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Hydrogen storage for a net-zero carbon future

Hydrogen ENERGY TRANSITION

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Aliaksei Patonia, Research Fellow, OIES
Rahmatallah Poudineh, Head of Electricity Research, OIES

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Abstract

If a hydrogen economy is to become a reality, along with efficient and decarbonized production and adequate transportation infrastructure, deployment of suitable hydrogen storage facilities will be crucial. This is because, due to various technical and economic reasons, there is a serious possibility of an imbalance between hydrogen supply and demand. Hydrogen storage could also be pivotal in promoting renewable energy sources and facilitating the decarbonization process by providing long duration storage options, which other forms of energy storage, such as batteries with capacity limitations or pumped hydro with geographical limitations, cannot meet. However, hydrogen is not the easiest substance to store and handle. Under ambient conditions, the extremely low volumetric energy density of hydrogen does not allow for its efficient and economic storage, which means it needs to be compressed, liquefied, or converted into other substances that are easier to handle and store. Currently, there are different hydrogen storage solutions at varying levels of technology, market, and commercial readiness, with different applications depending on the circumstances. This paper evaluates the relative merits and techno-economic features of major types of hydrogen storage options: (i) pure hydrogen storage, (ii) synthetic hydrocarbons, (iii) chemical hydrides, (iv) liquid organic hydrogen carriers, (v) metal hydrides, and (vi) porous materials. The paper also discusses the main barriers to investment in hydrogen storage and highlights key features of a viable business model, in particular the policy and regulatory framework needed to address the primary risks to which potential hydrogen storage investors are exposed.

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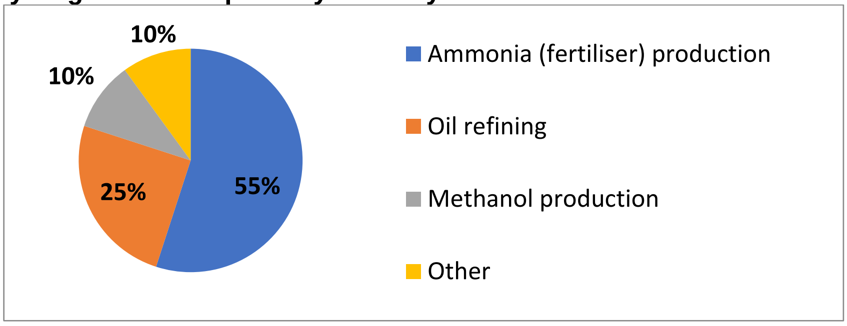
1. Introduction

Hydrogen (H_2) – the most abundant element in the universe – is widely viewed as a crucial element in the decarbonization strategies of many countries in recent years (US Energy Information Administration, 2022). This is so primarily because of its versatile potential applicability (e.g. it can be used as a fuel, feedstock, and means of energy storage) combined with the fact that it does not produce carbon dioxide (CO_2) when combusted[1] (Air Liquide, 2022). Moreover, in contrast to fossil fuels where deposits are geographically limited to specific geological conditions, green hydrogen – the H_2 generated from water with renewable power through the electrolysis process – could potentially be produced anywhere in the world, though not with the same cost efficiency (Patonia and Poudineh, 2022). That is why an increasing number of countries have been enthusiastically setting green hydrogen production targets that would supposedly help them in reaching their decarbonisation targets or generate export revenues when they have abundant low-cost renewables (Power, 2021).

At the same time, because of varying economic conditions as well as differing competitive advantage in producing low-cost decarbonized hydrogen, many countries also recognized the need to import hydrogen in order to achieve their net-zero carbon aspirations on time[2]. For this purpose, some have signed agreements and memoranda of understanding to explore the possibility of future hydrogen supplies (Landsvirkjun, 2020, RWE, 2021, dw, 2022). Others, for example Japan, have gone further and piloted first long-distance shipments of hydrogen and its derivatives (such as liquid organic hydrogen carriers and ammonia) from remote locations like Brunei and Saudi Arabia to their shores (Patonia and Poudineh, 2022). That is why, overall, in anticipation of the advent of a global hydrogen economy, both hydrogen production and transport aspects of the hydrogen value chain have already been focused on by scholars, policymakers, and energy practitioners.

One crucial element of this value chain that has been insufficiently explored up to this point is storage. The importance of hydrogen storage cannot be overstated. No viable business model for hydrogen as an internationally or even locally traded commodity could possibly omit the fact that this substance in most cases will have to be stored at least right after its production and before its delivery to the end user. Obviously, with the current model of hydrogen use for industrial purposes (mostly oil refining and ammonia fertilizer production)[3] (Figure 1), H_2 has been consumed primarily close to its generation point so that both storage and transportation of this substance have not played a decisive role in its value chain (IEA, 2019). At the same time, if a hydrogen economy is ever to be created, this approach will no longer be the dominant form of the hydrogen value chain. In fact, increasing the tradability of hydrogen will require considering the peculiarities and challenges associated with preserving H_2 in different quantities for various periods of time.

Figure 1: Global hydrogen consumption by industry



Source: WHA (2021)

With the growing demand and accelerated manufacturing of H_2 around the world, the need for hydrogen storage is likely to rise proportionally. The main driver of demand for hydrogen storage is likely to be the eventual imbalance between the production and consumption of hydrogen. For instance, in the future,

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[1] Although hydrogen is viewed as a substance that could be used for various decarbonisation purposes, it is most often regarded as an element that could potentially replace fossil fuels as sources of energy (Qazi, 2022). In this connection, if this replacement takes place in some form, hydrogen will not be a primary energy source (because it will have to be produced) but will rather serve the purpose of energy storage in a chemical form (Mohammadi-Ivatloo, Mohammadpour, and Anvari-Moghaddam, 2021).

[2] For instance, in his address to the European Parliament, Frans Timmermans, the European Commissioner for Climate Action, admitted that 'Europe [was] never going to be capable to produce its own hydrogen in sufficient quantities' (Recharge, 2022a).

[3] For instance, for ammonia production, hydrogen is normally generated from the main feedstock (usually, natural gas) as a part of the production process and is consumed on site (Patonia and Poudineh, 2020).

manufacturing rate of blue and turquoise H_2 – hydrogen generated from fossil fuels with carbon capture, utilization, and storage (CCUS) – will be reasonably flat (linear) to provide the maximum efficiency (Megia et al, 2021). At the same time, this production pattern is unlikely to coincide with hydrogen demand all the time, which could be addressed through storage. Indeed, storage is already a key component of existing fossil fuel supply chains.

More significantly, if hydrogen is produced through electrolysis using solar and wind power, the generation process will be intermittent. Here, apart from daily and seasonal variability associated with lower/ higher magnitude of wind speed and solar irradiation at different time of the day and year, weather conditions causing the so-called 'Dunkelflaute' events – anticyclonic gloomy windless days when little or no energy can be generated by wind and solar (Matsuo et al, 2020) – will significantly impact hydrogen production. As a result, H_2 manufacturing may not coincide with the time of its peak consumption. Here again, hydrogen storage will be of critical use to meet make both the supply and demand, since the demand side may not be extremely responsive to overproduction or underproduction of hydrogen[4].

Apart from that, with the variable nature of wind and solar – the energy sources that are going to play an even greater role in a decarbonized energy system of the future – hydrogen storage could become a means of grid balancing when overproduction and underproduction issues occur. Currently, when renewable generation often has to be curtailed due to overgeneration or local networks issues, converting electrons into molecules and back through the power-to-X technologies could help to avoid these issues (ITM Power, 2022). As a result, H_2 storage would play an extremely important role in the entire decarbonization process, since it would facilitate further spread of renewable energy sources through offering both backup and seasonal storage options where batteries and pumped hydro have significant capacity or geographical limitations[5]. This is so because natural gas, which is most often stored to contribute to meeting seasonal energy demand, is not a carbon-free solution and thus should be substituted with a more sustainable one. In this context, an increasing number of researchers view hydrogen and its derivatives as such substitutes (Guerra et al, 2020).

On the other hand, despite all the advantages of hydrogen storage as well as the opportunities that it may bring, keeping and preserving H_2 for later transportation or consumption does not appear to be the easiest task. In fact, due to the very nature of this simplest of all elements that is easily lost into the atmosphere, hydrogen storage is generally a challenging undertaking[6]. Additionally, because of its extremely low volumetric energy density, pure H_2 needs to be either compressed or liquefied. With both processes being energy intensive and expensive[7], it may not always be economic to store hydrogen in gaseous or liquid forms. In these situations, converting hydrogen into other substances that are easier to handle and store can be advantageous.

At the moment, however, there is no clear stance on which hydrogen storage option is the one that will offer more advantages than the rest. As a result, it is still uncertain if there will be a single preferred variant that will be adopted by most stakeholders in the to-be-created hydrogen economy. In fact, different hydrogen storage solutions are likely to be preferred depending on circumstances. This paper thus evaluates the relative merits of alternatives in different applications.

The outline of the paper is as follows. Section 2 provides an overview and comparison of major types of hydrogen storage options that are currently being explored and considered by scholars, policymakers and businesses. Factors to consider for investment in hydrogen storage and discussion on major barriers for such an investment are presented in Section 3. Section 4, in turn, elaborates on the business models and policy options that would facilitate investment in H_2 storage facilities. Finally, the Section 5 provides concluding remarks.

2. Overview of the main types of hydrogen storage

Although hydrogen is considered to be one of the key elements in the global decarbonisation debate, its storage is more complicated than storage of many other energy sources that we are much more used to, such as coal, oil, and even natural gas. This is so primarily because the H_2 molecule is the smallest and lightest in

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[4] The need for storage would be less acute in case of very responsive demand. In this context, incentives for demand-side flexibility could potentially be used as a competitive alternative to more short-duration storage.

[5] At the moment, chemical energy storage is generally more advantageous to electrochemical (batteries) solutions and has fewer limitations if compared with mechanical (pumped hydro) options (Patonia and Poudineh, 2020).

[6] For instance, being highly flammable per se, when dispersed into the air, hydrogen becomes explosive.

[7] For example, liquefaction that allows for reaching hydrogen's greater density presupposes cooling it down to -252.9°C and consumes more than 30 percent of the energy content of the hydrogen (US Department of Energy, 2022).

the entire universe (Ari Liquide, 2022). This, combined with the fact that hydrogen is a gas under ambient conditions, makes its 'taming' and preservation particularly challenging.

To make hydrogen storage less problematic and more economically feasible, its density should be improved so that the vessel where it is preserved could carry the amount of energy greater than or at least comparable to that of more commonly used fossil fuels. In general, however, under normal temperature and pressure, H_2 has extremely low volumetric density (around 0.0812 kg/m^3) (Møller et al, 2017). This indicator gradually rises when hydrogen is compressed or liquefied. For instance, under 700 bar, H_2's volumetric density is already 42 kg/m^3 and, as a liquid, it nears 70.8 kg/m^3 (ibid). Nevertheless, this would still not turn it into the energy carrying champion, as other substances may bear more energy within the same unit of volume (*Table 1*). That is why, although hydrogen has the highest gravimetric energy density of all known substances (120-142 MJ/kg), it falls short when compared to conventional fossil fuels with respect to volumetric energy density (GEN H2, 2022). In simple terms, for a 1-kg weight limit, hydrogen would contain the most energy, while for a 1-liter tank volume limit, other fuels would be capable of carrying more energy (ibid).

In this connection, although hydrogen often represents the focal element in energy transition and decarbonisation debates, improving hydrogen 'storability' may require this element to be converted into other substances that would contain H_2 but would simultaneously be easier to deal with and would have higher volumetric hydrogen density. Nevertheless, the preferred preservation option would depend not only on the H_2 density and content characteristics but also on many other factors including storage volume, duration, safety as well as the purpose for which the stored hydrogen would ultimately be used.

In general, H_2 and its derivatives could be stored in three aggregate states (gaseous, liquid, and solid) (*Table 1*). The hydrogen storage options that are currently attracting the greatest attention, in turn, could be divided into six major groups (types): (i) pure hydrogen storage, (ii) synthetic hydrocarbons, (iii) chemical hydrides, (iv) liquid organic hydrogen carriers, (v) metal hydrides, and (vi) porous materials (ibid).

2.1. Pure hydrogen storage

At the moment, pure hydrogen storage can be done in two ways: H_2 can be either compressed or liquefied (US Department of Energy, 2021). Hence, hydrogen can be preserved physically as either a gas or a liquid. Although storing hydrogen in a pure form may not always be the most economically advantageous option, there are still several benefits that this type of storage may bring. First and foremost, physical storage represents the most mature hydrogen storage technology available at the moment (US Department of Energy, 2020). This is also the technology that allows using pure H_2 directly after its preservation – that is, without any conversion. Nevertheless, both compressed and liquefied hydrogen storage have significant disadvantages over other storage options that need to be considered as well.

2.1.1. Compressed hydrogen

Hydrogen storage in a form of gas normally requires high-pressure tanks (350-700 bar) (US Department of Energy, 2021). Although this means that compressing H_2 will be associated with energy use (around 6 kWh/kg for compression to 700 bar) and thus further expenses, no additional steps would need to be taken in comparison to the preservation methods normally associated with hydrogen derivatives (e.g., hydrogenation/ adsorption, etc.) (Folkson, 2014). Apart from that, provided all the technological requirements for the storage vessels and facilities are met, the very process of storing compressed hydrogen as well as extracting it from the stored vessel would not require significant energy use (*Table 1*).

This, in combination with the ability to keep high purity of the preserved H_2 as well as relatively high speed of injection into/ withdrawal from the storage vessel, makes compressed hydrogen storage the option that is currently preferred for usage in fuel cell vehicles (Elberry et al, 2021). In fact, both the fuelling time (normally, under 3 minutes for a standard tank of around 0.2 m^3) as well the energy needed to cover the driving range of over 500 km are comparable to those of conventional gasoline- and diesel-propelled combustion cars (Sloth, 2013). Additionally, compressed hydrogen storage is also the only major H_2 preservation option for large-scale (e.g., country-scale) storage purposes – that is, it is the alternative that is often expected to replace underground natural gas storage[8] (Elberry et al, 2021).

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[8] Although, theoretically, synthetic natural gas (SNG) could be used for the same purposes, its generation at a scale comparable to the one of natural gas extraction is yet to be achieved (if at all) due to technology and financial constraints (see 2.2. Synthetic hydrocarbons).

Table 1: Key characteristics of some major hydrogen storage options[9]

State	Storage forms			Chemical formula/ example	Molar mass (g/mol)	Gravi-metric energy density (MJ/kg)	Volumetric H_2 density (kg/m^3)	Gravi-metric H_2 density (wt%)	Typical conditions for H_2 (ad-/ physi-) sorption/ hydrogenation/ production			Typical conditions for storage			Typical conditions for H_2 desorption/ de-hydrogenation/ release		
									Temperapture (°C)	Pressure (bar)	Energy (kJ/mol)	Temperature (°C)	Pressure (bar)	Energy (kJ/mol per day)[10]	Temperature (°C)	Pressure (bar)	Energy (kJ/mol)
Gas	Compressed hydrogen (700 bar)			H_2	2.016	120-142	42	100	Ambient**	700**	~9.798**	Ambient	700	<10	n/a		
	Synthetic hydro-carbons (e-fuels)		Compressed synthetic methane/ natural gas (SNG) (250 bar)	CH_4	16.043	53.6-55.6	~32.2	~25.13	250-350*	30-40* 250**	~206* >1.8**		200-250	>1.9	700-1000	3-25	~165
Liquid			Liquefied SNG				~101.78			>68	~19.008***	~-161	0.3-16	19.06-34.7			
			Synthetic gasoline (petrol)	C_8H_{18}	60-150	44-46.4	~119.8	16	400-500	>200	48.5-61*	Ambient	Ambient	n/a	>500	1-4	<40
			Synthetic diesel	$C_{12}H_{23}$	198-202	45.4-45.6	~119.1	14	700-1500	200-700	~80*				~800		48.5-61
	Liquid hydrogen			H_2	2.016	120-142	~70.8	100	-252.8	Ambient	>25.66***	-252.8		>28.3	n/a		
	Chemical hydrides		Liquid ammonia	NH_3	17.031	21.18-22.5	107.7-120	17.65	300-500	140-250	~92.4* ~0.9***	-33		~1	350-900	1-10	30.6-46
			Methanol (MeOH)	CH_3OH	32.04	20.1-22.4	95.04-99	12.1	200-300	10-70	>41.2*	Ambient		n/a	250-900	25-50	>70
			Formic acid	CH_2O_2	46.03	~4.58	~53	4.3	90-140	6-10	~34.7*				150-225	~Ambient	~29.81
			Isopropanol (i-PrOH)	C_3H_8O	60.1	~34.1	~25.9	3.3	20-65	60-200	40-48*				70-195	0.5-1.5	~61.4
	Liquid organic hydrogen carriers		Toluene/ Methylcyclohexane (MCH)	C_7H_8/ C_7H_{14}	98.186	~7.35	47.1-47.4	6.16	>350	Ambient	10.5-18.4***				~350	1-9	~68
			Naphtalene/ decalin	$C_{10}H_8$/$C_{10}H_{18}$	138.25	~42.97	~65.4	7.29	~280	>100	~16.3***				~240	~35	63.9-68.3
			Benzene/ cyclohexane	C_6H_6/C_6H_{12}	84.16	~3.9	~55.9	7.20	70-150	<20	~119.5***				~400	1-8	89-138
			Dibenzyltoluene (DBT)/ perhydro-dibenzyltoluene (PDBT)	$C_{21}H_{20}$/ $C_{21}H_{33}$	290.54	~12.9	~64	6.20	>150	15-50	~171***				300-390	<4	~65.4
Solid	Metal hydrides	Elemental metal hydrides	Magnesium hydride	MgH_2	26.32	9-10.8	86-109	6-7.6	260-425	30-300	~70.6***		Ambient-40	n/a-0.6	250-400	~Ambient	74.7-118
			Aluminium hydride	AlH_3	29.99	>36.68	~148	~10.1	~600	1-350	~104***				85-140	75-135	~20
		Inter-metallic hydrides	AB_5-type	$LaNi_5$/ $LaNi_5H_6$	432/438.4	40-60	~105	1-1.5	20-80	1.5-2.5	12.27-40***				~Ambient	1.6	~54.3
			AB_2-type	$ZrMn_2$/ $ZrMn_2H$	201/202.1		~100	2.15-3.8	20-50	30-60	>20***				Ambient-200	1-250	>29.9
			AB-type	TiFe/ TiFeH	104/104.7		~90	<5.4	300-400	10-65	10-28.1***				Ambient-40	1-25	10-28
		Complex metal hydrides	Alanates	$NaAlH_4$	54	~65	~54	3.5-5.4	~100	6-12	57.4-118***				85-260	6-66	79-92
			Borohydrides	$LiBH_4$	21.78		~121	~18.5	600-700	100-200	56.37-88***				300-450	>3	30-59
			Amides	$LiNH_2$	22.96		<54	4.5-5.2	~150	>20	~55.2***				285-500	~Ambient	40.4-73.6
	Porous materials	Carbon-based	Carbon fibres	C_n $(C_3H_3N)_n$	12.01 (carbon)	0.8-2	~18	<5.44	~-196-ambient	1-40	6-11***	~-196-ambient	<250	4.4-12	160-500		56.5-238
			Carbon nanotubes					5-10							135-325		
			Activated carbon	CH_2O_2		~0.0655	16.7	0.1-7.5					<59				
			Graphene	$C_{70}H_{30}$		~0.9	16-17	1-7.7					<100				
			Carbon aerogel	$V_2O_5 \bullet nH_2O$		0.014-0.023		<4.8					<65				
			Templated carbon	$C_{45}H_6O_2$		~0.3	<17	5.5-7.3					100-340				
		Metal-organic frameworks (MOFs)		$Cr_3F(H_2O)_2O(BDC)_3$	~709.4	~0.57	~11.5	<10		~100	~51.2***		15-80		60-85	~5	~78.7

Source: Adapted from Ryabov (1976), Alyea and Keane (1993), Eliaz et al (2000), Becher et al (2003), Tzimas et al (2003), Graetz et al (2006), Hodoshima et al (2006), Eigen et al (2007), AMF (2010), Banerjee and Tyagi (2011), Foudakis (2011), Subrahmanyam et al (2011), Mazloomi and Gomez (2012), Tozzini and Pellegrini (2012), Gao et al (2013), Nielsen et al (2013), Tian et al (2013), Franco and Casarosa (2014), Balakhonov, Vatsadze, and Churagulov (2015), Lototskyy and Yartys (2015), Nishihara et al (2017), Sivasubramanian et al (2017), Escola Europea (2018), European Commission (2018), Garcia-Holley et al (2018), Hao et al (2018), Mustafa et al (2018), Romanos et al (2018), Schollenberger et al (2018), Younis et al (2018), Wang et al (2018), Zhong et al (2018), Andersson and Grönkvist (2019), Li et al (2019), Modisha et al (2019), Potekhin (2019), Wijayanta et al (2019), Ding et al (2020), Gattia, Jangir, and Jain (2020), HimMax (2020), Huynh et al (2020), Kazakov, Bodikov, and Blinov (2020), Rao and Yoon (2020), Asif et al (2021), Jalid, Khan, and Haider (2021), Sultana, Saha, and Reza (2021), Thomas et al (2021), Campos et al (2022), Composites World (2022), Thijs, Ronge, and Martens (2022), Valentini, Marrocchi, and Vaccaro (2022), Vatsa and Padhi (2022), Wei et al (2022), Wilkler et al (2022).

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[9] Values represented in the table are approximate and based on the data from available in the literature. That is why they can vary for specific cases and should not be taken as precise numbers.

[10] Energy used for storage depends on such factors as tank/storage vessel insulation, efficiency of BOG reliquefication (for liquid storage of gaseous substances), etc.

***** - production, ****** - compression, *** - liquefaction/hydrogenation/sorption

On the other hand, although hydrogen compression (to 700 bar) is almost three times less energy intensive than its liquefaction, the amount of energy that is required is still quite impressive – it is comparable to 13-18 percent of the lower heating value (also known as net calorific value) (Jensen, Vestbø, and Bjerrum, 2007). In addition, when H_2 is compressed to 700 bar, its volumetric energy density will be much lower (5.6 MJ/l) than that of such fuels as gasoline (32.0 MJ/l) (Elberry et al, 2021). Although this challenge could partially be addressed through a combination of a high-pressure cylinder/tank and a solid-state material containing hydrogen (see 2.5. Metal hydrides and 2.6. Porous materials) (Møller et al, 2016), in economic terms, preserving compressed hydrogen in storage vessels of greater volume (e.g., tanks or spheres transportable by marine vessels) may not seem to be equally as attractive as storing liquid H_2 or its derivatives. Besides, storing highly compressed gases requires additional adjustments to the design and implementation of the storage cylinders because of safety concerns, whether perceived or real (Gupta, Basile, and Veziroğlu, 2015).

2.1.2. Liquefied hydrogen

Offering higher volumetric density (70.8 kg/m^3), which is almost twice of that associated with hydrogen under 700 bar (42 kg/m^3), liquefied H_2 can thus preserve a greater amount of hydrogen in the same unit of volume (Viswanathan, 2016). In addition, with fewer potential risks in comparison to those that compressed gases normally have as well as similar benefits of high H_2 purity and relatively quick refuelling, this higher density advantage of liquid hydrogen storage was taken into account by NASA when they opted for this mode of hydrogen storage for their Space Shuttle Program (NASA, 2018). This rationale also seems to lie behind the logic of Kawasaki Heavy Industries' project that built the world's first liquefied H_2 carrier that delivered the world's first liquefied hydrogen cargo from Australia to Japan in February 2022 (Recharge, 2022b).

At the same time, the main challenge associated with storing liquefied hydrogen is the need for cryogenic temperatures (-252.0ºC) that can keep the H_2 in liquid form, which, in turn, is associated with significant energy use. In fact, although the minimum theoretical energy to liquefy H_2 from ambient conditions is 3.3-3.9 kWh/kg$_{LH2}$, the actual liquefaction energy requirements are substantially higher – at least 10-13 kWh/kg$_{LH2}$, depending on the size of the liquefaction operation, the original temperature of hydrogen and other factors (US Department of Energy, 2009). As a result, although with novel liquefaction methods, such as an active magnetic regenerative liquefier, less energy will be required in the process, liquefaction with today's fully commercialized processes need 30-40 percent of the lower heating value (ibid).

Storing hydrogen as a liquid cooled to cryogenic temperatures also requires taking additional measures to prevent and minimize boil-off gas (BOG) challenges that would result in hydrogen loss, unless it is reliquefied or utilized in an efficient manner (Viswanathan, 2016). Since both H_2's production and liquefaction are highly energy intensive, BOG management plays an important role in preserving the liquid hydrogen produced. That is why vessels storing liquid hydrogen require sophisticated insulation techniques to minimize unavoidable heat transfer leading to hydrogen loss (ibid).

2.2. Synthetic hydrocarbons

Limitations associated with hydrogen's low volumetric density as well as high energy intensity of compression and liquefaction and the resulting safety and cost challenges made scholars and energy companies consider alternative ways of preserving this substance. In this context, converting hydrogen into synthetic hydrocarbons and back appears to be an option that is gradually gaining attention. Here, the logic is quite simple – through combining sustainably produced hydrogen with captured carbon (either from air or industrial processes), it would be possible to synthesize one of the fuels that are a lot easier to store and transport than H_2 itself: for example, methane, gasoline or diesel (Lee, Seidl, and Meyer, 2021). In the end, when hydrogen needs to be extracted, separation of carbon and its ultimate delivery back to the point of generation of synthetic hydrocarbons would theoretically 'close' the loop and make the entire process carbon-neutral[11]. This, in combination with already well-developed infrastructure that was originally tailored for hydrocarbons, makes this option very attractive.

2.2.1. Compressed and liquefied synthetic natural gas (SNG)

The term 'synthetic natural gas' (SNG) generally relates to a variety of natural gas alternatives that are as close as possible in composition and properties to natural gas (MAN Energy Solutions, 2022). Although SNG, in principle, can be derived from various sources (incl. coal, biomass and waste), the most common concept behind the production of carbon-neutral SNG at scale that is currently being

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[11] Here, the round-trip efficiency remains questionable though.

debated rests on the process that produces methane and water from a reaction of hydrogen with carbon dioxide – the Sabatier reaction:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_20$$

Here, an ideal scenario would be to couple green hydrogen production with the capture of industrially-generated CO_2 or the one directly from the air so that SNG is manufactured specifically for storage and transportation purposes and then is dehydrogenated – hydrogen is 'extracted' from it – before the final use (Navajas et al, 2022). With an already well-developed storage and delivery infrastructure for natural gas, preserving and transporting SNG would be no different and thus no infrastructure adjustments would be needed, which would also mean no related costs would be incurred (ibid)[12].

While, in theory, the Sabatier reaction could play an important role in solving the climate change problem through creating clean synthetic natural gas and hydrogen fuel from the captured CO_2 and water, the deployment of this reaction at an industrial scale has so far been limited. Some of the key reasons for the restrained applicability of this methanation relate to elevated temperatures (250-350^{o}C) and pressures (around 30-30 bar) as well as the need to use a nickel, ruthenium or alumina (aluminium oxide) catalyst, which results in high energy demand, significant costs and generally low economic efficiency (Wai et al, 2020). Although, for a net-zero carbon scenario, some of these challenges could be mitigated via biological methanation, since it replaces metallic catalysts with biocatalysts (methanogenic microorganisms) and works under much lower temperatures (35-70^{o}C) and pressures (1-15 bar), the industrial application of biomethanation has so far also been limited mostly because microorganisms require a lot more space and time to achieve the same production as a comparably rated Sabatier process (Ferrari, 2020). That is perhaps why the International Space Station seems to be the only place where methanation (through the Sabatier process) has been continuously used, though not for the purpose of methane synthesis[13] (NASA, 2011).

Since SNG's structure is broadly similar to that of natural gas, it's preservation would have the same advantages if compared to hydrogen storage, such as lower energy use for compression (normally, to 200-250 bar for synthetic CH_4 (methane) instead of 350-700 bar for H_2) and thus lower costs and durability requirements for storage vessels and facilities (Navajas et al, 2022). However, as seen from *Table 1*, even if compressed to 250 bar, SNG's volumetric hydrogen density would be quite low (around 32.2 kg/m^3), which, in part with its 'medium' gravimetric hydrogen content (around 25.13 wt%) may not make the energy-intensive and thus expensive synthesis process quite worth the effort. This is especially the case for small-scale preservation of hydrogen, given that a similar amount of energy would then be needed to dehydrogenate SNG for the ultimate use of H_2.

In such circumstances, even with additional energy consumption, liquefied SNG may become a better option for medium-scale storage[14], as it greatly increases the volumetric hydrogen density (to around 101.78 kg/m^3) (Table 1). In any case, although using SNG in both compressed and liquefied forms would require no major investment in its storage and delivery infrastructure, making the carbon management a 'closed loop' would need the creation of storage and transportation facilities for the CO_2 involved. This, in turn, would result in additional costs.

2.2.2. Synthetic gasoline (petrol) and diesel

To further simplify the storage process, synthetic fuels that are liquid under ambient conditions could be used. Here, both synthetic gasoline (C_8H_{18}) and diesel ($C_{12}H_{23}$) that do not need to include any 'liquefaction' in their value chains also have significantly higher volumetric hydrogen density (around 119.8 kg/m^3 and 119.1 kg/m^3 for synthetic gasoline and diesel, respectively) (*Table 1*). However, despite offering the advantages of well-developed infrastructure and near-zero storage costs, these fuels have a number of significant drawbacks that may prevent them from being considered as feasible options for hydrogen preservation.

In fact, the discussed carbon-neutral process of manufacturing synthetic gasoline and diesel is based on the Fischer-Tropsch process, which represents a collection of chemical reactions converting a mixture of carbon monoxide and hydrogen into liquid hydrocarbons:

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[12] This is the idea currently pursued by such companies as Tree Energy Solutions (TES) aiming to complete a new 'green gas' terminal at the German port of Wilhelmshaven that is supposed to be able to store the deliveries of its 'carbon-neutral' liquefied e-methane before the winter of 2025 (TES, 2022).

[13] The International Space Station uses the Sabatier system to produce water from carbon dioxide generated by crew metabolism and hydrogen synthesised while generating station oxygen (NASA, 2011). While water is then retained for recycling processes, the methane is vented outside of the space station (ibid).

[14] Natural gas is usually stored at a large scale in underground storage facilities as a gas compressed to around 200 bar (INES, 2022).

$$(2n + 1)\ H_2 + n\ CO \rightarrow C_nH_{2n+2} + n\ H_2O$$

Typically, these reactions need high temperatures (400-1500^{o}C) and pressures (over 200 bar) as well as the use of cobalt, iron or ruthenium catalysts (Höök et al, 2014) (Table 1). These high temperatures, pressures, and thus energy requirements generally make natural gas, coal, and biomass the most common types of feedstock, though a lot more attention has been recently paid to the development of economically sound projects for e-fuel production from water, air, and electricity as the raw materials needed (Lee Enterprises Consulting, 2021)[15].

On a more general note, while it is still perceived by many that manufacturing synthetic fuels through the Fischer-Tropsch process would only be economically feasible at very high oil prices and/or when heavily subsidised (Wang et al, 2017), even with improved efficiency and dramatically lowered cost, both synthetic diesel and gasoline will remain hydrocarbons and thus substances that would need to be dehydrogenated if H_2 needs to be used. In this connection, just as in the case of e-methane, dehydrogenation would also necessitate proper carbon management and most likely the creation of carbon storage and delivery infrastructure from scratch[16].

2.3. Chemical hydrides

Chemical hydrides represent another group of substances that could potentially be used for hydrogen preservation. Although this category is comprised of more diverse chemicals than such as synthetic fuels (e.g., they can be manufactured via non-related processes in a very different way), their storage is generally similar to that of synthetic hydrocarbons with all the main advantages of minimum energy costs, no need for infrastructure development, etc. in place. Apart from that, while their volumetric hydrogen density and gravimetric hydrogen content characteristics are similar to those of synthetic fuels, their production and dehydrogenation is mostly less energy intensive and thus cheaper.

2.3.1 Ammonia and methanol

Ammonia and methanol represent the most prominent chemicals in this group, as they are often viewed as some of the closest rivals to hydrogen itself for H_2 storage and delivery purposes (Aziz, Wijayanta, and Nadiyanto, 2020). This is so primarily due to a decent combination of their relatively high volumetric hydrogen density (107.7-120 kg/m^3 for liquid ammonia and 95.04-99 kg/m^3 for methanol) and high gravimetric hydrogen content (17.65 wt% for liquid ammonia and 12.1 wt% for methanol) (Table 1). Here, although ammonia is gaseous under ambient conditions and thus needs liquefaction to facilitate its storage, in contrast to hydrogen and SNG it needs a lot less energy for that, since it only needs to be cooled down to -33 ^{o}C, whereas SNG and H2 need to be cooled down to -161 and -252.8^{o}C, respectively (ibid). Methanol, on the other hand, is already liquid under normal atmospheric pressure and temperature and thus does not need any additional transformations.

When it comes to using a hydrogen derivative that would be completely carbon neutral, ammonia (NH_3) would represent the winner, since, in contrast to methanol (CH_3OH), it does not contain carbon (C) atoms in its molecule and thus would not need carbon management after it is cracked. Besides, although its most common production method rests on natural gas as the main feedstock, power-to-ammonia technologies have already been applied at scale for decades with such countries as Egypt, Iceland, India, Norway, and Peru which constructed cost-competitive large-scale renewable ammonia plants after 1945 (Krishnan et al, 2020). In fact, the largest renewable ammonia plant to date was built in the 1960s[17], in Aswan, Egypt as a response to the absence of natural gas and in order to provide food security for the country, as the ammonia would then be used to produce fertilizers (ibid).

At the same time, although the production, storage, and transportation of ammonia has been widely used (primarily due to the fertiliser industry), ammonia cracking – i.e. 'separation' of H_2 from NH_3 – may represent a less well-developed stage that nevertheless needs to be included in the hydrogen value chain, if ammonia is chosen as the storage option for hydrogen. This stage, however, being, in essence, similar to steam methane reforming, also requires high temperatures (350-900^{o}C) and elevated pressure (up to 10 bar) and takes place in the presence of a nickel catalyst (Johnson Matthey, 2022).

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[15] Here, Audi's e-gasoline and e-diesel production initiative that is supposed to be industrially piloted in the company's new plant in Switzerland seems to be the most scaled up one at the moment (Audi, 2018). This initiative, however, still does not completely eliminate CO_2 emissions – it is reported to only reduce it by around 80 percent (ibid).

[16] Although the production and use of e-fuels may potentially make sense to lower the carbon impact of transport, with all the complexities and questionable economic rationale make their use for hydrogen storage and transport highly debatable. Here, it may be more cost-efficient and reasonable to implement carbon capture, utilisation and storage technologies – i.e. completely omitting the use of hydrogen – to make the entire process carbon-free.

[17] With a production of 400-500 tonnes of NH_3 per day, the ammonia plant in Aswan was the largest renewable ammonia plant ever built (Krishnan et al, 2020). It was originally operated with alkaline electrolysers from De Nora, but they were later replaced with the ones from Brown Boveri (ibid).

Hence, it is energy-intensive and would result in further costs, as would the proper nitrogen management after the cracking process ($2NH_3 \rightleftharpoons N_2 + 3H_2$).

Similar is true for methanol, which should also be dehydrogenated before H_2 could be used[18] (Alberico and Nielsen, 2015):

$$CH_3OH \rightleftharpoons CO + 2H_2;\ CO + H_2O \rightarrow CO_2 + H_2$$

Just as in the case of ammonia, dehydrogenation of CH_3OH is an endothermic reaction and it requires high temperatures (250-900ºC), elevated pressure (25-50 bar) as well as homogenous precious-metal-based catalysts (Wakizaka et al, 2016). As a result, although the electrification of the process is possible, the exhaustive methanol dehydrogenation is currently realised primarily through steam reforming run mostly on fossil fuels (Alberico and Nielsen, 2015).

The conditions that are needed for the production of methanol are quite similar to those required for the synthesis of ammonia and that is why it most often uses natural gas as a feedstock, but could also be generated through the combination of green hydrogen and captured carbon (Haldor Topsoe, 2022):

$$CO + 2H_2 \rightleftharpoons CH_3OH;\ CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$$

In contrast to green ammonia, however, the world's first industrial-scale e-methanol production project is yet to be finished by European Energy (European Energy, 2022). In these conditions, when no large-scale production of green hydrogen-based methanol is available, relying on this substance for the future preservation of large quantities of H_2 for the to-be-created hydrogen economy is questionable.

2.3.2. Formic acid and isopropanol

Apart from ammonia and methanol, formic acid (CH_2O_2) and isopropanol (C_3H_8O) are often viewed as two other alternatives for the preservation of hydrogen. Here, the same logic applies: their volumetric hydrogen density (around 53 kg/m^3 for formic acid and 25.9 kg/m^3 for isopropanol) as well as gravimetric hydrogen content (4.3 and 3.3 wt% for formic acid and isopropanol, respectively) are making them suitable for being used for hydrogen storage (*Table 1*). In addition to that, although their characteristics are less impressive than those of, for example, , ammonia, both are liquid under normal atmospheric temperature and pressure. At the same time, since both are currently mostly produced from other fossil fuels-derived chemicals, the attention to them has been less significant in comparison to many other alternatives for H_2 storage.

At the moment, most of the formic acid currently produced at an industrial scale is made from carbon monoxide, either by heating it with sodium hydroxide to produce sodium formate, which is then acidified (Eppinger and Huang, 2017):

$$NaOH + CO \rightarrow HCOONa \rightarrow HCOOH$$

Alternatively, it is generated via the base-catalysed reaction of carbon monoxide (CO) and methanol to make methyl formate, which is then hydrolysed to the acid (ibid):

$$CH_3OH \rightarrow HCHO \rightarrow HCOOH$$

Formic acid also happens to be a major by-product of acetic acid production. In this case, however, as in the case of other major formic acid production pathways, all the raw materials are normally derived from petroleum (incl. methanol) and thus making this process completely carbon-neutral would rely on either implementation of CCUS or potential electrification of questionable efficiency (ACS, 2022).

Similarly, at the moment, the industrial production of isopropanol is almost entirely reliant on fossil fuels. This is so because this chemical has been largely manufactured from propylene via two major commercial routes – indirect hydration of refinery-grade propylene and direct hydration of chemical-grade propylene (Panjapakkul and El-Halwagi, 2018):

$$C_3H_6 + H_2O \rightarrow (CH_3)_2CHOH;\ CH_3COCH_3 + H_2 \rightarrow CH_3CH(OH)CH_3$$

Here, given that propylene is produced primarily as a by-product of petroleum refining and of ethylene production by steam cracking of hydrocarbon feedstocks (ibid), making this process completely carbon-neutral is likely to be extremely complicated. In addition, since the very molecules of both isopropanol and formic acid contain carbon, dehydrogenation of these elements will also raise the need for proper carbon management, if value chain of hydrogen derived from them needs to be considered carbon-neutral.

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[18] And the CO_2 will presumably have to be captured and stored.

2.4. Liquid organic hydrogen carriers (LOHCs)

Liquid organic hydrogen carriers (LOHCs) represent organic compounds that can absorb and release hydrogen via chemical reactions (Modisha et al, 2019). In the process, with the transformation (i.e. hydrogenation) of the basic substance into the one carrying hydrogen (i.e. hydrogenation) and back (i.e. dehydrogenation), the basic substance remains the same, which could allow for its continuous use in cycles. Apart from offering the possibility to potentially create a 'close loop' for carbon, LOHCs remain liquid under ambient temperature and pressure, which significantly simplifies and facilitates their storage with respect to both preservation conditions and infrastructure needed (ibid).

At the moment, some of the most promising LOHCs that are attracting the greatest attention of researchers are toluene/ methylcyclohexane (MCH) (C_7H_8/ C_7H_{14}), naphthalene/ decalin ($C_{10}H_8$/ $C_{10}H_{18}$), benzene/ cyclohexane (C_6H_6/ C_6H_{12}), and dibenzyltoluene (DBT)/ perhydro-dibenzyltoluene (PDBT) ($C_{21}H_{20}$/ $C_{21}H_{33}$) (Table 1). While none of these LOHCs requires specific adjustments for hydrogen storage and thus no additional energy and financial costs would be incurred, each of these chemicals has different requirements for hydrogenation and dehydrogenation. Though elevated temperatures and pressure would be needed for each, energy demand for the toluene/ MCH and naphthalene/ decalin couples would normally be lower than for benzene/ cyclohexane and DBT/ PDBT, which would ultimately make them slightly cheaper alternatives for use of H_2 storage (Table 1).

On a different note, while each of these substances contains carbon, none of them is generated in a carbon-neutral way either[19]. Although the carbon that each of these LOHCs contains could potentially be reused and thus not released into the atmosphere, their gravimetric hydrogen content varying between 6.19 and 7.29 wt% (Table 1) may not necessarily be attractive enough in all the cases, for example, when all the emissions need to be abated. This is particularly so if other more 'hydrogen-heavy' alternatives with similar storage characteristics and available power-to-X production pathways (e.g. ammonia or methanol) are on the list to choose from. As a result, the use of these LOHCs for the purpose of preserving hydrogen may be limited to some niche applications when other considerations (e.g. availability or cost) are prevailing.

2.5. Metal hydrides

Metal hydrides represent a broad group of materials that could be used for stable preservation of hydrogen in a concentrated solid form. They bond the stored H_2 to metal or metalloid elements and alloys and allow for some of the greatest volumetric hydrogen densities among all the storage options (Azzaro-Pantel, 2018) (Table 1). At the same time, although they can keep hydrogen in a very compact form, their gravimetric hydrogen content in most cases is less impressive, which generally means that this storage solution normally offers heavier preservation alternatives per unit of H_2 stored than the rest (ibid). Although this factor may limit the transportability of the storage substance, metal hydrides generally offer a low-risk and a stable way of H_2 preservation that is coupled with its high purity when it is released (Colbe et al, 2019). As a result, if these characteristics are prioritized, this hydrogen storage option may be favoured over the remaining ones.

While offering hydrogen storage in solid form under ambient conditions or those that are close to ambient, metal hydrides are currently considered mostly for tank storage. As a result, the volume of the H_2 they preserve is limited to small- and medium-scale. This, along with other challenges, still needs to be addressed with further research so that metal hydrides could become a well-spread hydrogen storage solution.

2.5.1. Elemental metal hydrides

Elemental metal hydrides such as magnesium hydride (MgH_2) and aluminium hydride (AlH_3) have been some of the first solid materials explored for their hydrogen storage potential since the late 1960s (Yartys et al, 2019). This is so because of several reasons with a combination of good H_2 capacity (up to 7.6 wt% for MgH_2 and 10.1 wt% for AlH_3) and low cost being, perhaps, the main ones (Wang and Wang, 2017). This is also why their level of technology readiness for hydrogen preservation at the moment appears to be more advanced than that of other metal hydrides (Table 2). Nevertheless, it does not mean that they are flawless.

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[19] In particular, toluene is produced during oil refining, directly as a by-product of styrene manufacture and indirectly as a by-product of coke-oven operations (Li et al, 2021). Naphthalene, in turn, is usually manufactured from either coal tar via its distillation and fractionation or petroleum by dealkylation of methyl naphtalenes in the presence of hydrogen (Prasad, Vithanage, and Kapley, 2019). Benzene, again, is predominantly synthesized from petroleum and coal via catalytic reforming, steam cracking and toluene disproportionation processes, as well as coal processing (Meng et al, 2021). Finally, DBT is normally produced from benzyl chloride, which, itself, is prepared industrially by the gas-phase photochemical reaction of toluene with chlorine (Wunsch, Berg, and Pfeifer, 2020).

In general, due to the abundance of cheap magnesium and the possibility of generating a lot of inexpensive hydrogen, MgH_2 could be labelled the archetype metal hydride (Matar, 2010). It has light weight and high stability (ibid). However, its desorption temperature is high (250-400°C) while the absorption kinetics is very slow (*Table 1*). As a result, although magnesium hydride meets almost all the key criteria for practical application, its main drawbacks – poor kinetics, severe thermal management, and high stability – that is, factors making its hydrogenation and dehydrogenation slow, energy- and cost-intensive which still hinder its full-scale commercial usage and successful implementation at an industrial scale (Wang and Wang, 2017).

Aluminium hydride addresses some of these challenges while also offering one of the best combinations of volumetric and gravimetric hydrogen contents out of all the hydrides viewed: 148 kg_{H2}/m^3 and 10.1 wt%, respectively (*Table 1*). In contrast to magnesium hydride, AlH_3 can easily release H_2 when heated and desorption requires lesser temperatures (85-140 °C) (Su et al, 2021). On the other hand, aluminium hydride is generally formed by reacting Al with H_2 at extremely high hydrogen pressure and temperatures (Table 1), which simultaneously makes this process lengthy and energy demanding and thus also limits its development and commercialisation success (Jiang, Wang, and Zhu, 2021).

2.5.2. Intermetallic hydrides

To circumvent some of the key drawbacks of elemental metal hydrides and investigate other advantages that solid-state H_2 preservation could offer, intermetallic hydrides were explored. Though it broadly depends on their specific type, in general, they require lower temperatures and pressures for hydrogenation/dehydrogenation (*Table 1*). On the other hand, just like other solid structures viewed for H_2 preservation, intermetallic compounds (here, AB_5, AB_2, and AB types being the main ones[20]) that are known to be able to store reversibly significant amounts of hydrogen have still not been fully commercialized (Sikora and Kuna, 2007).

AB_5-type intermetallic compounds and their derivatives have rich chemistry and suitable properties to be successfully used for hydrogen storage. Here, the derivatives of $LaNi_5$ (lanthanum penta-nickel) (e.g., $LaNi_5H_6$ and similar systems) are known in particular as prototypes of hydrogen absorbing and hydride forming intermetallic compounds (Joubert et al, 2021). However, despite such advantages as storage stability and relatively low temperatures, pressures and thus energy needed for the hydrogenation/dehydrogenation processes, the main deficiency of these options relates to the amount of hydrogen that they can store relative to the amount of metal alloy (e.g., 1-1.5 wt% for $LaNi_5H_6$) (Table 1).

In order to overcome this challenge, other metal alloys with similar crystal structures but which allow for higher H_2 mass densities such as Mg-based compounds, AB_2-type hydrides, have been explored (Naccarella, 2017). Their main advantage in comparison to AB_5-type alloys is that the amount of hydrogen that they can store is two-three times higher (Table 1). However, these systems still appear to be more demanding in terms of pressure needed for hydrogenation and extraction of hydrogen, which is less quick than that of AB_5-type compounds (ibid).

Finally, apart from having high H_2 weight capacities (up to 5.4 wt%), AB-type compounds have the lightest molar mass out of the viewed intermetallic hydrides (Lys et al, 2020). In this context, specifically, titanium-iron (TiFe) compounds are some one of the most promising hydrogen storage alloys because of their economic merit based on the abundance and low cost of their constituting elements (ibid). On the other hand, TiFe require laborious treatment after synthesis to promote the first hydrogen absorption, since they do not readily absorb hydrogen under ambient conditions because of a native passivating layer (Dematteis et al, 2021). In fact, TiFe alloys appear to be sensitive to air moisture and might react with it, which will result in the formation of oxides and hydroxides and thus hindered reaction with hydrogen (ibid). As a result, a successful application and use of this type of metal hydrides needs further research and improvement.

2.5.3 Complex metal hydrides

Finally, complex hydrides are the group of metal hydrides that are particularly interesting due to their relatively low weight (Züttel, 2004). Their molar mass (e.g., 21.78 g/mol for lithium borohydride ($LiBH_4$) and 22.96 g/mol for lithium amide ($LiNH_2$)) (Table 1), is generally lower than the molar mass of the most common intermetallic hydrides discussed above (201.1-432.37 g/mol) as well as many elemental metal hydrides (26.32-29.99 g/mol) (Table 1). Here, borohydrides, in general, and $LiBH_4$, in particular, represent the compound with the highest gravimetric hydrogen density at room temperature known today (around 18.5 wt%) (ibid). That is why they are often seen as 'ideal' storage material for mobile

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[20] Here, A = rare-earth atoms, B = transition metal (Sikora and Kuna, 2007).

applications. On the other hand, the scientific understanding of the mechanism of the hydrogen desorption from borohydrides as well as absorption by them still remains a challenge and further research is needed (ibid).

Alanates (e.g., lithium aluminium hydride ($LiAlH_4$)and sodium aluminium hydride ($NaAlH_4$)), in turn, have attracted extensive attention due to their decent H_2 storage capacity (3.5-5.4 wt%) that is combined with relatively low cost of raw materials (Zhao et al, 2021). However, just like most other complex hydrides, they also have high desorption temperature and sluggish kinetics (Walker, 2008) (Table 1). At the moment, this still significantly restricts their practical application and, as a result, commercialization (Zhao et al, 2021).

In general, thermal decomposition of amides alone usually gives off ammonia rather than hydrogen (Wang, Li, and Chen, 2013). Perhaps, this is the main reason why they had not been considered as candidates for H_2 storage until the $LiNH_2$-LiH composite was reported in 2002 to reversibly store a large amount of hydrogen (ibid). However, their de/re-hydrogenation kinetics are also sluggish and lead to unfavourable operating temperatures, which also further hamper their usage (Cao et al, 2012).

2.6. Porous materials

Although this review of hydrogen storage technologies is not exhaustive, porous materials represent the final group of H_2 preservation options discussed in this paper. This is so because of the special attention paid to their development by leading researchers as well as business initiatives. This attention owes primarily to the fact that solid-state porous materials can potentially store comparable amounts of hydrogen in a safer and more efficient manner relative to the technologies that are currently being used for most applications (such as e.g., fuel cell automobiles) (Chen et al, 2022). While other hydrogen storage alternatives are likely to be investigated as well, porous structures as a group of diverse solutions appear to be the last major array of options that are currently being explored most actively.

Here, carbon-based hydrogen storage options and metal-organic frameworks represent two of the most important families of porous materials praised for their significant hydrogen storage potential. Although a lot of effort has been made to near a successful market entry of these solutions, none of them has already approached the technology readiness level that is needed for fully-fledged commercialisation. Furthermore, none of the options has gone beyond application for small-scale storage.

2.6.1. Carbon-based materials

Carbon-based hydrogen storage solutions currently include a number of options with carbon fibres[21], nanotubes, aerogel, templated and activated carbon as well as graphene being some of the most promising ones for potential commercialization in the foreseeable future (ibid). Here, in contrast to e.g., metal-organic frameworks (see below), these materials are more resistant to oxidation, have better reversibility and cyclic ability and moderate thermodynamic stability (Fan, Wang , and Zheng, 2022). While activated carbon, carbon fibres and nanotubes appear to be at a higher level of technology readiness in contrast to the remaining carbon-based hydrogen storage options (Table 2), they still need further research and development efforts so that their deficiencies are successfully addressed.

Most notably, many carbon-based materials are characterized by a low hydrogenation level under ambient conditions. This means that, for a lot of them, hydrogen uptake significantly increases under cryogenic temperatures and significantly diminishes (down to 1 wt%) at room temperatures (Xia, Yang, and Zhu, 2013). This challenge coupled with high potential energy consumption needed for their quick decarbonization substantially limits their applicability.

2.6.2. Metal-organic frameworks (MOFs)

Metal organic frameworks (MOFs) represent the other most promising family within the category of porous hydrogen storage materials. In general, they are a class of organic-inorganic hybrid and crystalline porous materials, whose framework structures, pore environment, and functionality can be adjusted for specific conditions of hydrogen storage (Cai et al, 2021). Most of them consist of a simple cubic framework that provides them with a high surface area and large pores (Froudakis, 2011). In addition, their gravimetric hydrogen content is more significant (up to 10 wt%) (Table 1). These factors make MOFs superior to carbon-based materials in terms of suitability for increasing hydrogen storage capacity.

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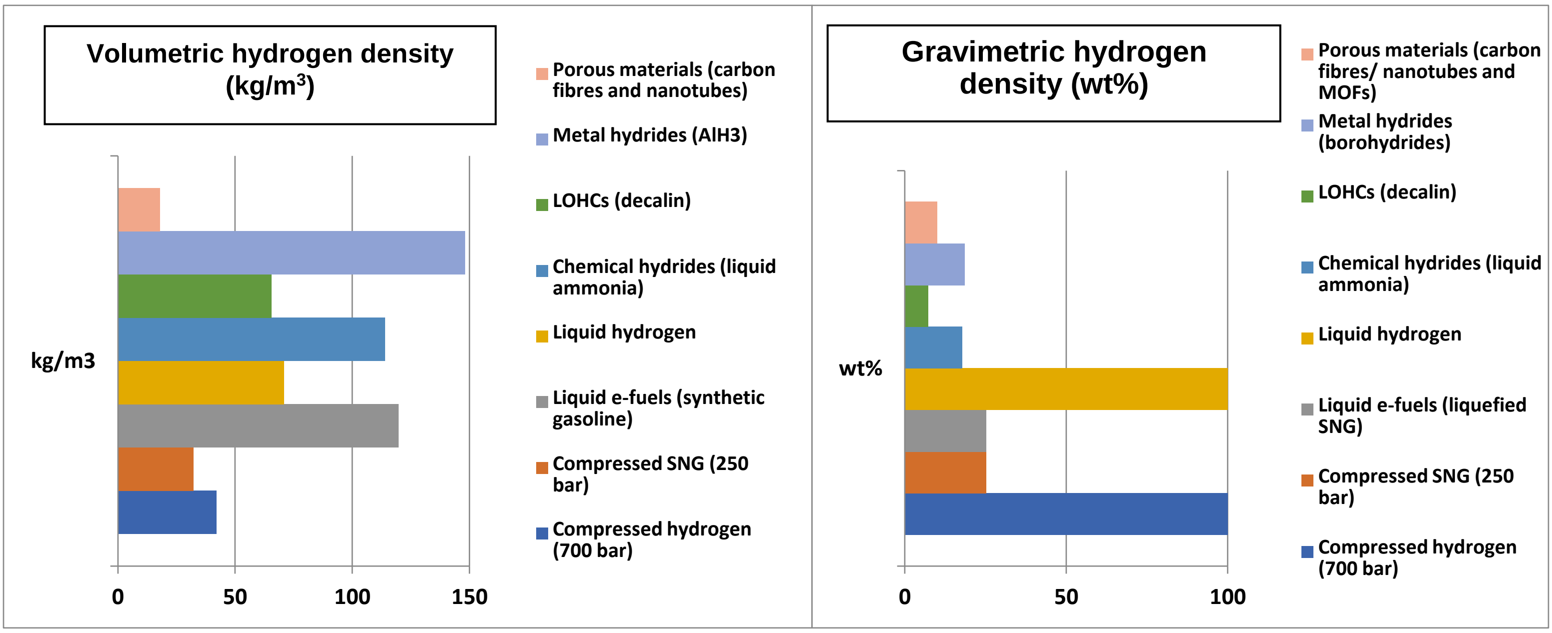
[21] Carbon fibres in a form of carbon fibre-reinforced polymer (CFRP) composites have already been used to reinforce hydrogen storage tanks for the preservation of compressed H_2 (Gardiner, 2022). At the same time, carbon fibres also show some unique advantages to be used as a solid-state hydrogen storage option due to its low gas-solid interaction, tunable texture, high pore volume and excellent chemical and thermal stability, among other characteristics (Fan, Wang, and Zheng, 2022).

At the same time, most MOFs are still very sensitive to humidity (ibid). Besides, they possess lesser structural stability to a wide range of processing conditions and require specific temperature and pressure prerequisites for stored hydrogen[22] (Cai et al, 2021). That is why, although metal-organic frameworks are currently some of the most intensively-researched hydrogen adsorbents, testing their applicability beyond the boundaries of small-scale H_2 preservation is yet to come (Ahmed et al, 2019).

2.7. Overall evaluation

As seen, each of the main types of the hydrogen storage technologies represented in this study has its own advantages and drawbacks. For instance, while storing pure hydrogen in either compressed or liquefied form will guarantee its maximum gravimetric content, these options are not the leading ones when it comes to providing the most competitive volumetric H_2 density (Figure 2). At the same time, metal hydrides, in general, and aluminium hydride (AlH_3), in particular, provide the highest volumetric H_2 density but fall short when it comes to delivering the highest gravimetric hydrogen content.

Figure 2: Volumetric hydrogen density and gravimetric hydrogen content of best performing substances for each type of major hydrogen storage options



Source: Visualization based on the information from Table 1

While such options as compressed and liquefied SNG/e-fuels seem to offer the next best solution in terms of volumetric and gravimetric hydrogen content correlation, the energy used for their generation and dehydrogenation is quite significant. This is also true for most of the remaining non-direct hydrogen storage alternatives, such as chemical and metal hydrides, LOHCs, etc. Therefore, from a technical perspective, the choice of optimum hydrogen storage entails tradeoffs between some of the key technical parameters such as volumetric and gravimetric hydrogen density, temperature, pressure and energy used for conversion and extraction of hydrogen, among others.

However, these parameters are not the only determinants here, as there are other factors that are also likely to influence the ultimate preference for one specific technology over another. Among those, such characteristics as maximum storage capacity safety, availability of infrastructure, technology, market, and commercial readiness levels would most likely play key roles.

3. Factors to consider for investment in hydrogen storage

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[22] Unfortunately, at the moment, no significant hydrogen storage capacity has been achieved in MOFs at ambient conditions (Zelenak and Saidan, 2021).

Table 2: Approximate indicators of hydrogenation/dehydrogenation, storage capacity and technology, market and commercial readiness levels for the viewed hydrogen storage options[23]

State	Storage forms			Approx. volume containing 100 kg of H_2 (m^3)	Approx. total weight containing 100 kg of H_2 (kg)	Most popular types of storage vessels currently available	Geometrical volume of maximum storage currently available (m^3)	Approx. weight of hydrogen stored in the maximum available volume (tonnes)	Readiness levels for the entire cycle of hydrogen use: hydrogenation/sorption – storage – dehydrogenation/desorption[24]		
									Technology readiness level (TRL)	Market readiness level (MRL)	Commercial readiness level (CRL)
Gas	**Compressed hydrogen**		**700 bar**	~2.38	100	Cylinders/ containers/tanks	~26[25]	~1.1	8-9	5-6	2-6
			350 bar			Salt caverns	~906,030[26]	~23,650			
	Synthetic hydro-carbons		**Compressed synthetic methane/ natural gas (SNG) (250 bar)**	~3.11	~397.93	Salt & rock caverns/ aquifers/ fields	<50.15 million[27]	1.6 million	6-9* 4-6**	3-6* 1-3**	1-5* ~1**
						Cylinders/ containers/ tanks	~9,500	~305.9			
Liquid			**Liquefied SNG**	~0.98		Tanks/ Horton spheres	~270,000	~27,480			
			Synthetic gasoline (petrol)	~0.83	~625	Cylinders/ containers/tanks	~100,000	~11,980			
			Synthetic diesel	~0.84	~714.29			~11,910			
	Liquid hydrogen			~1.41	~100	Tanks/ Horton spheres	3,800 (operated)	~269.04	6-9	3-6	1-5
							10,000 (planned)	~708			
	Chemical hydrides		**Liquid ammonia**	0.83-0.93	~566.57	Cylinders/ containers/tanks	~50,000	5,390-6,000	7-9* 6-7**	4-6* 3-4**	1-5* ~1**
			Methanol (MeOH)	1.01-1.05	~832.64		~100,000	9,500-9,900			
			Formic acid[28]	~1.89	2,325.58		<5,000	<265	7-9* 3-5**	4-6* 1-2**	1-5* ~1**
			Isopropanol (i-PrOH)	3.86	3,030.30		~30,000	~777			
	Liquid organic hydrogen carriers		**Toluene/ Methylcyclohexane (MCH)**	2.11-2.12	1,623.38		~100,000	4,710-4,740	4-7	1-4	~1
			Naphtalene/ decalin	1.53	1,371.74			~6,540			
			Benzene/ cyclohexane	1.79	1,388.89			~5,590			
			Dibenzyltoluene (DBT)/ perhydro-dibenzyltoluene (PDBT)	1.56	1,612.90			~6,400			
Solid	**Metal hydrides**	**Elemental metal hydrides**	**Magnesium hydride**	0.92-1.16	1,666.67-1,315.79		~4.5	<=0.26	7-9	4-6	1-5
			Aluminium hydride	~0.68	~990.10						
		Inter-metallic hydrides	**AB_5-type**	0.95	6,666.67-10,000				5-7	2-4	~1
			AB_2-type	~1.0	2,631.58-4,651.16						
			AB-type	~1.11	<1,851.85						
		Complex - metal hydrides	**Alanates**	~1.85	1,851.85-2,857.14				4-6	1-3	~1
			Borohydrides	~0.83	~540.54						
			Amides	~1.85	1,923.08-2,222.22						
	Porous materials		**Carbon fibres**	~5.56	<1,838.24		~0.2	~0.067	7-8	4-5	1-2
			Carbon nanotubes		1000-2000						
			Activated carbon	~5.99	1,333.33-100,000						
			Graphene	5.88-6.25	1,298.70-10,000				5-6	2-3	~1
			Carbon aerogel		<2,083.33				2-4	~1	~1
			Templated carbon	<5.88	1,369.86-1,818.18						
			Metal-organic frameworks (MOFs)	<8,70	<1,000						

Source: Adapted from US Department of CALEDON (1990), Newberry (2006), Energy (2012), Methanol Institute (2013), Fendt et al (2015), Pérez-Fortes et al (2016), CORDIS (2017), European Commission (2019), Kawasaki (2020), Mouchaham et al (2020), Royal Society (2020), Zhang et al (2020), Devaraj, Syron, and Donnellan (2021), Global Times (2021), Global Times (2022), IEA (2021), Offshore Technology (2021), Puhar et al (2021), BNamericas (2022), DEMACO (2022), EuroTankWorks (2022), GKN Hydrogen (2022), Technodyne International Limited (2022), Uniper (2022a).

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[23] Values represented in the table are approximate and based on the data from available in the literature.

[24] The represented levels are approximate, since MRL and CRL depend not only on TRL but also on the policy defining the price of CO2 avoidance.

[25] Although greater storage volume could potentially be achieved for compressed hydrogen, the volume indicated in the table is the biggest one currently used for storing and transporting compressed hydrogen (Hydrogen Europe, 2021).

[26] In 2017, Air Liquide commissioned the world's largest underground hydrogen storage facility in Spindletop Dome, Texas (Djizanne et al, 2022).

[27] Total capacity of the Zhongyuan gas storage cluster in North China commissioned by Sinopec (Offshore Technology, 2021).

[28] Due to the fact that acids are corrosive in nature, formic acid should not be stored in oxidizing materials such as e.g., metal containers/tanks. Instead, polyethylene and polypropylene can be used to store formic acid (CALEDON, 1990).

***** - Conventional/ thermochemical/ biochemical production pathways, ****** - power-to-X production pathway.

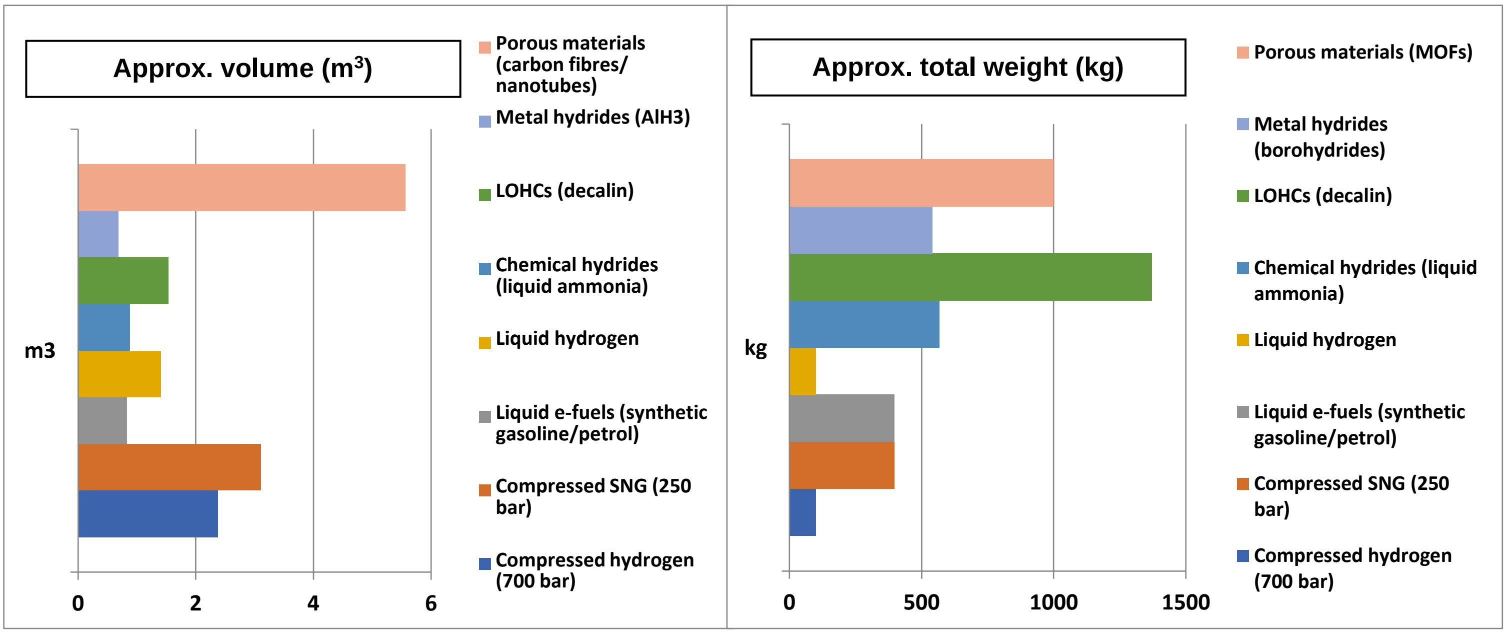
As mentioned in the previous part, although volumetric and gravimetric hydrogen densities as well as temperature, pressure and energy requirements for the hydrogenation/dehydrogenation and storage phases appear to be some of the key characteristics affecting the choice of a specific hydrogen preservation option, there are additional factors that should be included in the decision-making process. Here, most notably, the volume and weight of the stored substances under each specific storage mode as well as the scale and type of the storage vessels are important. In addition to that, the toxicity, corrosiveness and flammability of the stored matter itself are also features that cannot be ignored when thinking about ways of H_2 preservation. Finally, when planning investment in hydrogen storage, one should take into account technology, market, and commercial readiness levels (TRL, MRL, and CRL) – i.e. the indicators that would describe each of the studied technologies' progress in terms of technological maturity, preparedness for market introduction, as well as stage of offering 'success' as a commercial product (European Commission, 2019).

Apart from technical and technology-related challenges that would influence the ultimate cost and thus business attractiveness of a specific H_2 storage option, there is a range of barriers and uncertainties associated with hydrogen preservation and, on a more general note, with the entire hydrogen value chain that should be taken into account by the decision-makers. Here, such aspects as uncertainties associated with the demand for hydrogen, its regulation as well as the high potential cost and scale of storage are just a few that could be mentioned. In this respect, analyzing key issues would help to highlight the main challenges that a sound business model for the development of hydrogen storage would face.

3.1. Further technical and technology issues and challenges

Each of the main hydrogen storage alternatives reviewed in this paper has its own distinct volumetric and gravimetric H_2 densities (see Table 1). Their combination results in significant differences in the volume and weight that these options would occupy to preserve the same amount of hydrogen (see Table 2). For instance, while preserving 100 kg of H_2 in a form of aluminium hydride (AlH_3), only around 0.68 m^3 of space would be needed to accommodate it (compared to for example, around 2.38 m^3 for pure hydrogen at 700 bar). However, it will weigh almost a tonne – around 990.1 kg (compared to e.g. 566.57 kg of liquid ammonia).

Figure 3: Approximate volume and total weight containing 100 kg of H_2 of best performing substances for each type of major hydrogen storage options[29]



Source: Visualization based on the information from Table 2.

Therefore, if only these volume and weight characteristics are compared (Figure 3), none of the represented options could be viewed as the most advantageous that could be used as the ultimate, 'best' hydrogen storage option. At the same time, several substances would be quite close to the 'golden middle' – that is, offer a decent combination of volumetric and gravimetric densities allowing them to occupy neither excessive space nor weight. In this context, liquid hydrogen itself, liquid e-fuels

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[29] These data should be viewed as approximate since most of the represented substances still have low TRL level.

(synthetic gasoline/petrol), liquid ammonia and even some metal hydrides (specifically aluminium hydride and borohydrides) would demonstrate medium indicators, which could theoretically allow them for not only stationary preservation but also storage with the follow-up delivery without any transformations (which will obviously depend on the end use).

Table 3: Key advantages and disadvantages of major hydrogen storage options[30]

State	Storage forms		Characteristics													
			Volumetric hydrogen density	Gravimetric hydrogen content	Storage volume/ scale available			Energy use for storage	Speed of injection to/ withdrawal from storage vessel	Need for dehydrogenation/ desorption	Need for carbon management after dehydrogenation	Technology readiness	Development level of storage infrastructure	Corrosiveness	Toxicity	Flammability
					Small	Medium	Large									
Gas	Compressed hydrogen		Medium	High	Yes	No	Yes	High	High	No		High	Medium	Yes	No	Yes
	Synthetic hydrocarbons (e-fuels)	Compressed synthetic methane/ natural gas (SNG)	Low	Medium		Yes	No	Medium		Yes		Low-medium	High	No		
Liquid		Liquefied SNG	High					High								
		Synthetic gasoline (petrol)						Low/ none							Yes	
		Synthetic diesel														
	Liquid hydrogen		Medium	High				High	Medium	No		Medium-high	Medium	Yes	No	
	Chemical hydrides	Liquid ammonia	High	Medium				Medium		Yes	No	Medium	High		Yes	
		Methanol (MeOH)						Low/ none	High		Yes					
		Formic acid	Medium	Low								Low				
		Isopropanol (i-PrOH)	Low													
	Liquid organic hydrogen carriers	Toluene/ Methylcyclohexane (MCH)	Low-medium									Low-medium		No		
		Naphtalene/ decalin	Medium													
		Benzene/ cyclohexane														
		Dibenzyltoluene (DBT)/ perhydro-dibenzyltoluene (PDBT)														
Solid	Metal hydrides	Elemental metal hydrides	High	Low-medium		No			Low		No	Medium-high	Low	No	No	No
		Inter-metallic hydrides		Low					Medium			Medium				
		Complex - metal hydrides	Medium-high	Low-medium								Low-medium				
	Porous materials	Carbon fibres	Low					Medium	High			Medium-high				
		Carbon nanotubes														
		Activated carbon		Low												
		Graphene										Medium				
		Carbon aerogel										Low				
		Templated carbon														
		Metal-organic frameworks (MOFs)		Low-medium												

Source: Adapted from CALEDON (1990), Newberry (2006), US Department of Energy (2012), Methanol Institute (2013), Fendt et al (2015), Pérez-Fortes et al (2016), CORDIS (2017), European Commission (2019), Kawasaki (2020), Mouchaham et al (2020), Royal Society (2020), Zhang et al (2020), Devaraj, Syron, and Donnellan (2021), Global Times (2021), Global Times

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[30] In Table 3, 'favourable' characteristics are highlighted with green, 'less favourable' with yellow/amber, and 'unfavourable' with red.

(2022), IEA (2021), Offshore Technology (2021), Puhar et al (2021), BNamericas (2022), DEMACO (2022), EuroTankWorks (2022), GKN Hydrogen (2022), Technodyne International Limited (2022), Uniper (2022a).

At the same time, if investors need to consider the scale of hydrogen storage, the choice of preferred options may be significantly altered. In particular, at the moment, country-scale H_2 storage in large quantities similar to that of natural gas could only be offered by compressed hydrogen, which would then be pumped underground (Table 2).[31] Porous materials, in turn, would only be currently experimentally used in combination with pure hydrogen storage as sorbents in small-scale tanks that would lower the requirements for pressure and temperature (Chen et al, 2022). Similarly, due to their relatively novel nature, metal hydrides would be used as tank 'fillers' to facilitate H_2 preservation in safer and more stable conditions and would thus not be a medium- and large-scale hydrogen storage option that would potentially compete with batteries (Ferreira-Aparicio and Chaparro, 2019). Hence, at the moment, only liquid options (i.e. liquid synthetic fuels, chemical hydrides, and LOHCs)[32] seem to be able to offer both small- and medium-scale hydrogen storage.

In addition, not all the viewed potential hydrogen storage alternatives are equally mature in terms of technology, market, and commercial readiness. Specifically, with compressed and liquefied hydrogen being the 'ripest' options, synthetic fuels, chemical and elemental metal hydrides as well as some carbon-based porous materials (fibres, nanotubes and activated carbon) are the runners-up (Table 2). Nevertheless, the list of these options will have to shrink to compressed/liquefied H_2, elemental hydrides, methanol and ammonia as well as activated carbon with carbon fibres and nanotubes if only zero-carbon processes need to be considered. This list, however, will be reduced further to compressed/liquefied hydrogen, methanol and ammonia if both small- and medium-scale storage need to be provided.

On the other hand, if safety and stability of storage is counted, such aspects as corrosiveness, toxicity, and flammability of the stored substance should be taken into account as well. In this case, elemental metal hydrides will remain the only technologically advanced option that would guarantee safe preservation of hydrogen (Table 3). This, however, means that, only relatively small amounts of H_2 could be considered for storage with maximum safety. At the same time, this also means that all other viewed small-, medium-, and large-scale options ready for or close to commercialization pose some safety concerns.

In general, as demonstrated in Table 3, none of the hydrogen storage alternatives performs best across all the categories that are important for creating a sound business case for hydrogen storage. This suggests that there will likely not be a single preferred option for all the stakeholders dealing with H_2. It is thus more likely that the ultimate storage solution will be chosen based on the combination of the final use of hydrogen with the characteristics represented above. In addition, the decision-making process will most likely also include more general aspects of hydrogen storage.[33]

3.2. Other factors, uncertainties, and barriers for investment in hydrogen storage

Cost is among the most important aspects to consider when choosing a specific hydrogen storage option to invest in. Here, however, estimating the specific expenses that an investor would incur when choosing one option over another is hard because of different TRL/MRL/CRL as well as project-specific characteristics.

When it comes to preserving pure hydrogen, the Argonne National Laboratory provides the following brief estimates of capital, operation and maintenance costs that are associated with this mode of hydrogen storage (Table 4).

Here, as seen, adjusting the underground facilities that are currently being used for natural gas seems to be the least expensive option due to the overall similarity of the storage processes. On the other hand, the downside of this would be higher operation and maintenance costs as well as lack of flexibility in terms of storage scale, since it would only be economically reasonable to use these facilities for large-scale initiatives. Preserving H_2 in compressed or liquefied forms, in turn, would result in medium operation and maintenance costs but higher capital expenses (if compared to the most mature solid storage alternatives).

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[31] This is especially important when considering international trade, where large scale is almost certainly needed to obtain economies of scale (e.g. for hydrogen pipelines).

[32] Since it is not economical to liquefy hydrogen for small-scale storage, it is currently mostly done at a medium scale.

[33] As well as its final use.

Table 4: Approximate capital, operation and maintenance costs of storing pure hydrogen in different forms (USD_{2017}/kWh)

Storage form		**Costs[34]**		**Other potential considerations (costs)**	**Available storage scale**
		Capital	**Operation and maintenance**		
Compressed gas	*Cylinders/ containers/ tanks*	20.4	0.037	Compressor	Small/ medium
	Underground aquifers/ reservoirs/ caverns	0.21-0.52	0.11	Piping	Large
Liquid		15.4	0.062	Liquefier	Medium
Solid	*Metal hydrides*	15.6-225.2	0.02	n/a	Small/ medium
	Porous systems	13.7-17.9			

Source: Adapted from Ganda and Maronati (2018)

While small- and medium-scale hydrogen storage could be provided by a number of options (incl. those offered by hydrogen derivatives) and hence the investor will be able to choose the alternative that appears to be the most suitable for a specific business case, large- (country-) scale storage of hydrogen is still technologically limited to H_2 compression and injection underground. In addition to that, given the calorific content differences between compressed hydrogen and natural gas, storing the same amount of energy in the form of H_2 compressed to 350 bar (the maximum operating pressure for underground storage facilities) would require almost three times as much volume as it would for natural gas kept at 200 bar (Table 5):

Table 5: Storage volume needed to accommodate Europe's 2-week peak energy demand of 326 TWh[35]

Characteristics	**Unit of measurement**	**Natural gas/ SNG**		**Hydrogen**	
		200 bar	**Liquefied**	**700 bar**	**350 bar**
Volumetric density	**kg/m^3**	~180	430-470	~42	~26.1
Gravimetric energy density	**MJ/kg**	53.6-55.6		120-142	
	kWh/kg	14.89-15.44		33.33-39.44	
Amount needed to cover 326 TWh*	**Million tonnes**	21.11-21.89		8.27-9.78	
Storage volume needed to cover 326 TWh*	**Million m^3**	117.28-121.61	44.91-50.91	196,9-234,86	316.86-374.71

Key calculations:

1.1. Gravimetric energy density of natural gas/SNG: 53.6-55.6 MJ/kg = 14.89-15.44 kWh/kg

1.2. Gravimetric energy density of hydrogen: 120-142 MJ/kg = 33.33-39.44 kWh/kg

2.1. Amount of natural gas/SNG needed to cover 2-week peak demand:
326,000,000,000 kWh : (14.89-15.44 kWh/kg) = 21.11-21.89 million tonnes

2.2. Amount of hydrogen needed to cover 2-week peak demand:
326,000,000,000 kWh : (33.33-39.44 kWh/kg) = 8.27-9.78 million tonnes

3.1. Volumetric density of compressed natural gas/SNF at 200 bar = ~180 kg/m^3

3.2. Volumetric density of liquefied natural gas/SNF = 430-470 kg/m^3

3.3. Volumetric density of compressed hydrogen at 700 bar = ~42 kg/m^3

3.4. Volumetric density of compressed hydrogen at 350 bar = ~26.1 kg/m^3

4.1. Storage volume of compressed natural gas/SNG (200 bar) needed to accommodate a 2-week peak demand:
21.11-21.89 million tonnes : (180 kg/m^3 : 1000) = 117.28-121.61 million m^3

4.2. Storage volume of liquefied natural gas/SNG needed to accommodate a 2-week peak demand:
21.11-21.89 million tonnes : (430-470 kg/m^3 : 1000) = 44.91-50.91 million m^3

4.3. Storage volume of compressed hydrogen (700 bar) needed to accommodate a 2-week peak demand:
8.27-9,78 billion tonnes : (42 kg/m^3 : 1000) = 196.9-234.86 billion m^3

4.4. Storage volume of compressed hydrogen (350 bar) needed to accommodate a 2-week peak demand:
8.27-9,78 billion tonnes : (26.1 kg/m^3 : 1000) = 316.86-374.71 billion m^3

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[34] Capital costs would mostly relate to the adjustment of the already existing storage infrastructure (e.g. that previously used for natural gas) to the requirements of hydrogen storage in the respective form as well as the creation of new storage facilities (e.g. compressed storage tanks with porous systems/metal hydrides) (Ganda and Maronati, 2018). Operation and maintenance costs, in turn, would relate to the hydrogenation (absorption)/dehydrogenation (desorption) processes and related operations (ibid).

[35] According to Cihlar, Mavins, and van der Leun (2021), in 2019, a two-week peak demand in EU-27 and the UK that was covered by natural gas was 326 TWh.
1 TWh = 1,000,000,000 kWh
***-** calculated for natural gas/SNG compressed to 200 bar, liquid natural gas/SNG and hydrogen compressed to 700 and 350 bar for illustrative purposes. Underground hydrogen storage normally presupposes operating pressure of 15-315 bar (Cihlar, Mavins, and van der Leun, 2021).

For a two-week peak demand in Europe-27 and the UK that is normally covered by natural gas, which constitutes around 367 TWh (Cihlar, Mavins, and van der Leun, 2021), around 117.28-121.61 million cubic metres of natural gas stored at 200 bar would be needed. At the same time, if this energy is supposed to be provided by hydrogen that is stored under 350 bar, the volume needed would be significantly bigger: 316.86-374.71 million cubic metres.

While this may not look like a significant challenge per se, it turns out that out of the four options that are currently being viewed for large-scale underground hydrogen storage (salt and rock caverns, depleted fields/reservoirs, and aquifers), only salt caverns have been successfully tested in terms of suitability for this purpose –that is, they have the highest TRL of 8 and the remaining options are still far behind (Table 6):

Table 6: Some key characteristics of the main geological options for underground hydrogen storage

Characteristics	Caverns		Depleted fields/ reservoirs	Aquifers
	Salt	Lined rock		
General suitability for hydrogen storage	High		Site-specific	
Potential type of operation[36]	Peaking and seasonal		Seasonal	
Potential maximum number of cycles per year[37]	10		1-2	
Estimated facility working gas capacity (TWh H_2)[38]	0.01-4.12	0.04	0.03-14.29	0.05-3.23
Working gas capacity/ Total gas capacity (%)	70	>70	50-60	20-50
Depth (m)	300-1,800	~1,000	300-2,700	400-2,300
Operating pressure (bar)	35-210	20-200	15-285	30-315
Largest expenses (new development)	• Formation of the cavern • Disposal of the brine • Cushion gas • Compression	• Blasting of the cavern • Steel lining • Cushion gas • Compression	• Well • Infrastructure • Cushion gas • Compression	• Exploration and determination of geology • Well infrastructure • Cushion gas • Compression
Relative cost of development/ investment	Low	High	Low	
Relative cost of operation	Moderate			
Average injection/ withdrawal rate (site-specific)			High	Moderate
General suitability for hydrogen storage	Proven	First hydrogen storage in development	• Hydrogen-methane blending (up to 10-50% H_2 proven) proven. • Pure hydrogen storage under study	• Hydrogen-methane blending (up to 10% H_2) proven • Pure hydrogen storage under study
Estimated technology readiness level (TRL) for hydrogen storage	~8	5-6	3-6	~3
Further R&D needed	Precision in the timing of injections and withdrawals	Compatibility of lining materials with hydrogen	• Effects of residual natural gas • In-situ bacteria reactions	• In-situ bacteria reactions • Tightness of rocks

Source: Adapted from Cihlar, Mavins, and van der Leun (2021) and Epelle et al (2022).

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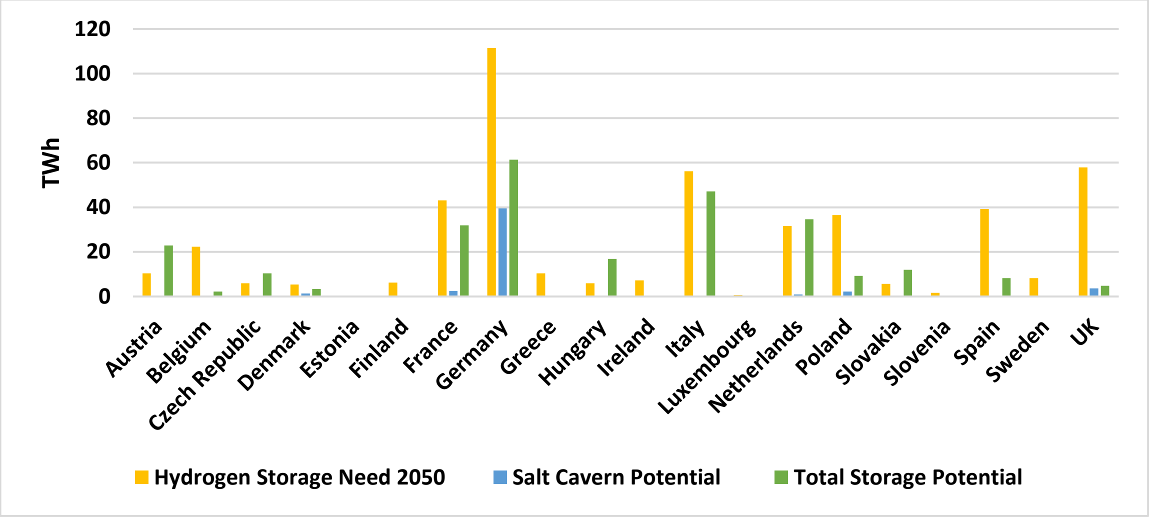
[36] Seasonal storage sites typically take months to complete a full injection/withdrawal cycle, so they are normally used to meet seasonal variations in demand (Cihlar, Mavins, and van der Leun, 2021). Peaking storage typically completes full injection/withdrawal cycles in days/weeks so they are normally used to meet hourly, daily, and weekly demand variations (ibid). Optimized cluster/hub storage operations can be used to provide short-term or peak services independently from specific geological characteristics (ibid).

[37] Estimates are based on current use for natural gas.

[38] Range of total working gas capacity per facility.

In these circumstances, given that salt caverns are not distributed equally across all geographies, preserving large quantities of hydrogen underground may not be available everywhere. For instance, with the ambitious targets for H_2 generation and import, Europe will need to be able to accommodate these quantities of hydrogen right after its production or import or before its final use. However, as seen from Figure 4, this will most likely not be possible to perform if only salt caverns are available.

Figure 4: Estimates of hydrogen storage need by 2050 vs. potential



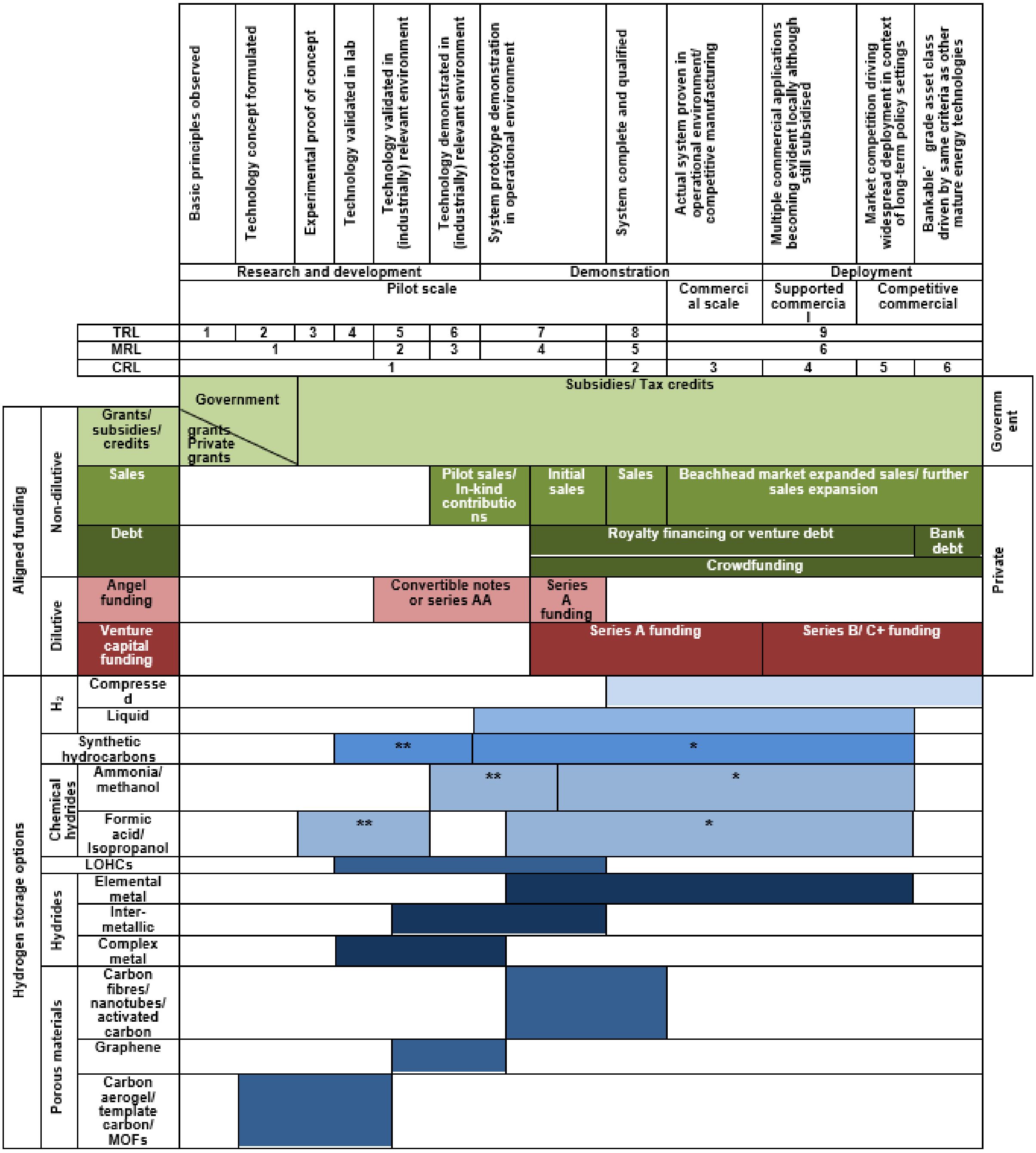
Source: Cihlar, Mavins, and van der Leun (2021).

On the other hand, it is likely that most significant hydrogen consumption in Europe will not occur before 2040 and will not have the same magnitude throughout the continent (Barnes, 2023). Hence, it is unlikely that H_2 storage will become a Europe-wide issue by the end of the next decade, since many countries will only make it an important component of their energy systems then. As a result, they will have time to develop various hydrogen storage alternatives.

This also demonstrates that, if hydrogen is to play a key role in decarbonization and is used across industries and sectors, small- and medium-scale H_2 preservation options that include not only pure hydrogen storage but also its derivatives will most likely have to complement the large-scale ones. In this case, given the uncertain costs of these undertakings that would include conversion expenses (e.g., from H_2 to NH_3 and back), investors may hesitate to engage in such projects in preference for well-known and most likely cheaper energy storage variants – here, fossil fuels such as natural gas. Since hydrogen storage in the form of its derivatives could be the same as the preservation of hydrocarbons or such chemicals as ammonia and methanol, both capital and operation and maintenance adjustments for launching and running these storage facilities are likely to be less significant than for those aimed at pure hydrogen storage. This, however, does not include the expenses associated with the additional pre- and post-storage treatment that would transform hydrogen into its derivative and back. As a result, while storage-related costs for such options may be lower than those for different alternatives to pure H_2 preservation, these ‘transformation’ expenses as well as those that are associated with hydrogen purification and carbon management will still go towards the final cost of H_2 at the end of its value chain. In the end, these cost-related uncertainties as well as the round-trip efficiency could determine what specific hydrogen storage option would ultimately be preferred.

On a more general note, these challenges would closely align with policy and regulation. In particular, given that hydrogen production, storage, and delivery – the main activities in the hydrogen value chain – appear to be more expensive than the same elements for hydrocarbons, lack of regulatory and policy support will most likely dissuade investment in hydrogen storage. In this respect, the starting point of an H_2-supportive regulation or policy should be to deal with the extra costs of producing it carbon free. This is because it is uncertain if expected future profit is able to cover costs and risks associated with producing and transporting zero carbon hydrogen. These uncertainties about commercial arrangements would also equally apply to hydrogen storage. Here, clarity should be achieved on such issues as storage ownership and usage (i.e. who owns the storage facility and who uses/operates it), access to storage infrastructure, and price of utilizing it, among others.

Table 7: TRL, MRL, CRL of various hydrogen storage alternatives and their aligned funding options



			Basic principles observed	Technology concept formulated	Experimental proof of concept	Technology validated in lab	Technology validated in (industrially) relevant environment	Technology demonstrated in (industrially) relevant environment	System prototype demonstration in operational environment	System complete and qualified	Actual system proven in operational environment/ competitive manufacturing	Multiple commercial applications becoming evident locally although still subsidised	Market competition driving widespread deployment in context of long-term policy settings	Bankable' grade asset class driven by same criteria as other mature energy technologies	
			Research and development						Demonstration			Deployment			
			Pilot scale								Commercial scale	Supported commercial	Competitive commercial		
		TRL	1	2	3	4	5	6	7	8	9				
		MRL	1				2	3	4	5	6				
		CRL	1							2	3	4	5	6	
Aligned funding	Non-dilutive	Grants/ subsidies/ credits	Government grants Private grants		Subsidies/ Tax credits										Government
		Sales						Pilot sales/ In-kind contributions	Initial sales	Sales	Beachhead market expanded sales/ further sales expansion				Private
		Debt							Royalty financing or venture debt Crowdfunding					Bank debt	
	Dilutive	Angel funding					Convertible notes or series AA		Series A funding						
		Venture capital funding							Series A funding			Series B/ C+ funding			
Hydrogen storage options	H_2	Compressed								■	■	■	■	■	
		Liquid							■	■	■	■	■		
	Synthetic hydrocarbons					**	**	**	*	*	*	*	*		
	Chemical hydrides	Ammonia/ methanol						**	**	*	*	*	*		
		Formic acid/ Isopropanol			**	**	**		*	*	*	*	*		
	LOHCs					■	■	■	■						
	Hydrides	Elemental metal							■	■	■	■	■		
		Inter-metallic					■	■	■						
		Complex metal				■	■	■	■						
	Porous materials	Carbon fibres/ nanotubes/ activated carbon							■	■					
		Graphene					■	■	■						
		Carbon aerogel/ template carbon/ MOFs		■	■	■	■								

Source: Adapted from US Department of Energy (2012), Buchner et al (2019), European Commission (2019), Royal Society (2019), EcosVC (2020), Müller, Skeledzic, and Wasserscheid (2021).

* - Conventional/ thermochemical/ biochemical production pathways, ** - power-to-X production pathway.

However, the most crucial uncertainty that may prevent businesses from allocating funds for H_2 storage projects is the doubt about sufficient demand for hydrogen. It may emanate from such factors as, for example, absence of strong policy support or unclear progress in the industries' conversion from hydrocarbons to hydrogen. More fundamentally, however, it may be based on a general disbelief in the possibility of creating a viable hydrogen value chain and rejection of the very idea that hydrogen can potentially replace fossil fuels in some of modern economy's key industrial processes. Here, to overcome these challenges and uncertainties, respective policies and regulations will have to be created to support demonstration projects, stimulate demand, incentivize investment in infrastructure and encourage producers and industries to switch to low-carbon hydrogen when it makes sense.[39]

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[39] There is also a risk that policy decides to focus on one technology when alternative net-zero carbon options could potentially be superior in some end uses.

As TRL/MRL/CRL characteristics of the existing hydrogen storage options differ significantly [40] (Table 7), the preferred support mechanisms for each of the specific storage options will also vary. The funding source also very much depends on the stage of the market, technology and commercial readiness levels of specific hydrogen storage technologies. For example, grant funding in a form of private or government grants would be most applicable for storage technologies such as graphene, template carbon, carbon aerogel, and MOFs, while overall government support would also relate to synthetic fuels, isopropanol and formic acid obtained via power-to-X pathways, LOHCs, intermetallic and complex hydrides (Table 7).

Overall, government funding is often used to support the early-stage research and development of nascent technologies that may be too risky for private investors to finance. It is also used to provide critical support to enable the development of a technology from the laboratory to the prototype stage. Also, government funding can be used to support the deployment of close to mature technologies that are strategically important for development of a hydrogen economy.

Other sources of funding, such as venture capital, corporate funding, and crowdfunding, are typically used to support the commercialization of technologies that have already progressed beyond the early research and development phase. Private investors may be more willing to invest in a technology that has already been demonstrated to be viable and has a clear path to commercialization, as this reduces the level of risk involved.

The next section discusses approaches to government supported business models for large scale and close to mature hydrogen storage technologies. Although both small- and large-scale hydrogen storage options are likely to be important in the future, government support for large scale storage can be justified for at least two reasons. First, is that large-scale storage facilities are likely to be more cost-efficient than smaller ones, as they can benefit from economies of scale in terms of equipment, infrastructure, and operation costs. Second, large-scale hydrogen storage facilities can help to accelerate the development and commercialization of hydrogen technologies by creating a market for hydrogen storage and stimulating private sector investment in the technology. The presence of a hydrogen storage market will benefit smaller and less mature technologies too over the long run.[41]

4. Business models and policies for hydrogen storage

The fundamental value of energy storage comes from the possibility of supply and demand imbalance at different time scales and in different periods of time. In essence, the very purpose of hydrogen energy storage is to transfer energy across time. When the cost of this transfer (production and storage) is lower than the cost of meeting demand from instantaneous production in the next period, energy storage represents an economic value.

On the other hand, this does not mean that all the energy systems currently in operation include a well-developed storage component. In fact, there are systems where large-scale energy storage is still technologically challenging or immature. For instance, the electricity sector in its current form is designed with an assumption of little energy storage in the system (US Department of Energy, 2016). As a result, the system is dimensioned to meet peak demand with significant spare capacity across the whole supply chain from generation to distribution networks (ibid). If, in the future, large scale storage of electricity becomes technologically mature and economically efficient, the entire power system would be more efficient.

At the same time, there are energy systems in which large scale energy storage is technologically mature but not necessarily economic under all conditions. For instance, in the case of natural gas, many storage facilities in Europe lost their economic attractiveness over time and some had to close (such as Rough storage in the UK) when they were operating under low gas prices and the winter/summer spread collapsed (Guardian, 2017). From the perspective of investors in gas storage, since new facilities take around half a decade to develop and need to run for about two decades to pay back their

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[40] While some of the H_2 preservation solutions are nearing full commercialization and are about to successfully enter the market, others are still either at a very early research and development or laboratory testing stage.

[41] Here, it might be useful to distinguish between the two key uses of hydrogen storage – for electricity storage or for transportation of hydrogen itself. For electricity storage, given that there is already a nascent forward market for power as well as term contracts, Contracts for Difference (CfDs) and capacity markets under active consideration, the commercial regulatory framework seems to be more advanced. For storage of hydrogen for delivery to consumers, the framework appears to be less mature and thus will require government support in the consuming market. In this connection, standalone storage projects are only likely to appear as the market matures and aggregation becomes possible.

investments, operation of such storage installations is subject to significant economic risks (Gaz System, 2022).

Although, in principle, hydrogen storage could face the same fate as gas storage in Europe, the economic and technical features of these two industries are not exactly similar. If the role of hydrogen in our economy increases to the extent it is expected, the rising demand for this substance will have to be met by sufficient magnitude of supply. This will most likely involve the need for hydrogen storage infrastructure. This is so because the low level of supply diversity (as least at an early stage of the sector's build-up) increases the probability of supply and demand imbalances. Specifically, because of the techno-economic complexity of hydrogen transfer, it is unlikely that the number of large-scale hydrogen suppliers will be greater than suppliers of natural gas. Apart from this, green hydrogen generated by wind and solar energy sources will have unstable (variable) production patterns – they will be intermittent (Armijo and Philibert, 2020). In fact, even CCUS-enabled H_2 production may not match the demand profile in certain circumstances and under certain conditions (Cloete, Pozo, and Álvaro, 2022). That is why, with this demand-supply imbalance in place, hydrogen storage is likely to have a positive economic value from a social welfare perspective despite the costs associated with it.

A question that arises here is that, if hydrogen storage does have an economic value, why is no one currently trying to capture it?[42] Here, the simple answer would be 'because of risk considerations'. In particular, there are two primary risks associated with investment in hydrogen storage. The first one is the *risk of insufficient demand for such services* –that is, the risk that after investment happens there is no strong need for H_2 storage.[43] The other one is *the risk of low price to utilize hydrogen storage capacity.* In other words, the price of hydrogen storage access might not be high enough to justify the investment, which can happen for various reasons, including competition among various modes of hydrogen storage as well as technology development.

These two risks lead to revenue uncertainty. Though this uncertainty may decrease over time as a hydrogen economy develops, it needs to be mitigated through efficient risk allocation between the government and a private party (IISD, 2015). These risks will be allocated through applying a specific business model.

To design a business model for hydrogen storage in a proper way, two critical questions have to be asked. The first question is *which H_2 storage technology should be incentivized?* For instance, if the government needs to create a well-functioning hydrogen economy, it needs to support the deployment of large-scale H_2 storage (Tank Storage, 2022). In this case, as seen from Part 3.2., it will have to support system-wide hydrogen storage that is currently available only in a form of compressed H_2 kept underground. Here, the cost of running such a storage system could be reduced due to the economies of scale and synergy of natural gas and hydrogen storage technologies, as some storage facilities could potentially be converted from natural gas to hydrogen (Uniper, 2022b).[44]

The second question in this respect is *who should be incentivized?* Should the government support the user of the storage facility or its provider? Preferring one over the other will have implications for the development of a hydrogen economy and deployment of a hydrogen storage infrastructure. Given the nature of risks involved in the hydrogen storage infrastructure investment, it is very likely that providers, rather than users of storage facilities, should be incentivised. The incentive needs to be provided through viable business models which require policy and commercial interventions.

4.1. Range of possible business models

In principle, business models for hydrogen storage can be arranged in many ways. In fact, they can be put on a spectrum between two extremes, with a range of possible ones in between (Figure 5). Here, one side of the spectrum represents a purely commercial (market-based) approach. In this model, market participants invest in hydrogen storage to benefit from the price difference across time. The main assumption behind this model is that the market is well-developed, and no government support is needed. The other side of the spectrum, in turn, represents a centrally coordinated model. In this case,

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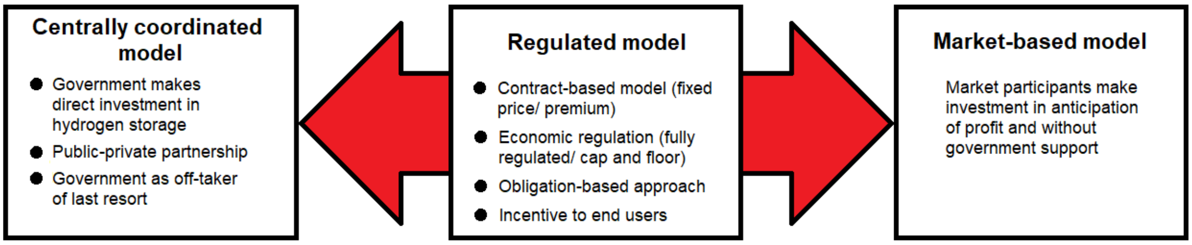
[42] Although large-scale hydrogen storage has existed in some places, it was there not because H_2 was viewed as a major component in decarbonization. Instead, while hydrogen stored in those facilities was treated as a commodity of its own, it was later used in specific sectors and thus had niche application. For instance, the Chevron Phillips Clemens Terminal in Texas has stored hydrogen since the 1980s in a salt cavern (Forsberg, 2006). The H_2 kept there is used for the manufacturing of chemical products synthesized in the region (ibid), which makes this model economically advantageous but neither representative nor replicable everywhere in a net-zero carbon context.

[43] Or, for example, in the absence of current large scale production, there is a risk that hydrogen generation and hence the need for storage does not take off at all.

[44] For instance, in January 2023, Storag Entzel and Gasunie annouced their intention to jointly develop two caverns at the Entzel site for H_2 storage in the future (Gasunie, 2023).

the government is directly involved in the project either as an investor, storage provider or storage user. This involvement can be in a full or partial manner.

Figure 5: Range of possible business models



Source: UK Department of Energy and Climate Change (2014), Bhagwat et al (2017), NS Energy (2019), Inspired Energy (2020), Net Suite (2021), Palovic and Poudineh (2022), European Commission (2023).

A broad range of options lying in between relate to the regulated model. Here, the government incentivizes private entities to provide hydrogen storage or buy storage services from a provider. This can be done in various forms such as:

- Contract-based models in which prices and revenues are regulated;
- Obligations that are imposed on either hydrogen producers or users to keep specific volumes in storage;
- Access to hydrogen storage is subsidised for end users.

Although all these models could theoretically be applied, not all of them will be suitable for a particular context when hydrogen storage needs to be created. The key issue will be to address the two specific risks outlined above – those of price and demand. In this case, it is important to identify which business model addresses the price risk and which one addresses the volume risk more efficiently.

4.2.1. Addressing the price risk

Not surprisingly, to address the price risk, focus is on the price in a contract-based scheme. There are various ways to do so. For instance, fixed-price contracts represent one of the simplest and most broadly-used options. In essence, such contracts serve a role which is similar to that of feed-in tariffs (FiT) for renewables and are contractual agreements with a predetermined value for the services provided (here, hydrogen storage) (Inspired Energy, 2020). This type of contract provides certainty, a clear and predictable revenue structure and reduces overall risk exposure. However, setting the right price for these contracts can be difficult not least because of uncertainty about the costs as well as unforeseen situations that may impact costs. An auction can be used to identify least cost providers but the success of such an approach depends on many factors including participation of a sufficient number of non-colluding bidders.

The experience from the electricity sector shows that, fixed price contracts such as FiT send a strong signal to investors. However, when they are set administratively, they can lead to significant inefficiencies in terms of overpayment or underpayment because of information asymmetry and constantly changing market conditions. That is why, in the absence of auction-based price setting, fixed-price contracts tend to be best suited for when a project's scope can be clearly determined upfront, and the costs of storage provisioned in the contract's terms can be estimated with reasonable certainty (Net Suite, 2021).

Alternatively, a fixed premium can be paid on top of the price achieved in the market. In general, a fixed premium means an operating support in the form of a premium per volume of stored hydrogen additional to the market price, the amount of which is normally determined by the grant award procedure (European Commission, 2023). A fixed market premium also means that it remains at a constant level, even if the market prices fluctuate (ibid). Usually, while exposing storage providers to some degree of market price risk, it also stimulates market development per se. At the same time, in cases of market inefficiencies, establishing fixed premiums may lead to overcompensation.

In order to avoid this, a sliding (variable) market premium can be applied instead. While similar to Contracts for Difference (CfD),[45] such premiums would normally pay developers a premium when the

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[45] Contrasts for Difference (CfD) (also known as 'symmetrical market premium') is a subsidy model in which both positive and negative deviations from a fixed reference price are paid out to the contractual partner (Next Kraftwerke, 2022). It is the model that is currently being used to procure low carbon generation sources in the UK (UK Department for Business, Energy & Industrial Strategy, 2022).

market price is below the agreed one (ibid). In general, however, a sliding market premium may vary depending on the evolution of market prices and cover the gap between the cost of hydrogen storage and its market price. A premise of this sort of model, however, is the existence of a market for hydrogen storage which is not the case at an early stage of hydrogen economy development.

4.2.2. Addressing the demand risk

Similar to the price risk, the demand risk can also be addressed through various business models. For instance, storage provider could be offered availability payment. Working in a way similar to that of capacity markets in the electricity sector, this type of payment would be used to pay for storage availability to meet peak hydrogen demand. In principle, it can improve supply adequacy and reduce consumer costs but can also fall victim to storage oversupply, with financial consequences to the provider if the availability-based payment does not cover full costs (Bhagwat et al, 2017).

Alternatively, the government can become the off-taker of last resort (OLR). In this case, it will provide some sort of guarantee to the storage provider if a given volume of storage capacity remains unsold. In this respect, the aim of the OLR is to encourage competition in the market, reduce the cost of investment in storage facilities, and lower costs to consumers (UK Department of Energy and Climate Change, 2014). At the same time, such a mechanism stimulating the development of hydrogen storage facilities may also result in a financial burden to the government in case of a massive influx of new providers (ACER, 2022).

The demand risk can also be addressed through a regulated return model such as regulatory asset base (RAB) or cost of service regulation, which can both be delivered within the cap and floor framework.[46] Here, usually representing a model used to incentivize private investment into public projects by providing a secure payback and return on investment for developers, RAB can serve as a perceived underpinning of investor expectations against retrospective ‘asset-taking’ and prospective asset-stranding (NS Energy, 2019). At the same time, opponents of such models suggest that they are effectively an ‘open cheque book’ for developers to spend what they like and that customers would have to shoulder the burden if a project goes wrong (ibid). Also, they may not incentivize efficient utilization of an asset. These negative consequences however could potentially be mitigated through appropriate regulatory oversight.[47]

4.2.3. Choosing an optimum business model for hydrogen storage

The choice of an optimal business model for hydrogen storage is likely to be influenced by many factors, including those pertaining to the two key risks mentioned above – the risk of insufficient demand for H_2 storage and the risk of the storage access price not being high enough to justify the investment. Therefore, it is likely that business models for hydrogen storage need to provide some degree of certainty with respect to both types of risks. In general, there are various ways that this can be done.

For instance, this can be done through a regulated revenue model such as RAB (with or without cap and floor) when the storage provider would agree on allowed revenue with a regulator ahead of a price control period so that it is reflective of the costs incurred by the owner of the operated storage facility (Snam, 2022). The storage provider then can recover an amount up to the level of the allowed revenue from storage users, which would be done in accordance with an agreed charging methodology. The downside of this approach, however, is that performance cannot be sufficiently guaranteed.

It can also be done through a CfD contract that could be awarded with or without an auction organized to determine the reference price. Here, a reference price is the price that a storage provider considers to be sufficient to invest in and operate the hydrogen storage. Although this option seems reasonable, it is likely that setting a specific reference price or designing an auction for this purpose would be a complex undertaking due to information asymmetry, (Matthäus, 2020).

Another approach would be to apply a hybrid model. In particular, a capacity payment can be combined with a fixed price contract. Here, the main advantages will be the simplicity of this mechanism that will be combined with its incentive provision for infrastructure utilization. At the same time, in this case just like in the previous one, setting the right price may be challenging due to the same challenge of information asymmetry (Mühlbacher, Amelung, and Juhnke, 2018).

At this very early stage of market development for hydrogen storage, it is likely that not all models will be equally effective. In fact, some of them will be more applicable and efficient later when the H_2 storage

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[46] The cap and floor model is currently being used for interconnections in the UK (Ofgem, 2016). Here, the cap is the maximum amount of revenue that a storage provider would be allowed to recover. Excess revenue would be transferred to whoever was expected to subsidize the floor (i.e., minimum amount) revenue if it was not reached.

[47] Such as RIIO (Revenue = Incentives + Innovation + Outputs), the UK incentive regulation of networks (Ofgem, 2010).

market becomes more mature. For instance, CfD contracts may currently not be suitable due to the lack of a market to determine the spread (Simhauser, 2019). RAB, in turn, will be theoretically implementable but will entail a likelihood of strategic behaviour because of the incentive it provides for overcapitalization (OECD, 2015). In these circumstances, it is likely that a hybrid model when the provider of H_2 storage receives both capacity payment and a fixed price contract will better balance investment incentives and market development despite challenges associated with setting an appropriate price.

4.3. Further challenges and questions

Although demand- and price-related concerns appear to be the key ones for the process of creating a viable business model for hydrogen storage, they will most likely be accompanied by other challenges. For instance, the capacity of hydrogen storage that would be needed may not be easy to predict not just because of the supply-demand uncertainty but also due to the lack of clarity with respect to the ultimate use of H_2, which will define its type and specifics. It is likely that the requirement for storage will be different if hydrogen is used in the heating, transport, or power sector, than if it is dedicated for a long-distance shipment right after the storage phase (TÜV SÜD, 2022).

Furthermore, a H_2 energy system can be designed to minimize the need for hydrogen storage. For example, if there is going to be a well-developed H_2 network, the amount of hydrogen storage needed is likely to be lower because it is possible to aggregate different storage facilities. In addition, if hydrogen production is co-located in industrial clusters or close to them (i.e., the situation resembles that of most H_2 generation today), the amount of storage that would be needed may decline (World Economic Forum, 2020).[48]

Identifying the most suitable location for hydrogen storage, in principle, is a very relevant task in this respect, since placing it close to producers rather than consumers will increase the cost of its delivery and vice versa (Patonia and Poudineh, 2022).[49] In this context, choosing the 'right' type of H_2 storage will also be crucial. A large-scale underground type of storage has geological and thus geospatial limitations whereas above ground solutions are not limited by this factor (see Part 3.2.). The preferred options for types of hydrogen storage may change in time as a mature and well-designed hydrogen network is developed.

Another aspect to consider while designing a business model for stimulating hydrogen storage is the issue of ownership. Specifically, in principle, storage facilities could be owned and operated by various actors, for example, H_2 producers, consumers, network operators, shippers or independent entities. Here, the most important task in relation to allocating ownership rights for an efficient organization of storage would be to make sure that the entity in charge of a storage facility is not incentivized to engage in strategic behaviour that would have a negative impact on the entire system such as withholding storage capacity to maximize the profit (Ofgem, 2011). This task also relates to a broader need to ensure that the party receiving subsidies for hydrogen storage makes efficient investment decisions.

In general, it is extremely important to ensure that storage infrastructure would be used in practice. While some business models such as capacity payment may incentivise the construction of a storage facility, they may provide little or no incentive for the use of this facility (Sioshansi, 2020). As a result, although a H_2 storage facility can be constructed through business models that focus on capital costs, if there is insufficient incentive for its use, it may be underutilized.

The government would also need to specify how to recover the cost of subsidies for hydrogen storage. Although there are several ways to do that, each of them has its own challenges. For instance, while, in principle, subsidies could be recovered from the users of hydrogen, the H_2 sector itself may not have a large enough user base. This cost can also be recovered from natural gas consumers via network charges but, in the current conditions of high prices for natural gas, such a decision is likely to cause social discontent. The same is likely to happen if this will be done through general taxation.

The role of competition in delivering an efficient business model for hydrogen storage should also be discussed in this context. While some business models are more easily combined with a competitive mechanism (e.g., an auction), others are more difficult in this respect (Baumgarte, Glenk, and Rieger,

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[48] However, even in this case, if the hydrogen production is from intermittent renewables, the storage aspect will still be important.

[49] For instance, the hydrogen storage caverns in Entzel that are currently being developed by Gasunie and Storag Entzel are located with a perfect connection to the Dutch and German hydrogen market, near the future Gasunie hydrogen network HyPerLink and the Energy-Hub Port of Wilhelmshaven (Gasunie, 2023).

2020). This brings up the question of whether the government should prioritize those models that can be delivered competitively.

Another relevant question is whether the business model itself should only focus on risk mitigation or should include additional features related to the development of hydrogen market. Here, one of the key trade-offs will be as follows. Specifically, adding extra features to a business model to meet other objectives (e.g., hydrogen market development) may increase value for money but, at the same time, may increase complexity of the business model itself to the extent that the original objective – the deployment of infrastructure – is not achieved efficiently or not achieved at all.

Finally, the government would need to consider the exit strategy. This is because, in principle, hydrogen storage should be paid for by its users eventually and not the government. That is why, having exercised support in the beginning, the government will eventually have to exit.

5. Conclusion

In this paper we have analysed six major hydrogen storage types that are currently being considered by researchers and industry, highlighted key barriers to their investment and discussed the specification of a viable business model to mitigate investment risks. The storage options analysed are pure hydrogen storage, synthetic hydrocarbons, chemical hydrides, LOHCs, metal hydrides, and porous structures. Although each of these options has its advantages and disadvantages and could be used for different applications and in different conditions, none of them is ideal and could address all the challenges of H_2 preservation. Besides, their technological readiness varies significantly, which means that some of them cannot be used for this purpose in the current conditions but are expected to be ready in years to come.

Being the most mature in terms of technology, market, and commercial readiness, the pure hydrogen storage option could be realized when H_2 is either compressed or liquefied. While both compression and liquefaction will significantly improve its volumetric density, both processes are extremely energy intensive and thus will incur further expense. Besides, storing both compressed and liquefied hydrogen would be associated with significant safety risks.

Synthetic hydrocarbons are often considered to be an option that would dramatically simplify hydrogen storage. This is because, being in essence an ‘artificial alternative’ to naturally deposited fossil fuels, these chemicals would already have well-developed storage infrastructure. More importantly, most of them will not be associated with additional costs related to their preservation. On the other hand, producing synthetic fuels in a carbon-free way (e.g. via the power-to-X pathway) as well as dehydrogenating them for further use of H_2 is likely to be extremely energy-intensive and thus costly. This is, perhaps, one of the key reasons why the technology readiness level of e-fuels is currently at a low level.

Chemical hydrides in a form of ammonia, methanol, formic acid or isopropanol are also often viewed as advantageous to pure hydrogen storage, as they are either liquid under ambient conditions or can become liquid without the need for significant energy (ammonia is liquefied under -33^{o}C). As a result, they are easier and cheaper to preserve and already have extensive storage infrastructure. On the other hand, it is still not completely clear how competitive their production and dehydrogenation in a carbon-free way will be in comparison to other hydrogen storage options.

Liquid organic hydrogen carriers (LOHCs), being mostly by-products of oil refining, represent another category of substances viewed as potentially suitable options for storing H_2. Although they are also liquid and would be easier to store in vessels and facilities suitable for hydrocarbons, their hydrogen content is lower than in many other hydrogen derivatives (e.g., ammonia, methanol, and e-fuels) thus they may not necessarily always be viewed as a top-tier storage option. In addition, producing and dehydrogenating LOHCs in a carbon-free way might not make economic sense under all conditions.

Metal hydrides represent one of the few options that would allow hydrogen to be stored in a solid and thus more concentrated form. While their volumetric hydrogen density indicators are often impressive, their gravimetric hydrogen density ones are less so. As a result, despite enabling the storage of H_2 in lesser volumes than most other storage alternatives, metal hydrides are usually the heaviest substances for storage. This, combined with relatively slow hydrogenation/dehydrogenation speed as well as the nascent nature of these technologies may result in their slower market penetration compared to other options.

Finally, porous materials represented by metal organic frameworks and carbon-based systems such as carbon fibres, nanotubes, templated and activated carbon as well as graphene are another type of hydrogen storage alternatives that would allow for safe and stable H_2 preservation. However, because of their low technological readiness, the scale of their application at the moment is quite low. So is the volume of hydrogen that they can currently store.

Since each of these options could potentially offer a unique combination of benefits that may be hard to beat in specific conditions of hydrogen application, it is likely that each of them would have prospects for being developed in the future. For instance, while metal hydrides and porous materials seem to be less competitive at the moment, they appear to be the only options offering a non-toxic, non-corrosive, and non-flammable storage mode. This feature is likely to be of extreme importance when the highest safety of hydrogen preservation needs to be prioritized.

Alternatively, synthetic fuels and chemical hydrides may be chosen when cost-efficient hydrogen storage needs to be coupled with transportation. LOHCs, in turn, could be chosen by entities having a substantial stake in oil refining and the chemical industry. Finally, hydrogen storage in pure form may be preferred in situations when high H_2 purity, quick discharge or extremely high storage volume is needed.

The very existence of this extremely large-scale hydrogen storage is often seen as a key prerequisite for the development of a viable hydrogen value chain and thus for the progress of a hydrogen economy. This is so because H_2 storage has significant value per se, since it can help to address the imbalance of demand and supply. At the same time, despite this high potential value, investment in hydrogen storage has so far been limited. This could be explained through the key existing risks that, in combination, create revenue uncertainty. These risks are the risk of low demand for H_2 storage as well as the risk of lower than break-even price for utilizing a hydrogen storage facility.

To address risks and make hydrogen storage more attractive for investors, various business models could be applied. In essence, a viable business model entails policy and commercial interventions to allocate the risks between the government and a private party in an efficient manner. While there are various ways to arrange risk allocation efficiently, possible business models for hydrogen storage could be broadly grouped into three main categories with the market-based one being the most liberalised type where market participants make investments in anticipation of profit and without government support. The centrally-coordinated category represents the other extreme where government either directly invests in hydrogen storage, creates a public private partnership or represents the off-taker of last resort. The regulated type, in turn, is comprised of various models and broadly describes cases when the government incentivizes private entities to provide hydrogen storage or buys the storage service from a provider.

Although not all the business models are useful in the current context, some of them could be applied to address the price risk and others to address the volume risk. In particular, fixed price contracts as well as fixed and variable premium contracts relate to the models dealing with the price risk. Allocating availability payments, organising the activity via a regulated return model such as RAB or making government the off-taker of last resort will help to address the demand risk.

At the same time, it is likely that an optimum business model will have to provide some degree of certainty with respect to both price and demand risks. In principle, this can be done in a number of ways. For instance, through a regulated revenue model or a CfD contract, though both options have significant challenges. Alternatively, a hybrid model could be applied: for example, a capacity payment coupled with a fixed price contract. While this is likely to maximise the benefits and minimise the drawbacks, even this hybrid approach will demonstrate its deficiencies and pose challenges in some conditions.

Finally, apart from the necessity to address price and demand risks, the designers of viable business models for hydrogen storage will have to face a number of other important complexities. These challenges will include, but will not be limited to, choosing the type of storage facilities that should receive support, specifying the relative location of storage facilities with respect to production and demand centres, determining the ownership model of storage, defining the characteristics of parties eligible for government support, deciding whether the business model should aim for objectives beyond investment incentive and risk mitigation, formulating an approach to recover the costs of subsidies and finally providing a path for government to eventually exit subsidies once the industry is mature.

Although the answer to each of these questions is likely to differ depending on specific circumstances (such as the characteristics of storage and end-use demand, the specific markets that countries consider suitable for hydrogen, and the extent of supply-demand imbalances), designers of business models for hydrogen storage will have to consider all these aspects in addition to making appropriate choices with respect to mitigating the two crucial risks. In practice this will mean that finding the most suitable combination of the answers to each of these questions will ultimately determine the approach that will be used in each particular case. These answers, choices, and approaches will help to reveal the greatest value of H_2 storage, which is crucial for the development of a sound and resilient hydrogen value chain and the creation of a hydrogen economy.

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