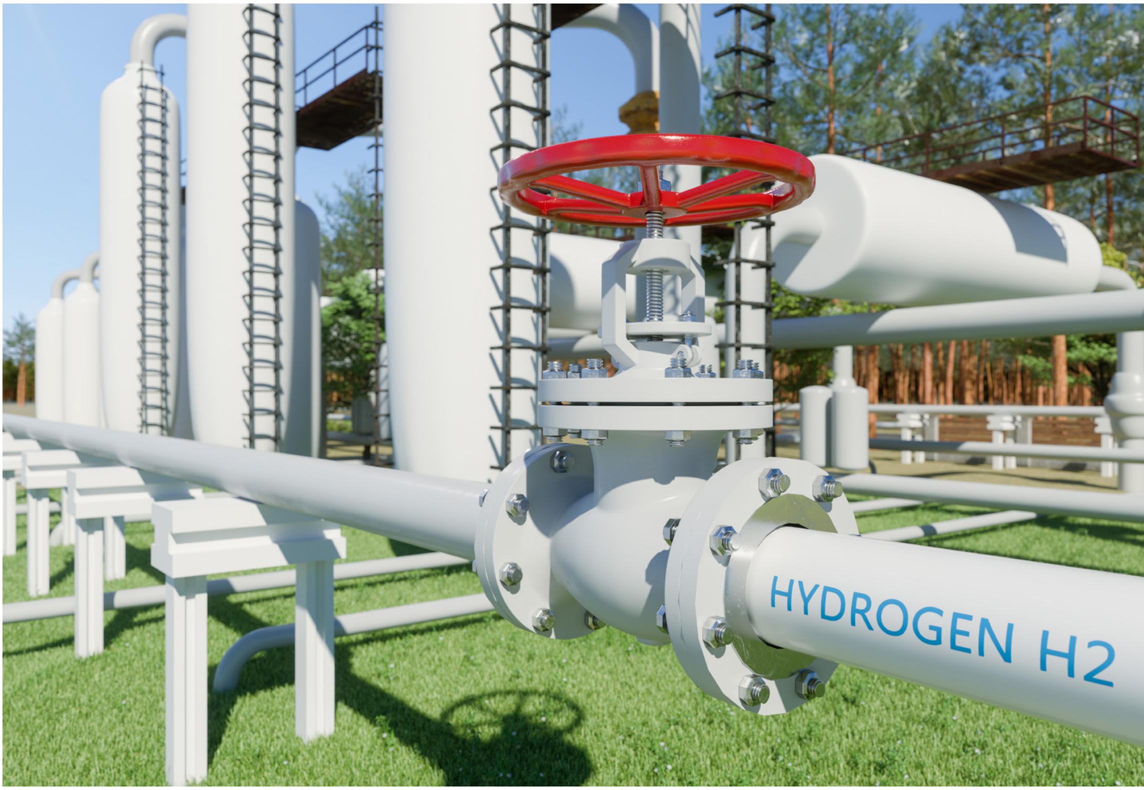
HYDROGEN COMPRESSION

BOOSTING THE HYDROGEN ECONOMY



EFRC
EUROPEAN FORUM for RECIPROCATING COMPRESSORS

NOVEMBER 2022

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INTRODUCTION

The European hydrogen economy is being shaped at this very moment. On a regular basis, governmental bodies and industrial parties or consortia present their plans for large scale hydrogen production sites, hydrogen import, hydrogen distribution networks and hydrogen storage. Press releases of end user intentions to investigate hydrogen as their preferred future energy source appear frequently. The ambitions of the European Commission stress that many more of these projects and ambitions are required to reach our climate goals and secure our energy supply. These ambitions and the growing demand boost the complete supply chain for the hydrogen economy, including the hydrogen compressor industry.

With years of experience in gas transport, storage and the petrochemical industry, the compressor manufacturers and supporting industrial parties have made significant investments to keep up the pace with the increasing demand on hydrogen compressors. The hydrogen molecule is not new to the industry, even up to relatively high percentages in a gas stream. However, for compression of nearly pure hydrogen, this situation is different.

The European Forum for Reciprocating Compressors (EFRC) presents this document with the purpose of providing the reader with the latest insights in compression technology for pure hydrogen (>95%). An objective overview of advantages and disadvantages of these technologies is provided to enable different applications that are foreseen in the hydrogen economy. It aims to showcase existing hydrogen compressor technology, the challenges ahead and the ongoing developments to support the transition towards a green hydrogen economy.
EFRC supports end users, manufacturers and scientists working in the field of reciprocating compressors in terms of technology and innovation, exchange of experience, formation and enforcement of precompetitive research, standards and guidelines, training and student exchange. Its geographical reach has grown from Central Europe to entire Europe and recently to the US. EFRC has conducted literature surveys, interviews and data processing to identify the status and challenges for compression in the hydrogen economy. This resulted in a detailed technical report for EFRC members and this white paper for the general audience.

HYDROGEN IN OUR FUTURE

Solar and wind energy have a significant potential in Europe, that is currently under-utilised. This potential is of great importance for the decarbonization strategies of European countries, and is now increasingly considered strategically important for future energy security. To exploit this potential, large volumes of variable wind and solar power will have to be integrated into the energy systems in European countries. The European Commission in their Green Deal see a significant role of hydrogen next to electricity in our future energy system (European Commission, 2020).

The combined potential capacities of renewable energy from sun and wind is expected to be much larger than what can be directly absorbed as electricity in the energy systems (Kakoulaki, et al., 2021). Using renewable electricity for water electrolysis, capturing wind and solar energy in hydrogen, provides an additional route to incorporate much larger amounts of variable renewable energy into the energy systems and markets. Hydrogen is a very versatile energy carrier that can be used as a gaseous fuel in various applications that are difficult to electrify, but also as feedstock and industrial gas in industry, a reactive agent for green steel production and for the production of electricity (see Figure 1). Moreover, hydrogen can be stored and transported from parts of the world with an abundance of renewables to areas where renewables are insufficiently available. In addition, electrolysis-based plants can represent a great source of flexibility on the demand side in supporting controlled integration of variable electricity supply into the electrical grid.

Hydrogen has been in our economy for a long time. Hydrogen compression has been performed in the petrochemical industry for decades and dedicated (and re-used) hydrogen transport pipelines are operational in Europe. The envisioned volumes of hydrogen (and related molecules like ammonia or methanol), as well as the number of applications for end use are expected to grow significantly over the next years (Council, 2022).

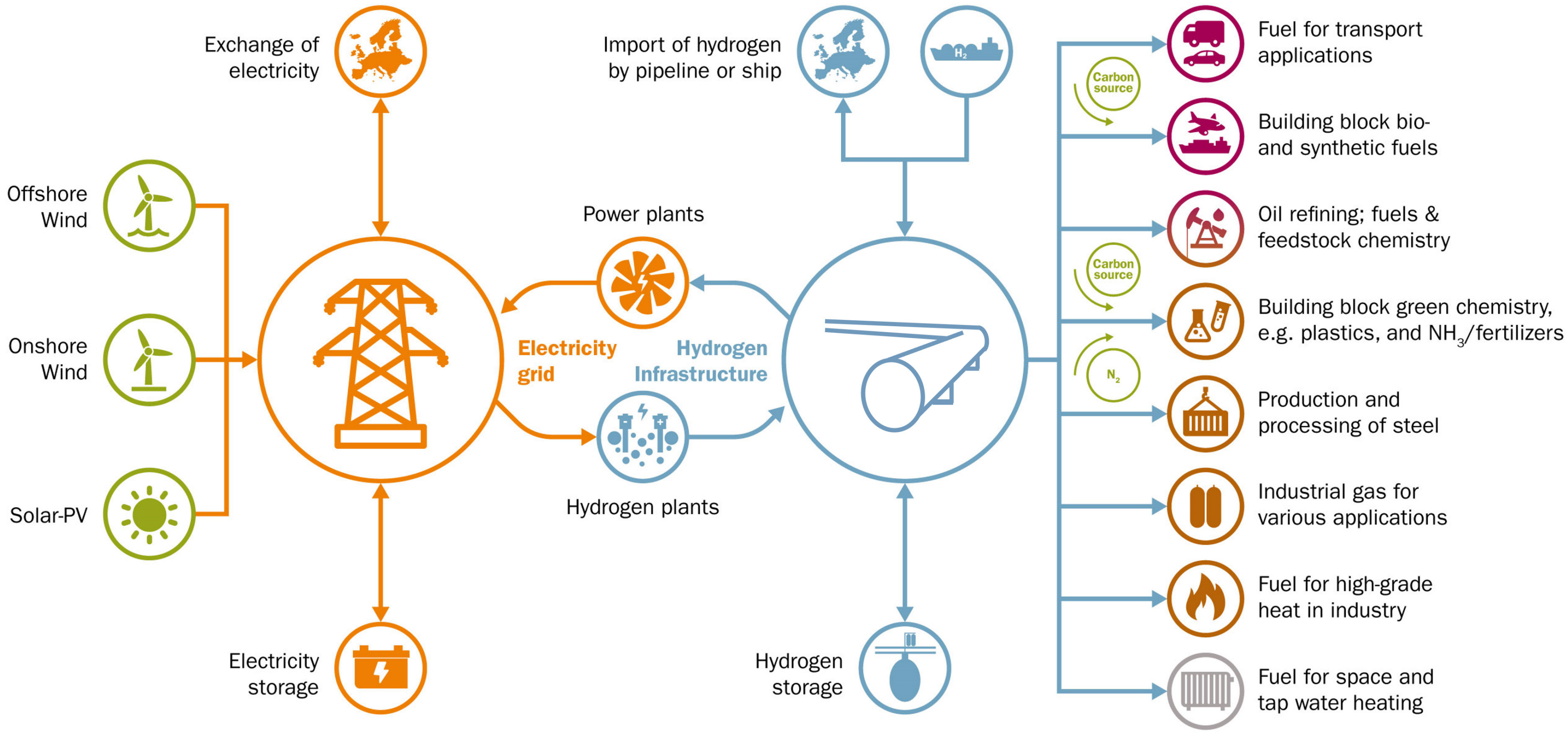


Figure 1. The roles of hydrogen and electricity in our future energy system.

HYDROGEN COMPRESSION

Although the hydrogen economy of the future is still being defined, it is evident that compression will be required at different applications and scales (see Figure 2). Over the past centuries several types of compressors have been developed, from the renowned mechanical compressors (such as reciprocating compressors and centrifugal compressors), to less frequently seen non-mechanical compressors like electrochemical compressors. Each compressor type has its own specific design, with its specific advantages and drawbacks.

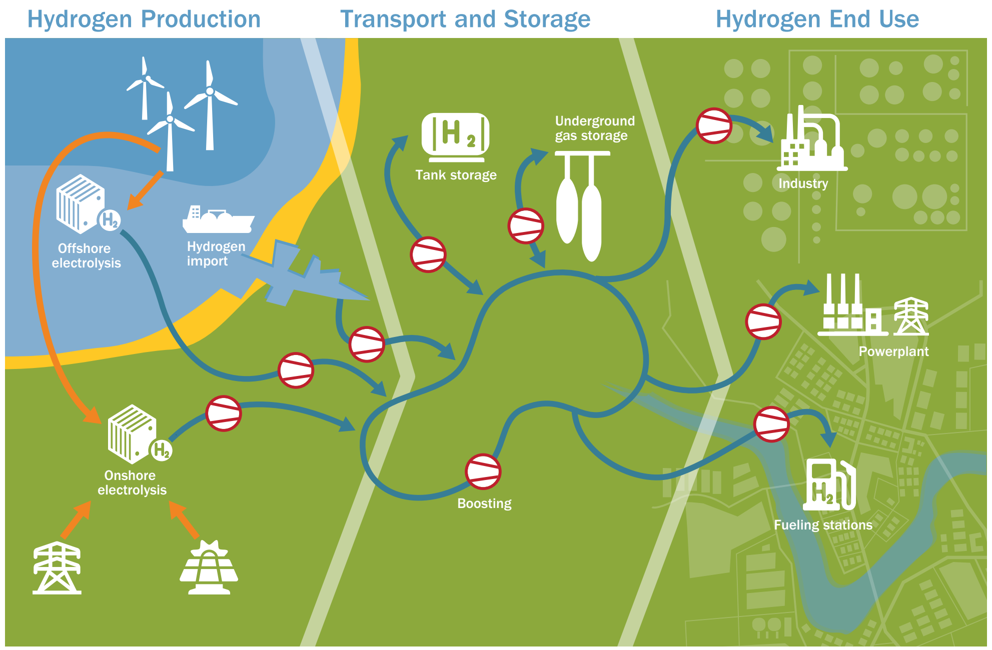


Figure 2. Typical applications where compression will be required in our future hydrogen economy, based on a hydrogen distribution grid.

HYDROGEN APPLICATIONS

The selection of compressor will depend heavily on the application requirements, as well as available space and total costs of ownership. Generally speaking, four roles for compressors are identified:

1. Injection into the transport grid

This application comprehends the boosting of hydrogen to approximately 30 to 80 bar, as is currently foreseen for the European Hydrogen Backbone (van Rossum, et al., 2022). In the early stage of (inter) national hydrogen distribution networks, the pressure is expected to be built up by the injection compressors only, which are located near electrolysers. In case of increased exploitation of these networks, larger pressure losses can be foreseen that may bring the need for booster compressors. Compressors will also be required at injection stations that blend hydrogen into existing natural gas streams.

2. Storage

Hydrogen storage is an important component in the hydrogen value chain to assure security of supply at periods of lower production. Tank storage sites are expected at different scales at several locations, both onshore and offshore. On a larger scale, salt caverns are currently prepared as underground hydrogen storage sites, to allow for larger capacities on longer time scales. Typical discharge pressures are foreseen to go up to 200 bara for salt caverns, whereas storage tanks may even be operated at higher discharge pressures.

3. Fueling stations

The discharge pressures, flow rates and number of starts and stops make the compressors used at fueling stations a topic on its own. Discharge (fueling) pressures are currently 350 bar for large vehicles, to 700 bar for personal vehicles. Although the use of hydrogen in passenger cars may be limited, the long distance heavy duty transport is a likely candidate to use hydrogen or a synthetic fuel as an energy source. Fueling station compressors are different from other storage compressors because of the requirements on high hydrogen purity, relatively small capacity and intermittent operation.

4. End user demand

Whether it is hydrogen use for high temperature heating in industrial processes, for feedstock in chemical processes or the use in power generation, each end user will have its specific requirements to the capacity, pressures, temperature, purity etc. of the hydrogen it will process. Tailor made compression solutions will therefore be required at the end users. End users that are located close to a hydrogen distribution grid may not require compression, in case the grid pressure is always higher than the required pressure.

COMPRESSORS FOR HYDROGEN APPLICATIONS

The major compression technologies used for hydrogen applications are (see Figure 3);

- Positive displacement (*reciprocating piston, diaphragm/hydraulic/ionic, and screw compressors*), where a certain volume of gas is captured, compressed by a gradual reduction within a control volume and discharged at elevated pressure.
- Dynamic (*centrifugal compressors*), where kinetic energy (impeller velocity) is added to the incoming gas stream and, subsequently, converted to into static energy (pressure).
- Non-mechanical compression, using different principles such as electrochemistry or via adsorption (or absorption) of hydrogen into porous materials

Different aspects of compressors determine which type is best applicable for the specific application or role. Not only shall the attainable **discharge pressure** of the machine be higher or equal to the desired pressure, also the **required capacity** shall be transported by one or multiple machines. If intermittent operation of the machine is expected, then **capacity control** and the impact of the **number of starts and stops** becomes more relevant. Some compressors operate only for a small range of **gas composition** changes, whereas others may not be able to meet the hydrogen **purity** requirements for certain applications. More general considerations, like **CAPEX, OPEX, efficiency, MTBF, technology maturity** and **pulsations, vibrations and noise** are also aspects used to determine the most suitable compression type for the specific application.

The interplay between capacity (e.g. flowrate) and head (differential pressure that is introduced on the gas) of a compressor provides an essential basis of comparison in between different compression technologies and can be seen in Figure 4. The coverage of the map, for the different compressor types, is comparable to generic maps that are found in reference text books on compressors. It shall be noted that the dots in the

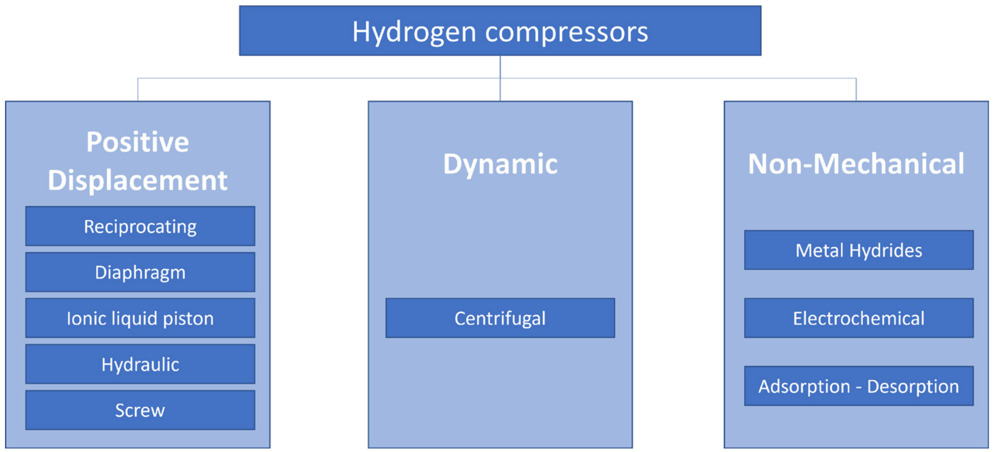


Figure 3. *Types of compressors.*

maps are actual, industrial reference cases, for compression of pure hydrogen (MW<2.5). The reciprocating compressors (green dots) span a large range of flows, up to a pressure of around 400 bar and include both lubricated and non-lubricated type. The diaphragm (black), hydraulic (red) and ionic (cyan) compressors extend toward very high pressure (1000 bar), but have a limited capacity. The screw compressors (blue) cover an intermediate range of capacity, but are limited to a discharge pressure of typically 30 bar. Centrifugal compressors are absent in this plot, as no industrial references were found on pure hydrogen (active field of development in industry).

In the next sections, an overview of a selected number of compressor types is presented that are either currently seen, or that may become operational at the appropriate scales in the future. It shall be noted that research is done on existing and new compressor types every day, to optimise performance at the required scales.

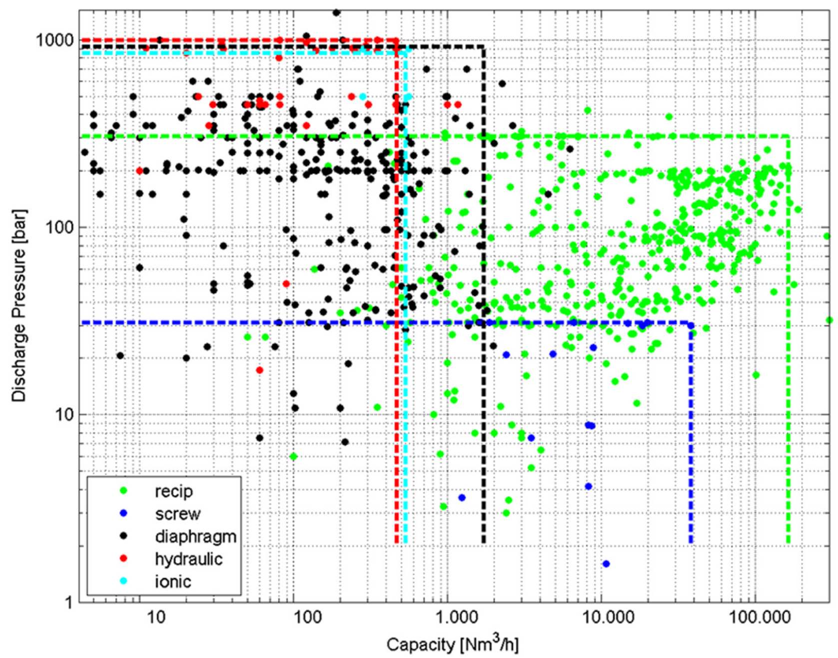


Figure 4. *Compressor map with current industrial references (dots) and performance ranges lines) for pure hydrogen applications. To the author's best knowledge, no pure hydrogen centrifugal compression references are available. Centrifugal compressors for natural gas applications typically operate at the lower right quadrant (high capacity, low to medium discharge pressures).*

POSITIVE DISPLACEMENT COMPRESSION

Positive displacement compressors have been in use for centuries, including for hydrogen compression, and therefore this technology is considered very mature.
Positive displacement compressors for hydrogen compression come in different configurations:

- reciprocating piston compressors;
- diaphragm, hydraulic and ionic compressors;
- screw compressors.

Positive displacement compressors use a simple and effective operating principle: direct compression by reducing a controlled volume by means of mechanical energy. The control of inflow and outflow is enforced by opening and closing valves (reciprocating and diaphragm compressors) or by mechanically driven geometrical openings (screw compressors). The volume expansion or compression is controlled by a moving reciprocating piston or revolving lobes. In case of diaphragm or hydraulic compressors, the membrane/piston movement is triggered by a hydraulic fluid. Positive displacement compressors provide a large range in capacity. The compressor capacity is directly related to the rotating speed, the number and size of the control volumes (compressor cylinders or screw compressor lobes).

Reciprocating compressors for hydrogen applications

The reciprocating compressor is the most traditional member of the positive displacement family, with the longest track record for hydrogen. It has a large range in capacity (up to 200.000 Nm3/h) and discharge pressure (in excess of 400 bar for lubricated compressors, up to 225 bar for non-lubricated compressors). The typical pressure ratio per stage is 1.6-2.5. In case a large total compression ratio is required, this is achieved by introducing multiple stages, typically up to 4 depending on the process. A schematic overview of the elements in a reciprocating compressor cylinder is presented in Figure 5.

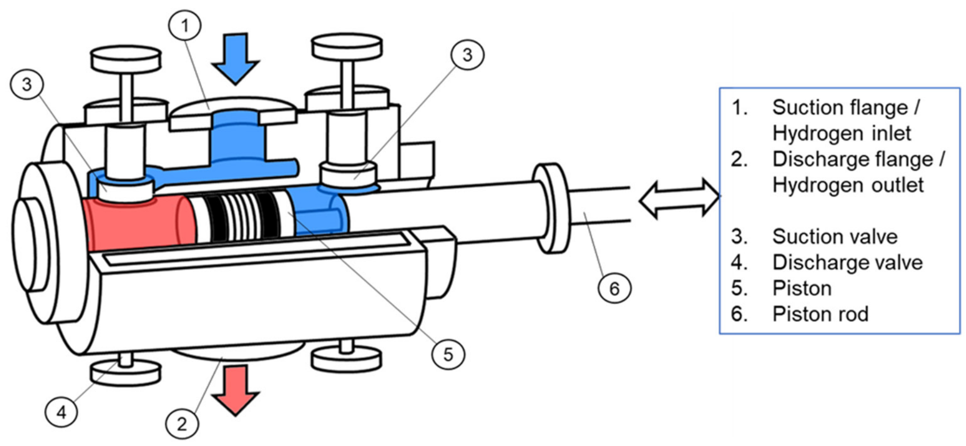


Figure 5. *Schematic overview of a reciprocating compressor cylinder.*

As a consequence of the operating principle, reciprocating compressors have a large ability to adapt to varying process conditions such as flowrate or gas composition changes. The gas composition and corresponding molecular weight of hydrogen gas is very sensitive to even small percentages of contamination.
In terms of capacity control, various proven techniques exist for reciprocating compressors, such as speed control, bypass lines, suction valve throttling, suction valve unloading, clearance pockets and stepless reverse flow capacity control.
The most common (proven) techniques for hydrogen compression are suction valve unloading and stepless reverse flow control. Speed regulation for hydrogen is limited to a minimum of 60-70% of the maximum capacity, to ensure proper operation of the compressor valves at lower speeds.
Reciprocating compressors are relatively insensitive to intermittent operation.
Reciprocating compressors have a robust track record, also in processes with many starts-stops, for example in underground natural gas storage systems.

By the nature of its design, the reciprocating compressor has wearing parts.
Most obvious are the compressor valves, but also pressure packings (piston rod), piston rings and rider rings (wear bands) are subject to wear. With adequate design and operation, replacement of wearing parts can be scheduled within the overall maintenance strategy. Intermittent operation may introduce extra challenges on wearing parts.

Depending on the application, the purity of the hydrogen may be a key aspect.
Many reciprocating compressors use lubricated pistons, thereby increasing the maintenance intervals. The lubrication, however, introduces oil into the hydrogen stream. For applications where high-purity hydrogen is required (e.g. fuel cells and hydrogen liquefaction), non-lubricated reciprocating piston compressors must be used. The absence of lubrication may introduce extra wear and may increase running surface temperatures due to friction.
Non-lube piston compressors have been used successfully up to 350 bar.
Development of pure hydrogen specific wear materials and seal ring designs will push this pressure limit higher in the near future. For current state of the art, higher outlet pressures require lubricated piston compressors which may then require additional equipment in the form of oil separation and filtering.

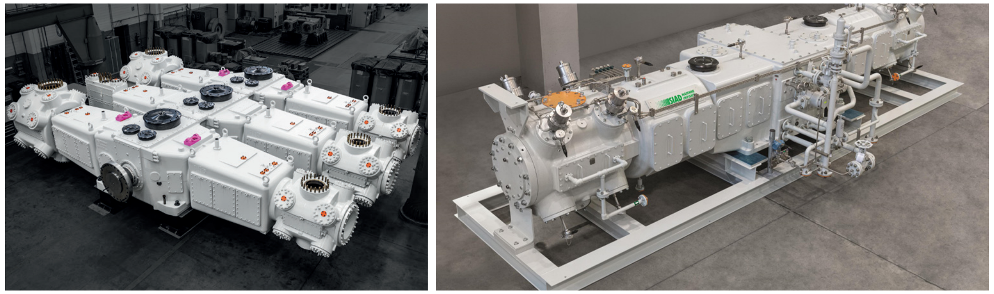


Figure 6. *Examples of two reciprocating hydrogen compressors. Courtesy of Neuman & Esser (left) and SIAD MI (right).*

The intrinsic design of a reciprocating compressor results in an unsteady flow of gas. The pulsating flow will lead to pressure pulsations (a fluctuation around the mean pressure), which may introduce vibration or damages to piping or equipment in the vicinity of the compressor. Typical methods to control harmful effects of pulsations are a good pulsation damper design, restriction orifice plates, adequate pipe routing and robust pipe supports. The risks of harmful noise radiation are typically limited for reciprocating compressors.

Diaphragm compressors, Ionic liquid piston compressors and hydraulic compressors for hydrogen applications

The diaphragm compressors, hydraulic compressors and ionic liquid compressors are typically applied when high-purity hydrogen is to be compressed, to high discharge pressures. The operating principle is similar to that of a reciprocating compressor, but in these machines hydraulic oil drives a membrane or a piston. In case of the ionic liquid compressor, the hydrogen is compressed and expanded by pumping the ionic liquid in and out of the compression chamber volume. The ionic liquid has a low solubility which eliminates the necessity of separation material between the hydrogen and the liquid (membrane or piston), which also increases cooling capacity and efficiency. Schematic overviews of the elements in these compressor cylinders are presented in Figure 7. Examples of the respective compressors are presented in Figure 8.

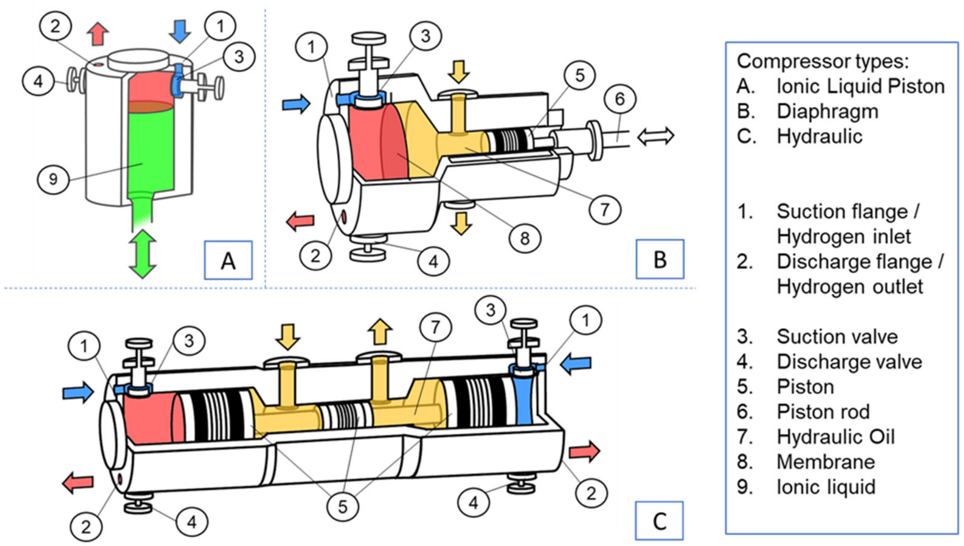


Figure 7. Schematic overviews of the principles behind a hydraulic piston compressor, an ionic liquid compressor and a diaphragm compressor.

The key design feature for diaphragm compressors is the hermetic sealing of the process gas from the lubricated parts. For diaphragm compressors, there is virtually no gas leakage across the membrane sealings, which allows for efficient compression up to very high pressures. For hydraulic compressors, the low running speed and the distance piece between the gas side and the hydraulic side, ensure very clean hydrogen. For ionic compressors, fractions of ionic liquid may carry over into the hydrogen flow; hence an outlet separation unit is required.

The capacity of these compressors is generally lower than the capacity of reciprocating compressors. This is caused by the limited swept volumes (diaphragm, ionic) and the low running speed (hydraulic). In (pure) hydrogen service, reported capacities range up to 1000 Nm3/h, with discharge pressures ranging up to 1000 bar.

Due to the minimal clearances, the favorable cooling capacity and higher allowed discharge temperatures for diaphragm compressors, the pressure ratio per stage in diaphragm compressors is generally higher (2.5-5.5) than for reciprocating compressors. This enables a design with less stages. Hydraulic compressors are generally run at low running speeds, to maintain integrity of piston seals and hydraulic seals. Thus, the capacity and efficiency is generally less favorable than for the diaphragm compressor.

The maturity of these compressors is considered high, with many examples running in hydrogen compression systems (in particular for the mobility sector). These compressors have wearing parts. The membranes, valves, sealings and packings shall be periodically replaced. Careful operation is required, in particular in intermittent service to ensure optimum reliability of the wearing parts. A typical replacement of a membrane (diaphragm compressor) is relatively time-consuming and expensive, compared to for example replacement of parts in hydraulic compressors.

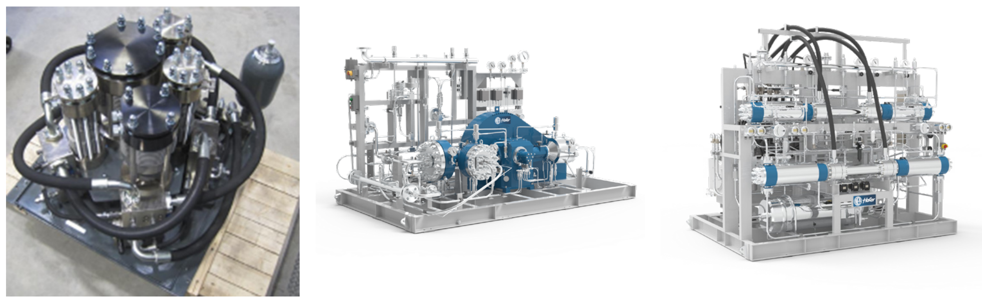


Figure 8. Examples of an ionic liquid compressor (left), a diaphragm compressor (middle) and a hydraulic piston compressor (right). Courtesy of Neuman & Esser for the diaphragm and hydraulic piston compressor examples.

Screw compression for hydrogen applications

Screw compressors are rotary type positive displacement compressors. The initial dry screw compressor design by Alf Lysholm dates back to 1930s (Lysholm, 1941). Since then, screw compressors found traction in applications where large capacities are required with small footprints but limited discharge pressures, e.g. fuel gas boosting of gas turbines, vapor recovery and refrigeration applications (Hanlon, 2001).

Similar to other positive displacement compressors, screw compressors rely on a gradually reduced compression chamber for pressurization. Unlike for the compressors described above, the compression chamber is formed by the interlocked lobes of male and female screws (sometimes sealed with oil) and compression is realised by the continuous rotation of the two lobes onto each other. The inlet and outlet ports of a screw compressor is open to suction and discharge lines respectively. Hence, the pressurization within the rotating lobes need to be carefully designed to achieve suitable discharge pressure with the gas before discharging into the process piping.
A schematic overview of the screw compressor is presented in Figure 9.

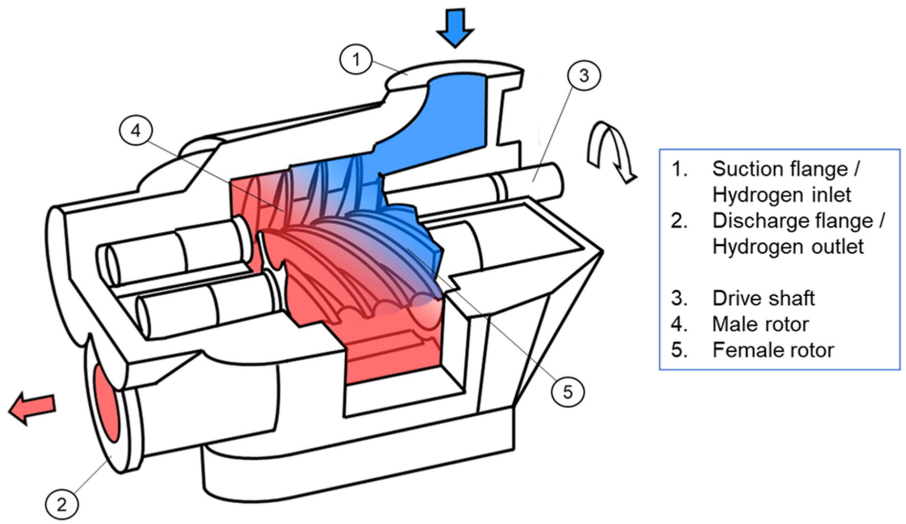


Figure 9*. Schematic overview of a screw compressor.*

Screw compressors operate at higher capacities than their reciprocating counterparts but fall short of surpassing dynamic compressors. The rotor sizes and lobe profiles define the swept volume and, hence, the maximum capacity of a screw compressor. The capacity control of a screw compressor can be achieved robustly in a variety of ways, e.g. variable speed control, internal spillback via slide valves, recycling in the process. Similar to capacity control, variable pressure operation can be realised efficiently by adjusting internal volume ratios.

Screw compressors operate up to discharge pressures of 30 bar. This limitation is caused by leakages inside the compressor (especially for low molecular weight gases like hydrogen), allowable discharge temperatures, and loads on the screw compressor shaft (Wennemar, 2009). Due to these limitations, dry gas screw compressors are rarely applied in hydrogen applications where significant pressure ratios are needed (Takao Ohama, 2006). The cooling and sealing benefits, that are inherent in oil or water injected screw compressors, help solve these challenges to a large extent. Oil injected screw compressors are commonly used for pure hydrogen applications with discharge pressures of 30 bar, as seen in Figure 4. Still, the load bearing capacity of the screw compressor shaft remains the bottleneck in achieving higher discharge pressures with oil injected screw compressors. Reaching higher discharge pressures is a research topic in the screw compressor industry (Amano, 2010). Furthermore, the benefits of oil injection comes at the expense of reduced capacities and require of oil separation units to maintain gas purity for downstream processes.

Screw compressors, similar to centrifugal compressors, contain a limited set of wearing parts, which allows for higher reliability and availability compared to reciprocating compressors.

CENTRIFUGAL COMPRESSION FOR HYDROGEN APPLICATIONS

Centrifugal compressors are a mature compression technology in hydrogen-rich applications, such as recycle gas compressors in refinery applications (Barton, 2021). However, centrifugal compressors that serve pure hydrogen applications (with comparable pressure ratios to natural gas applications) are in development phase.
Figure 11 presents the compression process, where gas is taken in through the inlet casing and into the eye of the impeller. The rotation of the impeller serves to increase the (kinetic) energy level of the fluid by whirling it outwards. Subsequently, the flow passes through the diffuser (or scroll) and the imparted kinetic energy is converted into pressure. This latter process can be enhanced by introducing a row of radial diffuser vanes.

Centrifugal compressors offer high capacities, yet only perform optimally in case the range of operating conditions is small and well defined. The flow range of a centrifugal compressor is defined by aerodynamic effects at the lower end (surge) and the choke point of the gas (reaching sonic velocity) at the higher end. Centrifugal compressors are designed to operate at their highest efficiency at a given design condition, but the operating efficiency can change significantly at off-design conditions. Typical polytropic efficiencies range from 70 to 90 percent (Gallick, 2006) and the loss of efficiency is strongly related to internal friction and incidence losses (especially at off-design conditions). Similar to reciprocating compressors, capacity control can be achieved with speed variation (with a variable speed drive), with the operation of a recycle line, or with the use of inlet guide vanes that help adjust the centrifugal compressor to changes in inlet flowrate conditions.

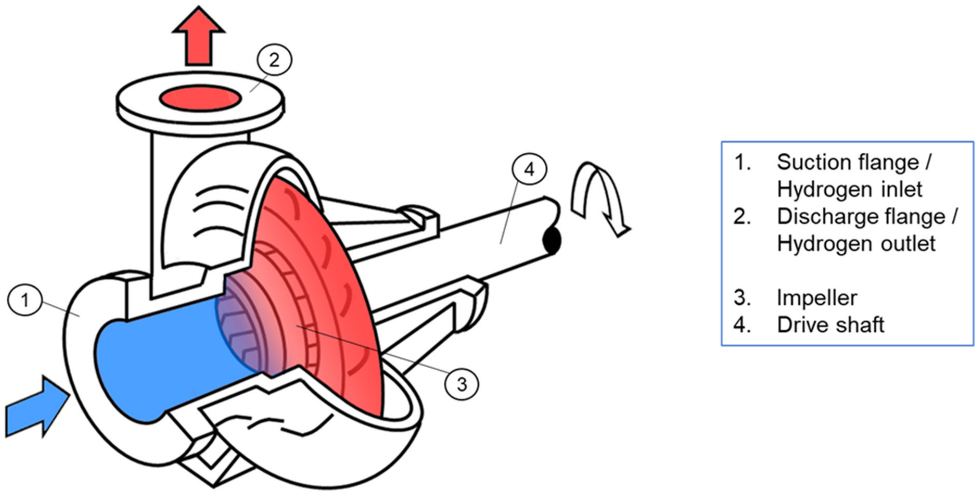


Figure 10. *Schematic overview of a centrifugal compressor stage.*

Centrifugal compressors are currently limited to low pressure ratios per stage for hydrogen applications. The head that a centrifugal compressor generates is highly dependent on the impeller rotational speed (i.e. the amount of imparted kinetic energy) and the number of subsequent stages of compression. Compared to higher molecular weight gases (e.g. methane), low molecular weight gases (e.g. hydrogen) require higher impeller rotational speeds in order to realise comparable pressure ratios per stage. Pressure ratios per stage of 1.1 are typical for hydrogen applications even when high tip speeds (around 350 m/s) are used (Brun, 2021).

Although the high speed of sound of hydrogen allows an increase in impeller speed, commonly used impeller materials are not able to withstand the high centrifugal forces generated due to required high impeller tip speeds. Therefore, mechanical considerations currently limit the compression of hydrogen to low pressure ratios per stage.
Considering the fact that number of stages in a casing is limited due to rotor dynamic stability, centrifugal compressors have traditionally been limited to lower pressure ratios for hydrogen applications. Overcoming these identified mechanical limitations and enabling higher pressure ratio compression of hydrogen lies at the heart of the current research and development focus of the centrifugal compressor industry.

Furthermore, compared to positive displacement machines, the compression process in a centrifugal compressor is more continuous by nature. Although, it is less likely to have vibration and noise problems in the attached pipe systems of a centrifugal compressor, any hydrogen compression system design should account for the expected higher hydrogen flow velocities and its impact on flow induced pulsations.

NON-MECHANICAL COMPRESSION FOR HYDROGEN APPLICATIONS

Hydrogen can be compressed in non-mechanical ways by exploiting different principles, e.g. electrochemically or via adsorption (or absorption) of hydrogen into porous materials. Compared to conventional compressors, key advantages of non-mechanical compressors are the absence of moving parts (no risk of vibrations, less wear of materials, no use of lubricants) and the ability to maintain and even improve the hydrogen purity during compression (up to 99.999%). There are still challenges to bring the technology readiness level (TRL) and scale on par with conventional compressors. Non-mechanical hydrogen compressors can be grouped in the following three categories: metal hydrides, electrochemical, and adsorption-desorption compressors. Their working principles are presented in Figure 10, and typical characteristics are summarized in Table 1 and in the sections below, based in input found in.

Characteristics	Metal hydrides	Electrochemical	Adsorption-desorption
Compression Rate (Nm3 h-1)	<10 Batch process	<10 Continuous process	No data Batch process
Outlet pressure (bar)	200	850	No data
Efficiency (%)	<10	~60	No data
Energy consumption (kWh kg-1)	10	4-8	No data
TRL	~6	~7	3
Applications	– Refueling stations	– Refueling stations	– Refueling stations
Advantages	– No moving parts – Thermally driven – Low footprint – High purity H2 production	– No moving parts – High compression efficiency – Low footprint – High purity H2 production	– No moving parts – Low costs of adsorbents – Low heat of adsorption
Disadvantages	– High desorption temperature – High heat of desorption – Limited heat transfer – High weight	– Difficulty in manufacturing of high-pressure cells – Difficulty in water management – High electrical cell resistance – Low efficiency at high outlet pressure	– Low thermal conductivity of adsorbents – Difficulty in thermal management – Low-temperature operation (77 K)

Table 1. Characteristics of non-mechanical compressor types, as found in (Sdanghi, et al., 2020), (Hyet, 2020), (Bellosta von Colbe, et al., 2019).

Metal hydride compressors

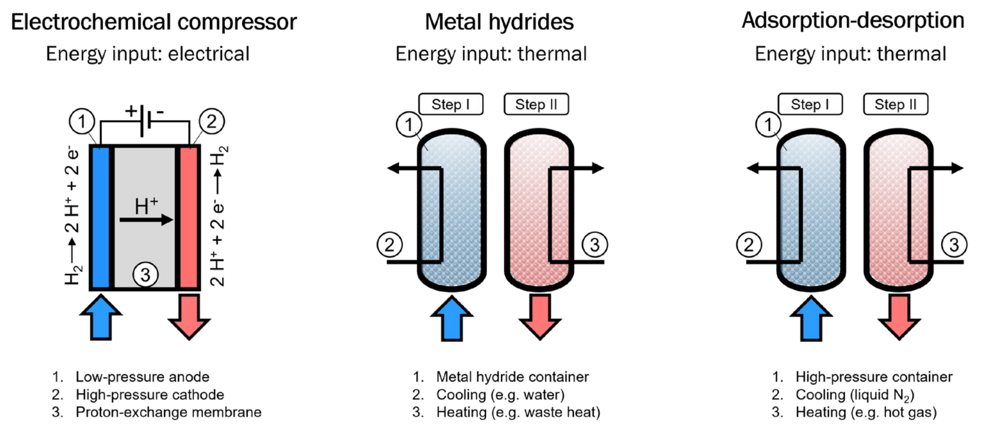
Metal hydride compressors exploit the property of some metals, alloys, and intermetallic compounds to absorb and desorb hydrogen forming hydrides. The working principle is a thermally-driven chemisorption process with reversible adsorption-desorption kinetics: hydrogen absorption occurs at low temperature, and lasts until the equilibrium pressure is equal to the feed pressure. When the metal hydride is heated, hydrogen can be desorbed and released at a higher pressure. Since the compression requires only thermal energy, this type of compressors can be advantageous in applications where waste heat is available. Metal hydride compressors are nowadays commercially available for pressures up to 200 bar, while compressors at higher outlet pressure are under development (Sdanghi, et al., 2019).

Metal hydride compressors suffer from slow adsorption/desorption kinetics in some cases, and require efficient cooling. Moreover, these compressors have relatively high specific energy consumption due to the low thermal conductivity of the absorbent materials and the high heat of adsorption.

Electrochemical compressors

Electrochemical compressors are based on the same principle of proton-exchange membrane (PEM) fuel cells: an electric current is applied to transport hydrogen through a proton-exchange membrane from the (low-pressure) anode side to the (high-pressure) cathode side. Unlike PEM fuel cells, the cathode side is blocked (i.e. no air is fed), and water is not a reaction product. Instead, water is fed (as water vapor) along with the hydrogen feed, or on the cathode side to maintain the membrane wet and ensure stable performance.

One of the main advantages of electrochemical compressors is low energy requirements, since they ensure isothermal compression. In principle, very high discharge pressures can be reached (up to 1000 barg, or up to 875 barg in a single stage (Hyet, 2020)), although the efficiency decreases considerably at high pressure due to back-transport of hydrogen through the membrane. In practice, the main applications are limited to discharge pressures up to 100 barg. Electrochemical compressors with capacity



in the range of 120-600 kg/day are already available in the market (Hyet, 2020). One of the disadvantages is that the high-pressure hydrogen is wet, and thus a desiccant must be used downstream of the electrochemical compressor to dry the compressed hydrogen (e.g., prior to a subsequent compression stage).

Adsorption-desorption compressors

The working principle behind this class of non-conventional compressors is thermally-driven bonding of hydrogen onto microporous materials, similar to metal hydride compressors. The difference is the operating temperature for adsorption (generally driven at temperatures as low as 77 K, i.e. the temperature of liquid nitrogen) and type of adsorbent used.

The main advantages of this type of non-conventional compressors is low heat of adsorption, and relatively high adsorption capacity, with hydrogen density comparable to liquid hydrogen (70 g/L) can be reached at T=77 K. However, these non-conventional compressors are still in their very early stage of development, and a number of technical challenges still need to be addressed for upscaling (for instance, chemical stability and ageing of the adsorbent).

COMPARISON OF TECHNOLOGIES FOR DIFFERENT APPLICATIONS

HYDROGEN FUELING

Critical aspects for fueling station compressor types are the discharge pressure that can be achieved, as well as the purity of the hydrogen that is discharged by the compressor. Other important selection criteria are the possibility of large numbers of starts and stops and the maturity or reliability of the compressor.

Figure 11. Fueling station for hydrogen. Courtesy of Shell.

The critical aspects, particularly discharge pressure, disqualify the screw compressor and centrifugal compressor types. As the hydrogen purity of key importance, a diaphragm, ionic liquid piston, hydraulic piston or a non-mechanical compressor type are well fit for the purpose. Looking at other aspects such as the required capacity or the maturity of the system technology, the diaphragm compressor, the hydraulic piston compressor and the ionic liquid piston compressor type are currently the most logical, and are therefore the most observed types.

Hydrogen is delivered to fueling stations in different forms, which has a significant impact on the final compressor type.
Often hydrogen is delivered in tube trailer form, where the compressor will deal with varying inlet pressures as the gas volume is gradually reduced in the supply tubes.
Liquid hydrogen delivery has a higher energy density of H2 per delivery load, but when expanded to gas state it has its own limitations on supply pressure and temperature to the final compression unit.

INJECTION TO TRANSPORT PIPELINES (FEED FROM ELECTROLYSERS)

The necessity of compression downstream of electrolysers depends on the type of electrolyser installed. For alkaline stacks, current (conceptual) designs assume that these operate at atmospheric pressure, resulting in the need for compression. For PEM stacks, it is often assumed that they operate at a pressurised mode up to 30 bar, which reduces the need for compression. Research to even higher production pressures has been reported (Hancke, et al., 2022). Hydrogen production at 200 bar appears an economically viable option. However, the techniques are considered to be in development phase, and the overall compromise (cost, scalability, footprint) may not favor this option for future, large-scale application.
Production rates can vary significantly for electrolysers, particularly in case they are off-grid, connected only to wind farms or solar plants. Electrolysers connected to the (onshore) grid, or connected to electrical storage facilities, can deliver a more constant flow of hydrogen, thereby demanding less capacity control and less starts and stops. Depending on the electrolyser type and connected equipment, the gas may contain significant moisture content that requires separation.

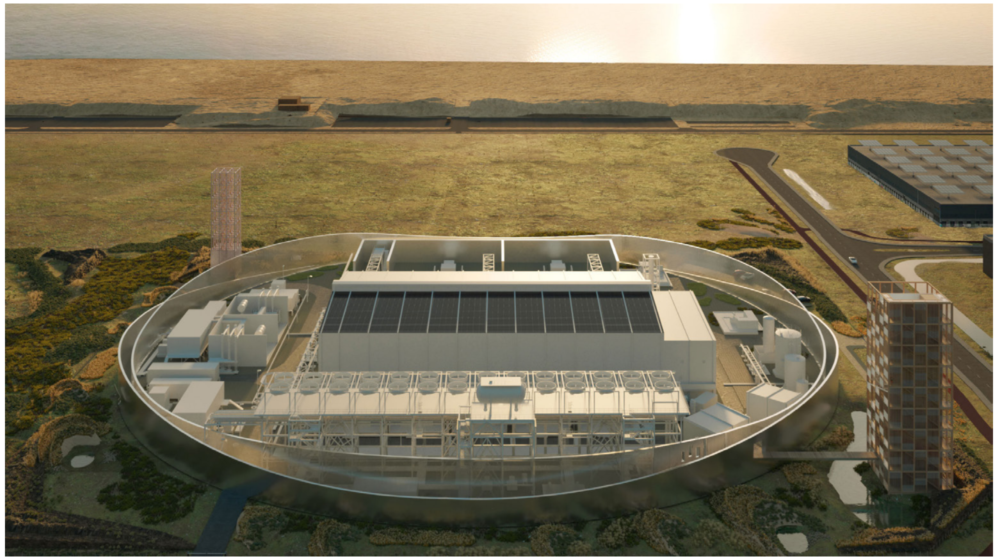


Figure 12. *Holland Hydrogen 1, 200 MW electrolyser with compression to backbone pressure of 55 bar. Courtesy of Shell.*

Compressors that feed the hydrogen into a transportation network will need to compress the hydrogen to a minimum of 30 bar. Temperature and purity are considered important but not critical, and could be treated post compression. As stated above, the capacity control and number of starts and stops depends heavily on the intermittency of the hydrogen production. For offshore hydrogen production, the footprint and dynamic loads induced by the compressor may also be important selection criteria.

For most onshore large scale Alkaline electrolyser systems, reciprocating compressors are currently selected for compression, particularly for their maturity as well as flexibly in capacity control.

UNDERGROUND HYDROGEN STORAGE

In natural gas storage, mode of operation in salt caverns is to have set-points 4-6 times per day. In case of hydrogen storage, the production rates may be intermittent and demand rates (and thereby required storage needs) are not yet well defined.
In case storage flexibility in salt caverns require the same flexibility as for natural gas storage, then the number of starts and stops, as well as capacity control are considered critical aspects for compressor selection. Expected capacities are in range of several 0.2 to 2 million Nm^3/h per facility (assuming similar volumetric performance as natural gas). However, depending on the function of hydrogen storage in the system, the frequency of loading and unloading of the cavern can differ significantly from a traditional natural gas storage

facility, requiring other performance of the compressor as well. Typical expected compressor discharge pressures are between 200 and 250 bar, to exceed the storage pressure and additional pressure losses in the well. The discharge hydrogen purity is not relevant for hydrogen storage compressors, as hydrogen will pick up impurities while stored in caverns (and reservoirs), which require cleaning post withdrawal.

The required discharge pressure disqualifies some of the compressor types such as the screw compressors. As long as the maturity of alternatives is low, reciprocating compressors are considered the most logical candidate for underground hydrogen storage, considering the required capacity, the intermittent operation, required capacity control, in combination with the low relevance of the discharge purity of the hydrogen.

Figure 13. *Underground storage facility for hydrogen in caverns. Courtesy of Gasunie/HyStock.*

END USE (HIGH TEMPERATURE HEAT)

In the petrochemical industry, fuel gases for combustion are most often a mixture of hydrocarbons and hydrogen (e.g. refinery off gas). The percentage of hydrogen is variable, but can amount up to 80%. Burners, designed to operate also at 100% hydrogen are already available and will be a likely candidate to provide high-temperature heat in process installation, based on pure hydrogen supply. For the traditional fuel gases, combustion pressures are typically low (~1 barg). On existing refineries, the fuel gas is typically supplied at a pressure of 2-4 barg. For pure hydrogen, the low volumetric heating value, will demand for higher volume flow rates, to achieve the same heating capacity. This, combined with the higher combustion speed for hydrogen, may demand an increased supply pressure. Still, the expected pressure increase will be relatively limited (probably < 10 bar). An increased pressure may require an updated design of the inlet piping (pressure class, inner diameter).
If a network supply of medium pressure for future hydrogen is available, no additional compression is required. If such a network supply is not available, then additional compression solutions may be required, depending on the hydrogen discharge pressure of the electrolyser. Typically, the requirement of considerable capacity of hydrogen at moderate pressures (with potentially fluctuating composition) favors the application of reciprocating compressors or screw compressors.

Finally, the fuel gas composition may have an impact on the stability of the combustion. Since existing burners already use a fluctuating mix of components, the gas purity is not considered the most critical requirement (probably lubricated compressors are a feasible option for this application).

END USE (POWER STATION)

For boosting the fuel into gas turbines, a moderate pressure is required, not exceeding the typical backbone pressure. In case local hydrogen production at low pressure is used, additional compression may be needed (examples are reported of hydrogen production using electrolysers at atmospheric conditions and 8 bar).
The purity of the gas is not a key aspect, so lubricated compressor solutions are valid. In existing gas turbine applications (natural gas or gas/hydrogen mixture), both reciprocating and screw compressors are used. For the transition to pure hydrogen as combustion fuel, screw compressors remain an attractive candidate, while reciprocating compressors provide a valid alternative with a higher efficiency.

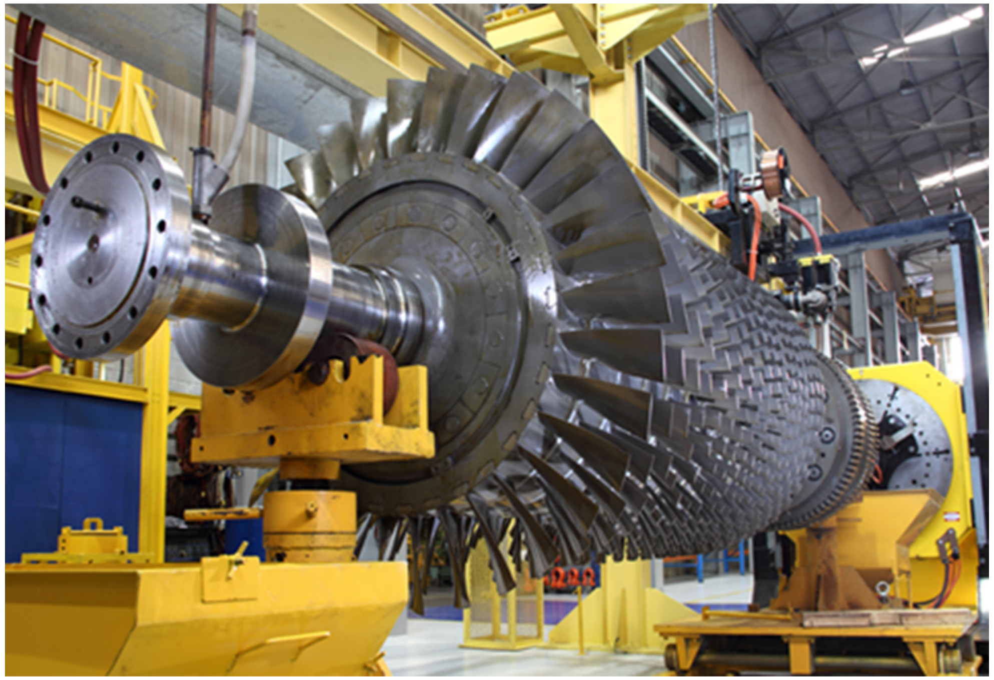


Figure 14. *Typical gas turbine rotor*

END USE (FEEDSTOCK)

For boosting the fuel into feedstock processes, typically a moderate pressure is required, not exceeding the typical backbone pressure. Similar to the use of hydrogen in gas turbines, compression may be required in case hydrogen is produced locally at low discharge pressures. The purity of the gas may be a key aspect, so lubricated compressor solutions are not always valid. The required purity of the hydrogen will be a key criterion for the selection of the compressor type.

The use of hydrogen for ammonia (NH_3) synthesis is a promising application, mainly in ship engine fueling. The requirements for compression for this synthesis process is limited to lower pressures and hydrogen purity is not a key critical aspect. For the synthesis process, depending on the required capacity, reciprocating compressors, screw compressors or centrifugal compressors may be valid options.

Production of liquid green methanol (e-methanol) requires CO and CO_2 (captured from waste or alternative combustion processes) and hydrogen. The volumetric energy density of methanol is approximately three times the energy density of hydrogen gas compressed to 700 bar. The methanol is also stable in liquid form and therefore easy to transport, such that it can be used as a fuel for heavy transport, for example for ships. For the synthesis process, a gas mixture at elevated pressure (50-100 bar at 250 °C) is required. Hydrogen purity is not a key critical aspect. For compression of large capacity of synthetic gas, often centrifugal compressors are used, but reciprocating compressors are equally valid candidates.

Conversion to liquid hydrogen (LH2), for example for transportation over sea, will become increasingly necessary in a global hydrogen economy. Production of liquid hydrogen for global transport requires pre-compression of pure, oil-free, hydrogen to modest 30-50 bar pressure levels. Reciprocating compression using non-lubricated cylinders is the likely compression technique for this application.

CONCLUSIONS

- Hydrogen is considered crucial to the decarbonization strategies globally, and is now considered strategically important for future energy security.
- Efficient and reliable compression is required throughout the hydrogen energy chain.
- For many parts of the hydrogen chain, proven compression techniques are available, for the capacities and operating conditions required. Still, some compression technologies, currently used for natural gas, cannot simply be applied to hydrogen compression. In those cases, the retrofit of compressor equipment may be needed.
- Current compressor performances will have to be stretched to comply with the foreseen demands. This applies for example in a trend to larger capacity, higher pressure and temperature and more intermittent operation.
- New, promising compression technologies are emerging and developing. These will be playing a role in the future hydrogen system, alongside the more traditional compressors.
- Looking at the challenges ahead of us, the following recommendations are put forward:
    - Stay ahead of market demands for hydrogen production, transport and usage. Innovations will be required as the market demands will stretch the traditional compressor performance boundaries, in terms of e.g. pressure, temperature, running speed and intermittency.
    - In parallel, maintain the high safety and reliability standards that this industry is used to. Research and development on the use of materials is needed to enable future operating conditions beyond traditional operating limits. In particular, the potential harmful effects of hydrogen embrittlement shall be considered and mitigated carefully. This research will be a combination of theoretical modelling and systematic testing.
    - Future hybrid compression solutions shall be explored. This could be combination of various conventional compression techniques, such as boosting with a screw compressor and the higher pressure stage with a reciprocating compressor, or a reciprocating compressor boosting a high-pressure diaphragm compressor. Also hybrid solutions with non-mechanical compression may be economically viable, for instance by using metal hydride/electrochemical compressor as pre-compressor stage, upstream of a reciprocating compressor.
    - Consider the compressor as a part of a larger system, and identify how integration between technologies may improve the bigger system. Connections shall be sought with manufacturers of other elements in the hydrogen value chain, like electrolysers, to improve total system performance. For example, a dynamic optimization of a complete hydrogen asset or system may result in different design or selection criteria than when all elements are considered individually.
- The authors foresee a bright future for hydrogen in our sustainable society. Platforms such as the European Forum for Reciprocating Compressors shall continue to demonstrate the robustness and versatility of the available compression techniques and promote future applications and developments.

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