27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

# COB-2023-1419
# HYDROGEN LIQUEFACTION, A REVIEW OF THE ONGOING METHODS AND A CRITICAL ANALYSIS OF THE CURRENT STUDIES

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***Abstract.*** *Human activity has had a significant negative impact on the environment, making decarbonization crucial for long-term sustainability. Hydrogen has emerged as a key player in this transition; however, certain challenges related to the technology's development, particularly in transportation and storage, have hindered its full decarbonisation potential. One promising solution to address this issue is the liquefaction of hydrogen, which offers advantages such as increased density, flexible transportation, and the absence of toxic substances. However, current liquefaction methods remain expensive, as the phase change at ambient pressure occurs at 20 K. Consequently, ongoing research and development efforts by various industrial and academic institutions are focused on reducing the costs associated with the process and improving cycle metrics. This work aims to investigate, summarise, and discuss the principal cycles and prototypes employed for hydrogen liquefaction, encompassing both conventional cooling techniques and novel non-in-kind technologies. The analysis includes descriptions of prototypes, plants, and intellectual property documents reported in scientific journals and conferences. They explore optimisation techniques, system architecture, component design, and innovative solutions. However, detailed information necessary for a comprehensive evaluation of the cycles is not always available, as much of the work conducted thus far consists of conceptual plants.*

***Keywords:*** *Decarbonization, Liquification of Hydrogen, Liquefaction-methods, Reduce the Costs, Optimization, Performance Metrics*

## 1. INTRODUCTION

From the 18th century, the use of fossil fuels was dominant in the world, starting after the first Industrial Revolution (1760). Along with this, the emission of greenhouse gases (GHG) has increased exponentially, and consequently, pollution and the gradual destruction of the ozone layer have caused the temperature of the planet to increase, bringing great problems to humanity. Over these centuries, various energy sources have emerged with the aim of gradually replacing fossil fuels; among them, eolic, solar, hydraulic, and nuclear. Each with its advantages, disadvantages, and limitations, is capable of sufficient technology maturity to replace current fuels in the present. As a very promising alternative from an energy and environmental point of view, hydrogen presents itself as a great option for decarbonisation and solution of the aforementioned problems. Its many unique characteristics are due to its high reactivity, GHG-free combustion, and the highest energy density among the gases (speaking in terms of mass), among others. Another factor worth mentioning is the high number of possible applications, which can be used in the production of fertilisers, in the production of green steel, in electric cars and fuel cells, rocket fuel, or replacing batteries, among other uses. All of this highlights the important role that hydrogen plays in our society (IEA, 2019).

However, with the application of hydrogen, some challenges became evident. Because of its low density, the volume required to transport or store the substance in the gaseous state is enormous, making the process currently unfeasible in economic terms. To improve this stage, several proposals were made, including compression and mixing in different substances, such as ammonia. One of the most interesting of these (considering economic and even environmental issues) is liquefaction, since the density of hydrogen increases almost 800 times, thus allowing much greater transport of the product, together with a high purity and flexibility in the mode of displacement.

In that scenario, this paper has as its main goal the exposition, organisation, and discussion of cycles that have the objective of liquefying hydrogen through conventional refrigeration processes and a brief overview of the so-called unkind cooling technologies. There is a lot of literature on the subject, but the lack of connectivity between them makes it difficult to compare results and obtain accurate conclusions. The path taken will pass through plants that already exist and are in operation, conceptual plants that seek to increase technical requirements such as efficiency, production of liquid hydrogen per day, and reduction of the amount of energy consumed during the process, exposing their differences and comparing real results (in the case of existing cycles) and numeric (in the case of conceptual cycles not experimentally implemented).

## 2. LIQUEFACTION SYSTEMS

The theoretical minimum value of energy required to liquefy hydrogen under ambient conditions (300 K, 1.01 bar) is 3.3 kWh/kg LH2 or 3.9 kWh/kh LH2 with ortho-para conversion (Gardiner, 2009). However, it will be seen that the actual values of the process are higher due to several factors, such as the inefficiency of the devices. The studies aim to reduce the energy spent and increase production to meet the need of 621 million tons per year until 2050 (Ishimoto *et al.*, 2017).

As stated earlier, hydrogen has two different spin isomers:

- Orthohydrogen (Ortho): Two protons in the nucleus rotate in the same direction, adding a spin number equal to 1;
- Parahydrogen (Para): Two protons in the nucleus spin in opposite directions, adding a spin number equal to 0.

The equilibrium concentrations of the isomers depend on the temperature of the substance; for example, at room temperature, the equilibrium concentrations of Ortho and Parahydrogen are 25% and 75%, respectively (called normal hydrogen). However, as the temperature drops, the parahydrogen concentration tends to increase, increasing to 100% as it reaches absolute zero. The passage is exothermic, releasing about 703 kJ/kg in the form of heat. Furthermore, the conversion without the use of catalysts is very slow, meaning that it can occur even after the hydrogen has liquefied. That is a very serious problem because the release of heat caused by the transformation will cause the hydrogen to return to its gaseous state (an effect known as boil-off), provoking an exponential increase of the pressure in the storage device, which can lead to rupture or even reservoir explosion. To avoid this phenomenon, catalysts are used during the liquefaction process, which convert according to the decrease in the temperature of the H2.

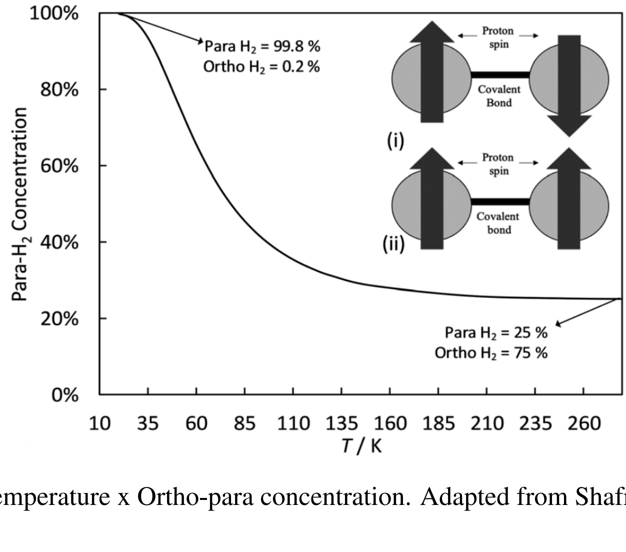


Figure 1. Temperature x Ortho-para concentration. Adapted from Shafri *et al.* (2022)

### 2.1 Conventional cycles

The cycles presented below are the theoretical basis for the construction of more complex cycles, which present the most general ideas of liquefaction. Normally, most hydrogen liquefaction cycles are divided into pre-cooling, which cools the hydrogen until 70-80 K, and refrigeration, which takes the gas to close to 30 K for it to pass through the expansion valve.

- **Linde Cycle**: In this process, hydrogen passes through a series of heat exhangers, where its temperature is reduced, until it reaches a throttling device, via a Joule-Thomsom effect it is liquefied. The gaseous hydrogen is employed to cool down the incoming hydrogen streams in the heat exchangers. Liquid or gaseous nitrogen is usually employed to pre-cool the incoming hydrogen streams. A schematic representation of the cycle is presented in Fig. 2. This cycle is usually used for small-scale plants, has a low efficiency, but is simpler to execute (Nandi and Sarangi, 1993).

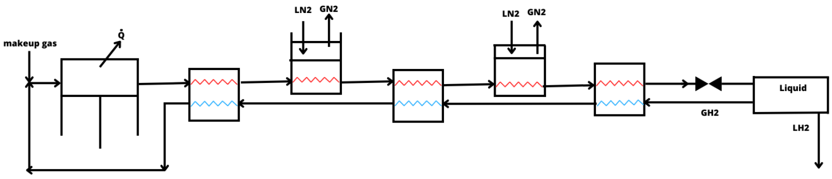


Figure 2. Schematic representation of the Linde cycle. Adapted from Nandi and Sarangi (1993). LN2 stands for liquid nitrogen, GN2 stands for gaseous nitrogen, LH2 stands for liquid hydrogen, GH2 stands for gaseous hygrogen, $\dot{Q}$ stands for heat dissipated by the compressor.

- **Claude Cycle**: The cycle is very similar to the Linde one, with the main difference of purging part of the incoming hydrogen stream into an expansion device, where it will cool down and recover work. The outflow of the expansion device is then directed to the returning hydrogen stream, where it will aid in the cooling of the incoming stream. This configuration enables the system to operate with higher efficiency and lower pressures Nandi and Sarangi (1993). Most of the hydrogen liquefaction plants developed in the last decades employ the Claude cycle or one of its variations. A schematic representation of the Claude cycle is shown in Fig. 3

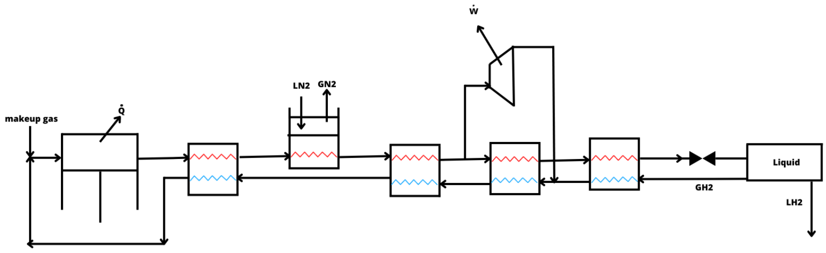


Figure 3. Schematic representation of the Claude cycle. Adapted from Nandi and Sarangi (1993). LN2 stands for liquid nitrogen, GN2 stands for gaseous nitrogen, LH2 stands for liquid hydrogen, GH2 stands for gaseous hygrogen, $\dot{Q}$ stands for the heat dissipated by the compressor, and $\dot{W}$ stands for the turbine power.

- **Helium-Brayton Cycle**: In this cycle, a secondary refrigeration cycle, usually employing helium, is used to cool the hydrogen stream in a heat exchanger. This allows hydrogen to operate at even lower pressures, which is advantageous for safety concerns. Moreover, 100% of liquid hydrogen can be obtained, since the helium streams can achieve temperatures below 20 K (Nandi and Sarangi, 1993). A schematic representation of the brayton cycle is shown in Fig. 4.

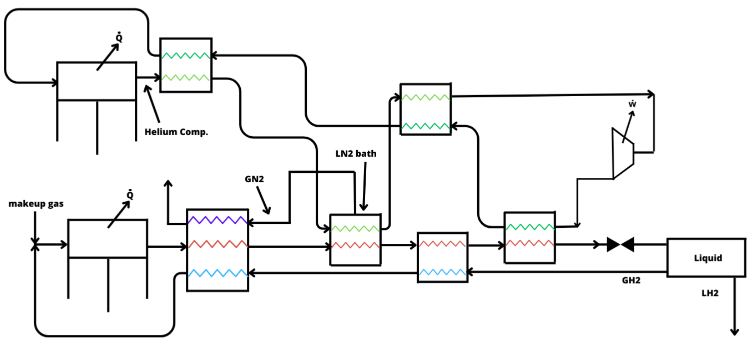


Figure 4. Schematic representation of the Helium Brayton process. Adapted from Nandi and Sarangi (1993). LN2 stands for liquid nitrogen, GN2 stands for gaseous nitrogen, LH2 stands for liquid hydrogen, GH2 stands for gaseous hygrogen, $\dot{Q}$ stands for the heat dissipated by the compressor, $\dot{W}$ stands for the turbine power.

### 2.2 Prototypes and plants

The theoretical cycles presented previously have been implemented in actual plants in different locations around the world. Given the limited technological readiness, investments, and industrial applications, current liquefaction plants have not reached the expected potential; however, several developments over the last years have significantly increased their performance. Among them, we can highlight:

- **Ingolstadt liquefier**: The plant was inaugurated in 1992 in Germany with a liquid hydrogen production capacity of 4.4 tons per day (TPD). The base cycle used is Claude, and liquid nitrogen is used for the pre-cooling phase. To reach approximately 30K, 3 oil turbines are used operating between 3 and 22 bar with a rotation speed around 70000 rpm. After that, the gas flows through the expansion valve, reaching the liquid state. The Ortho-Para conversion is carried out in four stages, two isothermal and two adiabatic, using Fe(OH)3 as the catalyst. The energy consumed in the liquefaction depends greatly on the energy used in the nitrogen liquefaction. Assuming it as 0.4 kWh/l LN2, the system performs with a power consumption of 13.6 kWh/kg-LH2 (Bracha *et al.*, 1994).
- **Leuna liquefier**: The plant was inaugurated in 2007 in Germany with a capacity of 5 TPD. It is very similar to Ingolstadt liquefier, with some modifications that led to significant improvements. The first major change was the use of 3 turbines operating between 20 and 5.2 bar with a rotation speed of 102000 rpm. The other major improvement is the packaging of Fe2(OH)3 catalyst on the hydrogen side of the heat exchangers to induce continuous ortho-to conversion. For this, the energy consumption of the plant is approximately 11.9 kWh/kgLH2 (Essler *et al.*, 2012).
- **Praxair**: Praxair has 4 hydrogen plants located in the United States, which generate around 20 to 36 TPD of liquid hydrogen, with an energy consumption of 12.5 to 15 kWh/kgLH2. In general, they are very similar to the two mentioned above, employing liquid nitrogen as pre-coolant and turbines for final cooling (Schawartz, 2011).

Adding to the above, there are many other hydrogen liquefaction plants around the world, for example in the United States has several plants spread across several states, the two largest produce 62.5 and 54 TPD, belonging to Stearns-Roger Mfg. Co. and Union Carbide, respectively. Other countries have hydrogen liquefaction stations as well, such as Japan, France, Germany, India, China and others, and the largest hydrogen liquefaction plant outside the USA is located in Canada producing 30 TPD and belongs to APCI. Table 1 summarises the main characteristics of most of them (Aasadinia and Mehrpooya, 2018).

### 2.3 Conceptual plants

Leaving the experimental scope and entering the computational area, this section of the paper aims to discuss some conceptual cycles existing in the literature, for which the results were obtained in numerical simulations. In this part of the paper, we address more advanced techniques and more sophisticated cycles. The main selected configurations are:

- **Quack (2013)**: It initially has 5 isothermal compressors (each with 85% efficiency) and proposes propane as the pre-coolant substance. From a temperature of 220 K to 25 K, a mixture of helium and neon is cooled by turbines and later used to refrigerate hydrogen. After that, the gas passes through an expansion valve and the non-liquefied part is compressed, cooled, and expanded again. It is assumed that the ortho-para conversion is performed continuously by placing the catalyst material inside the heat exchangers, on the side where the hydrogen flows, and the plant consumption is 7 kWh/kg-LH2 (when assuming the atmospheric pressure as input data).
- **SINTEF with MR pre-cooling**: A modified version of the process suggested by Quack (2013). The hydrogen supply conditions are 21 bar and 310K and the main difference is the initial cooling method, which uses a mixture of coolant liquids, namely C1-C5, Ethylene, Nitrogen, Neon, and R14, cooling hydrogen to 80K. From there, the hydrogen is cooled up with the reverse Brayton cycle of the same He/Ne mixture to 26.5K, passing through the expansion valve after that (exactly like the Quack proposal). The energy consumed at 6.2-6.5 kWh / kg-LH2 and exergy efficiency (EXE) is 44.5-46.6% (Berstad *et al.*, 2010).
- **Valenti and Macchi (2008)**: A complex and large-scale cycle with a production capacity of 860 TPD. It uses four stages of refrigeration, all of which use helium as the refrigerant and the Brayton cycle as the base cycle. The hydrogen feed is at 60 bar, with ortho-para conversion coupled to the exchangers and a specific energy consumption (SEC) of 5.04 kWh/kgLH2.
- **Baker and Shaner (1978)**: Baker and Shaner presented a study on the efficiency and economy of a 250 tpd hydrogen liquefactor. The cycle studied is a Claude cycle with nitrogen pre-cooling and a hydrogen turbine expansion at two different pressure levels. A dedicated nitrogen reliquefaction unit is assumed to supply the process with saturated LN2 and GN2 for hydrogen pre-cooling to 80 K. Ortho-para conversion is carried out in two stages: nitrogen and hydrogen cooled to 80 K and 20.2 K, respectively. The cycle has an estimated specific energy consumption of about 10.85 kWh/kg LH2.

Table 1. Existing plants. Adapted from (Aasadinia and Mehrpooya, 2018)

| Country | Location | Owner | Size (TPD) | Year established | In service |
|---|---|---|---|---|---|
| USA | Colorado | NBS | 0.5 | 1952 | – |
| USA | Ohio | APCIb | 1 | 1956 | – |
| USA | Painsville | Air Products | 3 | 1957 | No |
| USA | West Palm Beach | Air Products | 3.2 | 1957 | No |
| USA | Florida | APCI | 3.5 | 1957 | – |
| USA | California | Stearns-Roger Mfg. Co. | 1.5 | 1957 | – |
| USA | Florida | APCI | 30 | 1958 | – |
| USA | West Palm Beach | Air Products | 27 | 1959 | No |
| USA | Mississippi | Air Products | 32.7 | 1960 | No |
| USA | California | Stearns-Roger Mfg. Co. | 7 | 1960 | – |
| USA | Ontario, CA | Praxair | 20 | 1962 | Yes |
| USA | California | Stearns-Roger Mfg. Co. | 26 | 1962 | – |
| USA | California | APCI | 32.5 | 1963 | – |
| USA | Sacramento | Union Carbide | 54 | 1964 | No |
| USA | New Orleans, LA | APCI | 34 | 1977 | Yes |
| USA | New Orleans, LA | APCI | 34 | 1978 | Yes |
| Japan | Amagasaki | Iwatani | 1.2 | 1978 | No |
| USA | Niagara Falls, NY | Praxair | 18 | 1981 | Yes |
| Canada | Sarnia Ontario, | APCI | 30 | 1982 | Yes |
| Japan | Tashiro | MHI | 0.6 | 1984 | No |
| Japan | Akita Prefecture | Tashiro | 0.7 | 1985 | Yes |
| USA | Sacramento, CA | APCI | 6 | 1986 | Yes |
| Japan | Tane-Ga-Shima | Japan Liquid Hydrogen | 1.4 | 1986 | Yes |
| Japan | Oita | Pacific Hydrogen | 1.9 | 1986 | |
| Canada | Monterial | Air Liquide | 10 | 1986 | Yes |
| Holland | Rosenburg | APCI | 5 | 1987 | Yes |
| France | Waziers, Lille | Air Liquide | 10 | 1987 | Yes |
| Japan | Minamitane | Japan Liquid Hydrogen | 2.2 | 1987 | Yes |
| Canada | Becancour Quebec | Air Liquide | 12 | 1988 | Yes |
| USA | Niagara Falls, NY | Praxair | 18 | 1989 | Yes |
| Canada | Magog, Quebec | BOC | 15 | 1989 | Yes |
| Guyanac | Kouru F. | Air Liquide | 5 | 1990 | Yes |
| Canada | Monterial | BOC | 14 | 1990 | Yes |
| Germany | Ingolstadt | Linde | 4.4 | 1991 | Yes |
| India | Mahendragiri | ISRO | 0.3 | 1992 | Yes |
| USA | Pace, FL | APCI | 30 | 1994 | Yes |
| USA | McIntosh, AL | Praxair | 24 | 1995 | Yes |
| China | Beijing | CALT | 0.6 | 1995 | Yes |
| USA | East Chicago, IN | Praxair | 30 | 1997 | Yes |
| Japan | Kimitsu | Air Products | 0.3 | 2003 | Yes |
| India | Saggonda | Andhra Sugars | 1.2 | 2004 | Yes |
| Japan | Osaka | Iwatani | 11.3 | 2006 | Yes |
| Germany | Leuna | Linde | 5 | 2008 | Yes |
| Japan | Tokyo | Iwatani | 10 | 2008 | Yes |
| India | India | Asiatic Oxygen | 1.2 | – | Yes |
| USA | California | Stearns-Roger Mfg. Co. | 62.5 | – | – |
| USA | New Jersey | Air reduction Sales Co. | 6 | – | – |
| USA | Ashtabula, OH | Praxair | – | – | No |

- **Gas Equipament Engineering Corp (GEECO)**: The version of the process has similarities to the process proposed by Valenti and Macchi (2008), in the sense that only helium is employed as a refrigerant in a multistage reverse Brayton cycle, and subcooled liquid hydrogen is produced via a final liquid expander without flash gas. In contrast to Valenti and Macchi (2008) four different helium pressure levels, GEECO's Brayton helium process has only two pressure levels between which all expanders operate. Rather than assuming continuous ortho-para conversion within the heat exchangers, the current process scheme has four additional dedicated helium-cooled catalytic converters, which are likely to be less efficient than in the previous configuration as a result of off-balance operation. Liquid hydrogen with 95% para content is produced at 1 bar with a reported specific energy consumption of 8.73 kWh/kg (Shimko *et al.*, 2008).

- **IDEALHY**: The plant proposed by IDEALHY suggests a pressure of 80 bar during the process, with pre-cooling using a mixture of refrigerant gases consisting of nitrogen, methane, ethane, propane, and butane, reaching a temperature of 130 K. 26.9K, a Brayton cycle with a mixture of helium and neon is used, with a final expansion using gas bearing turbines or piston expander (Stolzenburg *et al.*, 2013).

- **WE-NET**: The Japanese WE-NET project proposes 4 large-scale hydrogen liquefaction cycles (300 TPD), each with a peculiarity. Table 2 shows the technical differences of the four proposals. The proposals coming from the plants based on the Claude cycle have a structural difference in that WE-NET H2-Claude has an intermediate gas expansion turbine for the hydrogen process stream that induces a temperature drop so that this stream does not need cooling in the interval of temperature of the second coldest heat exchanger. The proposals coming from plants based on the Brayton cycle have two differences, the liquid for cryogenic cooling, one uses helium and the other uses neon, the other difference being the number of cryoexpanders and the parallel configuration of the one using neon (Matsuda and Nagami, 1997) (Ohira, 2004).

Table 2. WE-NET proposals.

| Plant | Production [TPD] | Specific energy consumption [kWh kgLH2] | Based | Pre-refrigeration | Refrigeration | Ortho-para [conversion] | Exergy efficiency [%] |
|---|---|---|---|---|---|---|---|
| **WE-NET H2-Claude (1997)** | 300 | 8.53 | Claude | LN2 | Hydrogen | continuos | 46.0 |
| **WE-NET He-Brayton** | 300 | 8.69 | Brayton | LN2 | Helium | continuos | 45.1 |
| **WE-NET Ne-Brayton** | 300 | 8.58 | Brayton | LN2 | Neon | continuos | 45.7 |
| **WE-NET H2-Claude (2004)** | 300 | 8.72 | Claude | LN2 | Hydrogen | continuos | 45.2 |

- **Yuksel *et al.* (2017)**: This cycle leads to an innovative proposal. The first novelty is not to use a different substance for pre-cooling, such as (Valenti and Macchi, 2008). All stages of refrigeration are carried out by helium, which causes hydrogen to leave room temperature up to the liquefaction temperature. As a result of the nonexistence of other refrigerant gases, there is a need for more isentropic turbines (four in total) to reduce the enthalpy and, consequently, the temperature. The production capacity is 50 TPD with an energy efficiency of 70.12% and an EXE of 57.13% and due to the large mass deviations to the turbines, the helium flow must be considerably large.

- **Krasae-in (2014)**: This proposal has two stages: one for pre-cooling and one for liquefaction. The first stage consists of cooling the hydrogen from a temperature of 25°C to -193°C. For this, a coolant mixture is used (the article cites 4% hydrogen, 18% nitrogen, 24% methane, 28% ethane, and 26% butane) and this step occurs with great efficiency. The second stage consists of decreasing the temperature from -193°C to -253°C. For this, the "Joule-Brayton cascade refrigeration system" is used, which consists of cooling hydrogen with hydrogen itself in a kind of cascade. The process requires very extensive heat exchangers and does not use a Joule-Thomson expansion valve. The hydrogen gas flow is 1.157 kg/s, the operating pressure of the hydrogen that will be liquefied will be 21 bar and the inlet temperature is 25°C, the production is 100 TPD and deliveres 95% liquid parahydrogen.

- **Sadaghiani and Mehrpooya (2017)**: It has two stages, in which the pre-cooling is performed with a mixture of 9-component coolants and the cooling phase occurs with a mixture of coolants with 3 components (10% neon, 6.5% hydrogen and 83.5% of helium). The cycle produces 300 TPD, with an SEC of 4.410 KWh/kgLH2, EXE=0.5547, coefficient of performance (COP)=0.1797.

## 2.4 Not in-kind technologies

In addition to compression and expansion systems, hydrogen can be liquefied with emerging refrigeration technologies. Peixer *et al.* (2023a) reviewed both conventional technologies and also non-in-kind methods such as absorption

Table 3. Conceptual plants performance metrics

| Plant | Production [TPD] | Specific energy consumption [kWh kgLH2] | Based | Pre-refrigeration | Refrigeration | Ortho-para [conversion] | Exergy efficiency [%] |
|---|---|---|---|---|---|---|---|
| **Ingolstadt liquefier** | 4.4 | 13.6 | Claude | LN2 | Hydrogen | 4 stages | 21 |
| **Leuna liquefier** | 5 | 11.9 | Claude | LN2 | Hydrogen | continuos | 23.6 |
| **Praxair** | 20-36 | 12.5-15.0 | Claude | LN2 | Hydrogen | unknown | unknown |
| **Quack/TUD** | 86-170 | 7 | Brayton | Propane | Helium/Neon | continuous | 53.8-60.7 |
| **SINTEF** | 86 | 6.2-6.5 | Brayton | mixed | Helium/Neon | continuos | 44.5-46.6 |
| **WE-NET H2-Claude (1997)** | 300 | 8.53 | Claude | LN2 | Hydrogen | continuos | 46.0 |
| **WE-NET He-Brayton** | 300 | 8.69 | Brayton | LN2 | Helium | continuos | 45.1 |
| **WE-NET Ne-Brayton** | 300 | 8.58 | Brayton | LN2 | Neon | continuos | 45.7 |
| **WE-NET H2-Claude (2004)** | 300 | 8.72 | Claude | LN2 | Hydrogen | continuos | 45.2 |
| **Valenti & Macchi (2008)** | 860 | 5.04-5.29 | Brayton | - | Helium | continuos | 48.3 |
| **Baker and Shaner (1978)** | 250 | 10.85 | Claude | LN2 | Hydrogen | 2 stages | 36 |
| **GEECO** | 50 | 8.73 | Brayton | - | Helium | 4 stages | 44.6 |
| **IDEALHY** | 50 | 6.4 | Brayton | mixed | Helium/Neon | unknown | unknown |
| **Yuksel et al. (2017)** | 50 | unknown | Brayton | - | Heilum | 3 stages | 57.13 |
| **Krasae-in (2014)** | 100 | 5.91 | J-B | mixed | Hydrogen | stages | unknown |
| **Sadaghiani and Mehrpooya (2017)** | 300 | 4.41 | Brayton | mixed | He, Ne e H2 | 2 stages | 55.47 |

systems and electrocaloric technologies. Among these methods, the most promising one is magnetic refrigeration. However, one of the most important comments made in the work is the fact that, despite promising results and high expectations associated with magnetocaloric cooling, the technology is still at an early stage in terms of hydrogen liquefaction technologies, similarly to room temperature systems (Nakashima *et al.*, 2021; Peixer *et al.*, 2023c). Although liquefaction plants using conventional technologies are focused on increasing their capacity to tens of tons per day, magnetocaloric systems are still small-scale prototypes. Among many works in the literature, we can highlight:

- **Feng *et al.* (2020)**: This paper proposes a low-scale hydrogen liquefaction cycle with a production of 300 kg of liquid hydrogen per day. The cycle proposes pre-cooling with liquid nitrogen up to approximately 80K. For the rest of the refrigeration, the magnetocaloric effect is used, which has a 1T permanent magnet structure. To obtain the results, the authors used numerical simulations. The number of stages and temperature interval, particle size of the magnetocaloric material, porosity of the medium, geometry of the regenerator bed, mass of the magnetocaloric material, and helium flow were evaluated. The results obtained are shown in the Tab 4.

Table 4. Results of different AMR Cycles

| **Input Parameters** | **Case 1** | **Case 2** | **Case 3** | **Case 4** | **Case 5** | **Case 6** | **Case 7** |
|---|---|---|---|---|---|---|---|
| Model | SS | SS | TD | SS | SS | TD | TD |
| Temperature Span at each stage (K) | 4 | 5 | 5 | 5 | 10 | 10 | 20 |
| Frequency (Hz) | 10 | 10 | 10 | 1 | 10 | 10 | 10 |
| Number of stages | 15 | 12 | 12 | 12 | 6 | 6 | 3 |
| Magnetized Volume ($m^3$) | 0.642 | 0.609 | 0.609 | 0.727 | 0.4 | 0.416 | 0.446 |
| Mass Of MCM (kg) | 3.33 | 3.2 | 2.86 | 3.36 | 2.45 | 2.64 | 2.65 |
| COP | 0.23 | 0.26 | 0.26 | 0.22 | 0.27 | 0.24 | 0.23 |
| Second Law Efficiency | 68.40% | 77.80% | 76.40% | 65% | 81.20% | 71.80% | 67.50% |

- **Numazawa2014**: The paper consists of an experiment that proposes a system that liquefies 10 kg of hydrogen per day. The cycle proposes a pre-cooling with liquid nitrogen, reported that the cycle period is 8 seconds, a superconducting magnet with a maximum field of 6 T, the magnetocaloric material used is $Dy_{2.4}Gd_{0.6}Al_5O_{12}$ and a particle size of 0.4 mm, with helium as the heat transfer fluid and a Carnot efficiency of 50%.

## 3. Discussion

Firstly, it is important to point out that advanced studies on hydrogen liquefaction are relatively recent because the use of the substance has gained more spotlight in recent decades. Most of the works are revisions or proposals for new cycles, exposing data such as SEC, COP, EXE, and daily production. The issue to be debated is the differences between them and the lack of a conclusion about which ideas are more efficient on certain occasions. For example, as previously explained, there are several methods to carry out the pre-cooling phase, some of them using liquid nitrogen, a mixture of refrigerant gases (and within this mixture, there are infinite possibilities of components and concentrations), there is also the option of not using pre-cooling fluid and cooling everything with the same fluid; among other methods, but there are no studies that show the advantages and disadvantages, or even which of the methods is cheaper or more effective. This analysis extends to the refrigeration phase since some use hydrogen itself to reach the liquefaction temperature, others use helium, others use a mixture of helium with neon or even helium, neon, and hydrogen. The proposals of the WE-NET company are close to the study suggested but they're not ideal in this regard because they change the structural configurations from one plant to another. Therefore, the first to extract maximum efficiency at a lower cost is this substance analysis. In that scenario, methodologies that involve integrated optimisation at the system level Peixer *et al.* (2023b) have the potential to allow the determination of the optimal design parameters of the system.

The second part that must be analysed in detail is the structural part of the plants. There are three basic configurations for the liquefaction of hydrogen, each with its advantages and disadvantages. That said, an interesting evaluation to be performed is the quantity and the correct positioning of components, such as expanders, for example, within these predetermined proposals, as this directly interferes with the optimisation of the desired parameters (such as the specific energy consumption, SEC, and daily production). This study would have greater difficulty in implementation and a longer duration, due to the numerous existing configuration possibilities and perhaps would require the use of an AI or something similar. After these more macroscopic and idealised analyses, the last step would be an analysis more focused on details such as imperfections, such as pressure drop and efficiency analysis of the devices that make up the cycles.

Currently, with the existing work, it is possible to obtain many conclusions about hydrogen liquefaction plants. The first statement is the fact that some articles point out that the continuous ortho-para conversion has a better interaction, causing the cycle to spend less energy at the end of the process compared to the conversion done in stages. Another idea to be highlighted is that the higher the production, the lower the SEC tends to be proportionally. Finally, some work indicate that a mixture of He and Ne is more efficient in heat transfer and mechanical compression/expansion in cycles liquefaction than using pure He or Ne (article Conceptual design of a high-efficiency large-capacity hydrogen liquefier). However, as stated earlier, there are many other questions that must be answered to make hydrogen liquefaction cheaper, more efficient and therefore more viable.

## 4. Conclusion

It is concluded that the existing liquefaction plants are not yet as efficient as they could be, and the constant search to make the use of hydrogen increasingly viable in society requires their improvement. With this, studies in the area should seek greater objectivity and greater connection with each other, with the aim of improving the technologies already available and creating new ones, always seeking the economic and environmental viability of the process. For this there must be a greater investment in the area and a better focus of the studies carried out.

## 5. ACKNOWLEDGEMENTS

Financial support from CNPq, FAPESC, CAPES, and the EMBRAPII Unit Polo/UFSC is duly acknowledged.

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