost-efficient hydrogen technologies. To break this cycle, we have identified three areas that require action from policymakers, industry and investors alike.

1. SUSTAINED PUBLIC SUPPORT

Governments should support the expansion of industrial supply chains in the same way as they support investments in hydrogen projects

European policymakers have taken important steps in recent years to support the ramp-up of the new hydrogen economy with different policies and regulations. More than 15 European countries now have dedicated hydrogen strategies in place and almost all other countries are drafting theirs. As part of the REPowerEU communication, the European Commission has significantly upped the EU 2030 targets for hydrogen production and imports – along with dedicated regulatory and funding measures. Hydrogen policies now include direct support for hydrogen projects such as CAPEX subsidies for electrolyzers, hydrogen refueling stations and hydrogen applications, CCfDs, and quotas for clean hydrogen offtake. Policy support now also extends to the public funding of new manufacturing capacities – most notably direct state aid by EU member states under the framework of IPCEI.

European governments should continue to broadly support the industrialization of the sector, with a comprehensive array of policies and regulation that covers both value chain and supply chain investments. In addition to public funding, remaining gaps in standardization and certification should be closed; continental agglomerations of next-level industrial supply chains – similar to the IPCEI model – should be supported.

2. BOLD INDUSTRIAL MOVES

Future industrial leaders must be willing to take risks and define a growth plan to shift to mass production

Companies that want to play a major role in the hydrogen economy should not only rely on policy support, but also get ready to invest in more-advanced and larger-scale production. With more and more players entering the market and looking to capture increasing demand, competition will quickly grow. The next few years will see a race to find the predominant solutions, with time-to-market, reliability, safety and costs serving as the driving factors.

A growth plan can provide guidance on how to win this race by following a structured approach to the industrialization and scale-up of machines and equipment for the hydrogen economy. The plan must include the following levers:

- Aggressive cost reduction
- Standardization of products
- Manufacturability in series manufacturing (such as ease of automation)
- Scalability of solutions to support the ramp-up of the hydrogen economy (such as modularity)
- Focus on sustainable manufacturing (CO_2 footprint, energy sourcing, waste/recycling)

At Roland Berger, we see Next Generation Manufacturing as an overarching guideline to ramp up or transform any operations, including production plants for hydrogen machines and equipment. It is imperative to consider the six underlying trends mentioned earlier in this study – especially sustainability and industry disruption – in any growth plan.

Businesses that move fast and quickly gain experience will be able to better position themselves in the market and set market standards. Early movers might be able to secure advantageous positioning if they can leverage initial operational experiences and reduce costs.

3. SMART HYDROGEN ECOSYSTEMS

Companies need to find the right partners to boost their hydrogen offering

Existing industry platforms, like the Power-to-X for Applications working group hosted by the VDMA, play an important role in fostering exchange; they act as a strong voice toward policymakers and help drive standardization. These platforms can also provide navigation in the jungle of funding options and support companies in the funding application process.

However, companies must consider taking collaboration beyond pure knowledge exchange. This study shows that most technologies for the hydrogen economy are currently being developed in a decentralized way. Once a transition plan is outlined, we recommend that companies ask themselves the following critical questions:

Can you scale up alone or do you need a partner?

Investigate whether your solution has the potential to successfully compete as an individual component or system in the hydrogen ecosystem. Consider topics like integration with neighboring systems, access to customers as well as the ability to influence standards and norms in ways that are favorable to your solution. There is no one correct way – we have seen both industry consortiums and individual players with outstanding solutions on the path to success.

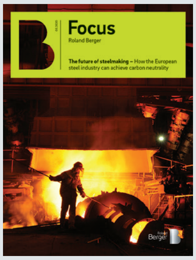
If you need partners, which ones can add the most value?

Partners must be selected carefully – look for strong synergies and common interests. Universities or other research institutes can provide insights from a scientific viewpoint, for instance, and may help develop new innovations; investors can make connections and provide valuable capital. We recommend taking the time to carefully evaluate whom you want to collaborate with. Industry associations can be a good starting point to find and get to know potential partners.

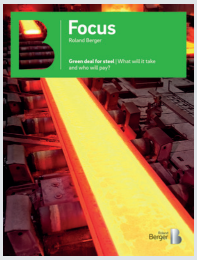
Discover more

From governments and large multinationals to ambitious start-ups, Roland Berger has worked with a variety of players in the emerging hydrogen economy. During these projects, we have gained an in-depth understanding of market dynamics, key technologies and other important factors, which we have compiled in a series of studies. This joint paper with VDMA now adds the perspective of manufacturing technologies to that series. If you would like to learn more about the development of the hydrogen economy, and how to enhance your role in it, please don't hesitate to get in touch. We look forward to hearing from you.

Hydrogen transportation
The key to unlocking the clean hydrogen economy



The future of steelmaking
How the European steel industry can achieve carbon neutrality

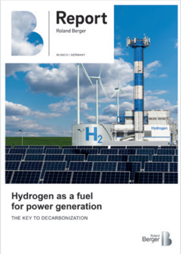


Green deal for steel
What will it take and who will pay?

Innovate and industrialize
How Europe's offshore wind sector can maintain market leadership and meet the continent's energy goals

Hydrogen
A future fuel for aviation?

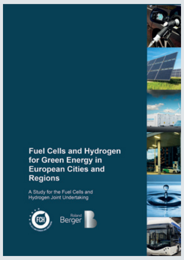
Next Generation Manufacturing gets ready to roll
After a long, slow ride, manufacturing is about to get exciting again



Hydrogen as a fuel for power generation
The key to decarbonization

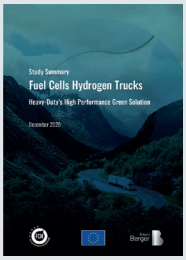
Hydrogen Valleys
Insights into the emerging hydrogen economies around the world

Potenziale der Wasserstoff- und Brennstoffzellen-Industrie in Baden-Württemberg



Fuel Cells and Hydrogen for Green Energy in European Cities and Regions

The potential for green hydrogen in the GCC region



Fuel Cells Hydrogen Trucks
Heavy-Duty's High Performance Green Solution

Photos: Roland Berger GmbH

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Photos: Roland Berger GmbH, VDMA

About us

ROLAND BERGER is the only strategy consultancy of European origin with a strong international presence. As an independent firm, solely owned by our partners, we are present in all major markets with 51 offices. Our 2,700 employees are characterized by a unique combination of analytical thinking and empathetic attitude. Driven by our values of entrepreneurship, excellence and empathy, we believe that business and society need a new, sustainable paradigm that looks at the entire value cycle. By working in cross-competence teams across all relevant industries and business functions, Roland Berger offers the best expertise worldwide to successfully master the profound challenges of our time, today and tomorrow.

The **VDMA** represents around 3,500 German and European mechanical and plantengineering companies. The industry stands for innovation, export orientation and medium-sized businesses. The companies employ around four million people in Europe, more than one million of them in Germany alone. The mechanical and plant engineering sector has a European sales volume of around 800 billion euros. In the entire processing industry, it contributes the highest share to the European gross domestic product with a value added of around 270 billion euros. VDMA Power-to-X for Applications is a cross-industry platform for exchange, communication, and cooperation in the P2X community. It involves all important stakeholders, from the development of manufacturing processes through the production of synthetic fuels and raw materials using power-to-X technologies to the end customer. With its activities, it promotes a holistic and technology-open approach to the transformation of energy systems, and rises public awareness of environmentally friendly energy use and mobility.

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