

Hydrogen: Help or Hype?

Discussion Paper

renew.



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Cover image: Siemens electrolyser to produce hydrogen from water. Source:

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Executive Summary

When produced from renewable electricity, hydrogen is a renewable, emission-free fuel. Its main downside is inefficiency, because the required energy conversions waste most of the original renewable energy in losses.

Hydrogen is potentially useful in several niche applications as summarised in the table below.

Item	Potential use of renewable hydrogen	Notes
A	Energy exports	Yes, e.g. to energy-poor Japan. Possibly in the form of ammonia.
B	Inter-seasonal energy storage	Yes. Supplementary supply during cloudy, calm weeks.
C	Industrial, e.g. producing steel	Yes. Longer-term priority.
D	Road transport	Only in niche roles. Battery electric vehicles are much more efficient.
E	Main electricity supply	No - more direct use of renewable generation is more efficient.
F	In homes and businesses	No - efficient electric appliances are much more economic ¹ .

For road transport, an average 30km round-trip daily commute can be powered by 14 solar panels² for a Fuel Cell Electric Vehicle (FCEV), versus only 5 panels for a battery electric car (BEV). This is shown in the following diagram.

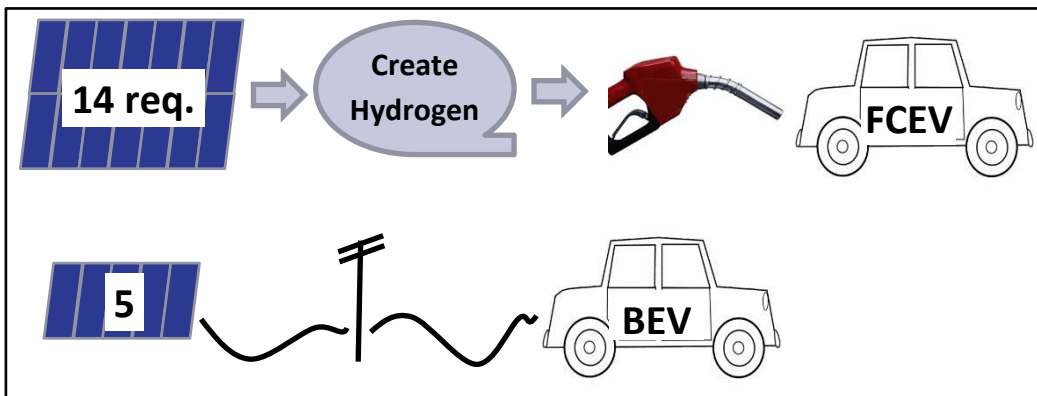


Figure 1 No. of panels required to propel FCEV & BEV 30km/day

The CSIRO is relatively optimistic about the economics of hydrogen for road transport³, but this considered only vehicles powered by fossil fuel rather than batteries, which are the real competitor for hydrogen vehicles.

Since FCEVs are so inefficient, Australia should not devote resources to a network of hydrogen refuelling stations. Such efforts should instead be devoted to chargers for BEVs.

¹ https://renew.org.au/wp-content/uploads/2018/08/Household_fuel_choice_in_the_NEM_Revised_June_2018.pdf

Also better for the environment. <https://renew.org.au/research/7809/>

² Installed in Sydney

³ CSIRO National Hydrogen Roadmap 2018 page xv:

<https://www.csiro.au/en/Do-business/Futures/Reports/Hydrogen-Roadmap>

For export to energy-poor Japan⁴, hydrogen’s inefficiency is offset by Australia’s much higher-quality renewable resources and Japan’s shortage of suitable land. In a low-carbon future, hydrogen could replace our present fossil-fuel exports. To ease shipping challenges, hydrogen may be converted into ammonia.

As shown in the following indicative diagram, one million Japanese homes could be supplied with renewable, storable electricity either via a local solar farm and a pumped hydro facility⁵, or from a larger solar farm in the Pilbara producing ammonia which is shipped to Japan and burned in a turbine to generate electricity.

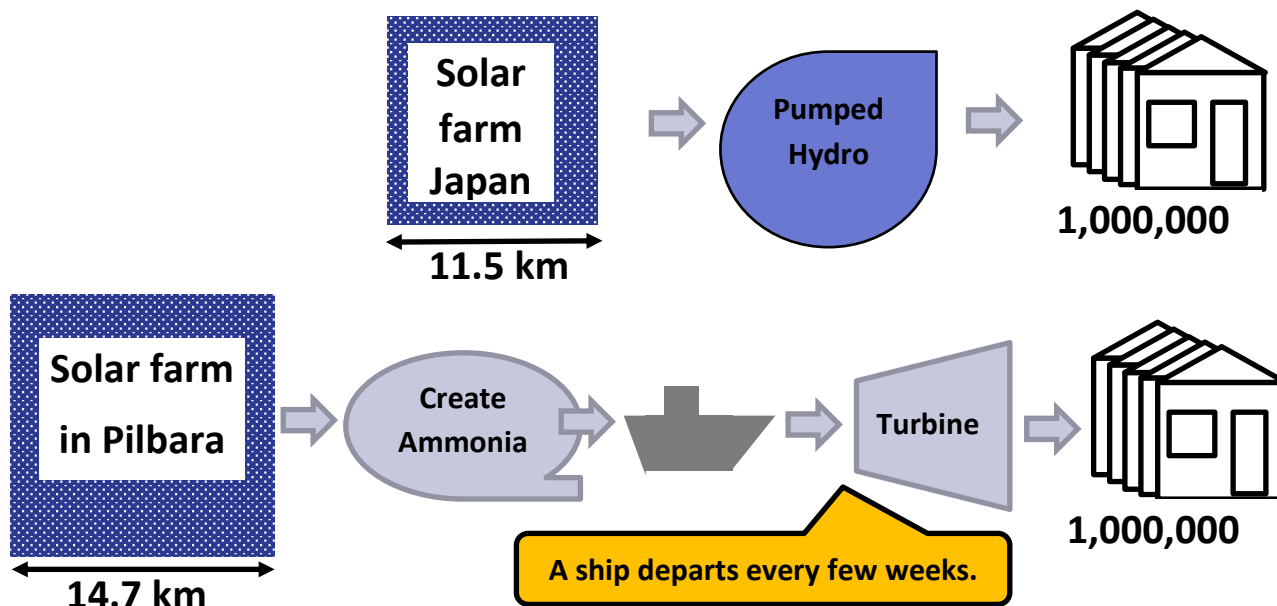


Figure 2: Two options to supply renewable, stored electricity to 1 million Japanese homes.

Within Australia, hydrogen may be very useful for inter-seasonal energy storage as we approach a future, fully renewable electricity grid, and perhaps to supplement solar and wind power for off-grid communities.

Piping hydrogen into homes and businesses instead of natural gas would result in higher consumer bills, as projected by the CSIRO. It also faces big obstacles such as identifying and replacing all gas appliances within a short timeframe. Instead, the renewable, cost-effective alternative to gas appliances is efficient electric ones.

As we plan and navigate Australia’s energy transition, hydrogen should not be allowed to distract us from the mainstream opportunity, which is wind and solar generation supported by transmission lines and energy storage. Renewable electrification provides the fastest, most cost-effective path to decarbonisation. Consumers should be informed to make decisions based on future developments’ realistic prospects.

Hydrogen proposals related to fossil fuels should be examined very carefully, because they are likely to increase emissions of greenhouse gases and/or prolong the lifespan of assets that emit those gases.

⁴ And similar countries such as Korea.

⁵ Japan has a firm strategy to import renewable hydrogen. It is unlikely to have sufficient local renewable resources to fully supply itself.

1. Introduction

Recently there's been much talk of hydrogen gas, including that for the Tokyo 2020 Olympic Games, hydrogen will burn in the Olympic torch relay and even power the athletes' village.² By some accounts, in the not-too-distant future we'll all be using hydrogen to fuel our cars, heat our homes, cook our food and power our electric appliances, as well as enjoying the economic benefits of hydrogen exports. But how much of this "hydrogen economy"³ is likely to eventuate, rather than hype?

Australian federal and state governments are working on a hydrogen strategy document⁴ to be completed by the end of this year, following a briefing paper from the Chief Scientist.⁵ Renew was represented at one of the roundtable discussions for this strategy. This paper discusses hydrogen's various uses and explores which have sensible prospects as we transition away from fossil fuels. Both its advantages and disadvantages are considered.

1.1. What is hydrogen anyway?

Hydrogen is the lightest and most abundant element in the universe. Although it's the main component of stars, unfortunately it's not readily available on Earth because it's a gas light enough to escape our atmosphere and float away into space.⁶ Hydrogen burns very readily even at low concentrations of oxygen. It filled the Hindenberg Zeppelin but modern blimps use helium instead for safety reasons. Hydrogen burns very cleanly leaving behind only water vapour – no greenhouse gases are emitted. Since it's colourless and odourless the Olympic torches will need additives to create a visible flame.

Currently Hydrogen is produced from fossil fuels and is used as a raw material by industries such as metalworking, glass and electronics. For this purpose it's compressed and supplied in cylinders like other industrial gases.⁷ It's commonly sold by the kilogram.



Figure 3: Heather Paul, flickr CC; BOC hydrogen truck

1.2. Hydrogen as a renewable, zero-emission fuel

Burning hydrogen gas produces energy which can be used to generate electricity, heat a building, propel a vehicle etc. However, until now it's been very rare to use hydrogen for such energy purposes. The main problem is obtaining the hydrogen – unlike fossil fuels there are no geological deposits of ready-made hydrogen gas that we can drill and extract. Instead renewable hydrogen must be created by splitting water in a process called electrolysis.

Unfortunately, to create hydrogen gas containing a given amount of energy you need to supply an electrolyser device with an even greater amount of electrical energy. This electricity must come from somewhere, so hydrogen is only involved as a *carrier* of energy rather than an energy source. Current plans are to use electricity generated by wind turbines and solar panels, the cost of which has dropped dramatically over the past decade. Hydrogen thus created is a renewable, zero-emission fuel.

2. Hydrogen's main problem: inefficiency

Using hydrogen for energy involves several steps, and unfortunately much energy is wasted in each one.

2.1. Propelling a car renewably: hydrogen vs batteries

One use of hydrogen is to propel a car such as the Toyota Mirai, a few of which have already been brought to Australia. This is a Fuel Cell Electric Vehicle (FCEV) – rather than being burned in an engine, hydrogen from the car's fuel tank is fed into a fuel cell which generates electricity. This electricity is then stored temporarily in a battery and powers the car's electric motor.

By the way, the fuel cell also emits water, whose release the driver can control to avoid puddles in the garage!⁸



Figure 4 Toyota Mirai FCEV in Sydney

Alternatively, you could use a standard Battery Electric Vehicle (BEV) in which renewable electricity is used more directly via the car's big battery.

So how do these two options compare for efficiency? The chart below provides an Australian context; it's only indicative since some specifications are quite hard to find. Newly-generated renewable energy is noted as 100% on the left and the proportion that's delivered to the vehicle's wheels is indicated at the right end of each series. Each major step is labelled on the horizontal axis.

Four scenarios were considered – they're listed here in order of overall efficiency.

1. Battery Electric High. A BEV is charged at home from rooftop solar using a well-sized charger.
2. Battery Electric Low. A BEV is fast-charged at night at a shopping centre using electricity generated at a remote wind farm as part of a 100% renewable grid.
3. Hydrogen Fuel Cell High. A FCEV equipped with a relatively efficient fuel cell is filled at a station with hydrogen produced with a high-efficiency electrolyser and compressor.
4. Hydrogen Fuel Cell Low. A FCEV equipped with a less-efficient fuel cell is filled at a station with hydrogen produced with lower-efficiency electrolyser and compressor.

All four scenarios assume that the vehicle's electric motor (including the motor controller) has an efficiency of 90%. Since this sets the upper limit for overall efficiency, Scenario 1's result of 77% is quite impressive. It's also not far off an electric train's efficiency, which is included for comparison. Of course, an electric train will have additional benefits outside the scope of this analysis such as lower rolling resistance and many more passengers per vehicle! Since they have batteries, both FCEVs and BEVs can use regenerative braking - again that's outside the scope of this analysis.

Scenario 2 adds transmission and distribution losses, but more significant are losses in grid-scale energy storage. In a future fully renewable electricity grid, some fraction of grid electricity will go through energy storage such as a pumped hydro facility. This scenario assumes that half the car's electricity has incurred a 20% energy storage loss. Scenario 2 also assumes that the shopping centre has a transformer dedicated to car charging, and that this transformer is loaded lightly causing a 15% loss. Overall efficiency: 53%

Scenarios 3 and 4 both incur large losses in electrolysis and compressing the hydrogen gas. Since these technologies have not yet been deployed at a large scale, there is a wide range of possible efficiencies for them. The two scenarios use high-end and low-end numbers for these efficiencies respectively. Similarly, scenario 4 assumes lower efficiency for the fuel cell in the vehicle than scenario 3. For the high scenario, efficiency losses include electrolysis 16%, compression 20% and fuel cell 43%. Both scenarios include the favourable assumption that hydrogen fuel is transported and transferred without energy loss. Overall efficiencies: 34% and 15% respectively.

A commonly quoted range for the efficiency of a petrol car is 17-21%. This is not directly comparable to the efficiency of a BEV or FCEV since it includes only in-car losses, ignoring the additional energy consumed in extracting, refining and transporting the fuel. And there's nothing renewable about fossil petroleum! Nevertheless, it's interesting to note that scenario 4's overall efficiency falls below this range.

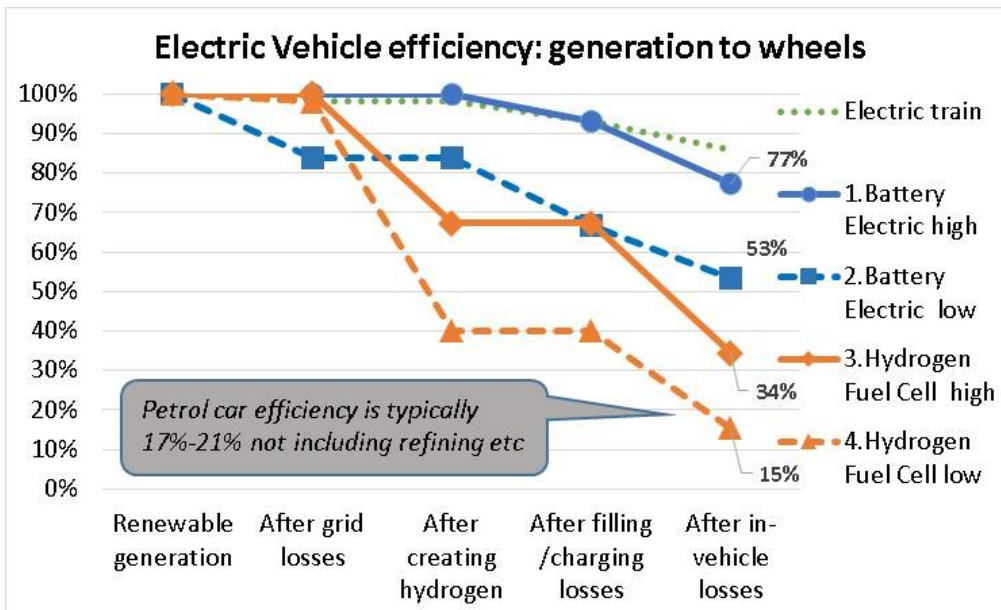


Figure 5 Electric Vehicle Efficiency: generation to wheels

Although these numbers include many uncertainties, when comparing the range of results in these four scenarios it's clear that renewable hydrogen is an inefficient option to propel a vehicle, compared to using renewable electricity via a battery. For more details on this analysis please see Appendix 2. In other fields such as heating buildings, hydrogen is also less efficient than more direct use of electricity – this will be discussed in subsequent sections.

2.2. The impact of inefficiency

Since hydrogen is an inefficient carrier of renewable electricity, it requires more generators to supply it. For example, five solar panels in Sydney can propel a BEV on daily 30km round-trip commutes on an annual average basis.⁹ A FCEV requires 14 panels, 2.8 times as many as the BEV. This is based on averages of the high and low scenario efficiencies for each type of vehicle, as noted above.

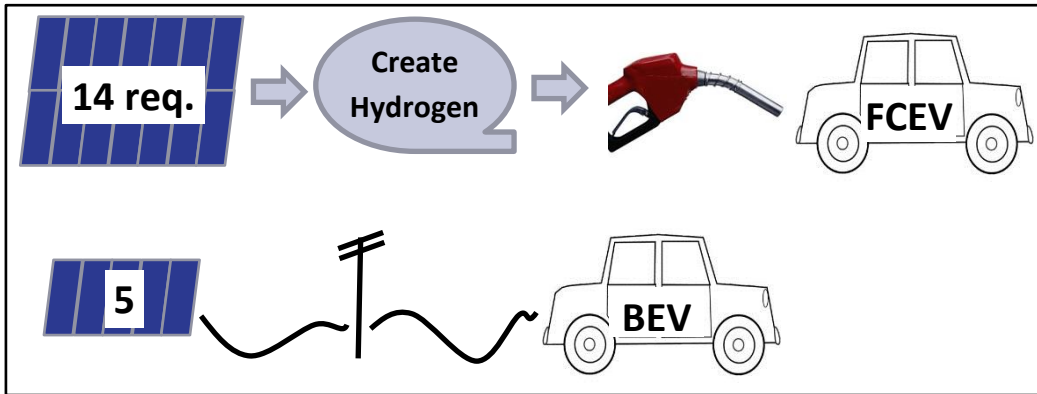


Figure 6 No. of panels required to propel FCEV & BEV 30km/day

Installing 14 panels obviously costs more than installing 5, inflating the cost of driving a FCEV compared to a BEV.

Construction of wind and solar is accelerating, but renewables still supply not much more than 20% of Australia's electricity. Efficiency of electricity consumption is crucial for a fast progress toward a 100% renewable economy.¹⁰ Where electricity can be used directly or via a battery, this is a much better approach than hydrogen.

3. Hydrogen for road transport

As explained above, hydrogen vehicles require several times as much renewable energy as battery electric vehicles. However, when making this comparison there are several other factors to consider.

3.1. Vehicle refuelling

Filling a FCEV's hydrogen tank at a service station takes about 5 minutes using a bowser resembling LPG.¹¹ The Toyota Mirai has two tanks made of thick carbon fibre with an empty weight of 88 kg and volume of 122 litres.¹² These tanks can hold 5 kg of hydrogen gas giving a usable energy of 166 kilowatt-hours. The gas is heavily compressed to around 700 atmospheres. For comparison, this is the sort of pressure developed in a shotgun barrel! The vehicle's range is 502 km.

An FCEV's fast refuelling is a clear advantage over charging a current BEV which might take 30 minutes at a service station, depending on the charger's power. However, most BEV owners charge overnight at home which involves no waiting time at all. Only on long rural trips would they require a service station. And higher-power service station chargers are emerging such as a BMW/Porsche unit which can add 100km of range in only 3 minutes.¹³

Constructing a network of hydrogen refuelling stations would be a massive undertaking. A Japanese station reportedly costs 4 to 5 times as much as a petrol equivalent, although the government aims to reduce this.¹⁴ Hydrogen is costly to work with since it's at high pressure (35 times as high as LPG) and can also soak through materials and embrittle steel.

FCEVs face a "chicken-and-egg" problem; manufacturers won't export them to Australia until there's a charging network, but investors won't build the chargers until they're confident of business. Breaking the dilemma would require clear government policy to support FCEVs, such as has already occurred in Japan and California.

A charging network for BEVs would also be expensive but fewer would be required since BEVs are mostly charged at home or at destinations such as workplaces and shopping centres. Even with few highway charging stations a strong market already exists for BEVs because they can be easily charged at these other places.

3.2. Long-distance freight

Some trucking routes may be especially suited to trucks running on hydrogen rather than batteries. For example the forthcoming "Tesla Semi" is a BEV with a range of 500 km and would be able to charge 400 km in 30 minutes using the forthcoming Tesla Megacharger.¹⁵ The competing, forthcoming Nikola "Tre Semi-Truck" is a FCEV with a maximum range of 1,200 km.¹⁶ Brisbane is around 900 km from Sydney, so it can be reached without refuelling by the FCEV but not the BEV.



Figure 7: Nikola One Semi-Truck

On the other hand this journey takes about 10 hours, over which time a truck driver requires at least 30 minutes of rest time anyway.¹⁷ A company with a regular freight schedule might make effective use of an electric truck charging station mid-way between Sydney and Brisbane, charging trucks while the drivers rest.

3.3. Vehicle price

FCEVs cost more than BEVs because they're more complex and their fuel cells are an expensive component. Last year the Toyota Mirai FCEV was listed in California at US\$57,500. The 2019 Nissan Leaf BEV presents similarly and is listed for US\$29,990.¹⁸

4. When might hydrogen become economic?

In 2018 the CSIRO studied hydrogen in some detail¹⁹ and projected that it could quickly become competitive in several applications, if it achieved economies of scale through widespread adoption²⁰. The following chart shows the cost of a kilogram of hydrogen gas in Aussie dollars.

CSIRO's "base case" hydrogen supply cost in 2018 is A\$5.80/kg. Note that this is *not* an actual price at which you can buy the gas, it's theoretical assuming a large-scale industry was set up. Actual retail prices are hard to find, but in California it's been quoted a few years ago at US\$14/kg.²¹ In that market, car manufacturers now provide fuelling as part of the vehicle purchase deal.

The CSIRO estimates that with economies of scale the price may drop to A\$2.54/kg by 2025.²² This cost of hydrogen is based on electrolysing water using electricity purchased for A4c per kilowatt-hour (kWh). This electricity cost seems quite low considering that a different CSIRO report estimated that the cheapest levelised cost of energy from generators built in 2030 is around 5c/kWh²³. This was for wind and solar without energy storage. In 2015, the US renewable agency NREL was much less aggressive, estimating that hydrogen prices might drop to US\$8/kg by 2025.²⁴

To be competitive with petrol passenger vehicles, hydrogen's cost must drop to A\$8/kg. However, the real competition for a FCEV is a BEV, which is not shown on this chart. In a few years the running cost of a BEV will be much lower than a petrol car, especially if electricity for charging becomes as cheap as the CSIRO' assumptions for FCEVs. If the cost of hydrogen drops to \$5-6/kg, it will become competitive with diesel fuel for buses, trucks and off-grid communities. At \$2-3/kg it's cheap enough for the big export markets.

Interestingly, the CSIRO projects the cost of hydrogen to flatline above \$2/kg. It never becomes cheap enough to compete with natural gas for heating buildings. Heating and exports are discussed in separate sections below.

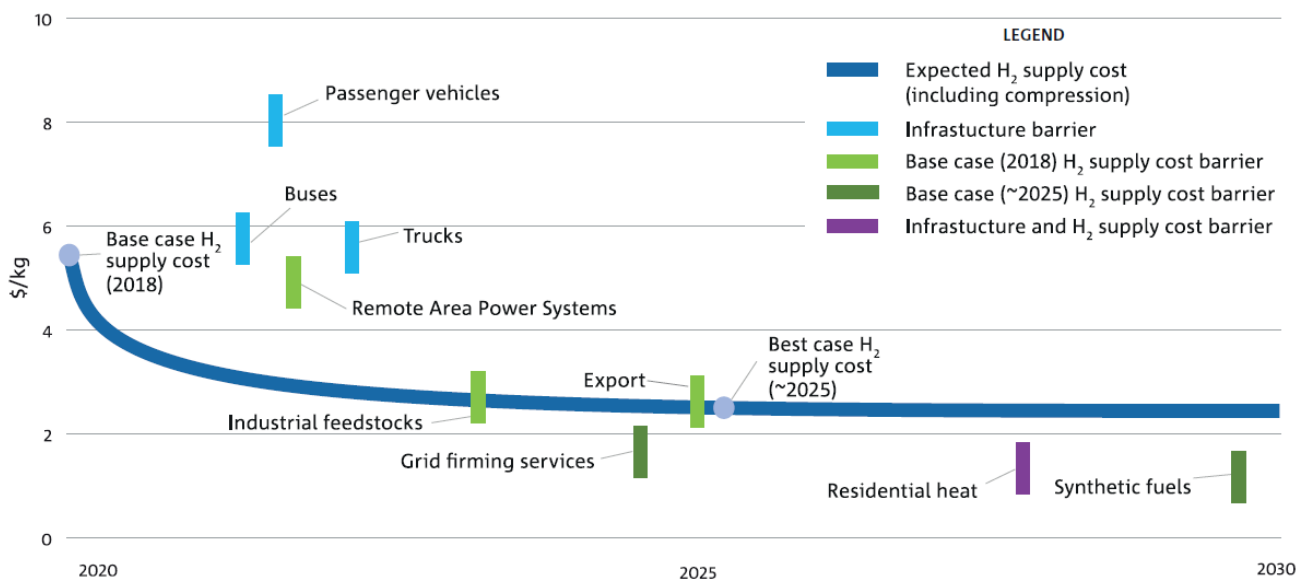


Figure 8: Hydrogen Competitiveness, CSIRO²⁵

In the CSIRO's vision, hydrogen first gains a foothold in passenger vehicles, which provide economies of scale to reduce costs and expand into the other markets. The "chicken and egg" dilemma still applies, as this all depends on subsidies to construct a network of HFCV charging stations.

5. Exporting hydrogen to Japan

5.1. Japan: seeking to import renewable energy

Japan is energy-poor and relies almost entirely on imports: oil and gas from the Middle East and coal, natural gas and uranium from Australia.²⁶ It's very vulnerable to supply disruptions such as conflict in the Persian Gulf or South China Sea, or simply market forces. Nuclear power generation was cut back sharply after the Fukushima disaster, and any resurgence would face strong public opposition.

Local renewables are increasing from a low base, with a goal to reach 20-24% by 2030, including hydroelectricity.²⁷ Unfortunately Japan has little suitable land available to host solar farms or wind farms. Offshore wind is a possibility. Japan already has pumped hydro generation capacity equal to 8.5% of its installed generation capacity, and further expansion may be difficult.^{28,29} Proposals have been suggested to import wind and solar power from Mongolia via transmission lines through China and Korea.³⁰ But this seems politically implausible as continuity of supply would be subject to friendly relations with China and North Korea. Japan faces an energy dilemma - imagine what you'd do in the energy minister's shoes!

Japan's response is a firm strategy toward hydrogen, which states that by 2030 the country will develop supply chains to import 300,000 tons of hydrogen annually.³¹ The clear intent is to import hydrogen generated from renewable energy rather than from fossil fuels, to meet Japan's commitment to the Paris agreement. Imported hydrogen will have multiple uses in transport, heating and electricity generation. Korea faces energy difficulties similar to Japan and also plans to import hydrogen. In the future, China and other countries may form an even larger market.³²

5.1.1. Shipping hydrogen

Shipping hydrogen is very challenging. One option is pressurised tanks - enormous versions of the Toyota Mirais mentioned above. Stresses on the tank become problematic at such scales, so the more economic option is to liquefy the gas by freezing it. The challenge is that this requires a temperature of -253 degrees: only 20 degrees above absolute zero! At first glance this seems like science fiction but Japan has a track record: in the 1970's the country pioneered the process to ship liquefied fossil natural gas (LNG), which requires a temperature of -160 degrees. The tanks are heavily insulated, and during the voyage some LNG is sacrificed as "boil off", which is used as fuel to propel the ship.³³ Over an 8-day journey from Australia to Japan, about 1% of the LNG is typically boiled off.

Kawasaki Heavy Industries is building the world's first hydrogen carrier ship, due for launch in 2020.³⁴ Its tanks are like giant thermos flasks - double-wall stainless steel with a vacuum in between.³⁵ Its capacity is 1,250 cubic metres, compared to the largest current LNG ships at over 200,000 m³. Naturally, future hydrogen carrier designs would grow toward parity with their LNG-carrying rivals. Japan is contemplating building a fleet of such hydrogen carriers.



Figure 9: Artist's impression of a hydrogen carrier ship under development. Source: Kawasaki

It takes a lot of energy to liquefy hydrogen – the process consumes 30% of the energy that's contained in the fuel.³⁶ The additional amount lost to boil-off is not yet known but even with the vacuum insulation, it may be higher than that for LNG.³⁷

Due to this energy loss it's quite inefficient to ship renewable electricity using hydrogen as a carrier. Transmission lines are much better; the loss in a high voltage direct current line is only around 3% per thousand kilometres.³⁸

5.2. The Pilbara: seeking to export hydrogen

In contrast to Japan, the Pilbara region of Western Australia currently has an enormous, high-quality renewable energy resource but no significant market. Local electricity consumption is relatively small, and the remote area has no transmission line to Perth, let alone the eastern states.

The Asia Renewable Energy Hub is a massive project between Port Hedland and Broome in the Pilbara, in early-stage development by CWP Renewables.³⁹ The project aims to generate electricity from wind and solar with a rated capacity of 11,000 megawatts. This is about three times the total capacity of solar and wind generators currently registered in the National Electricity Market.⁴⁰

The developer intends to use this electricity to produce renewable hydrogen by electrolysing desalinated seawater. First generation is expected in 2025/6. Original plans were to export electricity via an undersea transmission cable to Java in Indonesia; this is still a future possibility. Shipping gas from this region is nothing new - the Pilbara already exports massive quantities of liquefied fossil natural gas from Karratha and Barrow Island. The gas is sourced from undersea fields such as the Carnarvon Basin and Gorgon.⁴¹

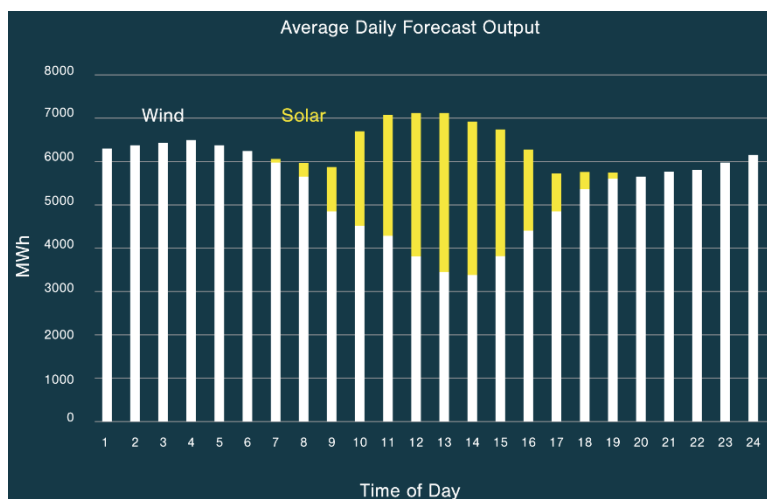


Figure 10: Generation expected by the Asia Renewable Energy Hub

Allowing for cost reductions in wind and solar over the next several years, CWP claims that it will produce “the cheapest power in Asia”.⁴²

The Pilbara faces competition from other countries and regions looking to export hydrogen produced from different energy sources, including the Middle East (solar), Brunei (fossil gas) and Norway (Hydroelectric).⁴³ Even within Australia, competition comes from Queensland (fossil gas and/or renewables) and Victoria (brown coal). Japan is engaging with all these countries and developing trials and pilots. The Kawasaki ship mentioned above is being developed as part of a project with Victoria.

Australia has a great opportunity to develop an industry to export renewable hydrogen and meet this demand. We are the world’s largest exporter of fossil natural gas, and Japan is the largest importer of gas carried by tanker ships.⁴⁴ Australian exports roughly equal Japanese imports. In a future where the world stops burning fossil fuels, our hydrogen exports could displace those of coal and gas.

5.3. Ammonia: hydrogen in disguise

Ammonia may address the problems with shipping hydrogen that were noted above. Ammonia is a smelly, toxic gas that's used to produce fertiliser, explosives, pharmaceuticals and other chemicals. Today it's produced from fossil fuels, usually natural gas. Ammonia is rich in hydrogen, as each molecule contains three hydrogen atoms.

Ammonia can be produced from renewable hydrogen, and vice-versa.⁴⁵ Ammonia can be shipped much more easily and efficiently than hydrogen because it liquefies at a much more moderate temperature of -34 degrees Celsius. It's already shipped around the world in the same class of vessel used to transport LPG gas, the largest of which are three-quarters the size of the largest LNG carrier.⁴⁶ Ammonia is a more compact option than hydrogen, since liquid ammonia contains more hydrogen than liquid hydrogen does!⁴⁷ A single ammonia ship holds nearly the same amount of energy as Snowy Hydro 2.0 pumped hydro facility.⁴⁸ Rather than being frozen, ammonia can alternatively be compressed - it liquefies under the pressure of a racing bicycle tyre (ten atmospheres), again much less extreme than hydrogen.

The idea is to generate renewable electricity (for example in the Pilbara), use it to produce renewable ammonia and ship this fuel to Japan. There it can be re-converted into hydrogen for various uses. Japan also has the option to use ammonia directly for energy. It can be burned in a gas turbine to generate electricity; small-scale turbines have already been proven.⁴⁹ Ammonia can also be used as a transport fuel – in the 1940s it propelled buses in Belgium.⁵¹ A ship engine is also under development.⁵² Ammonia emits no carbon dioxide when burnt.⁵³



Figure 11: LPG carrier suitable for ammonia. Source: <http://www.liquefiedgascarrier.com>

Coincidentally, Dampier Port in the Pilbara already exports six percent of the world's tradable ammonia, currently produced from fossil natural gas. The Yara company is currently building a trial plant to produce renewable ammonia, powered by 2.5 megawatts of solar panels.⁵⁴

The Renewable Ammonia Process

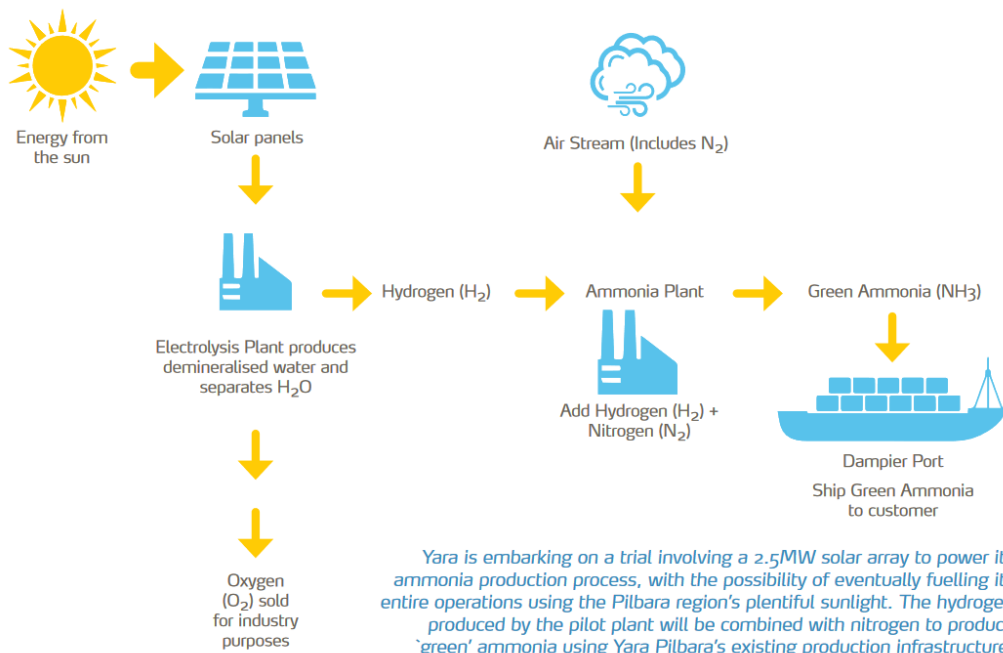


Figure 12: Process to create renewable Ammonia. Source: Yara company.⁵⁵

5.3.1. A breakthrough by the CSIRO

Unfortunately, hydrogen gas extracted from ammonia is impure, as it still contains a small amount of ammonia. These impurities disqualify that hydrogen from use in many fuel cells, so it wouldn't be suitable for transport applications such as the Toyota Mirai.

The CSIRO recently developed and proved a technique to filter out these impurities via a metal membrane.⁵⁶ The process is now being trialled on a larger scale,⁵⁷ and in future could be used by Japan to obtain pure hydrogen from incoming ammonia shipments. This promises to make ammonia much more attractive to Japan and improve the economics of exporting Australian renewable energy.

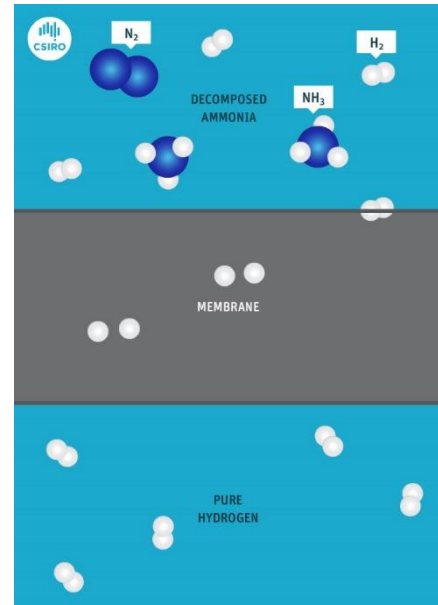


Figure 13: CSIRO process for pure hydrogen

5.3.2. Safety issues

Ammonia must be treated with great respect because although it's lighter than air, it can readily combine with water in the air to form a heavier-than-air vapour. This can form a cloud that spreads at ground level resembling a gas attack from the first world war. For example, in July 2018 a small leak occurred unloading ammonia from a ship to a fertiliser plant near Kwinana Beach in Perth, resulting in five people being taken to hospital.⁵⁸

The city of Haifa in Israel previously hosted a large ammonia tank supplying a fertiliser plant. It was closed in 2017 after a paper by academics exposed the catastrophic risk that it posed to the city in the event of a tank rupture.^{59 60}



Figure 14: Ammonia tank at Haifa. Source: *The Times of Israel* ⁶¹

It should be noted that safety risks are quite common in the energy industry. Hydrogen can produce very energetic explosions, and its flame is invisible.^{62 63 64} Even petrol must also be treated with caution.

5.4. Pilbara to Japan - how efficient is that?

Creating and shipping renewable fuel to Japan involves several steps that each involve efficiency losses. On the other hand, this fuel is storable which is a very valuable property when the grid's energy largely comes from intermittent wind and solar generation. Let's consider four options to supply stored renewable electricity into Japan's grid. Here's a list in order of overall efficiency.

- Electricity generated by a solar farm in Nagoya (a sunny location) and stored in a pumped hydro facility.
- Renewable ammonia created from a Pilbara solar farm, shipped and burned in a gas turbine for electricity.
- Renewable hydrogen created from a Pilbara solar farm, liquefied, shipped and run through a fuel cell.
- Renewable ammonia as for (b), converted to hydrogen in Japan and run through a fuel cell.

The following chart shows the relative efficiency of each option. Electricity generated at the Nagoya solar farm is taken as the reference and set to 100%. Since the Pilbara is far sunnier, its equivalent solar farm generates 150% as much electricity⁶⁵. All numbers are indicative only. In option (a), energy storage in the pumped hydro facility introduces losses of 20%. Adding a small amount in transmission, overall efficiency is 79%.

The next most efficient is option (b). Although having a head-start due to the Pilbara's sunny climate, major energy losses are incurred in creating ammonia and in the gas turbine, leading to an overall efficiency of 51%. Compared to option (a), the solar farm in the Pilbara must be 1.5 times as large as the one in Nagoya.

Although it involves transporting hydrogen rather than ammonia, option (c) goes through similar steps to option (b), ending with 42% efficiency. Its Pilbara solar farm would need to be 1.9 times as large as its Nagoya counterpart.

Option (d) suffers from losses in recovering gaseous hydrogen from ammonia, ending with an efficiency of 33%. Its Pilbara solar farm would have to be 2.3 times as large as the Nagoya farm.

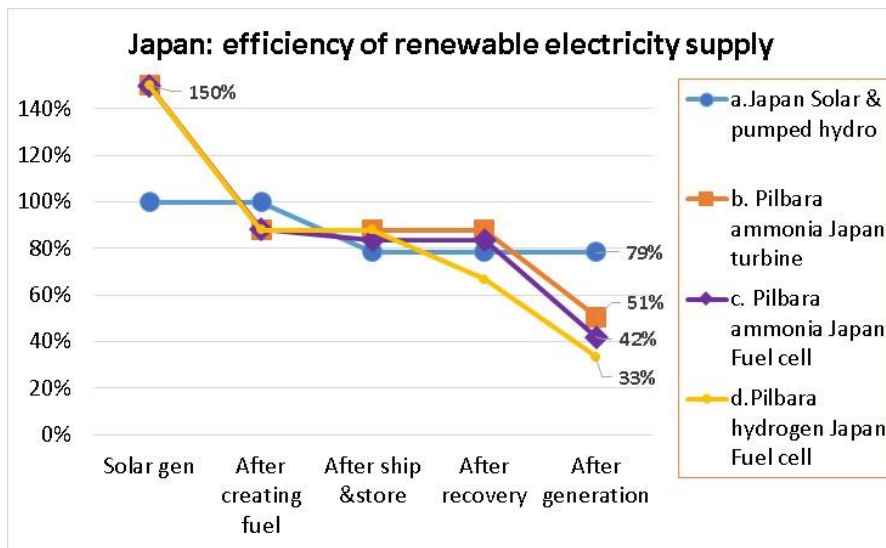


Figure 15: Efficiency of renewable electricity supply to Japan.

This analysis has focused on electricity delivered to the grid because it's such a flexible form of energy. As demonstrated above, electricity is generally a better option to propel vehicles than hydrogen fuel. It also provides very efficient heat for buildings and hot water, via an electric heat pump.⁶⁶ For further details on this analysis, please see Appendix 3.

5.4.1. Which option is best?

Option (b) seems quite attractive. Although it requires a larger solar farm than option (a), it has several advantages. Land in the Pilbara is cheap and abundant compared to Japan. In a high-renewable future, it seems unlikely that Japan could devote enough local land to supply sufficient wind and solar generation.⁶⁷

Potentially, ammonia delivered to Japan could be stored for weeks or months, helping to deal with periods of poor local generation due to calm, cloudy weather. In comparison, pumped hydro facilities are generally limited to storing energy for periods such as hours or days, restricted by the capacity of the upper and lower dams.

Ships to transport ammonia for option (b) are much simpler and cheaper than those required for option (c) which would need to hold liquefied hydrogen. In addition to its use for electricity generation, ammonia can also be burned directly (e.g. for heating or in vehicle engines) or used to produce fertiliser.

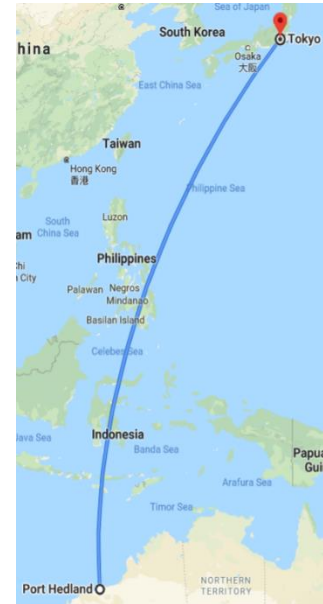


Figure 16: Map Data © Google 2019

5.4.2. The impact of inefficiency

Let's say we want electricity to supply one million Japanese homes on an annual average energy basis. We want it renewable and also storable to deliver when the wind's not blowing and the sun's not shining. Following option (a) above, the solar farm in Nagoya would need to be an 11.5 km square, while in option (b) it needs to be 14.7 km. Even though the Pilbara is sunnier option (b) is affected by lower efficiency. This is illustrated in the following diagram.

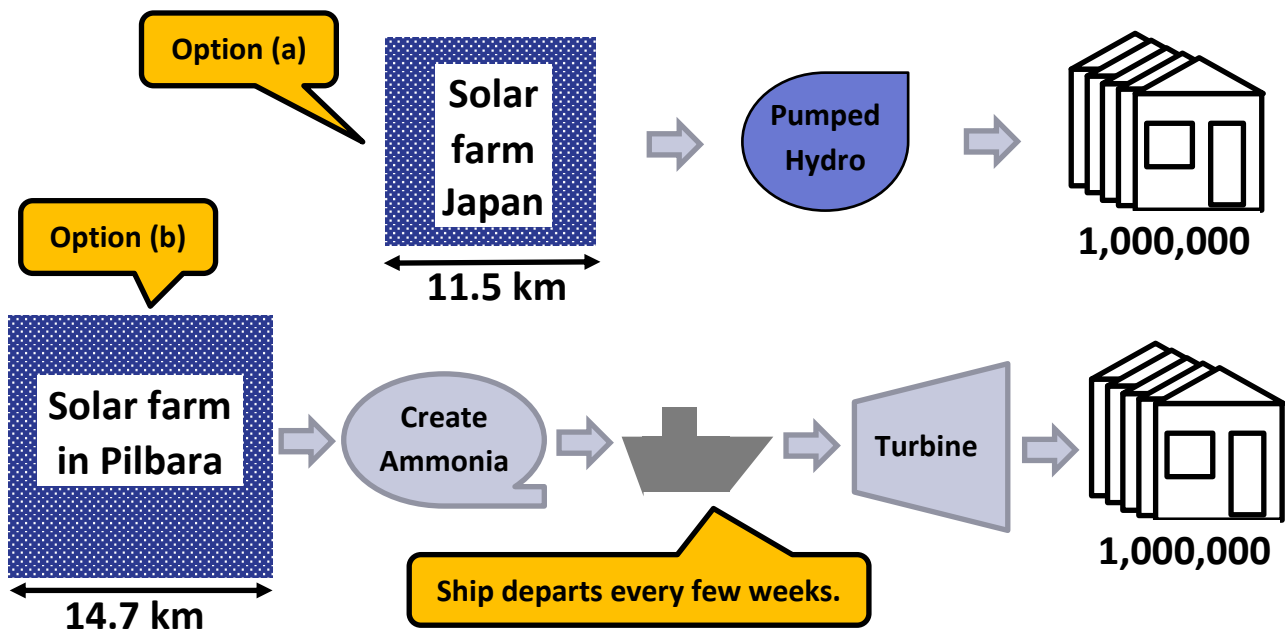


Figure 17: Two options to supply renewable, stored electricity to 1 million Japanese homes.

Estimates for the area of solar farm required per unit of rated power are based on the Darling Downs solar farm in Queensland, constructed in 2018. Actual areas would be smaller than indicated above because newer, more powerful panels would be used, and probably also single-axis tracking which tilts the panels to follow the sun. For further details on this indicative analysis, please see Appendix 3.

6. Producing renewable steel

When planning a fully renewable world, steel is a particularly thorny question. In traditional refining processes, coal is important not only for its heat but also for its carbon, some of which is included in the steel forming up to 2% of its weight.⁶⁸ Unfortunately most of the coal's carbon is emitted as carbon dioxide, so that iron and steel is responsible for 7 to 9 percent of all direct emissions from fossil fuels.⁶⁹

One way to produce emission-free steel is using hydrogen. A pilot "HYBRIT" plant is currently under construction in Sweden, with a demonstration phase planned to begin in 2025.

Iron ore is reduced directly to metallic iron known as "sponge iron". This requires further treatment to introduce the carbon required in steel. From early indications, HYBRIT steel would cost 20% more than traditional steel.

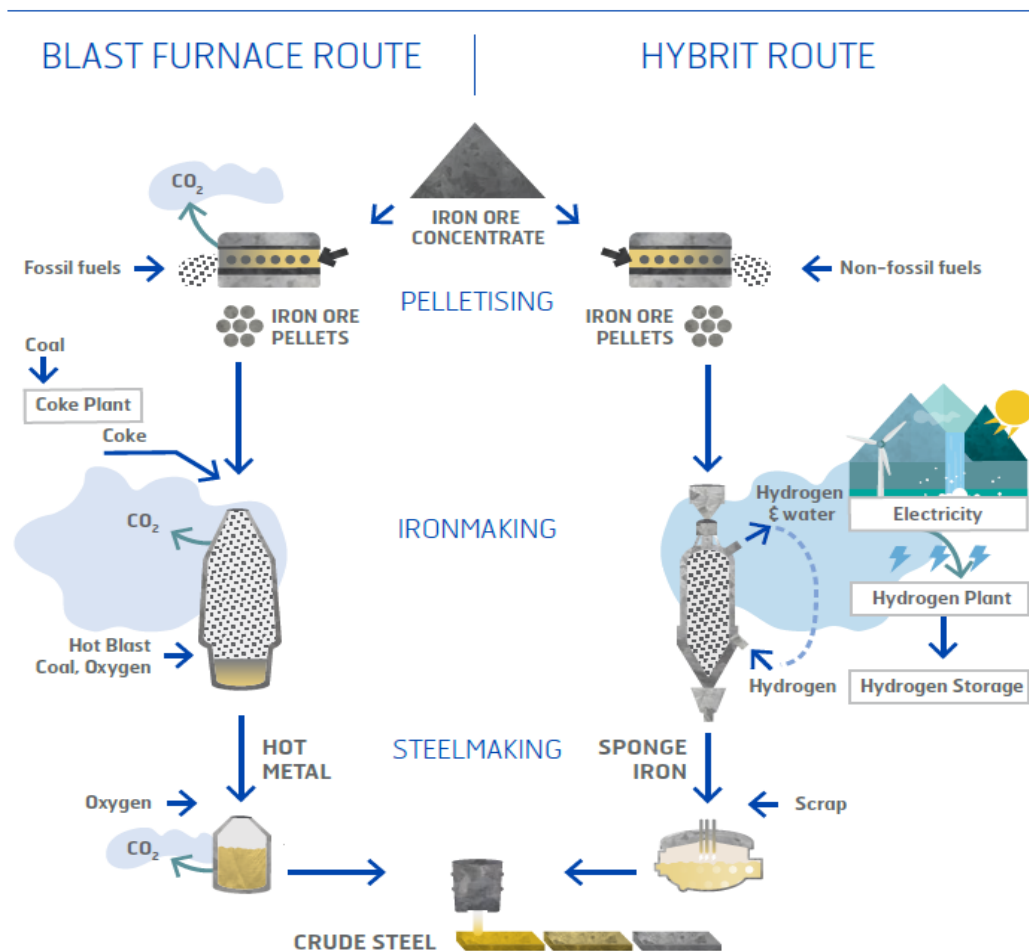


Figure 18: HYBRIT steel process. Source: HYBRIT.

Since Australia is a major exporter of both iron ore and energy, in a future low-carbon world it would seem logical to develop a local industry processing iron ore into steel, using renewable hydrogen. This adds value to the raw commodity, saves energy and cost by transporting a more compact product and reduces energy consumption by our customers, making it easier for them to achieve their own fully renewable energy supply. Professor Ross Garnaut is fond of this idea.⁷⁰

7. Firming intermittent renewables

7.1. Inter-seasonal energy storage

Australia currently obtains about 20% of its electricity from wind and solar. As we progress to a future high-renewable grid, energy will need to be stored in large quantities ready for supply during periods of low generation due to cloudy, calm weather. The Snowy Hydro 2.0 pumped hydro facility will meet some of this requirement, since it can supply as much power as a large coal-fired power station for a whole week. However, this asset alone will be insufficient. For example, the ANU found that even with a new transmission “backbone” to share renewable generation around the grid, 390 gigawatt-hours of energy storage would be required.⁷¹ AEMO’s 2018 Integrated System Plan does not provide clear advice on this matter, but one of its charts implies that even a 50% renewable grid would need quite extensive utility-scale energy storage.⁷²

Looking beyond just the electricity grid, if our entire energy system approaches 100% renewables, one of its hardest tasks would be to supply energy to Victoria through winter. Currently, most heat for Victorian buildings and hot water is supplied inefficiently by fossil natural gas.

To supply this need, one option is to create renewable hydrogen gas whenever there’s an oversupply of wind and solar generation. This gas would be stored until there’s a deficit, such as a cloudy, calm winter week. It would then be used to generate electricity, heating homes efficiently with electric heat pumps (reverse cycle air conditioners).

Hydrogen gas can be stored in salt caverns, such as in Bad Lauchstädt in Germany.⁷³ Gas storage has been proposed at salt caverns near Boree in Queensland.⁷⁴ Such storage is very cost-competitive.⁷⁵

Huge quantities of fossil natural gas are currently stored at the Iona Underground Storage facility (UGS) near Port Campbell in Victoria. The gas is held in a depleted gas field⁷⁶ which is currently used as a buffer by the gas industry. If its gas was used to run multiple gas turbines equivalent to a large coal-fired power station, it could sustain that power level for around 8 weeks⁷⁷. In a renewable future, Iona UGS would be available for storage of renewable hydrogen. However, there is not yet any information on whether it could be converted to hold hydrogen gas.

7.2. Supporting renewable microgrids

On a smaller scale, hydrogen could be used to provide energy to off-grid communities as a backup for solar and wind power. This would displace diesel generators currently used for that purpose.

A prime example is the Daintree region in far north Queensland, which has no electricity grid. Each property has its own off-grid energy supply, usually relying on solar panels, a diesel generator and often LPG gas as well.⁷⁸ Thanks to heavy rainforest vegetation, panels are often shaded and much diesel is burnt. In May 2019 the Federal government granted nearly \$1m to design and plan a solution including hydrogen. Apparently, the intention is a local electricity grid via cables buried under the roads, and a local solar farm with hydrogen storage attached.⁷⁹



*Figure 19: Daintree accommodation cabins.
Source: Sunverge.*

Such projects have great potential to reduce diesel consumption. As demonstrated above in the case of Japan, hydrogen is quite an inefficient way to store energy – but this is not so important in off-grid situations where excess renewable energy is otherwise wasted. If more efficient options such as pumped hydro are available, they would generally be preferred.

8. Hydrogen in homes and businesses

Natural gas is mostly methane and is piped into about half the homes and businesses in Australia.⁸⁰ It's used for space heating, hot water and cooking. Appliances burning this fossil fuel have traditionally been considered a cheaper and "greener" option than the electric alternative, but this is no longer the case as gas tariffs have risen and efficient electric appliances have been developed.^{81 82} As gas becomes increasingly sourced from coal seams and grid electricity from wind and solar, natural gas will become a liability in the context of reducing emissions.

It's possible to reduce emissions from gas appliances by piping renewable hydrogen instead of natural gas, but this has many downsides. Existing gas appliances cannot safely burn hydrogen, so they must all be replaced. Distribution assets such as valves and meters will similarly need replacement. The pipes themselves are less of an issue since they're increasingly made of plastic rather than metal. Homes with hydrogen appliances may require hydrogen detectors as well as smoke detectors, due to the risk of unburnt, flammable hydrogen accumulating at ceiling level.⁸³ Appliances could not be replaced gradually - rather installation must coincide with the gas change-over. To avoid dangerous operation on hydrogen, all old appliances must be hunted down and eliminated, which would be difficult. Piped hydrogen would need chemicals added to give it a smell and make it visible. Unfortunately, these additives would disqualify the gas from use in fuel cells, so it couldn't fuel vehicles such as the Toyota Mirai.



Compared to natural gas, consumer bills would increase with hydrogen. This is based on the CSIRO's projections in section 4 above, which show that hydrogen will not become economically competitive for residential heating.

If natural gas is to be replaced with a renewable alternative, electricity is a much better option than hydrogen. Efficient electric appliances reduce running costs, rather than raising them as hydrogen would do.

For heating, most houses already have one or more reverse cycle air conditioners, so to some extent, the replacements are already installed. The electric option enables dismantling of the gas distribution network, eliminating the cost of its maintenance which is currently borne by gas consumers. This saving could be invested in augmenting electric networks to support new, higher peak loads. Customers with a strong preference for gas (for example for specific cooking requirements) would still have the option of bottled LPG gas.

Owners of gas assets have put together analyses of the impact of switching gas appliances to efficient electric, but these tend to rely on unrealistic assumptions. For example, a note by AGIG⁸⁴ had the following problems:

- Assumed ducted systems would be used for all heating with no split systems;
- Assumed an unrealistically low coefficient of performance for heat pumps;
- Assumes no future improvement in building energy efficiency, although standards have improved;
- Ignored the cost of replacing gas appliances;
- Ignored the cost of replacing valves, meters etc and installing hydrogen detectors; and
- Unrealistically projected the uptake of heat pumps driven by hydrogen internal combustion engines.

8.1. Large Businesses

Renewable hydrogen gas may make sense for some large businesses with industrial processes in which electricity is no substitute. Such facilities are usually supplied by pipelines from gas transmission rather than distribution. These pipelines are good candidates to deliver renewable hydrogen.

Gas pipelines can also store a large amount of energy if the gas is compressed to a higher pressure than required. These existing assets would be useful for conversion to hydrogen in a high-renewable future.

9. Hydrogen pitfalls for Australia

Australia's energy systems are in transition - this has been confirmed by market and industry bodies and private companies.^{85,86,87,88} However, the form of this transition is not yet certain. Our nation's challenge is to steer the best course, avoiding dead ends and pitfalls. This task is complicated by pressure from stakeholders with various interests.

9.1. Fossil hydrogen

Proposals exist to supply hydrogen gas produced from fossil fuels. This makes little sense - oil, gas and coal are already easy to handle and transport. Converting them is both costly and problematic for handling and transport.

In the case of brown coal, its high water content makes it unsuitable for any use other than on-site electricity generation. And if dried out, it's prone to spontaneously combust. This is why the Victorian government is exploring the use of brown coal to create hydrogen for export to Japan^{89, 90}, as mentioned in section 5. Such proposals have been termed "brown hydrogen"⁹¹ and should be viewed critically for their impact on climate change.

Some projects to exploit new fossil fuel deposits use hydrogen as a marketing device to conceal their true nature as long-term emitters. For example, proposals to extract shale gas by fracking the Beetaloo basin (between Darwin and Tennant Creek) dangle the prospect of the new pipelines potentially transitioning to carry green hydrogen.⁹²

Another variant of fossil hydrogen is "blue hydrogen", which is brown hydrogen plus the suggestion of Carbon Capture and Storage (CCS). For example, the fossil fuel company Woodside is touting⁹³ hydrogen from its fossil gas.

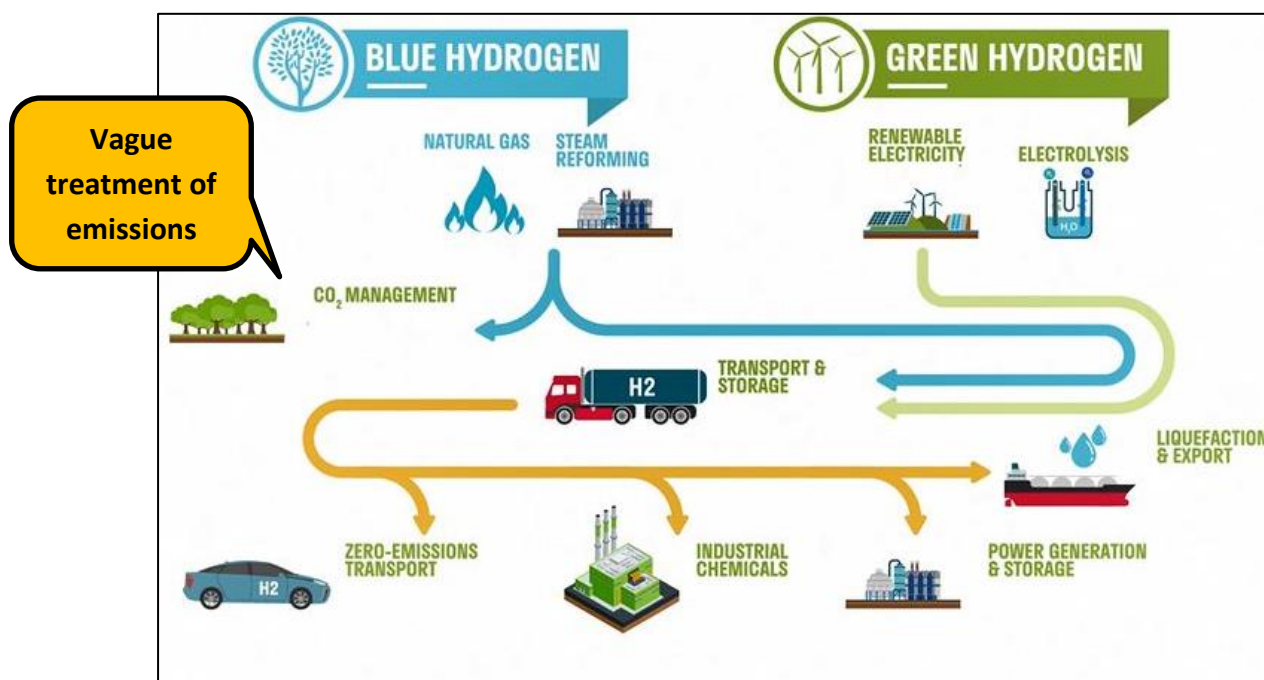


Figure 20: A marketing concept for fossil hydrogen. Source: Woodside

Unfortunately, CCS has consistently failed to develop, despite large government support.⁹⁴ For example, the Gorgon project in the Pilbara was meant to store carbon dioxide underground. Although fossil fuels are now being extracted in full swing, the CCS has not eventuated.^{95, 96} Even if it does start working, it will only store 40% of emissions.⁹⁷

9.2. Inefficient use of renewables

Wind and solar represent the current cheapest options to replace the ageing coal-fired power stations.⁹⁸ Compared to fossil fuel generators, these assets are cheap to operate but capital-intensive. For a fast transition to renewables we must make maximum use of their energy.

The most efficient use of renewable electricity is to employ it directly via transmission lines or via energy storage, as noted in Sections 3 and 5. If it's converted into hydrogen, most of its energy is lost in the process. Hydrogen should be used only where more direct methods are not practical.



Figure 21: Coleambally solar farm. Source: Bouygues Construction

As a specific example, Australia should not devote resources to a network of hydrogen refuelling stations. Such efforts should instead be devoted to chargers for battery electric vehicles.

9.3. Exports gazumping domestic consumers

Eastern Australia is currently experiencing high prices for natural gas, due to the majority of gas extracted being exported to fulfil over-ambitious contracts signed by private companies.⁹⁹⁻¹⁰⁰ Unlike all other gas exporters, there is no reservation of gas for domestic consumers.

New export markets for renewable hydrogen (or ammonia) could negatively affect the local electricity supply. For example, there are proposals to create renewable hydrogen in Queensland for export to Japan etc.¹⁰¹ Since Queensland is part of the National Electricity Market, these operations would draw electricity from the same grid that supplies much of Australia. If the new electricity consumption is not fully covered by new renewable generation, it will reduce supply available for domestic consumers.

Renewable energy exports could be beneficial to local electricity supplies if its production is coordinated with the local grid. For example, electrolyzers could run hard during sunny and/or windy periods, and vice versa. However, this may be precluded by export contracts guaranteeing a rigid shipping schedule.

9.4. Policy paralysis

A rapid, smooth energy transition requires clear policy. As laid out in AEMO's Integrated System Plan¹⁰², the best way forward is to construct wind and solar generation backed up with transmission lines and energy storage. Incompatible hydrogen proposals risk confusing and delaying this plan. To avoid mis-steps, hydrogen should be treated as supplementary and not allowed to distract from rapid, renewable electrification.

9.5. Poor outcomes for consumers

Decisions relating to Australia's large-scale energy systems flow through to consumers. There is a risk that due to poor planning, hydrogen projects may be implemented in preference to alternatives that would have delivered cheaper, cleaner or more reliable energy. This would impact energy consumers' bills. Also, unrealistic plans for hydrogen may lead consumers to make poor choices. For example, someone building a new home may decide to have expensive gas pipes installed, expecting them to deliver renewable hydrogen in the future. As discussed above, this is unlikely.

9.6. Water consumption

Nine litres of water must be consumed to create a kilogram of renewable hydrogen.¹⁰³ Driving a 30 km commute in a Toyota Mirai would consume about 2.7 litres of water. If every Australian passenger car was replaced with a Mirai, fuelling them all to cover the same distance travelled by passenger cars would require 1.8 million tonnes of hydrogen per year. Creating this amount of hydrogen would consume 16 gigalitres of water, or 6,500 Olympic swimming pools per year. This is a big number, but it's only about 0.6% of Australian household domestic water usage. This is a rough estimate - actual hydrogen and water consumption would probably be somewhat higher, since our passenger vehicle fleet includes many SUVs, utes etc much larger and thirstier than a Mirai! If hydrogen were used for other purposes such as heating buildings and energy exports, total hydrogen water consumption could be several times higher. For details on assumptions made in this analysis, please see Appendix 1.

In many parts of Australia water is already in short supply, so any additional demands to create hydrogen must be managed carefully. One option is water recycled from wastewater treatment plants. A downside of this option is that it restricts hydrogen production to locations close to cities etc. This was discussed in some detail in a recent report by Jacobs.¹⁰⁴

Another option is desalination which would work well for operations on the coast such as the proposed hydrogen export facility in the Pilbara. The CSIRO's cost estimates for hydrogen in section 4 assume that water is purchased for \$1.82 per kilolitre, which is similar to the residential retail price. However, sourcing desalinated water is estimated to cost around \$5 per kilolitre.^{105 106} Sourcing new, clean water will tend to increase the cost of producing hydrogen.



10. Conclusion

When produced from renewable sources, hydrogen is a renewable, emission-free fuel. Its main downside is inefficiency, because the required conversions waste most of the original renewable energy in losses. However, hydrogen is potentially useful in several niche applications as summarised in the table below.

For export to energy-poor Japan, hydrogen’s inefficiency is countered by Australia’s much higher-quality renewable resources and Japan’s shortage of suitable land. In a low-carbon future, hydrogen could replace our present fossil-fuel exports. To ease shipping challenges, hydrogen may be converted into ammonia.

Within Australia, hydrogen may be very useful for inter-seasonal storage as we approach a fully-renewable electricity grid in the future, and perhaps to supplement solar and wind power for off-grid communities.

The following table summarises prospects for hydrogen’s main potential uses.

Item	Potential use of renewable hydrogen	Notes
A	Energy exports	Yes, e.g. to energy-poor Japan. Possibly in the form of ammonia.
B	Inter-seasonal energy storage	Yes. Supplementary supply during cloudy, calm weeks.
C	Industrial, e.g. producing steel	Yes. Longer-term priority.
D	Road transport	Only in niche roles. Battery electric vehicles are much more efficient.
E	Main electricity supply	No - more direct use of renewable generation is more efficient.
F	In homes and businesses	No - efficient electric appliances are much more economic.

As we plan and navigate our energy transition, hydrogen should not be allowed to distract us from the main opportunity, which is wind and solar generation supported by transmission lines and energy storage. Little effort should be devoted to hydrogen vehicles, and none to hydrogen in homes and businesses. Consumers should be informed to make decisions based on future developments’ realistic prospects.

Hydrogen proposals related to fossil fuels should be examined very carefully, because they are likely to increase emissions of greenhouse gases and/or prolong the lifespan of assets that emit those gases.¹⁰⁷

Appendices

10.1. Appendix 1: water consumption

The following inputs and assumptions were made:

- Water consumed: 9l per kg of hydrogen
- Mirai range: 502 km
- Mirai hydrogen tank: 5 kg
- Total Australian passenger vehicle kilometres: 179,761,000,000 km/year¹⁰⁸
- Per capita household domestic water consumption: 103 kl/year¹⁰⁹
- Australian population: 25,400,000¹¹⁰

10.2. Appendix 2: PHEV & BEV analysis

The following inputs and assumptions were made:

FCEV “High” efficiency:

- Electrolysis: 84% efficiency. ¹¹¹
- Compress hydrogen: 80% ¹¹²
- Transfer hydrogen: 100% Optimistic - can't find info on pressure losses on transfer.
- Fuel cell: 57% ¹¹³
- Motor controller and motor: 90% ¹¹⁴

BEV “High” efficiency:

- Transmission, distribution etc: 100% efficient (generate at home from solar)
- Household wiring: 97%
- Charger EVSE: 98.6% ¹¹⁵
- Circuit breakers: 97.2%
- Car PEU: 97.9% ¹¹⁶
- Battery Charging: 99.4% ¹¹⁷
- Battery discharging during travel: 95%. ¹¹⁸
- Motor controller and motor: 90% ¹¹⁹

FCEV “Low” efficiency:

- Transmission: 100% Optimistic - assumes electrolyser is close to renewable generator.
- Electrolysis: 80% ¹²⁰
- Compress hydrogen: 50% ¹²¹
- Transfer hydrogen: 100% Optimistic - can't find info on pressure losses on transfer.
- Fuel cell: 43% ¹²²
- Motor controller and motor: 90% ¹²³

BEV “Low” efficiency:

- Transmission: 98.2% ¹²⁴
- Grid energy storage: 90% ¹²⁵
- Distribution: 95% ¹²⁶
- Household wiring: 97%
- Charger transformer: 85.4% ¹²⁷
- Charger EVSE: 98.6% ¹²⁸
- Circuit breakers: 97.2%
- Car PEU: 97.6% ¹²⁹
- Battery Charging: 96.1% ¹³⁰
- Battery discharging during travel: 95%. ¹³¹
- Motor controller and motor: 90% ¹³²

10.3. Appendix 3: Japanese electricity supply analysis.

The following inputs and assumptions were made:

a. Japan solar -> pumped hydro

- Transmission 98.2% Assume same as Macarthur wind farm.
- Pumped hydro 80% As for Snowy Hydro 2.0, round-trip.

b. Pilbara ammonia -> Japan ammonia gas turbine

- Solar gen 150% ¹³³
- Produce ammonia 58.7% ¹³⁴
- Transport ammonia 100% Assume no losses because temperature is relatively benign.
- Store ammonia 100%
- Burn in gas turbine (CCGT) 57.5% ¹³⁵

c. Pilbara hydrogen -> Japan stationary hydrogen fuel cell

- Solar gen 150%
- Electrolyse hydrogen 84% As for “high” case in vehicle analysis
- Liquefy hydrogen 70% Giddey et al, Ammonia as a Renewable Energy Transportation Media.
- Transport hydrogen 95% Assumption only on boil-off - no data available.
- Store hydrogen 100% Optimistic assumption
- Compress hydrogen 100% Assume fuel cell takes close-to-atmospheric pressure.
- Fuel Cell 50% ¹³⁶

d. Pilbara ammonia -> Japan stationary hydrogen fuel cell

- Solar gen 150%
- Produce ammonia 58.7%
- Transport ammonia 100% Assume no losses because temperature is relatively benign.
- Store ammonia 100%
- Recover hydrogen 76% ¹³⁷
- Fuel Cell 50%

Hectares per million households

- Reference solar farm: 100 MW, 250 ha. ¹³⁸
- Japanese household consumption: 5,513 kWh/yr ¹³⁹

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- ⁸ <https://www.carsguide.com.au/car-news/toyota-mirai-hydrogen-car-hits-australia-36236>
- ⁹ Assumes BEV can travel 5 km on each kWh of electricity, and each panel's rated power is 310W.
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https://renew.org.au/wp-content/uploads/2019/01/One_Hundred_Percent_Renewable_Grid.pdf
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- ¹¹ <https://www.youtube.com/watch?v=lfBeJbXf4w4>
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- ²⁶ <https://www.eia.gov/beta/international/analysis.php?iso=JPN>
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- ²⁸ http://eprints.whiterose.ac.uk/98992/1/Manuscript_final.pdf
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- ⁴³ Page 16, <https://arena.gov.au/assets/2018/08/opportunities-for-australia-from-hydrogen-exports.pdf>
- ⁴⁴ China recently overtook Japan in imports of natural gas, but much of this comes in via gas pipelines.
- ⁴⁵ The process to produce renewable ammonia also extracts nitrogen from the air via the well-known Haber-Bosch process, again powered by renewable electricity.
- ⁴⁶ <http://www.liquefiedgascarrier.com/Fully-Refrigerated-Ships.html>
- ⁴⁷ <https://phys.org/news/2018-01-link-solar-hydrogen-ammonia.html>
- ⁴⁸ Assumes 80,000 m³ ship volume, 15.6 GJ/m³. Snowy Hydro 2.0: 350 GWh.
- ⁴⁹ <https://www.ammoniaenergy.org/ammonia-fueled-gas-turbine-power-generation/>

- ⁵⁰ P149, <https://arena.gov.au/assets/2018/10/Comparison-Of-Dispatchable-Renewable-Electricity-Options-ITP-et-al-for-ARENA-2018.pdf>
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- ⁷² Figure 6, https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/ISP/2018/Integrated-System-Plan-2018_final.pdf
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