How can Hydrogen Help with the Energy Crisis?

The world needs to overhaul its energy system, and fast. In 2023, 81% of the world's energy was supplied by burning fossil fuels (Davenport, 2024). The effects of global warming are already causing havoc around the world, and if we don't stop emitting CO_2 soon, the planet will be damaged beyond repair, and the energy sector is responsible for 73% of global greenhouse gas emissions (Ritchie, 2020). Fossil fuel supplies are predicted to run out by 2060 (Spencer, 2023), leaving us with no alternative but to shift to new sources. Also, an estimated 10.2 million people per year die due to air pollution (Vohra, 2021) caused by burning fossil fuels. If we are to limit global warming to 1.5° C above pre-industrial levels, which 196 countries agreed to do in 2016, which will avoid the most serious impacts of climate change, then we will have to reach net zero CO_2 emissions by 2050 (Abergel, 2021). Additionally, the world's population is expected to increase by 1.5 billion people by 2050 (Ritchie, 2023), and the global middle class will expand as more economies start to emerge, so global energy demand will probably increase by at least 20% by then. This can justifiably be called an energy crisis.

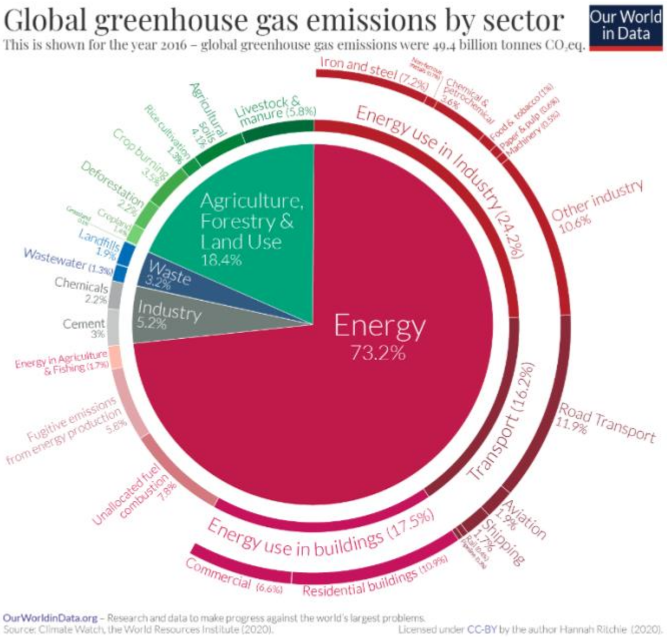


Figure 1 - a pie chart showing the share of different sources of greenhouse gas emissions. https://ourworldindata.org/ghg-emissions-by-sector

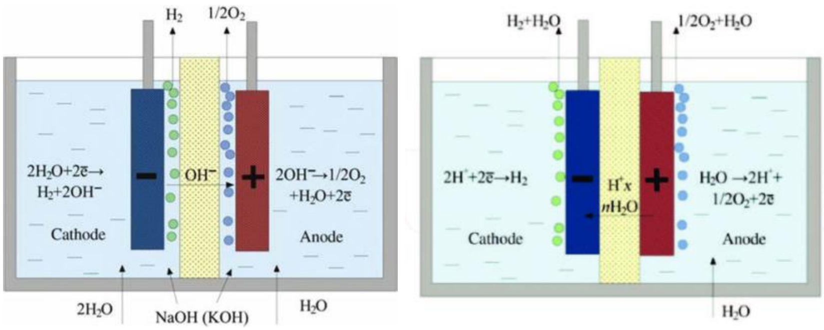
Luckily, we have other ways of generating electricity that don't emit CO_2 - renewables. But we cannot electrify all of our energy consumption, because electricity is difficult to store and transport. While a kilogram of gasoline holds 13kWh of energy (Alvera, 2021), a kilogram of the best lithium-ion battery today can only hold up to 0.71kWh (Dume, 2023), although that figure is constantly rising. Batteries work well in cars and trains, but for planes and ships, their low energy density means that they would take up too much space, and they would weigh too much. Electricity is also unsuitable for many uses in heavy industry. The chemical industry uses fossil fuels as a raw material as well as an energy source, like in the fractional distillation of crude oil and the processing of natural gas, to produce petrochemicals, which “are present in just about every material that is not 100% organic, mineral or metallic,” (Byrum, 2024). Other industries like the steel industry require very high temperatures of up to 1600° C (Wondris, 2024), and using electricity to generate this heat is much more inefficient and expensive than burning fossil fuels directly. The applications that are difficult to electrify are called the hard-to-abate sectors (Alvera, 2021), and they make up around 20% of global energy consumption (Ritchie, 2020).

Electricity is also difficult to transport over long distances. All transmission lines have some resistance, causing energy to be wasted as heat. Currently, up to 10% of energy is lost is transmission and distribution between the power station and the home in the US (Wirfs-Brock, 2015), but electricity is generally not transported very far. If we shift to renewables, and have to transport electricity from offshore wind farms, or from solar panels in countries which receive more sunlight, then the percentage of energy lost in transmission will increase significantly. We would also have to build new transmission lines, many of which will be underwater, which will be extremely expensive. The cost of electrical transmission per MWh delivered is 11 times higher than for natural gas pipelines (DeSantis, James, Houchins, Saur, & Lyubovksy, 2021), and there is already a large gas pipeline network that should be taken advantage of. Also, renewables can be intermittent – in that solar panels only produce 10-25% as much power on cloudy days (Sendy, 2024), and that the power output of wind turbines depend on the windspeed. We will need a better way of storing electricity during power output peaks when supply is greater than demand, to use when demand is greater than supply. For all of these problems, hydrogen is a potential solution.

Hydrogen is a gas that can be combusted directly to produce energy, or it can generate electricity through a hydrogen fuel cell. We already produce hydrogen for some non-energy uses like making fertilisers and refining crude oil (Alvera, 2021), but this mainly comes from fossil fuels, and producing it releases CO_2. Currently, 62% of global hydrogen production is from natural gas (IEA, 2023) in a process called steam reforming, where natural gas is mixed with steam and thermally decomposed at high temperatures to produce hydrogen, carbon monoxide, carbon dioxide and water (Alvera, 2021), at an efficiency of 65-75%. Another 21% of production is from coal in a process called gasification, where coal is heated to 1800°C, where it becomes a gas, and decomposes into carbon monoxide, carbon dioxide and hydrogen, at an efficiency of 64% (Gray & Tomlinson, 2002). These processes account for 2.2% of global emissions, and hydrogen produced in these ways is called grey hydrogen (Alvera, 2021). But we have a number of ways of producing hydrogen that don’t emit CO_2.

Firstly, if we capture and store the CO_2 from producing hydrogen from fossil fuels, then no CO_2 is emitted into the atmosphere – this is blue hydrogen. However, blue hydrogen is not ideal because natural gas supplies could run out as soon as 2060 (Spencer, 2023), so it can only be a temporary solution, and the process is unsuitable to be powered by renewable electricity because using electricity to provide the high temperatures required is very inefficient. Hydrogen can also be produced from the pyrolysis of natural gas, i.e. the thermal decomposition of methane into hydrogen and solid carbon, and the hydrogen produced is called turquoise hydrogen (Alvera, 2021). The advantages of turquoise hydrogen are that it doesn't rely on primitive, expensive carbon capture and storage (CCS) technology, and the carbon it produces as a by-product has many uses, including being used in rubber products, and being used to make dye. However, turquoise hydrogen has the same problem as blue hydrogen in that it can only be a temporary solution. Hydrogen can also be produced in a number of ways from biomethane, including steam reforming, which is good because it is already an established technology. If the CO_2 produced is captured and stored, then the process is carbon-negative because the carbon in the biomethane had already been absorbed from the atmosphere. Hydrogen produced in this way is called dark green hydrogen (Alvera, 2021). Biomethane is produced from the decay of human and agricultural waste. As with natural gas, biomethane can be thermally decomposed into solid carbon and hydrogen, eliminating the need to capture and store the CO_2. But the scope of dark green hydrogen is smaller because it is limited to the waste we produce. The main way we produce hydrogen sustainably today is through the electrolysis of water.

Figure 2 - Diagrams of an alkaline electrolyser and a PEM electrolyser. Source: Hydrogen Production by Water Splitting Technologies, Kamaroddin, Sabli and Abdullah, https://www.researchgate.net/figure/Schematic-diagram-of-the-alkaline-electrolysis-cell-34_fig4_327179309



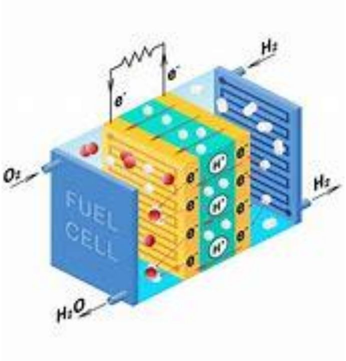


Figure 3 - The diagram on the right is of a hydrogen fuel cell. Source: Bjorn Fehrm, Bjorn's Corner: The challenges of hydrogen. Part 22. Hydrogen fuel cells, January 29, 2021, https://leehamnews.com/2021/01/29/bjorns-corner-the-challenges-of-hydrogen-part-22-hyd

There are two main types of electrolyser: the alkaline electrolyser and the PEM electrolyser. The alkaline electrolyser uses a concentrated alkaline solution (5M KOH/NaOH) as the electrolyte (Kumar & Lim, 2022), and consists of a cathode and an anode in the electrolyte which are connected to an external circuit, and they are separated by a diaphragm, which prevents bubbles of oxygen and hydrogen reacting with each other and exploding (Alvera, 2021). Water molecules are reduced at the cathode, producing H_2 molecules, and hydrogen gas is collected in a gas chamber above the cathode (Kumar & Lim, 2022). In a Proton Exchange Membrane (PEM) Electrolyser, the electrodes are separated by a very thin polymer membrane, which is a solid electrolyte (Power, 2023). Water molecules are oxidised at the anode, producing oxygen gas (which is stored in a gas chamber), electrons, and protons. The protons travel across the membrane to the cathode, where they are reduced to form hydrogen atoms, and again hydrogen gas is collected in a chamber (Power, 2023). PEM Electrolysers are a modern technology, and can be up to 83% efficient, as opposed to up to 78% for alkaline electrolysers, and they operate at lower temperatures than alkaline electrolysers, but at the moment they are more expensive (Kumar & Lim, 2022). There are also other types of electrolyser, such as the solid oxide electrolyser and the AEM electrolyser, which are in earlier stages of development but may well become viable options as well. Electrolysers already can be more energy-efficient at producing hydrogen than producing it from fossil fuels, and they can be powered by renewable electricity, so that the process is carbon neutral. Hydrogen produced in this way by renewable electricity is called green hydrogen, and hydrogen produced in this way from nuclear power is called pink hydrogen. A benefit of pink hydrogen is that it can be produced from the electrolysis of the steam from a nuclear power plant, thus exploiting energy and water that would have been wasted. A 1,000MW nuclear reactor could produce more than 200,000 tonnes of pink hydrogen a year (Alvera, 2021). The problem with electrolysis is that it is expensive – as much as $1500 per KW of power used, but the technology is not complex, and when electrolysers become mass produced, the price could fall to $250 per KW by 2050 (Palladino, 2023).

A hydrogen fuel cell can convert hydrogen back into electricity. It works like an electrolyser in reverse, and has a similar structure, with two electrodes in an electrolyte separated by a membrane, which allows protons but not electrons to travel through it. Hydrogen enters the fuel cell through the anode, where it reacts with a catalyst on the electrode and splits into protons and electrons. The protons travel through the membrane to the cathode, which oxygen gas from the air flows through, and react with the oxygen to produce water, and the electrons flow through an external circuit, generating a current (Airbus, 2020). The best hydrogen fuel cells are 60% efficient at turning hydrogen into electricity. As electricity can be turned into hydrogen, and that hydrogen can be turned back into electricity, hydrogen can be a way of storing electricity. And as hydrogen can be produced in different ways, many countries can exploit it – countries like Russia and Saudi Arabia which have good natural gas supplies can use blue or turquoise hydrogen, and sunny or windy places like Northern Africa and Canada can use green hydrogen. These countries can then export this hydrogen to countries with less access to renewables, in many cases through existing natural gas pipelines, so new infrastructure doesn't have to be built. Hydrogen may only contain a third of the energy of natural gas per unit volume, but it has lower viscosity, so it can flow through pipelines faster (Alvera, 2021). Natural gas pipelines can be repurposed to carry 100% hydrogen, transporting 80% of the energy that could be supplied by natural gas, at just 10-35% of the cost of building new pipelines (Monsma, 2024). Transporting hydrogen over long distances is 8 times cheaper than transporting electricity over long distances (DeSantis, James, Houchins, Saur, & Lyubovksy, 2021), and natural gas pipelines can already carry a mixture of up to 25% hydrogen and 75% natural gas (Franco & Rocca, 2024), and appliances work with this mix as normal. This is called blending, and using it will increase demand for hydrogen, meaning that companies will increasingly look at ways of producing hydrogen more efficiently and cheaply, without needing to upgrade pipelines at all, so it could be key for the transition to 100% hydrogen.

Hydrogen gas has a very low density – 1 kg of hydrogen takes up 3.44m^3 in standard conditions, whereas 1 kg of natural gas takes up 0.43m^3. This means it must be stored under very high pressure. But hydrogen can be stored in salt caverns underground, at pressures of 200 atmospheres or more, at a price of around $10/MWh (Alvera, 2021), much cheaper than storing energy in lithium ion batteries, and used to generate electricity when demand is greater than supply, solving the problem of renewables' intermittency, although more salt caverns would have to be dug. Hydrogen can also be stored as a liquid, but it has to be cooled to -253° C, requiring a lot of energy. But liquid hydrogen may be able to be stored in existing liquified natural gas (LNG) terminals, albeit with some modifications, which is seen as technically challenging, but feasible (Riemer, Schreiner, & Wachsmuth, 2022). Hydrogen can also be turned into other chemicals such as ammonia for storage, but the inefficiency of converting and reconverting means that a significant amount of hydrogen would be lost.

Hydrogen could power some hard-to-abate sectors without releasing CO_2. In steel production, hydrogen can be used to reduce iron oxide to iron, which can be melted in an electric arc furnace to produce liquid steel (Rechberger, 2020). 5 megatons of hydrogen were used for this in 2022 (IEA, 2023), and when hydrogen's price comes down it can be used for all steel production. Hydrogen can be used in the transport sector, in the way of hydrogen fuel cells for large trucks, as they weigh less than batteries and take up less space. It is also good for vehicles that need to be refuelled quickly: for example, 20,000 forklifts are now powered by hydrogen fuel cells, so they don't lose productivity by taking hours to refuel (Toyota, 2019). Airbus plans to make a hydrogen-powered commercial aeroplane by 2035. Thirty-six hydrogen trains are now in operation in Germany. Hydrogen can also give rise to other zero-carbon fuels, such as ammonia, which is more energy dense than hydrogen, so doesn't need to take up as much space. Ammonia can be used to power ships – 150 ammonia-powered ships were ordered in 2022 (Remme, 2023). Synthetic fuels are made from combining hydrogen with CO_2 captured from the atmosphere, and could be used as fuel for transport which is carbon neutral, as the CO_2 emitted originally came from the atmosphere.

However, hydrogen is currently a long way off being economically viable for most applications. Green hydrogen currently costs between $3/kg and $6.55/kg, and blue hydrogen costs around $2.40/kg (DiChristopher, 2021), whereas natural gas is more like $2/kg, although this price is normally lower, but 1kg of hydrogen takes up 8 times as much volume as 1kg of methane at the same pressure. Natural gas prices are expected to stabilise at around $50/MWh of energy, whereas the current cost of hydrogen is over $150/MWh, not including transport or storage (Palladino, 2023). A mixture of 20% hydrogen and 80% natural gas in a pipeline has only 86% of the energy of the same volume of pure natural gas, so you would need to burn 16% more of the blended mix to get the same amount of energy, meaning CO_2 emissions are only reduced by around 7% (Dijk, et al., 2024). Blending hydrogen into natural gas pipelines is essentially using a more expensive gas to dilute a less expensive gas, to reduce the overall amount of energy you transport (Martin, Carter, McCann, Poljack, & Grant, 2021), which makes no financial sense. Currently, if you convert electricity to hydrogen, and the hydrogen back to electricity again, you end up with less than half the electricity you started with, so using hydrogen is only sensible where direct electrification is not possible. The current difficulties in storing hydrogen, and the inefficiency of producing it, means that even in some hard-to-abate sectors, such as heavy industry, using electricity is still more efficient. There has been more progress in battery technology than hydrogen technology in the last decade – the energy density of lithium-ion batteries has tripled in only the last ten years (Dume, 2023), meaning that hydrogen fuel cell cars lost out to electric cars, which are more efficient (Miller, 2024), and they only make sense in niche markets where vehicles need to be refuelled quickly, such as forklift trucks. Lithium-ion batteries are becoming feasible for small propellor planes, something that was inconceivable only a decade ago. Clean hydrogen currently only makes up less than 0.7% of global hydrogen production (IEA, 2023), and if using hydrogen to store electricity is to become financially viable, we are relying on electrolysers and fuel cells to become substantially more efficient, and fast.

Graeme Miller, the commercial director of Haventus, who has delivered hydrogen projects before, believes that barring a major innovation, clean hydrogen's only uses are in replacing grey hydrogen in its current uses, direct iron reduction in steel-making, and long-haul aviation, in the form of synthetic fuels. But if we replace all grey hydrogen with clean hydrogen, the sensible thing to do as it requires little new infrastructure to be built, and increase demand for clean hydrogen, then that innovation may come. He believes hydrogen is over-hyped, but if it can decarbonise those sectors, then it will still be a massive success. Transporting hydrogen through natural gas pipelines is actually likely to be more expensive than transporting electricity through D.C. transmission lines per unit of energy transferred because of the inefficiency of hydrogen and the need for new infrastructure, and blending is just "throwing away energy". Using hydrogen to store electricity is not yet feasible either, and batteries can regulate flows through the transmission network. The world is shifting towards batteries and electricity, which are becoming ever more efficient, and hydrogen's use cases stem from reusing fossil fuel infrastructure with a different molecule (Miller, 2024).

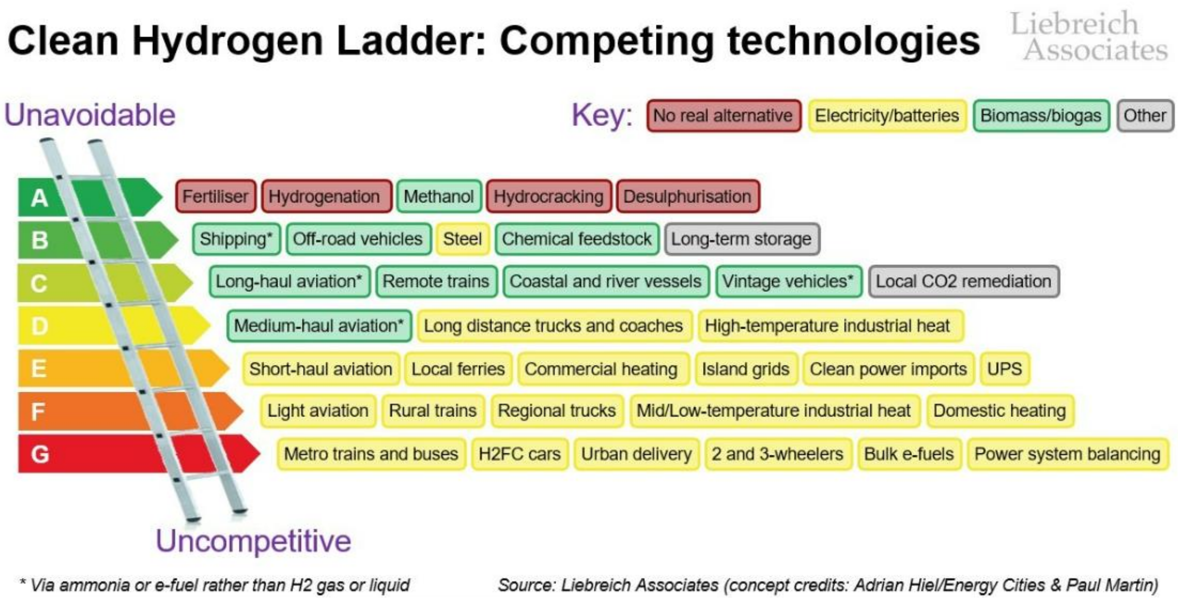


Figure 4 - the higher the sector on the ladder, the more suitable hydrogen is. The key shows which technology is competing with hydrogen. https://www.liebreich.com/the-clean-hydrogen-ladder-now-updated-to-v4-1/

To conclude, hydrogen has the potential to help with the energy crisis, by supporting renewable electricity, and powering the hard-to-abate sectors, but it needs a major innovation, like the lithium-ion battery in the world of batteries, to fulfil this potential. We must replace all existing grey hydrogen with clean hydrogen, which is necessary to reach net zero anyway, and see how prices drop and technology improves. A carbon tax should be introduced to encourage companies to look into hydrogen more, and some of the money raised can be invested in hydrogen, and companies looking to use green hydrogen should be subsidised to make it affordable. Creating a green hydrogen economy may require up to $20 trillion dollars of investment (Palladino, 2023), but if we reach a major breakthrough in production, storage, or transportation of green hydrogen, then this number will decrease. We are in an energy crisis, and investing in clean hydrogen now may give us an energy source which will help save us all.

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