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The Hydrogen Economy

Potential benefits and difficulties

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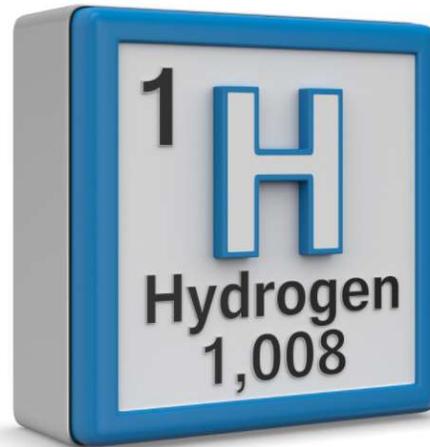
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Cover Slide

Why hydrogen?

- Most abundant element in the universe
- High energy content
 - 140 MJ/kg for H₂
 - 44 MJ/kg for petrol
- Emission = water



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Hydrogen is everywhere, but rarely exists as a gas in Earth's atmosphere because of its extremely low density.

Although hydrogen has a high energy content by mass, it does NOT have a high density by volume.

The huge advantage of using hydrogen for power is that it combines with water via combustion or in fuel cells, with water as the only emission product.

Brief history of hydrogen

- 1776 – formally identified
- 1800 – produced from electrolysis of water
- 1839 – first hydrogen-powered fuel cell
- 1920s to 1930s – used in airships crossing the Atlantic
- 1960+ – used extensively for spacecraft
- 1970s – GM proposes term “hydrogen economy”



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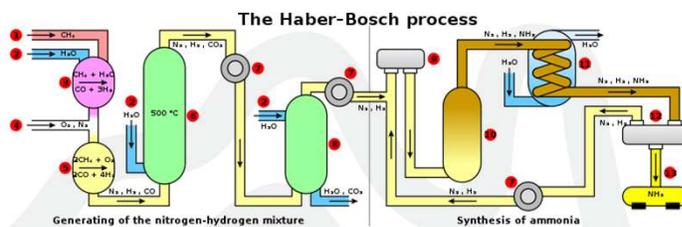


Hydrogen has been used in commercial quantities for more than 100 years. Although we think of hydrogen fuel cells as a future innovation, the first one was created by William Robert Grove in 1839. Its first transport use was in airships (blimps) that crossed the Atlantic. From the 1960s, the powerful combustion of hydrogen and oxygen was used to power space craft. The term ‘hydrogen economy’ was first used in the 1970s by engineers at General Motors as they discussed future innovations.

How do we use hydrogen today?

Hydrogen is typically produced from fossil fuels

- 50% in Haber process to make ammonia
- 40% to hydrogenate petroleum products
- Remainder: glass production, electronics manufacture, coolants



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The vast majority of hydrogen used today is produced from fossil fuels using heat and chemical reactions. Hydrogen production for industry accounted for 85 million tonnes in 2016. This process accounted for equivalent to the CO₂ emissions of the UK and Indonesia combined.

Hydrogen is mainly used to make ammonia in the Haber process. This process consumes 3-5% of the world's natural gas production. The ammonia is used as a fertiliser as is or as ammonium nitrate or urea.

Hydrogenation of petroleum is used to break long carbon chains into lighter products that are used as fuel.

References:

Dawood F, Anda M, Shafiullah GM (2020). Hydrogen production for energy: An overview. *International Journal of Hydrogen Energy* **45**(7): 3847-3869.

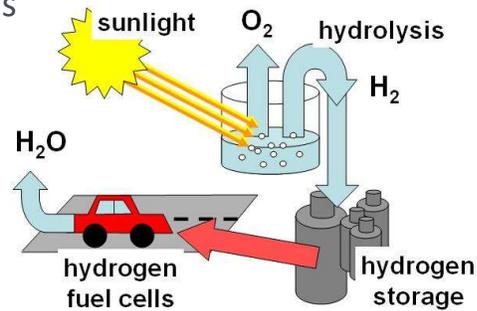
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<https://www.nrel.gov/docs/fy15osti/60948.pdf>

Hydrogen fuel for clean energy

- Renewable energy produces hydrogen by electrolysis of water
- Hydrogen is stored until needed
- Fuel cells power transport and utilities
- Only emission is water



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The vision of a hydrogen economy is a compelling one.

- Intermittent renewable energy is used to create hydrogen from the electrolysis of water.
- Hydrogen is stored and shipped to locations for use, just like fossil fuels can be transported to areas for use.
- Power is released in hydrogen fuel cells.
- Only emission from the process is water.

Unfortunately, this simple vision is not simple to implement.

What difficulties must be overcome?

- Safety
- Production
- Storage
- Setting standards



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Given the long history of hydrogen production and use, there are clearly some hurdles to be overcome in implementing hydrogen power on a large scale. These include safety, production, storage and setting standards. Each will be summarised.

Safety

- Hydrogen and oxygen combine explosively
- Makes metal brittle
- Safety procedures needed if general public is going to handle hydrogen (e.g., refueling cars)



Hindenburg disaster. May 6 1937 in Lakehurst, New Jersey

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Hydrogen and oxygen combine explosively. Students use this to test for hydrogen on a small scale in the “pop test”. Hydrogen combustion releases large amounts of energy and presents significant safety challenges.

In 1937 the hydrogen-filled German airship Hindenburg caught fire and was destroyed while attempting to dock in New Jersey. The accident left 36 people dead and many severely injured. It shattered public confidence, abruptly ending the airship era.

Hydrogen can make metal brittle. This presents a challenge for storage, transport and use.

Hydrogen is used on an industrial scale by skilled workers. If the general public is going to use hydrogen to refuel cars, safe delivery systems are vital.

On a positive note, hydrogen spills are not a problem. Any leaking gas quickly dissipates and eventually escapes Earth’s atmosphere.

Reference:

C Rivkin, R Burgess, W Buttner (2015). Hydrogen technologies safety guide. National

Renewable Energy Laboratory Technical Report NREL/TP-5400-60948.
<https://www.nrel.gov/docs/fy15osti/60948.pdf>

Safety answer: Fuel cells

- Produce electricity by combining oxygen and hydrogen without combustion



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Hydrogen fuel cells allow hydrogen and oxygen to combine in a controlled manner without combustion. The energy stored in hydrogen is released as electricity. Thus, hydrogen fuel cells can be used to power electric vehicles and be used as backup generators for stationary uses. Single fuel cells are combined into stacks, much like single cells are combined into batteries to provide adequate power for different uses.

Providing hydrogen to fuel cells still has safety challenges. Some of these are addressed in the production and storage slides.

Recommended viewing:

The truth about hydrogen fuel cell – a future beyond cars? From Undecided with Matt Ferrell (9:33) <https://youtu.be/DTPt32IZY30> He discusses how fuel cells work and their efficiency. Spoiler alert – he thinks fuel cells are not terribly efficient, but still have their uses. Not reasonable for passenger vehicles, but many opportunities for stationary power. (Other presenters argue more strongly for hydrogen vehicles.)

Production

- More than 90% is from fossil fuels
- Electrolysis of water is more expensive and less efficient
- Biological production options



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Currently, 96% of hydrogen production is from fossil fuels. This is sometimes called grey hydrogen.

Green hydrogen, from the electrolysis of water and powered by renewable energy, is the most promising source for a zero-emissions use of hydrogen, with no impurities in this process. (Hydrogen from fossil fuels contains nitrogen and other impurities.)

At present, it is more expensive and less efficient to produce hydrogen from the electrolysis of water than from fossil fuels. As renewable energy infrastructure grows and hydrogen infrastructure is developed, the cost will decrease.

There are a variety of biological options for production. These include obtaining hydrogen from biogas (methane) rather than natural gas (fossil fuel methane) or via photosynthetic algae. The most promising large-scale bioproduction is via dark fermentation. Dark fermentation by bacteria produces hydrogen through the breakdown of organic waste. This could be used for on-site production in many settings.

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CSIRO. Dark fermentation. From: <https://www.csiro.au/en/work-with-us/ip-commercialisation/hydrogen-technology-marketplace/Dark-fermentation>

Tatiane da Silva Veras, Thiago Simonato Mozer, Danielle da Costa Rubim Messeder dos Santos, Aldara da Silva César (2017). Hydrogen: Trends, production and characterization of the main process worldwide, *International Journal of Hydrogen Energy*, **42**(4): 2018-2033 <https://doi.org/10.1016/j.ijhydene.2016.08.219>

Storage

- Low density ($11 \text{ m}^3 = 1 \text{ kg}$)
- Storage choice depends on use
 - pure gas or liquid
- Compressed
- Liquefied
- Adsorbed onto material
- Chemically bonded



Liquid hydrogen storage tank at Kennedy Space Center was used to fuel the space shuttle. (TomFawls 2013, creative Commons 3.0)

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Hydrogen storage is challenging because of its low density ($11 \text{ m}^3 = 1 \text{ kg}$). Energy input is needed to increase density. The chosen storage option will affect how quickly hydrogen can be released and where it can be released. Different storage solutions suit different applications.

Compressed hydrogen gas is not suitable for aboveground applications. However, underground storage in salt cavities is the lowest cost with minimal contamination. Suitable geology limits this application.

Liquefaction of hydrogen is energy intensive and it is expensive to build plants. Tanks to store the hydrogen must be well insulated with double walls and insulation between them. Nonetheless, the tanks are less costly than for pressurised gas. The largest existing tanks are at Cape Canaveral (230 – 270 t). They are spherical for the most favourable surface –area-to-volume ratio.

Adsorption refers to van der Waals bonding onto other materials. It requires low temperatures and is still at a research stage.

Chemical bonding offers great advantages for stable transport of hydrogen but

requires energy to release the hydrogen. Metal hydrides are easy to store and control as solids. Chemical hydrides are liquids such as methanol and ammonia. These chemicals are commonly synthesised. The infrastructure for transport and handling are in place. It is predicted that they may outperform hydrogen liquefaction in the future.

Reference:

J Andersson, S Grönkvist (2019). Large-scale storage of hydrogen. *International Journal of Hydrogen Energy* **44**: 11901-11919.

Setting standards

- ISO standards being developed for:
 - Use
 - Production
 - Storage
 - Transport
 - Refuelling
 - Measurement
 - Purity



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We don't notice the many international standards that help to make life easier.

The standards around petrol are a good example of the application of international standards. Although cars made in many different countries are available in Australia, all use the same standardised fuel pumps and can use the fuel produced by different companies because this is also standardised.

One problem with electric cars is different charging connectors. Hydrogen fuel standards are needed so that we can refuel with hydrogen as easily as we do with petrol.

Reference:

Dawood F, Anda M, Shafiullah GM (2020). Hydrogen production for energy: An overview. *International Journal of Hydrogen Energy* **45**(7): 3847-3869.

<https://doi.org/10.1016/j.ijhydene.2019.12.059>

Lilly C (2020). EV connector types. From: <https://www.zap-map.com/charge-points/connectors-speeds/>

The future of hydrogen

- Hydrogen cars: Toyota Mirai, Hyundai Nexo
- Advantages:
 - Quick refilling
 - Lighter mass
- Disadvantages:
 - Lack of infrastructure
 - More expensive to run
 - 35-40% efficiency vs 70-80% for battery-powered vehicles



Toyota Mirai (2015, public domain)

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Hydrogen fuelled cars from Toyota and Hyundai are commercially available. Hydrogen infrastructure is slowly being rolled out. However, many commentators believe that battery-powered electric vehicles will be the major choice because they are cheaper to recharge and more efficient. Battery-powered vehicles are 70 – 80% efficient, while hydrogen powered ones are 35 – 40%. Advantages for hydrogen are quicker refuelling time and lighter mass.

BMW and Volkswagen have both declined to develop hydrogen cars because of the greater efficiency of battery-powered passenger vehicles. Hydrogen may have the advantage for heavy vehicles such as trucks, where the battery mass required for operation limits running time. Hyundai has already produced hydrogen-powered trucks.

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Baxter T (2020). Hydrogen cars won't overtake electric vehicles because they're hampered by the laws of science. From: <https://theconversation.com/hydrogen-cars-wont-overtake-electric-vehicles-because-theyre-hampered-by-the-laws-of-science-139899>

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The future of hydrogen

- Heating
- Electricity production
- Fuel cell backup power
- Steel refining



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One promising use of hydrogen is to replace natural gas, using existing distribution networks. Hydrogen boilers or fuel cells could be used for heating and cooking instead of natural gas.

Hydrogen and ammonia can be used in gas turbines to replace at least some of the natural gas.

An important role for hydrogen is in the provision of backup power. At present, this is usually supplied by diesel generators.

Andrew Forrest is investing in 'green steel' refineries that would burn hydrogen rather than coal.

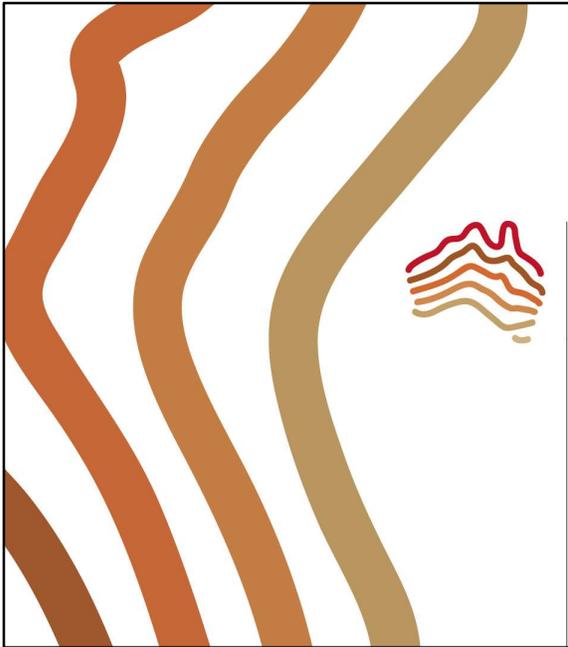
Hydrogen will be one of the important fuels of the future, but its roles are still being explored.

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Ferrell M (2020). *The truth about hydrogen fuel cell – a future beyond cars?* From Undecided with Matt Ferrell (9:33) <https://youtu.be/DTPt32lZY30>

IEA (2019). The future of hydrogen: Seizing today's opportunities. From:
<https://www.iea.org/reports/the-future-of-hydrogen>

Purtill J (2021). What is green hydrogen, how is it made and will it be the fuel of the future? From: <https://www.abc.net.au/news/science/2021-01-23/green-hydrogen-renewable-energy-climate-emissions-explainer/13081872>



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