Hydrogen storage for a net-zero carbon future

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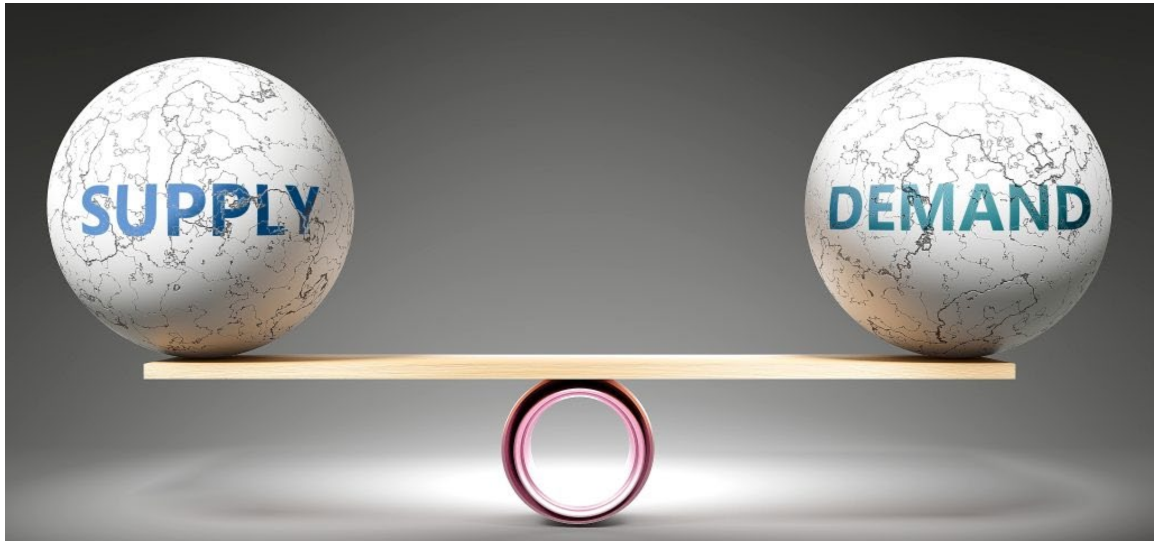
The importance of hydrogen storage

- Possibility of imbalance between production and consumption of H2

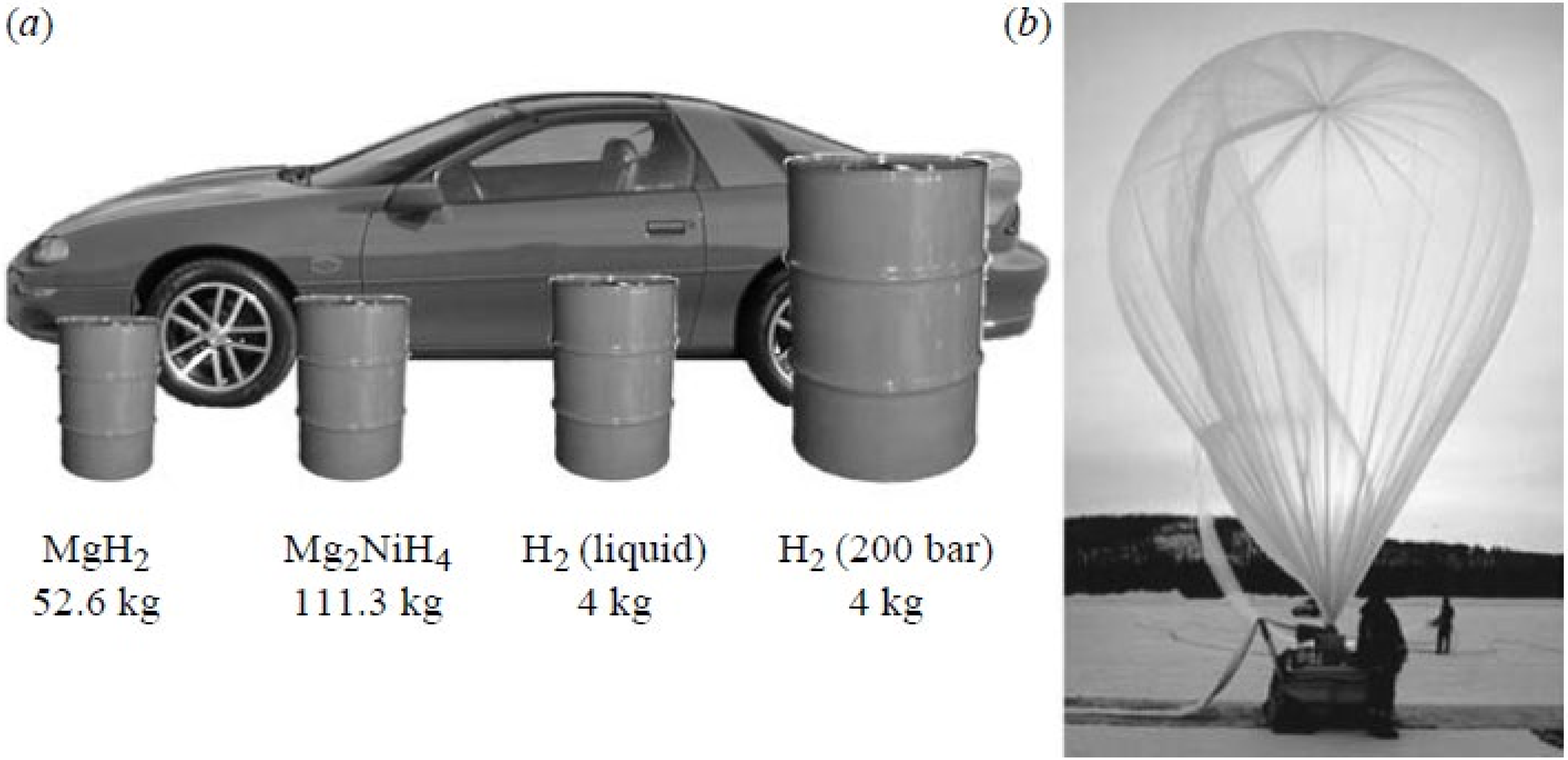


Source: https://blacksmithint.com/supply-chain-vs-demand-chain-for-apparel-brands/

  – Intermittent' green hydrogen and 'non-intermittent' blue hydrogen production
  – Hydrogen demand potentially non-responsive to supply
- H2 storage can support decarbonisation of the energy system via integration of variable renewables

But hydrogen storage is challenging

4 kg of pure hydrogen in different storage options



Source: Edwards, Kuznetsov, and David (2007)

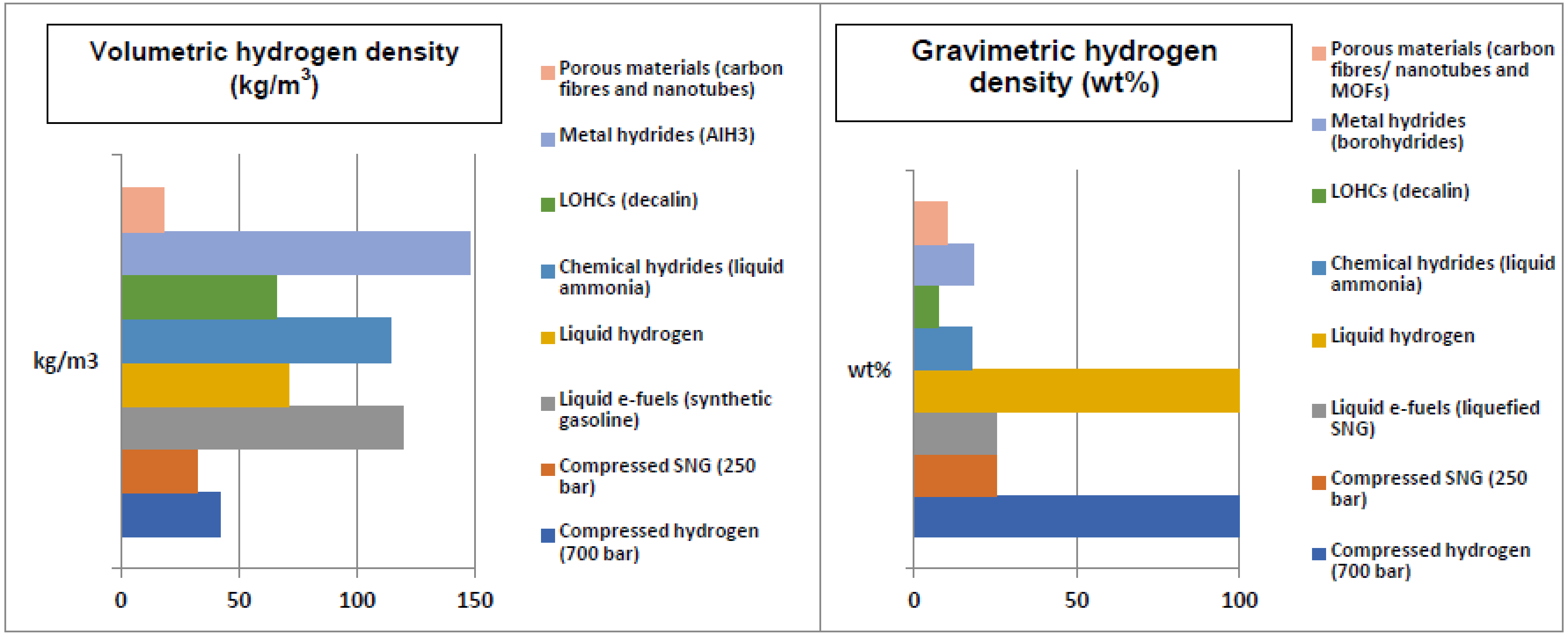
Key characteristics of some major hydrogen storage options

Source: Patonia and Poudineh (2023)

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		
									Tempe-rapture (°C)	Pressure (bar)	Energy (kJ/mol)	Tempe-rature (°C)	Pressure (bar)	Energy (kJ/mol per day)[10]	Tempe-rature (°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	$V_2O_5{\cdot}nH_2O$		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

Other factors to consider

Source: Patonia and Poudineh (2023)



1. Available storage volume (small/medium/large)
2. Speed of injection to/ withdrawal from storage vessel
3. Speed for dehydrogenation/desorption
4. Need for carbon management
5. TRL/MRL/CRL
6. Development level of storage infrastructure
7. Corrosiveness/ toxicity/ flammability

Key risk and uncertainties and the task of business model

- Two primary risks:
  - Demand for hydrogen storage capacity
  - Price of utilising hydrogen storage capacity

Revenue Uncertainty

- What is a viable business model?
  - A viable business model is the one that is deigned to overcome the key risks to enable investment. In practice this means allocating risk between government and the private party efficiently.
- Policy and commercial interventions are required to achieve this.

Business model for hydrogen storage

Market-based model

- Market participants make investment in anticipation of profit and without a government support

Regulated Revenue model

- Contract-based models (fixed price or premium)
- Economic regulation (fully regulated, cap and floor)
- Obligation-based approach
- Incentive to end users

Centrally coordinated model

- Government makes direct investment in the hydrogen storage
- Public private partnership
- Government as the off-taker of last resort

Challenges of designing a government-supported business model

- How much storage capacity is needed?
- Where storage infrastructure needs to be built?
- Governance issues: who should own/operate hydrogen storage?
- How to ensure the party receives subsidies makes efficient investment decision?
- What role competition plays in delivering the business model?
- How to ensure storage infrastructure is used in practice? (and not just built)
- How to recover costs of subsidies for hydrogen storage?
- Should the business model only focus on risk mitigation to enable investment or it should also include additional features?
- What is the exit strategy for subsidy support (if there is any)?

Thank you for your attention!

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