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AN OVERVIEW AND A COMPARATIVE ANALYSIS OF THE MAIN TECHNOLOGIES FOR HYDROGEN STORAGE

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Abstract. *Every aspect of human life depends on energy. Fossil fuels have been the primary source of energy since the Industrial Revolution, and their unregulated and unrestricted use over the past few decades has led to numerous environmental hazards. As a response, new proposals and alternative sources of clean energy have been developed. Despite the difficulties associated with its production, storage, and transportation, hydrogen appears to be a promising new and environmentally friendly energy source and a great candidate for replacing fossil fuels. However, the technology struggles with difficulties, such as the large amount of energy spent during the storage process, which also impacts directly in the way it is transported and applied. For this reason, comparative analysis with current technologies and evaluations of their efficiency are complex. Recent work has been developed with the aim of improving existing storage methods, most commonly through compressed gas, liquid hydrogen, cryo-compressed hydrogen, liquid organic hydrogen carriers, cyclic agents, and solid carriers. Each method presents advantages over the others and receives increased attention depending on their final goal. In this paper, we present a comparative analysis of these technologies and proposals on how these difficulties can be overcome.*

Keywords: *Clean Energy, Hydrogen, Hydrogen Storage, Comparative Analysis, Technology Assessment*

1. INTRODUCTION

Innovation is an ongoing effort that affects all areas of human development, so its no surprise that the energy sector is also influenced by it. There is an urge in the need to change the main energy source of the world, a direct result of the high use of fossil fuel, which creates several environmental hazards. In an attempt to find a long-term solution, hydrogen is at the center of an ongoing debate involving researchers worldwide. Among the technologies on discussion, the hydrogen stands out as a source that is highly commented due to its abundance, elevated energy per kilogram ratio - i.e -, 120 MJ/kg which surpasses the gasoline in almost 3 times (Faye *et al.*, 2022), and also because it is a clean energy source, since its combustion results only in energy and water as final products. Furthermore, according to Niaz *et al.* (2015), other applications for hydrogen are seasonal storage, which is paired with other renewable energy sources, where the production of hydrogen would be done during periods of energy abundance, and during moments of need, the energy would be extracted from the hydrogen, thereby reducing the fluctuations of energy production attached to renewable sources.

Because hydrogen is the lightest molecule, 1 kg of hydrogen occupies 11 m^3 under ambient conditions, which is a result of its volumetric density (0,09 kg /m^3). Hence, it is impractical to transport it under ambient conditions (Reuß *et al.*, 2017). Therefore, with the goal of overcoming this obstacle, a variety of alternatives for hydrogen storage methods have emerged over the last few decades. However, all of the storage methods developed so far require improvements, which creates a great space for innovation, such as methods with higher efficiency and subprocesses with a better rate of performance. It is difficult to make a straightforward comparison of the alternative because each method has a different advantage correlated to it. Therefore, the main methods of hydrogen storage and a brief explanation of how each one is performed will be presented in this paper.

2. STORAGE METHODS

Hydrogen storage techniques can be divided into physical storage, where hydrogen would remain pure throughout the process (Faye *et al.*, 2022) and chemical storage, where hydrogen is attached to others elements by adsorptive or absorptive technologies. Figure 1, adapted from Abdin *et al.* (2021) compares the volumetric density, the amount of energy contained per unit of volume, and the gravimetric capacity that is the representation of the amount of energy in terms of the total mass on the main storage methods.

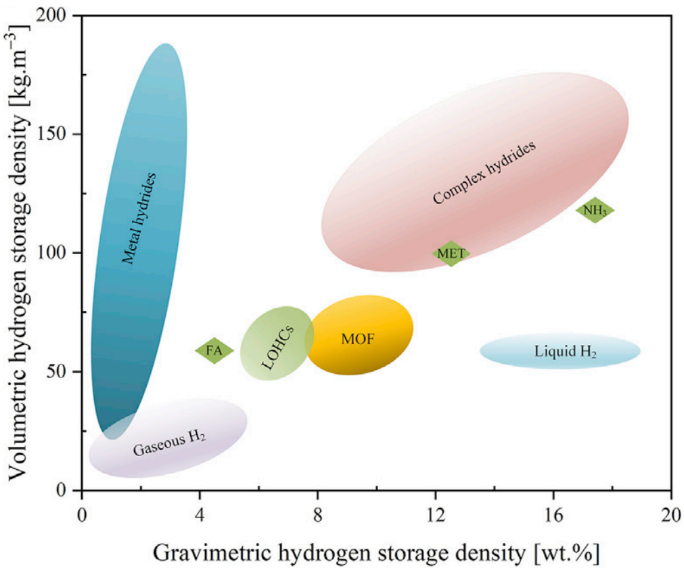

Figure 1. Comparison of the main hydrogen storage methods. Adapted from Abdin *et al.* (2021).
FA = Formic acid; LOHC = Liquid organic hydrogen carriers; MOF = Metal-organic frameworks; MET = Methanol; NH3 = Ammonia.

The graphic above shows a relation between two important physical traits, the volumetric density, and the gravimetric capacity. The main goal is an elevated value for both traits. However, it is not always possible, and depending on the application the downsides of a low trait is not an impending factor, such as for stationary applications, that the gravimetric capacity is not highly relevant when compared to the volumetric capacity.

2.1 Physical methods

The main goal of physical methods is to maintain the purity of the hydrogen during the entire processes. It also aims to increase the volumetric density and gravimetric capacity of the hydrogen through a pressure increase, liquefaction of the element, or mixture of both.

2.1.1 Compressed gas

The first method to be explored is the compressed gas, since it has been a well-established technology. It consists of the increasing pressure to gain volumetric density. However, hydrogen is a very small molecule, therefore pressure needs to increase to 200-700 bar to achieve a density of 40 kg/m^3 (Faye *et al.*, 2022). Also, a relevant fact is the non-linear density variation, which is a function of pressure and temperature (Faye *et al.*, 2022), as shown in Fig. 2.

The energy consumption to compress hydrogen is a direct result of the aforementioned variations. For example, according to the Department of Energy (DOE) (Gardiner, 2009) the minimum energy consumption to compress hydrogen from 1 to 20 bar is 1,02 kWh/kg, and 1,05 kWh/kg is needed to obtain 350 bar from the initial pressure of 20 bar. Due to the non-linear behavior, the energy required to compress the gas from 20 to 700 bar is 1,36 kWh/kg. These values represents approximately 4% of the lower heating value of hydrogen (LHV) (Gardiner, 2009), which is the amount of energy that can be extracted from it. As a consequence of the low difference in the consumption to high pressure compression, the transport of hydrogen through compressed gas is very attractive, although there are serious security risks attached to this method, such as explosions.

Compared with other methods, compressed gas offers significant advantages, including a wide range of available transportation methods and the ability to reach various locations. Transportation by high-pressure tanks in trucks also provides fast fueling and discharge. However, it also poses explosion hazards and elevated costs of the tanks that can have

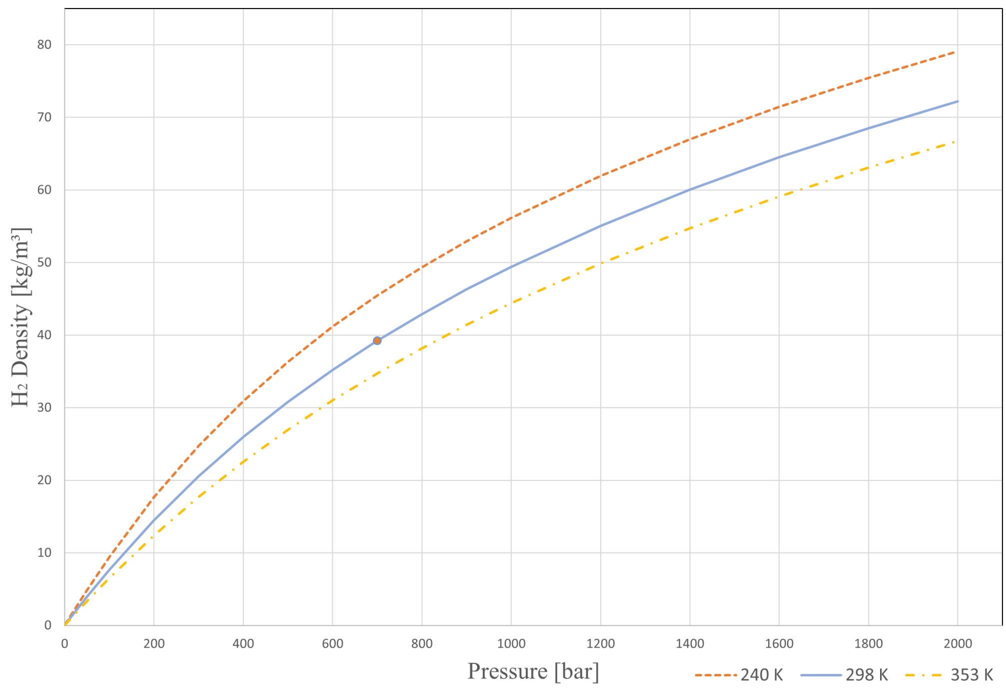

Figure 2. Pressure x density for hydrogen.
The point above shows the density under 700 bar.

values of $800 dollars per kilogram of hydrogen. Furthermore, another way to transport compressed gas is by underground pipes, similar to those that transport liquefied petroleum gas (LPG) (Andersson and Grönkvist, 2019), which has a high initial cost, but its low operational costs would pay off the investments over time. Lastly, it is a safer and more durable method (Faye *et al.*, 2022).

With the goal of overcoming the main challenges of this method of transportation, options such as storage in salt caverns were proposed, because they are less expensive than tanks and support pressures up to 200 bar. In addition, new tanks and pipes materials have been developed, with the aim of achieving safer and more efficient storage. If all these innovations are achieved, it is possible that compressed gas can be spread as a storage method for quick uses and short range of applications.

2.1.2 Liquid Hydrogen

As an alternative to hydrogen compression, there is the hydrogen liquefaction process. This method is based on the achievement of the boiling point of hydrogen, which is 20 K (-253°C) at ambient pressure. The advantages of this method are the low pressure during transport and the high volumetric density of 70,8 kg/m^3 (Faye *et al.*, 2022), which allows the transport of a larger amount of hydrogen during each journey. However, its extremely low temperature has been the reason for a series of difficulties since the beginning of the liquefaction path. As a base for the liquefaction cycles, there are Linde, Claude, and Brayton cycles. A common technique used to improve the performance of the process is the use of a nitrogen bath (Raab *et al.*, 2021), which reduces the hydrogen temperature to 77 K. Hydrogen liquefaction systems consume large amounts of energy. The specific energy consumption (SEC) of the current constructed plants varies between 11 and 15 kWh / kg, which represents 30-45% of the LHV of hydrogen (Reuß *et al.*, 2017; Niermann *et al.*, 2021; Raab *et al.*, 2021). Some analyses suggest that, for the wide application of liquid hydrogen, its SEC must achieve values of 5,9-6,6 kWh/kg (Cardella *et al.*, 2017). A comparison of the power consumption of ongoing and theoretical technologies for hydrogen technologies is shown in Fig. 3.

In the literature, it can be found that the theoretical minimum energy consumption for hydrogen feeding liquefaction at 25 bars is 2,7 kWh / kg (Cardella *et al.*, 2017), considering the ortho-para transition, that consumes up to 0,65 kWh/kg (Gardiner, 2009). Such values represent only 10% of the LHV of hydrogen. Therefore, ongoing plants have great opportunities for innovation to be explored. To improve liquefaction plants, the main alternatives are the integrated design of the liquefaction system (Peixer *et al.*, 2023b), hybridization with other renewable energy sources (Peixer *et al.*, 2023a), and evaluation as innovative cooling technologies, such as magnetocaloric refrigeration (Nakashima *et al.*, 2021; Peixer *et al.*, 2023c).

Recent research focuses on the reduction of operational costs and a higher cycle efficiency, not taking in consideration

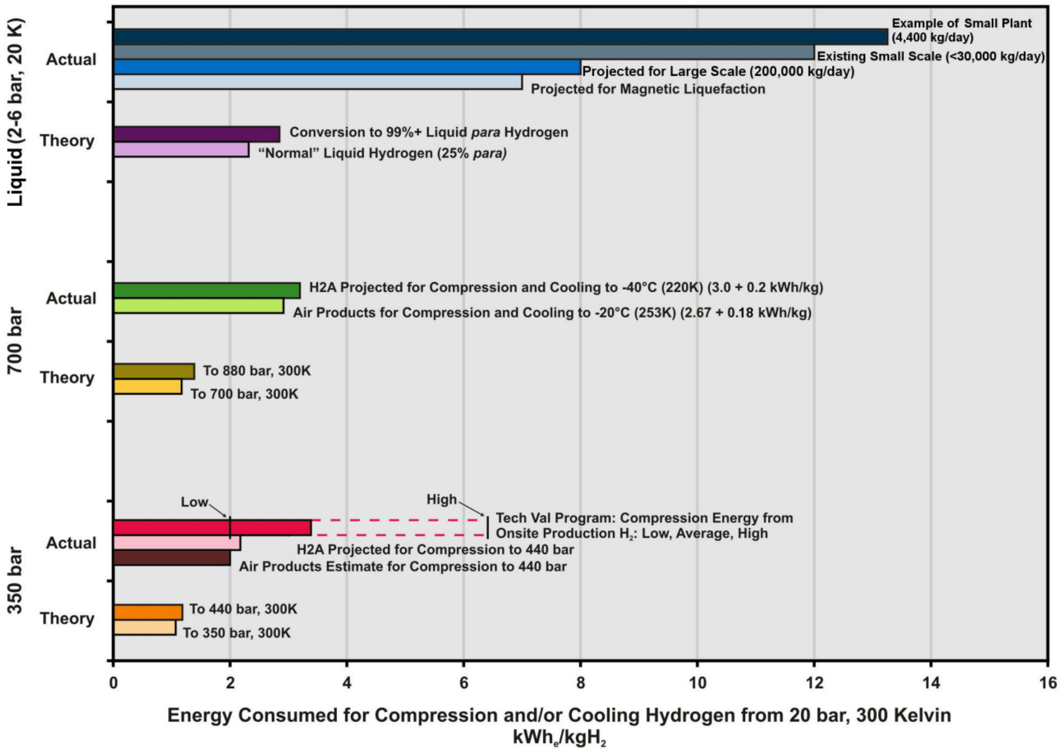

Figure 3. Power consumption comparitive of ongoing and theoretical technologies for hydrogen storage. Adapted from (Gardiner, 2009).

that the initial cost of plant implementation has a huge impact in considering whether the plant will be constructed (Cardella *et al.*, 2017). Therefore, a conciliation between initial investment and operational costs is crucial for this kind of project.

Furthermore, there is the boil-off problem, a phenomenon that is a result of the loss of hydrogen caused by the liquid gas transformation during the transportation process. This can occur by external heat transfer or due to the fact that hydrogen has two molecular states, they are related to the spinning rotation of its atoms and are called ortho-hydrogen and para-hydrogen (Aziz, 2021), these states vary their stable proportion depending on the temperature of the molecule. Under ambient conditions, the so-called normal hydrogen is a relation of 75% ortho and 25% para hydrogen, and as the temperature is reduced, the proportion changes as a nonlinear function.

During the liquefaction process, the reduction of temperature is done rapidly, which does not provide enough time for the ortho-para transition to occur naturally. Therefore, the transformation will occur spontaneously until it reaches the proportion of 0,2% ortho and 99,8% para hydrogen. And to do this reaction, it releases enough energy to evaporate the liquid, creating serious difficulties for long-term storage of hydrogen.

With the goal of reducing the boiling effect, suggestions emerged, such as the use of better catalysts during the liquefaction process so in the end the hydrogen obtained would be ortho-para balanced. Furthermore, the reduction in contact area with spherical tanks would reduce the amount of heat transferred from the environment, due to the lowest area per volume ratio of geometrical forms, and the development of new materials for better insulation of these tanks (Ratnakar *et al.*, 2021). Further, an alternative and a viable short-range application is the use of constant refrigeration during the transport process, maintaining the hydrogen in the liquid state; however, this method represents more expensive costs and high technology involved. Furthermore, it is possible to use the vaporized gas as a fuel in the vehicle transporting the hydrogen, resulting in a cost reduction in the transportation process, although this leads to a loss in the amount of hydrogen transported, causing a reduction in the overall efficiency of the method (Raab *et al.*, 2021; Ratnakar *et al.*, 2021) as it results in a loss of the transported hydrogen.

Also, another idea is the cogeneration of energy at utilization sites, using the need for cryogenic hydrogen to be heated to ambient temperature, creating a proper condition for liquid nitrogen plants (Wijayantaa *et al.*, 2019), using this cryogenic energy that is normally disregarded. As promising as it is, the liquid hydrogen still needs several studies and optimizations.

2.1.3 Cryo-compressed hydrogen

The cryo-compressed method aims to take advantage of both low-temperature and high-pressure methods, where it has a higher density than the two separately. However, it also inherits the main difficulties of each method, causing big losses due to Boil-off and higher cost of high pressure and well-insulated tanks for transportation (Faye *et al.*, 2022). Due to these factors, even with research in the area, the effectiveness of the cryo-compressed hydrogen method is uncertain; therefore, it is more likely to use the compressed gas and liquid hydrogen technologies separately.

2.2 Chemical methods

The chemical methods use chemical reaction to bond the hydrogen to certain materials, where the transport is easier and done under ambient conditions. It is possible to bond the hydrogen with adsorption, exploring the weak bonds governed by the Van der Waals forces, carrying the hydrogen on the surface of the substrate (Langmia *et al.*, 2014). Other possibility its the absorption method, that bonds directly the hydrogen to the molecule of a compound, requiring chemical reactions for the hydrogenation and dehydrogenation process.

2.2.1 Liquid Organic Hydrogen Carriers

Recent works suggest a liquid absorptive method in which the hydrogen would be carried in an organic compound and an alternation would occur between a rich compound of hydrogen and a poor one. The cyclic process is done through a hydrogenation step, which is an exothermic reaction that needs to be subjected to moderate temperatures and high pressures; afterwards the compound is transported and then subjected to a dehydrogenation step, as shown in Fig. 4. This last step of the process is endothermic and requires high temperatures and catalyzers to occur. Normally the catalyzers are noble metals such as platinum, palladium, gold, nickel, and rhodium. The condition of operation differs depending on the LOHC used; many were explored, but the main candidates to further implementation are: Benzene (BZ) & Cyclohexane (CHE); Toluene (TOL) & Methylcyclohexane (MCH); Naphthalene (NAP) & Decalin (DEC); N-ethyl-carbazole (H0-NEC) & Perhydro-N-ethyl-carbazole (H12-NEC); Dibenzyl toluene (H0-DBT) & Perhydro dibenzyl toluene (H18-DBT).

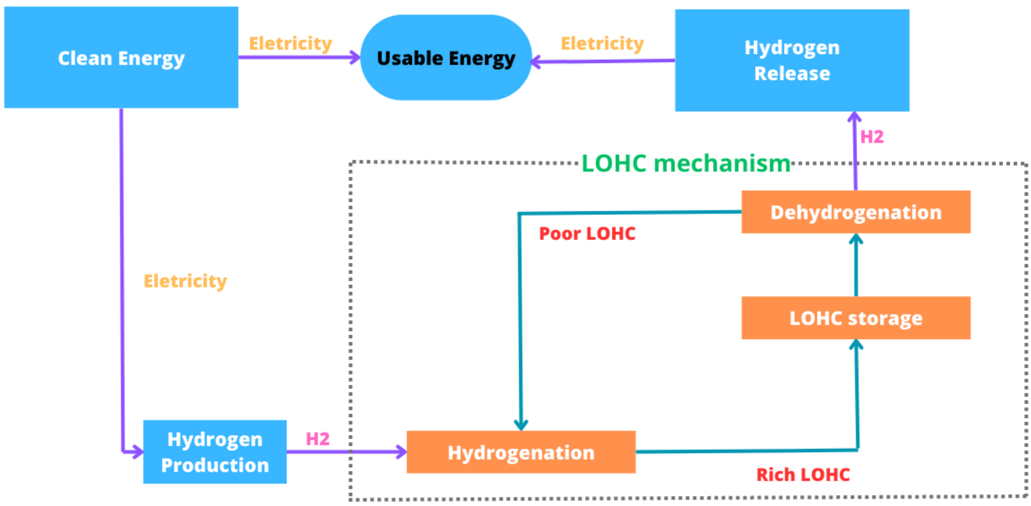

Figure 4. Diagram of LOHC mechanism.
Adapted from (Faye *et al.*, 2022)

In order to put forward a model of perfect LOHC a set of requirements was established. The total gravimetric capacity of the LOHC must be at least 6% by weight, the volumetric density must exceed 56 kg/m^3, and it should have a reaction enthalpy of 42-54 kJ/mol. Additionally, its melting and boiling points must be below 30°C and above 300°C, respectively.

The presented values of gravimetric capacity and volumetric density aim at a better efficiency and a higher quantity of hydrogen transport. The enthalpy of the reaction is directly associated with energy consumption during hydrogenation and dehydrogenation, so for a better economic performance, low values are the main goal. However, if the enthalpy of the reaction becomes too low, there is the risk of the inability of a new hydrogenation, which interrupts the main idea of the cyclic process (Bourane *et al.*, 2016). Furthermore, phase-changing temperatures are really relevant, so during all the transport processes, the compound is in liquid form, and after the dehydrogenation there is no need for a purification step. Also, according to Abdin *et al.* (2021) there are other important factors to consider, such as the toxicity of composts and the need for low cost organic compounds (Modisha *et al.*, 2019).

Each pair of LOHC possesses different attributes and properties. The BZ/CHE have a high gravimetric density.

However, their toxicity, high inflammability, and low boiling point implicates in a series of problems. Furthermore, the TOL/MCH pair has a great equilibrium in their properties, but they are a volatile compound and suffer from a low boiling point, similar to the BZ/CHE pair, which implies the need of a purification step at the end of the process. The pair composed of NAP/DEC has the highest volumetric density and gravimetric capacity on these compared LOHCs, but the DEC, the rich hydrogen compost of the pair, has a high melting point, which makes transportation to be done in the solid state, an undesired effect, and to prevent this, constant heating is needed, increasing the cost of the cycle; also, its reaction is not totally reversible (Modisha *et al.*, 2019). There is the NEC pair, which possesses the lowest enthalpy reaction, but it has a low gravimetric capacity and a high melting point, which involves a series of difficulties, similar to the DEC. Finally, the DBT compounds exhibit low toxicity, high gravimetric capacity, and high volumetric density, although their hydrogenation temperature is higher than the other LOHCs (Modisha *et al.*, 2019), causing higher energy consumption, and added to it, after several cycles, the DBT shows a loss in efficiency (Abdin *et al.*, 2021).

The LOHC is a promising technology for hydrogen storage and is even more notable if paired with seasonal storage. It operates under ambient conditions and does not have losses like the Boil-off or diffusion through tanks (Faye *et al.*, 2022). Furthermore, its similarity to crude oil makes it possible to use the already constructed structure, resulting in a great reduction in the installation cost (Niermann *et al.*, 2021).

The energy consumption of this method varies between 7 and 29% of the LHV, and is different for each of the pair utilized (Niermann *et al.*, 2021). Suggestions for cost reduction are under development, such as the use of a fraction of the liberated hydrogen to provide the rest of the energy required for the dehydrogenation process, and the usage of new catalysts made of metallic bonds, which are more efficient and economically viable. Therefore, with the right investments and enough research, the LOHCs can enable a wide spread of hydrogen use in a wide range of sectors, such as stationary energy or as a fuel for automobiles.

2.2.2 Cyclic agents

Cyclic agents act similarly to LOHC, however, the synthesis and decomposition steps are substituted by the capture and release of hydrogen bonding elements. Since it is not cost-effective to transport these chemicals separately (Raab *et al.*, 2021), this characterizes a semi-circular method. As the most promising cyclic agents, there are methanol (MET), formic acid (FA) and ammonia (NH3). Figure 5 from (Abdin *et al.*, 2021) presents a comparison between these agents and the LOHC already mentioned.

MET is a chemical that has a high gravimetric capacity and a low reaction enthalpy, it is liquid throughout the transport process, and has a synthesis temperature in a range between 230 °C and 330 °C. However, its low boiling point presents difficulties to separate the carbon dioxide gas from the hydrogen, so it implies the need of a purification step after the decomposition. Furthermore, during the same decomposition process, it produces 9-12 tons of carbon dioxide for each ton of hydrogen, which is against the idea of sustainable fuel (Abdin *et al.*, 2021).

As an alternative there is formic acid, which is the synthesis of hydrogen with carbon dioxide, and after the reaction they become a nontoxic, noninflammable, noncorrosive and easy-to-manipulate chemical. But the FA has a low gravimetric capacity compared to the other chemicals carriers, and added to it, during its decomposition occurs the release of monoxide and carbon dioxide (Sreedhara *et al.*, 2018), a non-desired by-product. So, to an effective usage of the FA several studies must be done.

The storage method of ammonia is the most researched storage method for hydrogen because of its high gravimetric capacity and higher volumetric density even in comparison to liquid hydrogen, facts that certainly attract a great amount of research. Furthermore, ammonia possesses a boiling point of -33°C, so it would need a less complicated thermal management during transportation. However, ammonia is a highly toxic product, which creates several risks in its manipulation (Faye *et al.*, 2022). Its synthesis is carried out by a method called Haber-Bosch and consumes large amounts of natural gas under high pressures and temperatures (Abdin *et al.*, 2021). Afterwards, its decomposition consumes high amounts of energy, due to the elevated operation temperature and the need for purification at the end of the whole process. All of this energy consumption represents 13% of the LHV of hydrogen (Wijayantaa *et al.*, 2019), a value that can be optimized with new catalysts and better techniques.

Similarly to the other technologies, the cyclic agents need further research to reduce the risks attached to this method and to increase the overall efficiency. However, in a short period of time, ammonia presents itself as the main storage method, due to its vast qualities and well-established production technology, in addition to that it can also use LPG pipes without the need of several modifications, as its characteristics are very similar (Wijayantaa *et al.*, 2019), thus avoiding the need to create a distribution network.

2.2.3 Adsorption

In the adsorptive method, the hydrogen bounds weakly to solid materials, these links are governed by the Van der Waals forces, and as a consequence of the weak interactions the hydrogen is maintained on the surface of the substrate, and porous materials are used for better results to obtain a higher surface of contact.

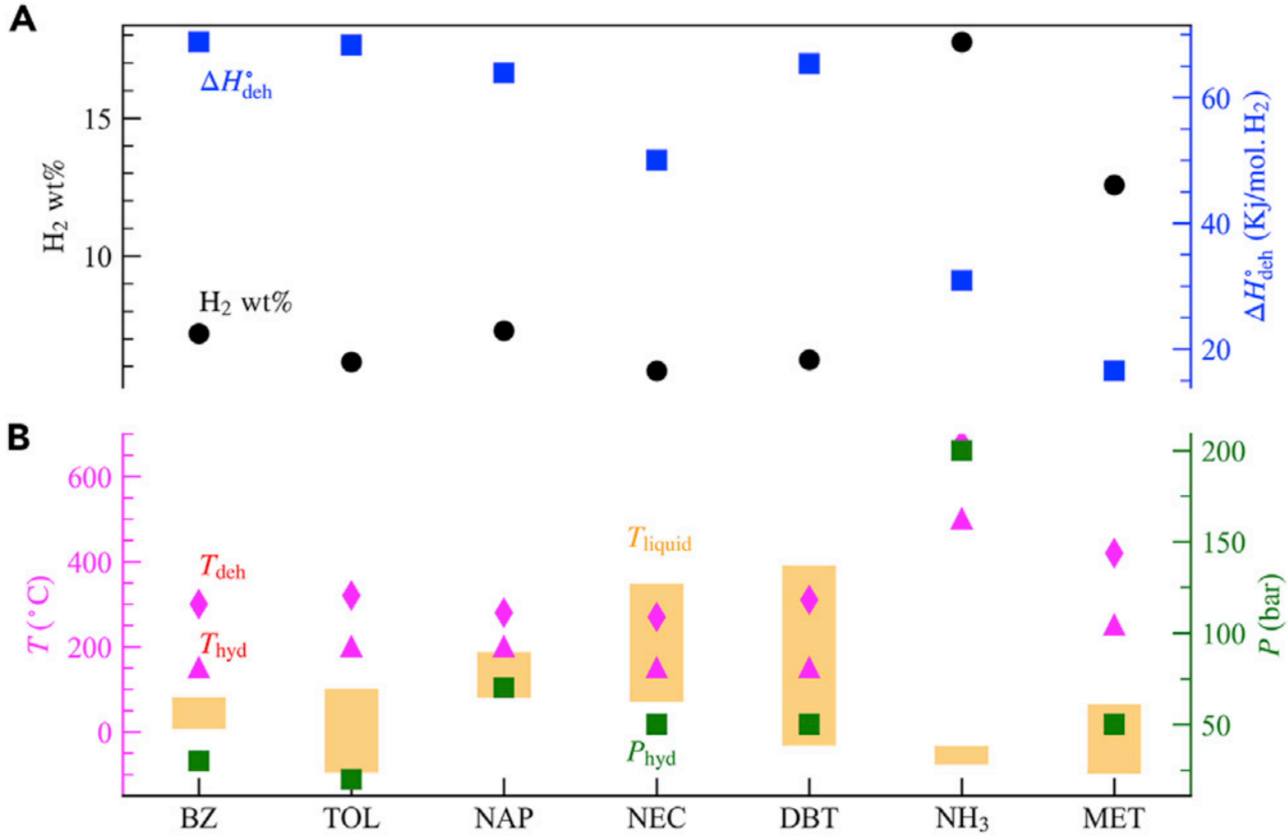

Figure 5. An analysis of the LOHC and cyclic agents.
A- Contains the gravimetric capacity and the reaction enthalpy.
B- Contains the common reaction temperatures and the liquid range, also possesses the hydrogenation pressures. Adpated from (Abdin *et al.*, 2021).

When dealing with weak forces, the ambient conditions are not optimal, since it has a low gravimetric capacity - i.e, 0,5-1 wt%, and a volumetric density of only 15 kg/m³ (Langmia *et al.*, 2014). This values are extremely low and unpractical for utilization. Therefore, the combined solid and hydrogen needs to undergo low temperatures and high pressures, where it can achieve values of 40-50 kg/m³ (Andersson and Grönkvist, 2019). The pressure uptake is advantageous only to a certain point, where the adsorptive capacity reaches a maximum, and after that point the compressed gas is the method with higher efficiency (Andersson and Grönkvist, 2019).

For optimal results, adsorptive materials need to be under pressures greater than 10 bar and temperatures lower than 77 K, a fact that creates the need for constant thermal management during the entire transportation process (Andersson and Grönkvist, 2019; Adametz *et al.*, 2014). However, these weak bonds leads to a low reaction enthalpy, resulting in fast reactions, and also the absence of a purification step (Adametz *et al.*, 2014), added to a complete reversibility of the process. All of these advantages are essential for a hydrogen storage method.

As an adsorptive material, the metal-organic framework (MOF) receives attention due to its high porosity, which is directly attached to its structure of crystalline materials, formed by metallic ions or clusters surrounded by organic binders, creating a series of porous and channels (Langmia *et al.*, 2014), resulting in an empty volume of 90%, hence a large contact area (Langmia *et al.*, 2014), achieving gravimetric capacity values of 9 wt% at low temperatures and moderate pressures (Faye *et al.*, 2022).

Innovations are under constant development, and one of the main proposed suggestions is to reduce the pore size on the substrate, so its size would approach the kinetic diameter of hydrogen, overlapping the potential field energy, and improving the interactions with the material (Sreedhara *et al.*, 2018; Langmia *et al.*, 2014). Considering the fact that adsorption is an emerging technology, several studies need to be done before its efficiency can be confirmed.

2.2.4 Solid absorption

Finally, similar to the reaction with LOHC, the solid absorption method bonds the hydrogen strongly in a chemical reaction. However, the transport of this method is done under ambient conditions and in the solid state, which results in higher volumetric densities, and its enthalpy of reaction can also achieve 30-40 kJ/mol (Modisha *et al.*, 2019). This type of storage is suggested for applications where volume and weight do not have a great relevancy, such as the replacement of diesel generators (Adametz *et al.*, 2014).

In these types of storage, there is a subdivision depending on what they are made up of, the main ones are called metallic hydrates, complex hydrates, and chemical hydrates. Metallic hydrates possess advantages over others due to low operation pressure and high volumetric density achieved with a low reaction enthalpy, but tend to have a low gravimetric capacity and a high material cost, an example is TiFe (Tarhan and Çil, 2021; Züttel, 2003).

In terms of complex hydrates, they are composed of sodium, lithium, or potassium bonded to aluminum, which creates the alanates. They also can be bonded with boron to form the borohydrides, or with the nitrogen to create the nitrites. All of them possess high values of density and transport capacity (Tarhan and Çil, 2021). More specifically, alanates have a high gravimetric capacity and low reaction enthalpy, and the main representative of this family is sodium alanate, which has a two-step decomposition process that occurs under high temperatures and pressures, also they have difficulties in rehydrogenating after use (Abdin *et al.*, 2021). For borohydrides, the main example is lithium borohydride, which has a high gravimetric capacity of 18,5 wt%. However, during the release of hydrogen, lithium hydride is created - a very stable and undesirable by-product (Andersson and Grönkvist, 2019). Finally, chemical hydrides are made of lighter elements, with a higher storage ratio and easier composition compared to the other absorption solids. Ammonia borane, for example, has a gravimetric capacity of 19,6 wt% (Tarhan and Çil, 2021). However, during its decomposition, there is the production of ammonia instead of pure hydrogen, which reduces the overall reversibility of the process (Andersson and Grönkvist, 2019; Tarhan and Çil, 2021).

High temperature and the use of catalyzers is needed for the decomposition of all absorbed solids, both are a result of the low reaction kinetics of the solids (Faye *et al.*, 2022), this difficulty impacts even more if there is the need of a rapid release of hydrogen (Andersson and Grönkvist, 2019). Several techniques were proposed with the goal of solving this problems, such as the size control of the absorbent particles, which increases the contact area and would facilitate the uptake and release of the hydrogen (Sreedhara *et al.*, 2018). With the innovation and variation of techniques, a precise analysis can be complex and time consuming to be done, due to the great number of variables in the equations (Sreedhara *et al.*, 2018).

3. DISCUSSION

The discussion above does does not offer a conclusive answer in which is the best method, since the final application of the hydrogen has a great impact on the storage method choice, and also there is a lack of economic and energy analysis in most of the proposed suggestions. However, some important values are shown in Tab. 1.

Table 1. Main performance metrics of the selected methods for hydrogen liquefaction.

Performance Metric	LH2	BZ; CHE	TOL; MCH	NAP; DEC	H0-NEC; H12-NEC	H0-DBT; H18-NEC	MET	FA	NH3	MOF	NaAlH4	LiBH4
Gravimetric capacity [wt%]	100	7,2	6,2	7,3	5,8	6,2	12,5	4,4	17,8	9,2	5,6	18,5
Volumetric density [kg-H2/m³]	70,8	55,9	47	65,4	54	64	99	53	120,3	40-50	95	121
Entalpy [kJ/kg-molH2]	-	68,8	68,3	63,9	50	65,4	16,3	-	30,7	3-10	37 e 47	75
Hydrogenation temperature [°C]	-	150	90-150	120	80-180	180	230-330	100-180	300-600	-196	125	350
Hydrogenation pressure [bar]	-	30	30	20	30-100	>10	50	105	150-300	10-100	100	50
Dehydrogenation temperature [°C]	-	300	320	320	130-260	300	250	100	400-700	-	160	400-600
Melting Point [°C]	-	6,47	-95	80	68	-32	-97,6	8,3	-77	-	-	-
Boiling Point [°C]	-253	81	100,9	190	377	390	64,7	100,8	-33	-	-	-

For applications that require a high purity of the hydrogen, the compressed gas, liquid hydrogen and adsorption methods possess a crucial advantage, that is the absence of purification at the end of the process. Furthermore, for seasonal storage the LOHCs, cyclic agents, and absorption solids are prioritized, a result of the ambient conditions under which they can be stored and low losses attached to them. For maritime transportation, the LOHCs and cyclic agents have great advantages, directly involved with the high volumetric density and gravimetric capacity, and also liquid hydrogen is highly suggested for the same application, but only if the Boil-off problem is solved. In addition to these important factors, another parameter to be analyzed is the price of the elements and how they are extracted, because this economic factor will have a huge impact on which of the methods is selected.

4. CONCLUSION

The need for a replacement in the main energy source of the world has led to several studies that propose ways to transport the energy, and one that looks very promising is hydrogen, due to its high quantity of energy per mass and low environmental impact. However, hydrogen has several difficulties that are under investigation. There are six big storage methods, and they have subdivisions. The compressed gas is a well-established and used method, but it is inefficient, has a high consumption, and has moderate costs, so it is not compensatory. In addition, liquid hydrogen has great physical properties, although, because of the extensive liquefaction process and boil-off losses, the wide spread of the method is not diffused. LOHC is an emerging technology with great potential; however, the lack of large-scale application data makes the affirmative of the method a complex task to do. As for the cyclic agents, ammonia is selected as the main method for a short-range spam of time, due to the well-established technology of synthesis, great overall propertand, similarly to the LPG that enables the use of the already constructed infrastructure. As options for solid storage, the adsorptive method is a method with fast reaction, low reaction energy, and moderated properties. In addition, there are absorption materials that have balanced attributes for transportation, however, there is a lack of technology and large-scale applications. Therefore, research aiming to optimize cryogenic cycles and new catalyzers for the LOHC, solid absorption and for ammonia will make the wide use of hydrogen slowly achievable for all the society.

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