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Review Article

Recent advances in hydrogen compressors for use in large-scale renewable energy integration

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HIGHLIGHTS

- Green hydrogen is a promising link between production and use of renewables.
- Low molecular weight of hydrogen makes compression a crucial step in the green hydrogen chain.
- Various operations in this industry need compressors with output pressures of 20 bar–200 bar.
- Only reciprocating and centrifugal compressors can handle the required capacity in this industry.
- Review of resources proves rapid progress in the design and reliability of hydrogen compressors.

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ABSTRACT

Given global warming, which limits the use of classical energy sources, renewables can provide a solution to the dilemma between environmental protection and sustainable economic growth. In this complex and changing context, green hydrogen can become a promising link between renewable energy sources and end users. However, although hydrogen has a high gravitational energy density, it has a very low volumetric energy density. This challenge requires hydrogen compression at several stages in the supply chain from electrolysis units to conversion, storage, and distribution. Recently, many studies have focused on hydrogen compression technologies. This paper provides an overview of recent advances in large-scale hydrogen compression. First, the role of hydrogen compression in providing clean energy for the future is explored. Then the thermodynamic concept of hydrogen compression is investigated. Gaining a proper understanding of compressor operating conditions in various operations in the large hydrogen industry is the next focus of this paper. Later, the capabilities and limitations of available mechanical compressors for the hydrogen industry, including reciprocation and centrifugal, are summarized. Finally, research gap and recommended new areas in this field are recognized. The presented insightful concepts provide students, experts, researchers, and decision-making working on large-scale hydrogen industry with the state of the art in hydrogen compressors industry.

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Introduction

Energy transition and green hydrogen

With growing concerns on energy security and climate change, sustainable energy transition has attracted worldwide attentions. The global transition of energy generation and consumption from traditional biomass energy system to new renewable energy system seems to be the key to address the problem. If new renewable energy is going to play an effective role maintaining the quality of energy services for end users, it should comprise of two main aspects, including providing enough renewable emission free energy sources as well as having a variety of energy carriers to cover all demands.

Renewable energy sources contributed only 18% of primary energy consumption by 2015. Renewable Energy roadmap (REmap), a global roadmap prepared by the International Renewable Energy Agency (IRENA), suggests that renewables can make up 65% or more of total final energy consumption [Fig. 1] [1].

As discussed by Moriarty [2], the main forms of renewable energy (RE) used today are biomass energy, hydroelectricity, wind energy, solar energy, and geothermal energy. Along energy conservation measures, the transition to a reliable, affordable, and sustainable energy system requires using different energy carriers while decreasing dependence on fossil energy in the longer term [Fig. 2].

Solar and wind energy comprise a major share in renewable energy generation by 2050 and their corresponding generated energy is mostly in the form of electricity. Hence, electricity includes nearly half of the future energy carrier. In this condition, the energy transition needs to overcome five major challenges [3]. 1) More use of variable renewable energy in the electricity sector unbalances supply and demand; 2) Global and local energy infrastructure needs a fundamental transformation to ensure supply security; 3) Buffering the energy system through other fossil fuels will not be enough to ensure the smooth operation of the system; 4) Some end-use energy can hardly be supplied via batteries, especially in transportation; 5) Renewable energy sources cannot replace all fossil fuel uses.

Recently, the unique properties of hydrogen have made it a promising solution to overcome these challenges in the energy system. Hydrogen alone can facilitate the storage of large amounts of energy to balance long periods of poor wind and

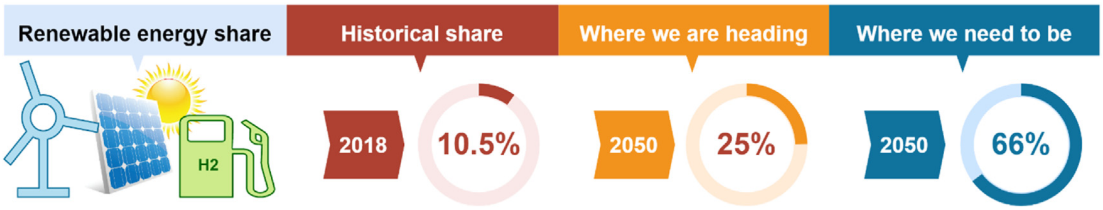

Fig. 1 – Renewables in the world's energy mix: Six-fold increase needed [1].

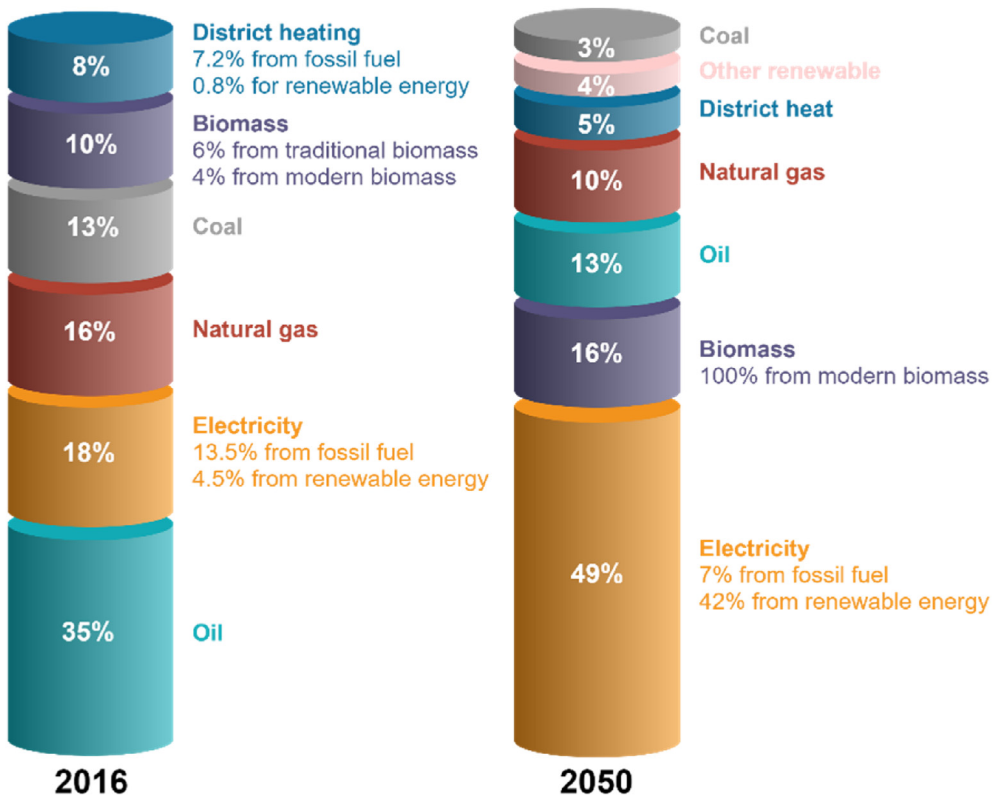

Fig. 2 – Breakdown of total final energy consumption by energy carrier in 2016 and REmap target by 2050 [2].

solar power supply and seasonal fluctuations [4]. Green hydrogen from renewables can be generated through a variety of methods, most of which use renewable electricity to split water into hydrogen and oxygen in the electrolyzer. To achieve emission free targets, global hydrogen production needs to rise from about 60 million tons a year to 500–700 million tons by mid-century [5]. Coupling hydrogen production with renewables is a viable path to achieve this goal. Fig. 3 shows the integration of variable renewable energy by means of hydrogen.

The role of hydrogen compressors in large scale green hydrogen industry

As seen in Fig. 4, hydrogen can become an important link between renewable energy and chemical energy carriers. A "Hydrogen Economy" is projected as the ultimate solution for energy and the environment; however, a major challenge need to be addressed properly. Although hydrogen is very heavy (about three times that of gasoline), it has very little energy in terms of volume (liquid hydrogen is about four times less than gasoline) [6]. Hydrogen has the lowest volumetric energy density between common energy carriers [Table 1].

As Table 1 shows, at standard conditions, the volumetric energy of Natural Gas is 36.4 while for hydrogen is 10.05, or at a higher pressure of 200 bar, compressed Natural Gas (CNG) has around 7000 MJ/m^3 energy while the energy level of H_2 is 1825 MJ/m^3. This makes hydrogen storage a challenge.

To overcome this challenge, three strategic pathways solutions are suggested [Fig. 4].

- The first pathway focuses on gaseous hydrogen storage, including three approaches: 1) High pressure (up to 700 bar) compressed hydrogen storage (CH_2); 2) High pressure (up to 350 bar) and cooled (to −196 °C) Cryo-compressed hydrogen, 3) Large scale hydrogen storage using geological storage, spherical pressure vessels, and underground pipe storage (up to 200 bar).
- The second route is based on storage of hydrogen by converting it to liquid through cooling to −235 °C at a pressure

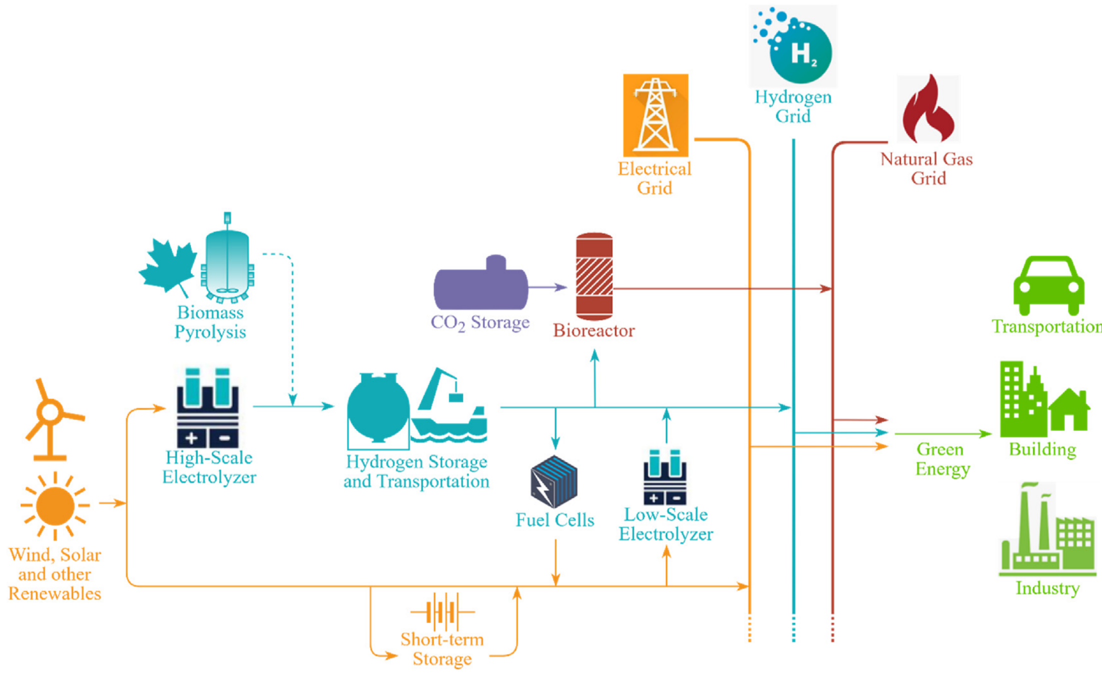

Fig. 3 – The integration of variable renewable energy.

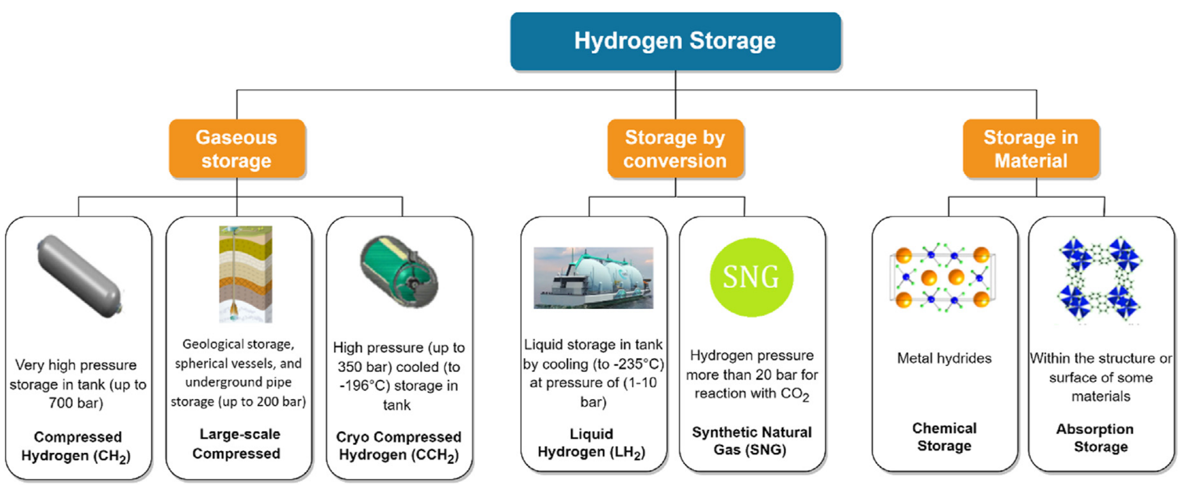

Fig. 4 – Hydrogen storage solutions.

of 1–10 bar, or to Synthetic Natural Gas (SNG) which needs hydrogen compression to 20 bar.

- And the third pathway focuses on materials-based hydrogen storage technologies, including chemical and absorption hydrogen storage in materials [7].

Since storage in the material are now only available for low volume storage and still in research level, it cannot be counted as solution for large scale hydrogen production. For all other available options in pathways 1 and 2, a stage of pressure increase using a compressor is an inseparable part of hydrogen storage.

The need for a suitable and reliable compressor in the hydrogen industry is greater, more than ever before, given that this equipment accounts for a large Capital Expenditure (CAPEX) in a hydrogen chain [8]. In addition, improvement in several key points of hydrogen compressors including size, efficiency, and reliability brings about significant decreases in dispensed hydrogen costs.

In recent years, a family of research studies has been performed in hydrogen compression, which amplifies the importance of compressors in the variable renewable energy industry when the energy carrier is hydrogen. Many developments in the theory, application, and implementation of compressors have been recently summarized in review articles. Elberry et al. [9] focused on the large-scale compressed hydrogen storage options with respect to three categories including storage vessels, geological storage, and other underground storage alternatives. This study investigates a wide variety of compressed hydrogen storage technologies,

Table 1 – A comparison between volumetric energy of hydrogen and common energy carriers.

Fuel Type	Energy level
Gas (MJ/m^3)rowhead	
H_2 (1 atm 15 °C)	10.05
Natural Gas (1 atm 15 °C)	36.4
H_2 (200 atm 15 °C)	1825
Natural Gas (CNG) (200 atm 15 °C)	6860
H_2 (690 atm 15 °C)	4500
Liquid (MJ/L)rowhead	
H_2	8.5
LNG	22.2
Gasoline	34.2
Diesel	36.8
Liquid (MJ/kg)rowhead	
H_2	120
LNG	50
Gasoline	44
Diesel	42

Table 2 – Properties of hydrogen at 25 °C and atmospheric pressure.

Properties	Unit	Value
Atomic number	–	1
Atomic weight	–	1.008
Molar mass (mw)	kg/kmol	2.016
Specific gravity (air = 1)	–	0.0696
Density	kg/m^3	0.08375
Gas constant ®	kJ kg^{-1} K^{-1}	4.124
Specific Heat at Constant Pressure	kJ kg^{-1} K^{-1}	14.307 @300 K
Specific Heat at Constant Volume	kJ kg^{-1} K^{-1}	10.183 @300 K
Specific Heat Ratio, k = Cp/Cv	1	1.405 @300 K
Boiling point	°C	−253
Melting point	°C	−259

discussing in fair detail their theory of operation, potential, and challenges. Moradi and Gorth [10] discuss hydrogen storage and delivery options investigating the main existing safety and reliability challenges in hydrogen systems. Sdanghi et al. [11] summarize the state of the art of the most classical hydrogen compression technologies including innovative non-mechanical technologies specifically conceived for hydrogen applications, such as cryogenic, metal hydride, electrochemical and adsorption compressors. In completing these valuable articles, this review aims to highlight the recent trend in hydrogen compressors in large scale hydrogen production and especially focused on mechanical compressors.

The remainder of this paper is organized as follows. Thermodynamic of hydrogen compression Section introduces the thermodynamic of hydrogen compression. Compressor in large scale hydrogen production Section describes where and on which scale compressors are employed in the hydrogen industry. A comparison of the capabilities and limitations of the available compressor for hydrogen industry is summarized in Selection of compressor for hydrogen service Section. Finally, Concluding remarks and future challenges Section offers concluding remarks together with research directions needed for the next generation of compression technology development in large scale hydrogen industry.

Thermodynamic of hydrogen compression

Thermo-physical properties of hydrogen

Hydrogen is a chemical element with the chemical symbol H and atomic number 1. Under normal conditions, it is a colorless, odorless, and tasteless gas formed by the dual atomic molecules H_2. Hydrogen is the lightest element of the periodic table and the most abundant chemical in the world. Table 2 shows the main properties of hydrogen. At normal conditions, hydrogen is in a gaseous state. It has the second-lowest boiling point and melting points of all substances after helium. The low boiling point of hydrogen indicates the high effort needed to cool down the gas to store and use it as a liquid [12].

Generally speaking, hydrogen compression applications can be separated into two categories: pure (100%) hydrogen and hydrogen rich. An example of a 100% pure application would be a hydrogen production facility, where hydrogen is produced – ideally from an electrolyser powered by renewables – and then compressed and stored for various applications. Hydrogen-rich applications are typical in refineries and chemical plants where recycle or make-up compressors are used to handle process gas containing high hydrogen content and other constituents.

Gas equation

While the behavior of most gases can be approximated with good accuracy by the simple equation of the state of an ideal gas, there is a significant deviation for hydrogen behavior. One of the simplest ways of correcting this deviation is through the addition of a compressibility factor, which adjusts the ideal gas law to fit actual gas behavior, Eq. (1) [13].

$$PV = m\overline{R}ZT \quad (1)$$

where P is the gas absolute pressure in (Pa), V is the total volume in m^3 , m is the mass in kg, Z is the compressibility factor, $\overline{R}$ is the specific gas constant for hydrogen (4124.2 J/kg K), and T is the absolute temperature in K.

At present, there are three ways to achieve the compressibility factor including query the NIST Chemistry WebBooks [14], using a compressibility factor graph, or calculating the compressibility factor by equations of state [15].

If in Eq. (2), both sides are divided by time, the gas equation can be used to convert mass flow rate to volumetric flow rate.

$$\dot{V} = \frac{\dot{m}Z\overline{R}T}{P} \quad (2)$$

where $\dot{V}$ is the volumetric flowrate in m^3/h, and $\dot{m}$ is mass flowrate in kg/h. Another useful relationship to relate the hydrogen gas state is as below.

$$\frac{P_1\dot{V}_1}{Z_1T_1} = \frac{P_2\dot{V}_2}{Z_2T_2} \quad (3)$$

Using this equation, the volumetric flowrate at one state of pressure and temperature can be calculated based on the volumetric flowrate at another state of pressure and temperature.

Compression work

The first low of thermodynamic for the compression can be written as below.

$$\dot{W}_{in} = \dot{Q}_{loss} + \dot{m}\,(h_{2t} - h_{1t}) \quad (4)$$

where $\dot{W}_{in}$ is the rate of work input to the compressor or power input (Watt), $\dot{Q}_{loss}$ is the rate of heat loss from compressor body, bearing, seals etc. (Watt), $\dot{m}$ is mass flowrate in kg/s, and h_{2t} and h_{1t} are the total enthalpy (J/kg) at outlet and inlet conditions respectively. Theoretically, there are three cases of process compression which can be used for benchmarking the performance of an actual compression process described in below [16].

Adiabatic process

If compression or expansion of gas takes place with no flow of heat energy either into or out of the gas, the process is said to be adiabatic (or isentropic since with good accuracy the compression process in the compressor can be assumed as reversible). It means $\dot{Q}_{loss}$ in Eq. (4) is zero and hence compressor work can be calculated by:

$$\dot{W}_{in} = \dot{m}\,(h_{2t} - h_{1t}) = \dot{m}dh_t \quad (5)$$

Using the second law of thermodynamic, work done by the compressor can be calculated

$$\dot{W}_{in} = \dot{m}dh_t = \dot{m}\,(Tds + vdP) \quad (6)$$

In adiabatic, isotropic, process, $ds = 0$, making $Tds = 0$, and hence:

$$\dot{W}_{in} = \dot{m}dh_t = \dot{m}\,vdP \quad (7)$$

For an isentropic, adiabatic, process, $Pv^k = Constant = C$, and using gas equations, work done by the compressor in an adiabatic, isentropic process can be calculated using Eq. (8) together with Eq. (5):

$$H_a = dh_{ta} = Z_{avg}\bar{R}T_1\frac{k}{k-1}\left(r_p^{\frac{k-1}{k}} - 1\right) \quad (8)$$

where H_a is the adiabatic head kJ kg^{-1}, Z_{avg} is the average compressibility factor between inlet and outlet of the compressor, r_p is the compression ratio, k is the hydrogen specific heat ratio, $\bar{R}$ is the gas constant for hydrogen (kJ kg^{-1} K^{-1}), and T_1 is the absolute temperature in K.

Isothermal process

If compression or expansion of gas takes place under constant temperature conditions, the process is said to be isothermal which can present the upper limits of cooling and horsepower savings. Even though this compression process is not achievable but can be closely approached using some stages of intercooling. However, the capital cost of the coolers, the piping, and the installation must become a part of any evaluation. For an isothermal process $Pv = C$ and from this, a theoretical value for the power used by the compressor can be achieved.

$$\dot{W}_{in} = Z_{avg}\bar{R}T\ln(r_p) \quad (9)$$

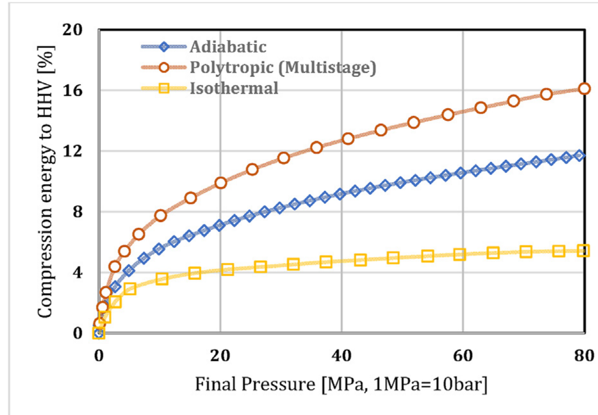

Fig. 5 – Energy required for the compression of hydrogen compared to its higher heating value, HHV [17].

Polytropic process

An ideal isothermal process must occur very slowly to keep the gas temperature constant. On the other hand, an ideal adiabatic process occurs very rapidly without any heat in or out of the system. In practice, most processes are somewhere in between, known as the polytropic process. The polytropic process can be expressed as $PV^n = C$, where n is polytropic exponent. For a polytropic (reversible) process, Eqs. (10) and (11) present the polytropic efficiency and head.

$$\eta_p = \frac{n/n-1}{k/k-1} \quad (10)$$

$$H_p = dh_{tp} = Z_{avg}\bar{R}T_1\frac{n}{n-1}\left(r_p^{\frac{n-1}{n}} - 1\right) \quad (11)$$

In practice, the compressed gas must be cooled down after each stage to make compression less adiabatic and more isothermal, which is a polytropic process. This means hydrogen typically is compressed in several stages. The difference between adiabatic, isothermal, and polytropic compression of hydrogen is presented in Fig. 5. In this Figure, while the horizontal axis shows the final pressure of hydrogen, the vertical axis is the energy required to compress hydrogen to that pressure compared to the higher heat value of hydrogen (HHV) at that pressure. Multi-stage compressors work between adiabatic and isothermal processes and their process is a type of polytropic process. It is worth noting that for a final pressure of 800 bar, the compressive energy requirement of a multistage compressor is about 12% of the hydrogen energy content [17].

Compressor in large scale hydrogen production

The development of hydrogen energy applications requires hydrogen compression at several stages in the supply chain.

Compressor is an integral aspect of any hydrogen gas storage, transport, and distribution system. To determine what type of compressor system is needed to accomplish the job, a variety of detailed data needs to be identified. At a minimum, a thorough understanding of gas analysis, suction and discharge pressures, suction temperature, and flow rate should be known.

To have an initial understanding of these properties, it should be understood where and on which scale these compressors are employed in the hydrogen industry. It should be noted that production and storage in different sizes in strategically desirable locations are required. Small-scale storage facilities are typically utilized at the distribution or final-user level, while large-scale storage facilities are typically applied at the production or transport level including the production sites, the terminals of pipelines, and other transportation paths. Terms such as small-scale and large-scale are often used in the literature without any specific magnitude of size. Nevertheless, some resources have introduced good measures for large-scale production. For example, Tietze et al. [18] presents the following definitions for the scale of hydrogen production; Small-scale bulk storage is storage below 5 tons of hydrogen, medium scale bulk storage reaches up to 500 tons of hydrogen, and large-scale bulk storage covers everything above 500 tons. Or Wolf [19] corresponds large scale hydrogen production to the storage of energy in terms of watt-hour, and large-scale storage on the scale of three-digit megawatt-hour to the gigawatt-hour range. Till now, the world's largest green hydrogen facility is planned to be built in northeast Brazil that could produce more than 600 million kilograms annually as part of 3.4 GW of combined wind and solar power plant [20]. The EU has also laid out plans to install 40 GW of renewable hydrogen electrolysers and produce as much as 10 million metric tons of renewable hydrogen by the year 2030 [21]. In Fukushima, Japan, a 10 MW electrolyser has been ordered by Toshiba to provide 900 tons per year of hydrogen from renewables, to be used for transport applications. Hydrogen is produced from a 20 MW solar PV project [22].

With this definition for the scale of hydrogen production, the present article is focused on largescale hydrogen production, storage, transport, and conversion. Fig. 6 illustrates a schematic drawing of an integrated power-to-gas concept with the different compression operations needed.

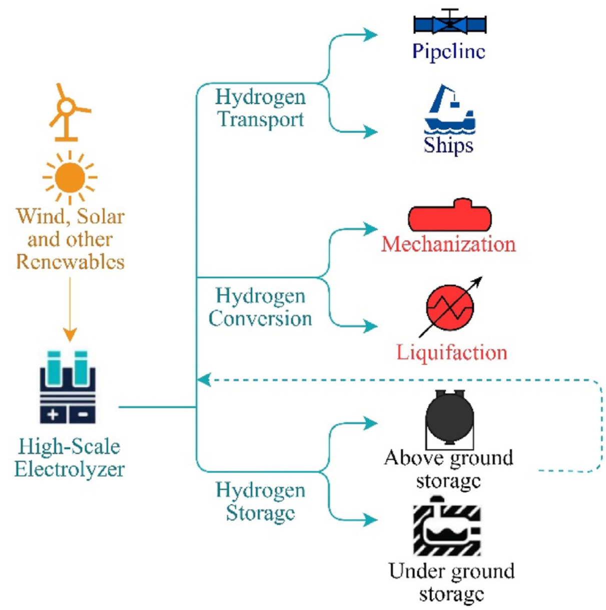

Fig. 6 – The application of compressors in large-scale hydrogen production from renewable.

Hydrogen production via electrolysis

Two majors electrolyze technologies are fairly developed today. Alkaline (ALK) electrolyzers have been used by industry for nearly a century. Proton exchange membrane (PEM) electrolyzers are commercially available today and are rapidly gaining market traction as, among other factors, they are more flexible and tend to have a smaller footprint. Table 3 provides a general overview of the techno-economic characteristics of ALK and PEM electrolyzers in 2017 and their expected future improvements till 2025 [23].

The advantage of PEM over AEL is the ability to work at higher current densities with a more compact design. However, the fixed cost per PEM unit is currently higher than AEL [12]. Fig. 7 shows a typical system design and basic components of water electrolyzer plants. As can be seen, the system goes beyond the electrolyzer stack and includes cooling equipment, hydrogen processing (e.g. for purity and compression), input power conversion (e.g. transformers and rectifiers), water treatment (e.g. deionization) and gas outlet (e.g. of oxygen) [24].

In order to size a compressor, it is important to have an understanding of compressor capacity in a water electrolyze plant. The flowrate of produced hydrogen in a plant can be calculated by Eq. (12).

$$\dot{m}_{H2} = \frac{10^3 \times PW_{plant}}{\eta} \quad (12)$$

where $\dot{m}_{H_2}$ plant hydrogen production mass flowrate in kg/h, PW_{plant} is the green power input to the plant in MW, and η is plant efficiency in kWh/kgH_2. Based on the information presented in this section, Table 3 presents a simple calculation for flowrate and pressure of water electrolysis plants.

As mentioned earlier, the hydrogen production in plants that the power inlet is in order of three-digit megawatt-hour can be categorized as large-scale energy storage. In this condition and base on the data presented in Table 4, a large-scale hydrogen production plant has an output flow rate of around 200,000 Nm^3/h or 500,000 kg/day at standard conditions, while the output pressure is between ambient pressure to 15 bar for ALK electrolyzes and 30–60 bar when using PEM electrolyzers.

Compressor for gas hydrogen storage

After the electrolysis process, the energy carrier hydrogen can be stored as compressed gas. The storage of compressed hydrogen can be situated either above or below ground level.

Large amounts of hydrogen are already stored underground. Salt cavities are the most suitable option however, not all regions have the proper geological prerequisites for salt cavity storage [25]. An alternative is to keep the stored gas in a metal container. While a metal container increases investment costs, storage stability ensures the purity of stored hydrogen and can be used independently of the location.

While there is little experience with the large-scale storage of hydrogen in metallic vessels, it is a relatively common practice for natural gas, and the same types of vessels could be

Table 3 – Production characteristics of ALK and PEM electrolysis (planned for 2025).

Technology	Unit	ALK		PEM	
		2017	2025	2017	2025
Energy consumption	kWh electricity per kg of H_2	51	49	58	52
Typical output pressure	bar	Atmosphere	15	30	60
Operating temperature	°C	50–80 °C	80 °C	70–90 °C	90 °C

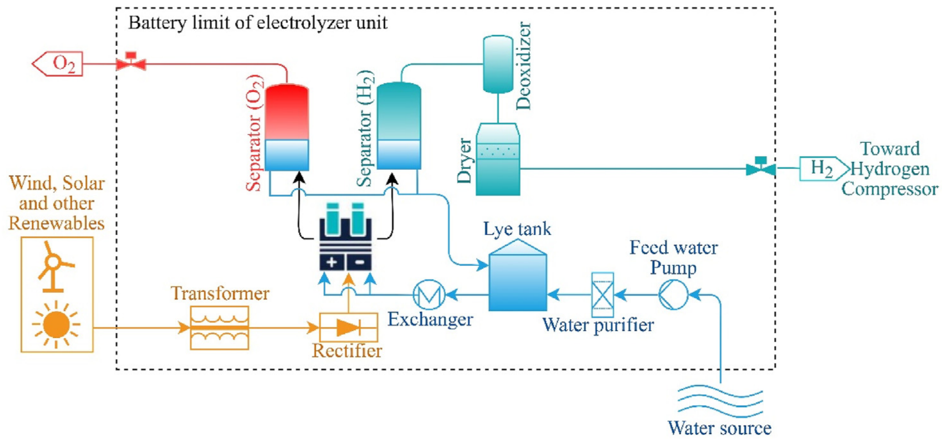

Fig. 7 – Typical system layout of an alkaline electrolyzer operating at nearly atmospheric conditions.

Table 4 – Production output of a fed green energy electrolyze plant.

Plant green energy input (MW)	Mass flow rate [kg/h]		Volumetric flowrate at discharge condition (outlet pressure and 15 °C) [m^3/h]		Volumetric flow rate at standard condition (1.03 bar, 0 °C) [Nm^3/h]		Water electrolyze outlet pressure [bar]	
	ALK	PEM	ALK at 15 bar	PEM at 60 bar	ALK	PEM	ALK	PEM
1	20	19	16	4	223	210	ATM to 15	30–60
10	205	192	163	40	2232	2103		
100	2041	1923	1633	400	22,320	21,032		
1000	20,408	19,231	16,330	3999	223,196	210,319		

applied for the storage of hydrogen [26]. Two main types of metallic vessels are currently used for the storage of larger amounts of hydrogen [27]:

- Spherical pressure vessels, with maximum storage pressures up to approximately 20 bar.
- Pipe (tube) storage, with maximum storage pressures of approximately 100 bar.

Due to the higher storage pressure and consequent compaction, storage in tube is more promising [28]. However, since both pressure vessels and pipe are metallic, Hydrogen Embrittlement (HE) is a big challenge. Suitable metallic materials hydrogen service are austenitic stainless-steel, aluminum and copper alloys, which are known for their resistance and opposition to effects of hydrogen at ambient temperatures [29]. Due to material properties and operating costs, large amounts of gaseous hydrogen are usually not stored at pressures of more than 100 bar in ground tanks and 200 bar in underground storage. Fig. 8 summarizes all possible compressed hydrogen storage with maximum compressed pressure.

Compressor for hydrogen distribution

As shown in Fig. 9, the suitable choice of hydrogen distribution method generally depends on the distribution scale.

Pipeline transportation seems to be the most economical means of transporting large amounts of hydrogen over long distances. It requires less energy per unit than trucks but provides more safety. The existing natural gas grid can be converted to transport hydrogen for pipeline distribution, or a new hydrogen network can be created parallel to the existing grid [30]. In the design of a hydrogen transmission pipeline, the most important problem is to find the maximum safe transport distance to prevent choke in the pipelines. The pressure drop along the pipeline is dependent on the flow velocity, ambient temperature, thermal insulation layer, and the geometric characteristics of the pipeline, such as diameter, length, and elevation changes. These parameters must be considered in selecting the appropriate pressure upstream of the pipeline. While the existing natural gas pipelines are usually operated at fairly low-pressure levels, that is, 20–30 bar as suggested by Andersson and Grönkvist [31], new

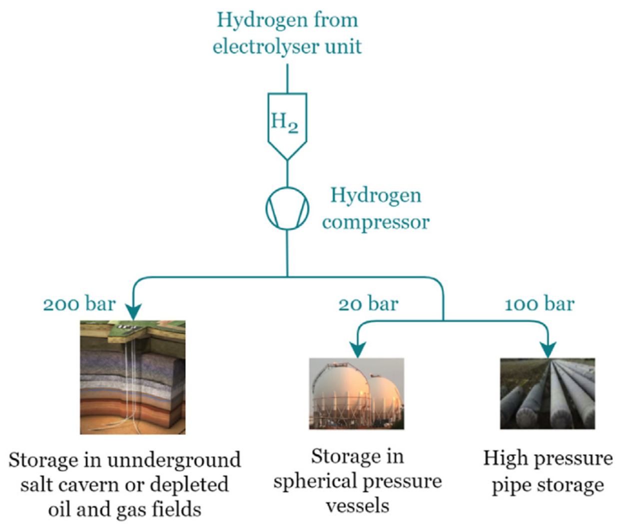

Fig. 8 – Overview of pressurized large scale gaseous hydrogen storage.

pipelines for hydrogen are designed at higher pressure levels, up to 100 bar.

In addition to pipelines, hydrogen transport by tanks, in the gas phase, is used for small-scale delivery and storage. Many gas suppliers deliver hydrogen gas in a cylinder or tube trailer, which can be delivered in the same way or filled on-site via trucks. Cylinders are offered in various sizes and working pressure. As mentioned by Reddi et al. [32], cylinders with a capacity of 50 L and a pressure of 200 bar are available in trailers of 16 cylinders. Bulk hydrogen gas distribution for maximum capacities of 5000 Nm^3/h in standard conditions is recommended for medium industrial customers [33]. To increase the amount of hydrogen transported under these conditions, the gas pressure can be increased, but as mentioned in Compressor for gas hydrogen storage Section, it cannot be more than 20 bar for balk storage in spherical pressurized vessels.

Compressor for hydrogen conversion

Liquefied hydrogen

Storing hydrogen as gas can prove difficult and must be stored at high pressures for relatively low energy increases. One option is to store hydrogen in the liquid phase (LH_2) at temperatures below −252.9 °C in order to increase the volumetric energy density by 4 compared to 200 bar gas storage. Liquefaction requires significant cooling and more advanced storage methods but is an often-applied technology for larger consumers. The major downside of liquid hydrogen is significant conversion losses of about 15%. The hydrogen is stored in cylindrical, vacuum-insulated tanks with capacity ranging from 5 up to 100 m^3. LH_2 can be transferred using trucks with a capacity of 45–65 m^3. Furthermore, LH_2 ships are being developed by some suppliers which aims at a capacity of 2500 m^3 set for 2020 [34]. Research has been conducted into the design of a 200,000 m^3 tanker [35]. The development of these ships enables international trade in hydrogen and large-scale storage.

As discussed by Quack [36], the liquefaction of hydrogen can be divided into four stages including:

- Compression (at ambient conditions)
- Precooling (ambient to about 80 K)
- Cryo-cooling (80 K–30 K)

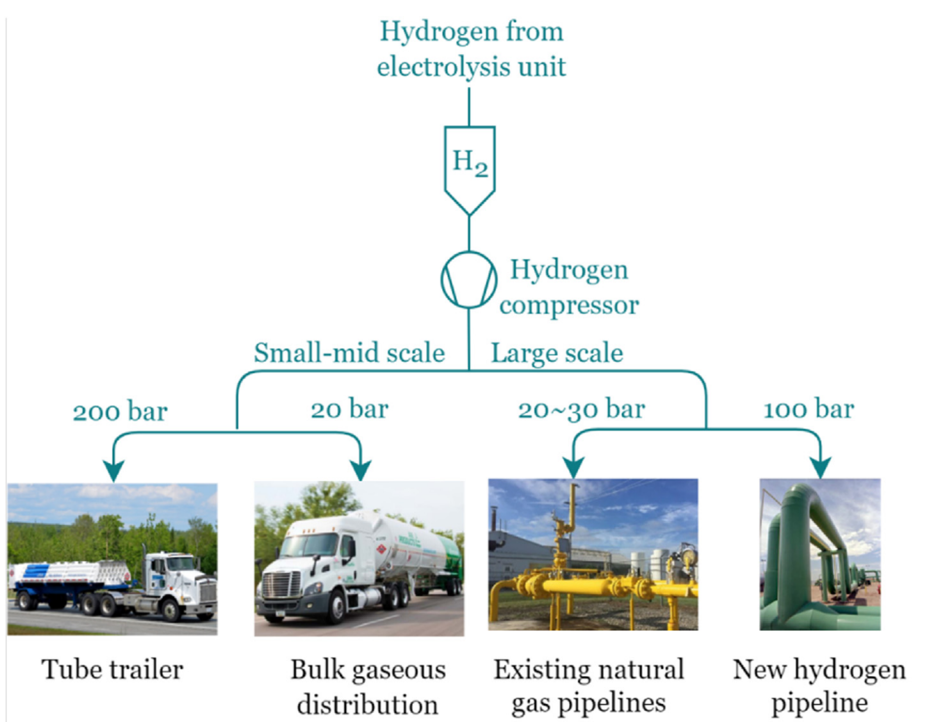

Fig. 9 – Pressure requirement for various methods of pressurized gaseous hydrogen distribution.

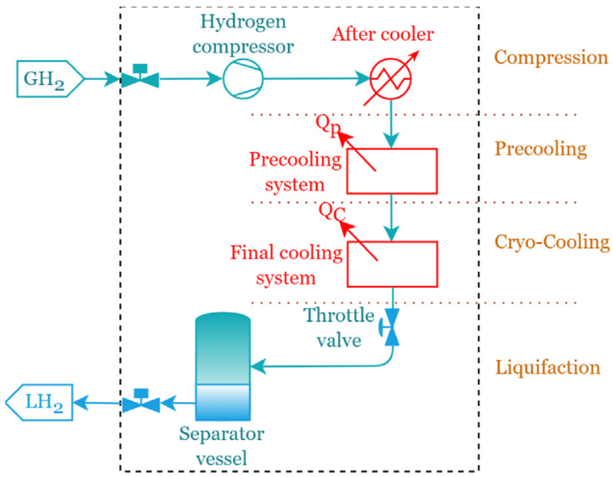

Fig. 10 – Generic process flow diagram for a hydrogen liquefaction unit.

Table 5 – Compression pressure and cooling temperature in the evolution of hydrogen liquefaction.

Time period	Compression outlet pressure	Temperature after Cryo-cooling
Till 1960	80–100 bar	40–45 K
After 1960	25–40 bar	22–30 K

- Liquefaction (30 K, 8 MPa to LH_2 at 0.1 MPa)

Fig. 10 shows the flow diagram for a hydrogen liquefaction plant.

A summary of hydrogen liquefaction process is presented in Table 5 [37]. As can be seen, for most system designed till 1960, compression up to 100 bar is needed while cooling is done to 40–45 K. But to increase the process and cost efficiency, system developed after 1960 mostly focused on cooling to lower temperature of 22–30 K, however the compression of fed hydrogen is limited to 25–40 bar.

Hydrogen methanation

Hydrogen methanation, a process for the production of synthetic natural gas (SNG) by the reaction of CO_2 with H_2 on a metal catalyst, has been proposed as a means of reducing CO_2 emissions from fossil power plants. However, using hydrogen feed from non-fossil sources is the key to this concept. In this condition, using hydrogen produced by water electrolysis can be a very potential solution to store excess electrical energy from renewable sources [38].

The following two-step reaction mechanism is assumed for hydrogen methanation.

$$CO_2 + H_2 \leftrightarrows CO + H_2O$$

$$CO + 3H_2 \leftrightarrows CH_4 + H_2O$$

Methane formation from carbon monoxide and hydrogen requires high temperature up to 600 °C [39]. Carbon monoxide formation from carbon dioxide, on the other hand, is favored at temperatures above 800 °C. On the other hand, the formation of

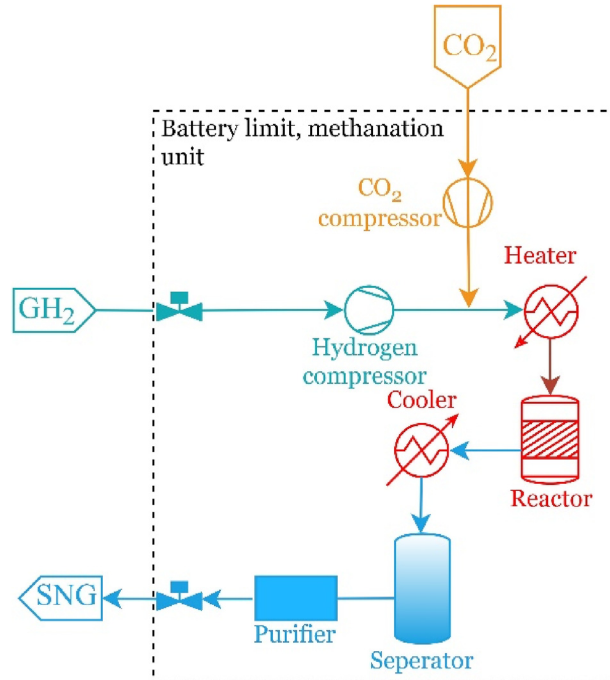

Fig. 11 – Generic process flow diagram for a methanation unit.

ethane is expected at temperatures below 400 °C. Hence, it can be concluded that the reaction should be taken place at temperature between 400 °C and 800 °C. This research also indicates that the conversion of carbon dioxide increases with increasing pressure and decreasing temperature. At an atmospheric pressure of 1 bar and a reaction temperature of 450 °C for instance, a carbon dioxide conversion of 78% could be achieved. While by increasing the pressure to 20 bar and keeping the temperature at 450 °C, the carbon dioxide conversion reaches approximately 93%. Different reactor concepts are currently being developed [40] where the operating pressure varies from 20 bar to 80 bar. Since output pressure of electrolysis unit may be less than this demanding pressure, hydrogen compression should be a part of methanation plant. Fig. 11 shows the process flow diagram of the methanation plant.

Selection of compressor for hydrogen service

Classification of compression technologies for hydrogen service

Choosing a proper type of compressor for hydrogen service requires comparing the requirements of the compression service with the capabilities and limitations of the available machine. Numerous factors must be considered, such as access to technology, efficiency, size and weight, capital costs (CAPEX), operating costs (OPEX), delivery, and so on.

Sdanghi et al. [11] summarizes the classification of current hydrogen compression technologies. According to this paper, existing hydrogen compression technologies are divided into two main categories of mechanical and non-mechanical compression (Fig. 12).

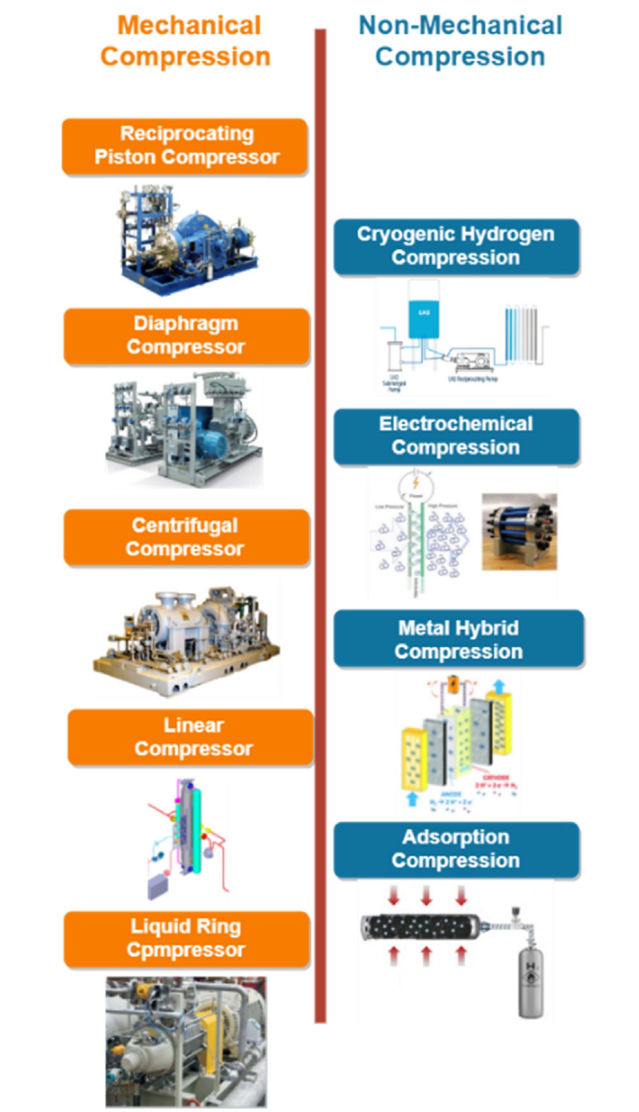

Fig. 12 – Classification of the available hydrogen compression technologies, adapted from Ref. [41].

As shown in Fig. 12, mechanical compressors can be divided into five main groups, namely reciprocating piston, diaphragm, centrifugal, linear and liquid ring compressors. Positive-displacement rotary screw compressors are not commonly used in hydrogen service because it is very difficult, if not impossible, to achieve such very tight tolerances to reduce hydrogen leakage and maintain efficiency [42]. Non-mechanical compression technologies, on the other hand, include cryogenic compression [43], metal hydride compression [44], electrochemical compression [45,46], and adsorption compressors [47]. Table 6 presents a comparison between different type of these hydrogen compression methods.

As can be seen in summary Table 6, most of the compression technologies presented have a maximum flow capacity of less than 1000 Nm^3/h. As concluded in Hydrogen production via electrolysis Section, large-scale hydrogen production should produce a scale of 200,000 Nm^3/h hydrogen. Therefore, these low-capacity compressors are not suitable for large-scale energy storage in the form of hydrogen. The only methods that can be counted on for this purpose are reciprocating compressors and centrifugal compressors, and other methods, especially non-mechanical ones, have been developed more for small-scale hydrogen production. Therefore, the rest of this article is about examining the capabilities, competencies and limitations of centrifugal and reciprocating compressors that are used in various applications through large-scale green hydrogen technology.

Centrifugal vs reciprocating compressor for hydrogen service

Design and configuration

Reciprocating compressors, known also as piston-type compressors, are the most common type of compressors. They can produce high pressures regardless of the density of the compressed gas. Reciprocating compressors are currently the only compressor available for pressures above 1000 bar [48]. As summarized in Table 7, reciprocating compressors can be classified in different categories considering various perspectives [49].

Table 6 – A comparison between different types of hydrogen compressors [41].

Compression Type	Max Flow [Nm^3/h]	Max Pressure [MPa]	Method of Compression	Main Merit	Main Limitation
Reciprocating Piston Compressor	4800	85.9	Positive displacement	Very high discharge pressure	Difficult maintenance
Diaphragm Compressors	581	28.1	Positive displacement	Seal less design	Diaphragm failure
Centrifugal Compressor	50,000	84.7	Dynamic	Low moving parts	Operation complexity
Linear Compressor System	112	95	Positive displacement	High reliability	Sophisticated piston control
Liquid Piston Compressor	750	100	Positive displacement	Long service life	Cavitation phenomena
Cryogenic Hydrogen Compressor	1000	90	Thermal – Positive displacement	High hydrogen density	Energy cost for liquefaction
Electrochemical Compression	470	100	Electrochemical – Positive displacement	Low cost	Difficult in manufacturing cell assembly
Metal Hydride	10	30	Thermal	No moving part	Low efficiency
Adsorption Compressor	560	10	Thermal	No moving part	Difficult in thermal management

Table 7 – Classification of reciprocating compressors.

Aspect	Classification
Number of stages	- Single stage - Multi stages (more than one cylinder)
Process stage*	- Single process stage (without intercooling) - Multi-process stage (with intercooling)
Frame configuration	- Trunk type - Cross head type
Piston configuration	- Single acting - Double acting (compression on both sides of cylinder)
Number of Parallel cylinders	- Simplex - Multiplex (more than one cylinder working in parallel)
Lubrication	- Oil free - Lubricated
Arrangement	- Horizontal - Non-horizontal o Vertical o V-arrangement o L-arrangement

A process stage is a process block equal to an uncooled portion of one or more steps, and as described in Thermodynamic of hydrogen compression Section, Compressor in large scale hydrogen production Section, Selection of compressor for hydrogen service Section and Concluding remarks and future challenges Section, coolers can be used to reduce the required compressive power needed. Each compression stage can achieve a limited pressure ratio, so more than one stage must be used to achieve a higher-pressure ratio . Crosshead type compressors provide better options for compression, sealing and lubrication in comparison to trunk type. Vertical and inclined machines (non-horizontal) are developed to save space and are mainly employed in small size applications (say below 300 kW). Multistage double acting multiplex horizontal type with intercooling is mostly used for large size applications. Fig. 13 shows an example of this type of reciprocating compressor.

Centrifugal compressor is another widely used compressor and is probably second only to reciprocating compressors in the process industry. The compressor uses a rotating set of impellers which transfer the energy in the form of velocity and pressure to the gas and later pressure conversion takes place in the stationery elements. Same as reciprocating compressors, centrifugal compressors are also developed in various classes considering different perspectives (Table 8) [16,71].

The concept of stage and process stage in centrifugal compressor is same as those explained for reciprocating compressors except that stage is defined as pair of impeller-diffuser. Barrel type casing is a double casing construction used for high pressure or low molecular weight gases which provides limited leakage areas and is a preferred design for hydrogen rich service. The double flow configuration is useful for large volumetric flow rates that are often associated with low inlet pressures. Axial split machines permit the removal of the upper casing half for maintenance purposes without disturbing the process piping. Maintenance of radial split machines requires removal of the compressor internal assembly from the non-drive end of the compressor and needs sufficient plot space for maintenance. API standard 617 [50] recommends for services where the partial pressure of hydrogen at the casing exceeds 14.0 bar, radially split casing shall be used. Except one stage integrally geared high-speed compressors, other types of centrifugal compressors are mostly developed with horizontal arrangement.

Fig. 14 shows a schematic drawing for of an integrally geared centrifugal compressor.

Capacity and pressure ratio

An essential step in choosing the type of compressor for a given service is to ensure that a suitable compressor that provides the required pressure and capacity is commercially available. Fig. 15 shows a typical application range chart for centrifugal and reciprocating compressors [16].

For services where the volume flow rate and discharge pressure fall in the range of both compressors, a compressor type selection study must be made.

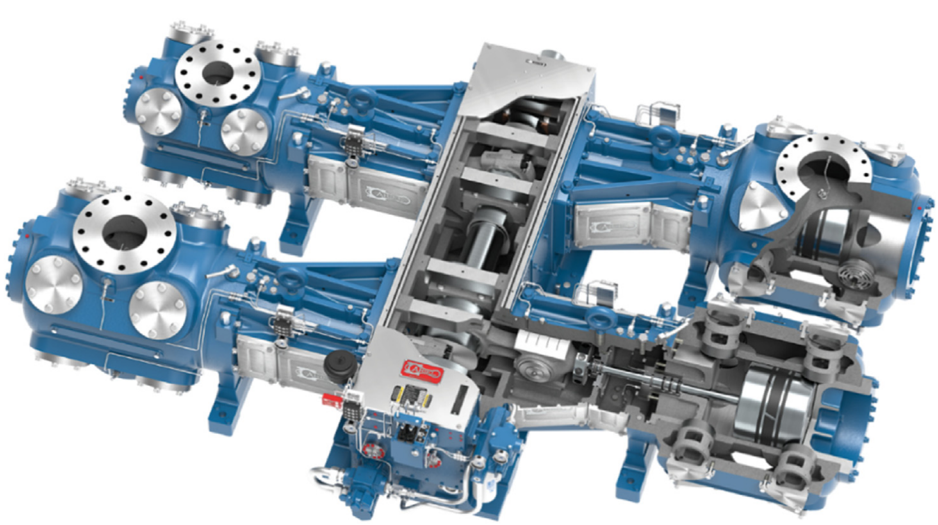

Fig. 13 – An example of a large size horizontal-type reciprocating compressor, courtesy of Arielcorp

Table 8 – Classification of centrifugal compressors from different perspectives.

Aspect	Classification
Number of stages and configuration	- Single stage o Overhung o Between bearing o Integrally geared - Multistage o Between bearings o Between bearings with back-to-back impellers o With side streams o Integrally geared
Process stage	- Single process stage (without intercooling) - Multi-process stage (with intercooling)
Design of casing	- Single casing - Double casing (barrel type)
Flow direction design	- Single flow - Double flow o With two inlets o Flow split integrally
Casing split	- Horizontal split - Vertical split
Arrangement	- Horizontal - Vertical inline

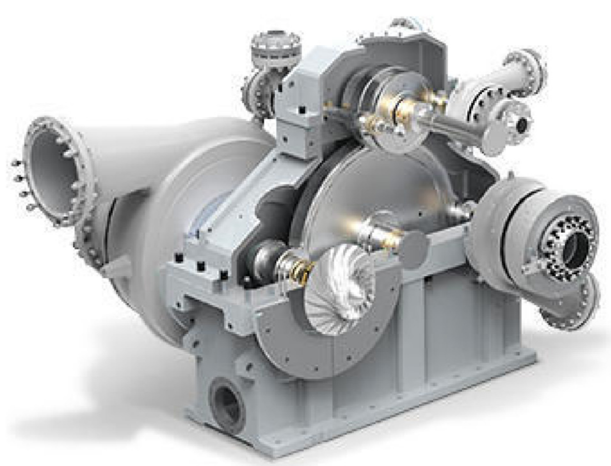

Fig. 14 – Integrally geared centrifugal compressors, courtesy of Howden

The minimum and maximum flow in the reciprocating compressor is limited by the size and speed of piston in cylinder. On the other hand, the minimum and maximum capacities of centrifugal compressors are limited by chock and surge phenomenon, respectively [52]. This fact puts the reciprocating piston compressors in a better position than the centrifugal compressor in terms of flow control. The typical turn down for reciprocating compressors may go up to 80%. Basic methods of capacity control on a reciprocating compressor can efficiently reduce process capacity and power consumption. Plug, port, or finger unloaders can be used to unload compressor cylinder ends – facilitating 100% capacity. On the other hand, the typical turn down ratio for constant speed multi-stage centrifugal compressor is approximately 20–30%. By changing the speed or adjustable inlet guide vanes, the turning down ratio can be increased to 40–50% or more [53].

For reciprocating compressors, the pressure ratio for a single stage of compression is limited to 4.5–5.0 at low pressures and to 2.0–2.5 at inlet pressures above 70 bar [54]. The pressure ratio is limited by the stress imposed on the piston rod. For a given piston and rod selection and a given pressure ratio, the force across the piston increases as the inlet pressure rises. This increases rod load so that at high inlet pressures the achievable pressure ratio is less than that at lower inlet pressures. Pressure ratio is also limited by the decrease in volumetric efficiency and increase in discharge temperatures which occur as the pressure ratio increases.

But for centrifugal compressors, low hydrogen density is the main reason limiting the use of centrifugal compressors for this service. In centrifugal compressors, the gas is accelerated mainly in impellers, to increase the kinetic energy, and subsequently is decelerated in the diffusor, to convert kinetic energy to pressure. The simplified Bernoulli equation describes this process.

$$p_1 + \frac{1}{2}\rho_1 v_1^2 = p_2 + \frac{1}{2}\rho_2 v_2^2 \tag{13}$$

$$\Delta p = \frac{1}{2}\left(\rho_1 v_1^2 - \rho_2 v_2^2\right) \tag{14}$$

where p_1, p_2, ρ_1, ρ_2, v_1, v_2 are, respectively, the pressures, densities, and velocities at the inlet (1) and outlet (2) of the diffusor. The achieved pressure difference in a single compression stage depends therefore on the velocity of the impeller as well as on the gas density. This means that a relatively high-pressure difference (and therefore pressure ratio) can be achieved by compressing a heavy gas (like argon, krypton, and xenon), while the pressure ratio for light gases is limited, such as hydrogen which will be limited to 1.05–1.2 [37]. At high discharge pressures, the impeller operating speed of centrifugal compressors must be increased, or additional compressor stages must be added. The latter can significantly increase rotordynamic complexity. In some instances, the maximum permissible shaft length may not provide sufficient space to incorporate the required number of stages. In such cases, the only option is to increase the operating speed of the impellers. Consequently, numerous high-speed compression stages and subsequently several intermediate coolers along with pressure losses are necessary for hydrogen compression. This makes the centrifugal compressor for hydrogen service a very complex and expensive machine.

In an interesting study, Witkowski et al. [55] analyzed hydrogen compression and pipeline transportation processes at the distance of 50 km and the pressure of 10 MPa upstream a pipeline. The study shows for a relatively low volume flow rate of 0.2 kg/s to 0.5 kg/s, the compression process is proposed by using three-stage reciprocating compressor. At larger flow rates of 1.0 kg/s to 2.0 kg/s, the concept is to use a compression train consisting of a conventional, two-section multistage centrifugal compressor followed by a two-stage reciprocating compressor. At a higher flow rate of 2.8 kg/s, an advanced eight-stage, integrally geared centrifugal

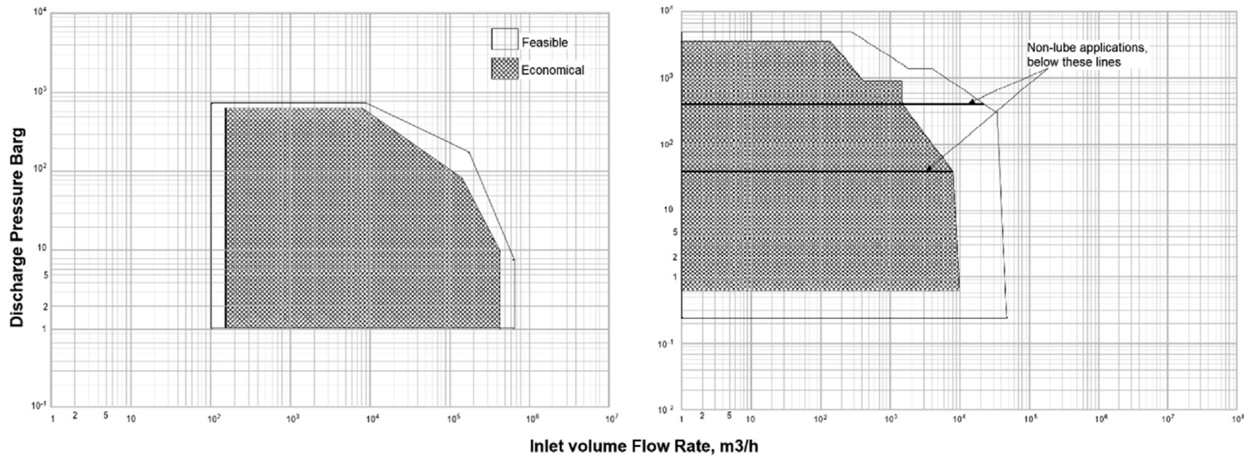

Fig. 15 – Centrifugal and reciprocating compressor application range chart [70].

compressor operated at a high speed with the blade tip velocities of almost 600 m/s is proposed.

Lubrication limitation

A common problem in hydrogen gas compressors is lubrication. It is practically impossible to use hydrocarbon products such as mineral oils for this purpose because hydrogenation, a chemical reaction between molecular hydrogen and some of the organic compounds in mineral oils, may happen in the presence of a catalyst.

Usually, a special type of reciprocating compressors called dry or oil-free compressors are used for hydrogen service, which work without lubricating oil. These types of compressors usually require frequent replacement of piston rings because of failure due to high non-uniformity of pressure distribution inside the compression chamber [56]. Non-lubricated cylinders are available to 200 bar discharge pressure. Special materials are applied on wear components, typically proprietary polytetrafluoroethylene [PTFE] or PEEK alloys, to guarantee adequate lifetime. Overall, the best design for each application will involve factors such as tolerance of the process to oil carry-over and expected maintenance intervals, among others.

Centrifugal compressors are generally of oil free compressors. Heshmat et al. [57] suggest the use of foil bearings can successfully improve the oil-free high operation of high-speed centrifugal compressors.

Discharge temperature limitation

In reciprocating compressors, high discharge temperatures can cause problems with any sealing element (any non-metallic component in contact with the compressed gas), lubrication, and failure of the cylinder valve. Therefore, the discharge temperature should be checked for all possible working conditions, at least for the average and maximum suction temperature. As recommended by API std 618 [58], the maximum predicted discharge temperature shouldn't exceed 150 °C or 135 °C for hydrogen-rich services (molecular weight of 12 or less). The latest trend is to hold the gas discharge temperatures below 120 °C to extend the life of wearing parts [48].

On the other hand, the maximum discharge temperature of centrifugal compressors depends on the compressor design and is usually between 200 and 230 °C [59]. Higher temperatures are possible but require special design such as center-supported diaphragms, improved sealing design, and the use of high-temperature O-rings.

Safety and leakage control

Hydrogen molecules are the smallest of all and this makes it difficult to contain them as they are prone to leak. However, hydrogen gas has an extremely low density at normal temperatures and pressures, and as a result the gaseous form is significantly lighter than air. When leaked, hydrogen gas rises rapidly and quickly diffuses, which can be a safety related benefit when outdoors. However, when the gas is released in a confined space (e.g., indoors), it will rise and accumulate at the ceiling, and hence hydrogen concentration in the top is much higher than that in the bottom [60]. The primary hazards associated with handling gaseous or liquid hydrogen are explosion, asphyxiation, and exposure to extremely low temperatures [61].

Hydrogen gas is highly flammable and will burn in air at a very wide range of concentrations between 4% and 75% by volume. The ignition energy of a flammable hydrogen–air mixture is extremely low, and mixtures may be ignited by spark, heat, or sunlight. Hydrogen will also spontaneously ignite in air above 500 °C (932 °F) [62] and when released at high pressures. In addition, this gas reacts with every oxidizing element, and this is the second hazard. It can react spontaneously and violently at room temperature with chlorine and fluorine to form the corresponding hydrogen halides, hydrogen chloride and hydrogen fluoride, which are also potentially dangerous acids.

Moreover, even though hydrogen is non-corrosive, however some materials are prone to embrittlement in hydrogen exposed applications. Typically used materials such as steel, copper, aluminum, and brass are suitable at normal temperatures. Steels with an ultimate tensile strength of less than 1000 MPa (~145,000 psi) or hardness of less than 30 HRC (Rockwell scale) are not generally considered susceptible to hydrogen embrittlement. However, high-strength and low-

Table 9 – Development of a Centrifugal Hydrogen Compressors to meet DOE targets [65,66].

Characteristics	DOE Target	MiTI and MHI	Concepts NREC
Efficiency (%)	98%	98%	98%
Hydrogen Capacity Target (kg/day)	200,000	240,000–500,000	240,000
Hydrogen Leakage (%)	<0.5	0.2	0.2
Hydrogen Purity (%)	99.99	99.99	99.99
Inlet Pressure (psig)	300–700	350–500	350
Discharge Pressure (psig)	1000–1200	1226–1285	1285
Total Compressor Package ($Million)	$15.6	$7.3–$12.5	4.5 ± 0.75
Maintenance Cost (% total Capital Investment)	3%	<3%	<3%
Annual Maintenance Cost ($/kW-h)	$0.007	<$0.005	$0.005
Package Size (sq-ft)	300–350	145–160	260
Reliability (# of Systems Required)	High – Eliminate redundant systems	Very High – Oil-Free Foil Bearings Eliminates Need for Redundant Systems	High – no redundancy required

alloy steels as well as nickel and titanium alloys are more susceptible [60].

In order to decrease the hydrogen compressor leakage and corresponding risks, deployment of a proper sealing system in compressors is necessary to guarantee the safe operation.

In reciprocating compressor, a packing is required to provide a barrier to leakage across the rod where it passes through the crank end cylinder closure. The packing may consist of several rings and may include a lantern ring which provides a space into which a gas or liquid may be injected to aid in the sealing process. In addition to sealing, the distance piece which is a separable housing that connects the cylinder to the frame, help to collect and control packing leakage. In this case, the leakage can be directed to a flare or other disposal points. Recently, a novel concept of reciprocating compressors named Linear Motor Reciprocating Compressors (LMRC) is developed by SwRI, ACI Services, Inc. (ACI), and Libertine FPE Limited. The LMRC is an advancement which minimizes the mechanical part count and reduces leakage paths [63].

On the other hand, centrifugal compressors mostly use dry gas seals to prevent shaft leakage. In this type of sealing, the gas leakage to the atmosphere is limited and controlled by a small, self-regulating gap between the rotating and stationary seal rings. A balance of spring forces, hydrostatic forces, and hydrodynamic forces acting on the stationary seal ring controls the width of this gap. Gas pressure leakage is broken done across one or two sets of seal rings and the leakage is vented to the flare system. A second or third set of seal rings serves as a backup in the event of damage to the primary seals. Recently, a group of research are conducted to improve dry gas seals for the hydrogen applications. Zhou [64] studied the on-fretting behavior of rubber O-ring seal in high-pressure gaseous hydrogen. Heshmat et al. [57] developed and demonstrated feasibility of using a close clearance, non-contacting, and dynamic compliant foil seal for hydrogen compressors.

For all hydrogen compressors, the use of ex-proof components is recommended. And for those installed in confined space, sensors for measuring the hydrogen concentration on the anode side and the surroundings of are required.

Other parameters

The US Department of Energy (DOE) has adjusted some engineering targets to develop advanced hydrogen compression solutions for the large-scale hydrogen industry. Depending on the characteristics of reciprocating and centrifugal compressors, the targets of each type of compressor are different.

Table 9 shows the DOE engineering specifications for the development and demonstration of an advanced centrifugal compressor system for high-pressure hydrogen services to support the strategic infrastructure plan of its hydrogen economy. This table also indicates that the design suggested by MiTI and MHI [65] and Concepts NREC (CN) [66] succeeded to achieve these targets.

For reciprocating compressors, DOE has set targets to improve the quality of Linear Motor Reciprocating Compressors (LMRC) for low to medium capacity hydrogen compressor up to 100 kg/h. Table 10 compares these set target and the achievement by SwRI, ACI Services, Inc. (ACI), and Libertine FPE Limited which developed LMRCs to meet the DOE goal of increasing the efficiency and reducing the cost of forecourt hydrogen compression [67]. Data presented in table indicates that available compressors can provide the targets. However, it should be noted these data are for LMRC not for classic reciprocating compressors.

The inherent design of the reciprocating compressor, in which a volume of gas is drawn in and positively displaced by the action of a reciprocating piston, means that the molecular weight of the gas does not compromise compression efficiency. This enables the reciprocating compressor to achieve

Table 10 – Development of a Centrifugal Hydrogen Compressors to meet DOE targets [67].

Characteristics	DOE Target for 2020	ACI and Libertine FPE Limited
Efficiency Isentropic (%)	80%	80%–all 3 stages
Hydrogen Capacity Target (kg/h)	100	>100
Losses of H_2 throughput	<0.5%	<0.4%
Inlet Pressure (bar)	100	100
Outlet pressure capability (bar)	860	875
Uninstalled capital cost	$275,000	$195,000
Annual maintenance cost (% of installed cost)	2.0	1.2
Reliability	High	High
Availability	≥85	TBD[a]

[a] To be determined.

high overall compression ratios in fewer stages than centrifugal compressors. For example, achieving a pressure ratio of 4:1 in an equivalent application typically requires six stages in a centrifugal compressor, while in a reciprocating compressor, this can be accomplished with two stages.

Compressor valve designs in centrifugal compressors should be reviewed and optimized for operation with hydrogen-rich gases. When excessive power is needed to force suction and discharge valves to open (allowing gas to flow into and out of the compressor cylinder), power is lost. Reducing excessive differential pressure across the valves will result in more efficient use of power. When compressing hydrogen-rich gases, valve lift and effective flow area are significantly less than that required for heavier gases. Performing a dynamic valve analysis (DVA) optimizes valve flow area and differential pressure to improve valve reliability and allow for efficient use of power.

As discussed in Capacity and pressure ratio Section, the design of centrifugal compressors for hydrogen services requires high operating speed impellers. In this case, it is necessary to consider the strength limits of the material. The limitation of the mechanical strength of the impellers is directly related to the tip speed. The maximum allowable speed of the impeller varies depending on the specific materials used and the geometry of the impeller. These material strength limitations are usually not a concern when designing compressors for service with higher molecular weight gases because the Mach numbers limit the operating speed. However, in the case of hydrogen, mechanical strength and impeller stress levels can be limiting factors [68]. This issue is further complicated by the potential for hydrogen embrittlement, i.e., hydrogen-induced cracking (HIC). HIC occurs when atomic hydrogen diffuses into an alloy [72]. Depending on the materials used, this can reduce toughness and lead to breakdowns below documented yield stresses [69]. Titanium impellers with specialized surface coatings have been shown to be successful in reducing the risk associated with HIC. Other design improvements, such as intermediate cooling, can also reduce the likelihood. Extensive studies on blade design and impeller geometry have shown that when high-strength titanium alloys are used, these stress levels can be reduced to allow for pressure ratios of up to 1.45:1 per stage [66].

Concluding remarks and future challenges

To address global warming and environmental problems, interest in renewable energy systems is growing. However, providing sustainable and reliable energy from renewable sources such as solar and wind can face many challenges. One possible solution is the production of hydrogen by water electrolysis, which has the potential to replace current energy carriers. But hydrogen as an energy carrier has the problem of low energy density. This challenge requires hydrogen compression at several stage through large scale hydrogen production. Numerous research efforts have examined hydrogen compression methods. Investigation in publications suggests that there are three main areas in need of consideration and improvement.

First, the thermodynamic complication of hydrogen compression needs to be reviewed. This complication is mainly due to the small size and low molecular weight of hydrogen. Since this information is a fundamental for any research in this field, Thermodynamic of hydrogen compression Section of the present study summarized the most important relationships, equation, and data necessary in hydrogen compression context.

Second, since there is no clear information about the size of hydrogen compressors in large-scale hydrogen production, Compressor in large scale hydrogen production Section of this paper was conducted to investigate the performance of compressors in various plants through this industry. Toward this goal, several significant plants are being explored, including electrolysis plants, hydrogen storage, hydrogen distribution, and hydrogen conversion. The result shows that an electrolyzer unit with 100 MW green energy can produce about 2000 kg/h hydrogen with maximum output pressures of 15 bar and 60 bar using ALK and PEM electrolysis, respectively. This flowrate and pressure are considered as the inlet pressure to the hydrogen compressors. Compressor outlet pressure depends on the type of plant. In storage units, the output pressure of the compressors depends on the type of storage, i.e., underground storage 200 bar, storage in spherical pressure vessels 20 bar, and pipe storage. Large-scale distribution of hydrogen can be done through pipelines. If existing natural gas pipelines are used, the outlet pressure can be 20–30 bar. But for new hydrogen pipelines, the proposed design pressure is 100 bar. For hydrogen liquefaction systems, the output pressure of the feed compressors should be up to 40 bar. And the hydrogen inlet pressure for methanation reactors can be up to 80 bar.

Finally, Selection of compressor for hydrogen service Section of this study reviews the selection of suitable compressors in the large-scale hydrogen industry. A review of the published literature shows that only reciprocating and centrifugal compressors can handle the required flow rate of 2000 Nm^3/h. Therefore, the design and configuration of these two types of compressors have been studied in more detail. The comparison of capacity and pressure ratio shows that reciprocating compressors can give a pressure ratio of up to 5 while the low molecular weight of hydrogen is a big problem in centrifugal compressors and their pressure ratio is limited to 1.2. To deal with this shortcoming, it is recommended to use very high-speed impellers, but the limitation on the mechanical strength of the impellers is a big obstacle, especially due to the embrittlement caused by hydrogen cracking. On the other hand, lubrication and discharge temperature limits are the two main problems that must be addressed in use of reciprocating compressors. A review of the literature shows that oil-free reciprocating compressors are only available for hydrogen services up to 200 bar and 150 °C. In this section, the DOE objectives for the development of hydrogen compressors are also reviewed and the results of studies which meet these requirements are discussed.

An overview of the resources shows that improving the design and increasing the reliability of compressors will play an effective role in the future of large-scale green hydrogen production. Although proof exists of rapid development in the recent years, some of the key challenges that need to be addressed by the compressor community are summarized as follows.

- Knowledge of the thermodynamics of the rich hydrogen compression is essential for compressor developments. Additional research in this area can enhance the accuracy of design development and improvement.
- Further study of compressor performance in various applications through large-scale hydrogen production such as Green Methanol or Green Ammonia can help compressors researchers and manufacturers better understand the demands of the industry.
- Finally, a detailed focus on the reliability, CAPEX, and OPEX in compressors supports users, many of whom do not have complete information when choosing and using compressors, during engineering and operation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

[1] Kempener R, Assoumou E, Chiodi A, Ciorba U, Gaeta M, Gielen D, et al. A global renewable energy roadmap: comparing energy systems models with IRENA's remap 2030 project. In: Informing energy and climate policies using energy systems models. Cham: Springer; 2015. p. 43–67.
[2] Moriarty P, Honnery D. Global renewable energy resources and use in 2050. In: Managing global warming. Academic Press; 2019. p. 221–35.
[3] Robles JO, Almaraz SDL, Azzaro-Pantel C. Hydrogen as a pillar of the energy transition. In: Hydrogen supply chains. Academic Press; 2018. p. 3–35.
[4] Yilmaz F, Ozturk M, Selbas R. Design and thermodynamic modeling of a renewable energy based plant for hydrogen production and compression. Int J Hydrogen Energy 2020;45(49):26126–37.
[5] Dolf G, Taibi E, Miranda M. Hydrogen: a renewable energy perspective. Abu Dhabi: International Renewable Energy Agency; 2019.
[6] Zanfir M. Portable and small-scale stationary hydrogen production from micro-reactor systems. In: Advances in hydrogen production, storage and distribution. Woodhead Publishing; 2014. p. 123–55.
[7] Miller E, Papageorgopoulos D, Stetson N, Randolph K, Peterson D, Cierpik-Gold K, Satyapal S. U.S. Department of energy hydrogen and fuel cells program: progress, challenges and future directions. MRS Advances 2016:2839–55.
[8] Sdanghi G, Maranzana G, Celzard A, Fierro V. Towards non-mechanical hybrid hydrogen compression for decentralized hydrogen facilities. Energies 2020;13(12):3145.
[9] Elberry A, Thakur J, Santasalo-Aarnio A, Larmi M. Large-scale compressed hydrogen storage as part of renewable electricity storage systems. Int J Hydrogen Energy 2021;46(29):15671–90.
[10] Moradi R, Gorth K. Hydrogen storage and delivery: review of the state of the art technologies and risk and reliability analysis. Int J Hydrogen Energy 2019;44(23):12254–69.
[11] Sdanghi G, Maranzana G, Celzard A, Fierro V. Review of the current technologies and performances of hydrogen compression for stationary and automotive applications. Renew Sustain Energy Rev 2019;120:150–70.
[12] Sherif S, Goswami D, Stefanakos E, Steinfeld A. Handbook of hydrogen energy, Hydrogen storage and compression. CRC Press; 2014.
[13] Chen H, Zheng J, Xu P, Li L, Liu Y, Bie H. Study on real-gas equations of high pressure hydrogen. Int J Hydrogen Energy 2010:3100–4.
[14] Linstrom P, Mallard W. The NIST chemistry WebBook: a chemical data resource on the internet. J Chem Eng Data 2001.
[15] Zheng J, Zhang X, Xu P, Gu C, Wu B, HoU Y. Standardized equation for hydrogen gas compressibility factor for fuel consumption applications. Int J Hydrogen Energy 2016;41(5):6610–7.
[16] Brown R. Compressors: selection and sizing. Gulf Professional Publishing; 1997.
[17] Makridis S. Hydrogen storage and compression. In: Methane and hydrogen for energy storage; 2017. arXiv preprint arXiv:1702.06015.
[18] Tietze V, Luhr S, Stolten D. Bulk storage vessels for compressed and liquid hydrogen. In: Hydrogen science and engineering: materials, processes, systems and technology; 2016. p. 659–90.
[19] Wolf E. Large-scale hydrogen energy storage. In: Electrochemical energy storage for renewable sources and grid balancing. Elsevier; 2015. p. 129–42.
[20] Energix.com. Enegix energy to build US$5.4 billion green hydrogen facility in Brazil. https://pressroom.enegix.energy/; 2021.
[21] E Commission. A hydrogen strategy for a climate-neutral Europe. https://ec.europa.eu/; 2020.
[22] Ohira E. Hydrogen cluster in Japan – regional activities to promote hydrogen. 2019.
[23] Taibi E, Miranda R, Vanhoudt W, Winkel T, Lanoix J, Barth F. Hydrogen from renewable power: technology outlook for the energy transition. 2018.
[24] Smolinka T, Ojong E, Garche J. Hydrogen production from renewable energies—electrolyzer technologies. In: Electrochemical energy storage for renewable sources and grid balancing; 2015. p. 103–28.
[25] Kruck O, Crotogino F, Prelicz R, Rudolph T. Overview on all known underground storage technologies for hydrogen. In: Project HyUnder – assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe; 2013.
[26] Witkowski A, Rusin A, Majkut M, Stolecka K. Comprehensive analysis of hydrogen compression and pipeline transportation from thermodynamics and safety aspects. Energy 2017;141:2508–18.
[27] Barthélémy H, Weber M, Barbier F. Hydrogen storage: recent improvements and industrial perspectives. Int J Hydrogen Energy 2017;42(11):7254–62.
[28] Raddi K, Elgowainy A, Sutherland E. Hydrogen refueling station compression and storage optimization with tube-trailer deliveries. Int J Hydrogen Energy 2014;39(33):19169–81.

[29] Michler T, Lindner M, Eberle U, Meusinger J. Assessing hydrogen embrittlement in automotive hydrogen tanks. In: Gaseous Hydrogen Embrittlement of Materials in Energy Technologies, vol. 2. Woodhead Publishing; 2012. p. 94–215.
[30] Cerniauskas S, Junco A, Grube T, Robinius M, Stolten D. Options of natural gas pipeline reassignment for hydrogen: cost assessment for a Germany case study. Int J Hydrogen Energy 2020;45(21):12095–107.
[31] Andersson J, Grönkvist S. Large-scale storage of hydrogen. Int J Hydrogen Energy 2019;44(23):11901–19.
[32] Reddi K, Mintz M, Elgowainy A, Sutherland E. Challenges and opportunities of hydrogen delivery via pipeline, tube-trailer, LIQUID tanker and methanation-natural gas grid. In: Hydrogen science and engineering, materials, processes, systems and technology; 2016. p. 849–74.
[33] Tietze V, Luhr S. Near-surface bulk storage of hydrogen. In: Transition to renewable energy systems. John Wiley & Sons; 2013. p. 659–90.
[34] Cappellen L, Groezen H, Rooijers F. Feasibility study into blue hydrogen: technical, economic & sustainability analysis. CE Delft; 2018.
[35] Abe A, Nakamura M, Sato I, Uetani H, Fujitani T. Studies of the large-scale sea transportation of liquid hydrogen. Int J Hydrogen Energy 1998;23(2):115–21.
[36] Quack H. Conceptual design of a high efficiency large capacity hydrogen liquefier. AIP Conf Proc 2002;613(1):255–63.
[37] Alekseev A. Hydrogen liquefaction. In: Hydrogen science and engineering: materials, processes, systems and technology; 2016. p. 733–62.
[38] Witte J, Calbry-Muzyka A, Wieseler T, Hottinger P, Biollaz S, Schildhauer TJ. Demonstrating direct methanation of real biogas in a fluidised bed reactor. Appl Energy 2019;240:359–71.
[39] Schaaf T, Grünig J, Schuster MR, Rothenfluh T, Orth A. Methanation of CO_2-storage of renewable energy in a gas distribution system. Energy Sustain Soc 2014;4(1):1–14.
[40] Ronsch S, Ortwein A. Methanisierung von Synthesegasen. Chem Ing Tech 2011;83(8):1200–8.
[41] Sdanghi G, Maranzana G, Gelzard A, Fierro V. Review of the current technologies and performances of hydrogen compression for stationary and automotive applications. Renew Sustain Energy Rev 2019:150–70.
[42] Peschel A. Industrial perspective on hydrogen purification, compression, storage, and distribution. Fuel Cell 2020;20(4):385–93.
[43] He M, Lv C, Gong L, Wu J, Zhu W, Zhang Y, et al. The design and optimization of a cryogenic compressed hydrogen refueling process. Int J Hydrogen Energy 2021;46(57):29391–9.
[44] Tarasov BP, Fursikov PV, Volodin AA, Bocharnikov MS, Shimkus YY, Kashin AM, Yartys V, Chidziva S, Pasupathi S, Lototskyy M. Metal hydride hydrogen storage and compression systems for energy storage technologies. Int J Hydrogen Energy 2021:13647–57.
[45] Rhandi M, Trégaro M, Druart F, Deseure J, Chatenet M. Electrochemical hydrogen compression and purification versus competing technologies: Part I. Pros and cons. Chin J Catal 2020;41(5):756–69.
[46] Durmus G, Colpan CO, Devrim Y. A review on the development of the electrochemical hydrogen compressors. J Power Sources 2021;494:229743.
[47] Sdanghi G, Nicolas V, Mozet K, Schaefer S, Maranzana G, Celzard A, Fierro V. A 70 MPa hydrogen thermally driven compressor based on cyclic adsorption-desorption on activated carbon. Carbon 2020;161:466–78.
[48] Almasi A. Latest practical notes and recent lessons learned on reciprocating compressors. Aust J Mech Eng 2016;14(2):138–50.
[49] Bloch H, Hoefner J. Reciprocating compressors: operation and maintenance. Elsevier; 1996.
[50] American Petroleum Institute. API standard 617 axial and centrifugal compressors and expander-compressors. 8th ed. 2014.
[52] Brun K, Kurz R. Enhancing surge control. Turbomach Int Mag 2007:38–9.
[53] Gallick P, Phillippi G, Williams B. What's correct for my application – a centrifugal or reciprocating compressor?. In: Proceedings of the 35th Turbomachinery Symposium. Texas A&M University, Turbomachinery Laboratories; 2006.
[54] Mokhatab S, Poe W. Handbook of natural gas transmission and processing. Gulf Professional Publishing; 2012.
[55] Witkowski A, Rusin A, Majkut M, Stolekcka K. Comprehensive analysis of hydrogen compression and pipeline transportation from thermodynamics and safety aspects. Energy 2017;141:2508–18.
[56] Dianbo X, Jianmei F, Liqing D, Donghui Y, Xueyuan P. Experimental investigation of pressure distribution between the piston rings and its formation in reciprocating compressors. Proc Inst Mech Eng C – J Mech Eng Sci 2012.
[57] Heshmat H, Ren Z, Hunsberger A, Jahanmir S, Walton J. Oil-free foil bearings and seals for centrifugal hydrogen compressor. In: International Tribology Conference, Hiroshima, Japan; 2011.
[58] American Petroleum Institute. Reciprocating compressors for petroleum, chemical, and gas industry services. 5th ed. 2007.
[59] Van den Braembussche R. Design and analysis of centrifugal compressors. John Wiley & Sons.; 2019.
[60] Ma Z, Lu. Y, Chen R, Xiao H, Wang M, Su GH, et al. Study on the hydrogen risk in venturi scrubber filter of filtered containment venting system under PWR severe accident. Nucl Eng Des 2018;327:61–99.
[61] I. 15916. Basic considerations for the safety of hydrogen systems. 2015.
[62] Cao Z, Cao HG. Unified field theory and topology of nuclei. Int J Phys 2014;2(1):15–22.
[63] Deffenbaugh D. Advanced reciprocating compression technology. DOE Award No. DE-FC26-04NT42269, SwRI Contract No. 18.11052. 2005.
[64] Zhou C, Chen G, Xiao S, Hua Z, Gu C. Study on fretting behavior of rubber O-ring seal in high-pressure gaseous hydrogen. Int J Hydrogen Energy 2019;44(40):22569–75.
[65] Heshmat H. Oil-free centrifugal hydrogen compression technology demonstration. No. DOE-MiTi-18060-01. Albany, NY: Mohawk Innovative Technology Inc.; 2014.
[66] Di Bella F. Development of a centrifugal hydrogen pipeline gas compressor. No. TM-1785. Concepts ETI, Inc. dba Concepts NREC; 2015.
[67] Broerman E, Bennett J, Poerner N, Strickland D, Helffrich J, Coogan S. Hydrogen compression application of the linear motor reciprocating compressor. In: DOE hydrogen and fuel cells program; 2015. FY 2015 Annual Progress Report.
[68] Miller H, Sorokes J. Pushing the limits of compression. Hydrocarb Eng 2019:81–4.
[69] Sazali N. Emerging technologies by hydrogen: a review. Int J Hydrogen Energy 2020;45(38):18753–71.
[70] Bloch H, Godse A. Compressors and modern process applications. John Wiley & Sons; 2006.
[71] Almasi A. Practical notes and latest technologies on modern centrifugal compressor component and system selection. Aust J Mech Eng 2012;10(1):71–80.
[72] Jewett RP, Walter RJ, Chandler WT, Frohmberg RP. Hydrogen environment embrittlement of metals. No.NASA 1973;CR-2163.