AUSTRALIAN
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How we get to scale

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The clean hydrogen industry is still emerging, with most aspects of the value chain still pre-commercial. The costs of producing hydrogen need to fall significantly, and we do not yet have (pure) hydrogen-ready infrastructure, equipment or vehicles/vessels at any meaningful scale.

As of August 2021, the largest Australian electrolyser – the machine to make green hydrogen (see below) – is 1.25MW.[18] Three 10MW electrolyser projects are scheduled to come on-line in 2023, where the project proponents were the recipients of A$103.3 million from the Australian Renewable Energy Agency (ARENA).[19]

These are the green shoots we need to see. However, the task to get to scale is still significant. For example, Deloitte[20] provided demand scenarios for the National Hydrogen Strategy where the two most ambitious scenarios had Australian production for 2030 at 724 kilotonnes (kt) per year and 1,777 kt per year. To produce this much hydrogen by 2030 Australian projects will likely need to have deployed multiple electrolysers closer to the 1GW scale – 100 times the size scheduled to come online in 2023.

There will be different mixes of project sizes in the coming years, but for the sake of simplicity, if we only produced hydrogen with 1GW sized electrolysers we would need seven and 18 of these to get to the production figures in the respective Deloitte scenarios.

Figure 2 shows a comparison of several estimates of global hydrogen demand by 2050. We can see there is some difference in perspective, and this is largely due to the scenario and assumptions employed. The more ambitious demand figures are around 800 million tonnes (Mt) per year, which we see from BNEF and the Energy Transitions Commission. Importantly, most scenarios see industry demand as a major proportion of total demand, closely followed by transport applications.

The International Energy Agency's recent analysis about how to reach net zero by 2050 sees global hydrogen consumption reaching 530Mt per year,[21] with the main categories of demand being transport (road transport, shipping and aviation, and as ammonia and synfuels as well as hydrogen), chemicals, and iron and steel. Hydrogen and hydrogen-based fuels make up 13 per cent of total energy demand in 2050.

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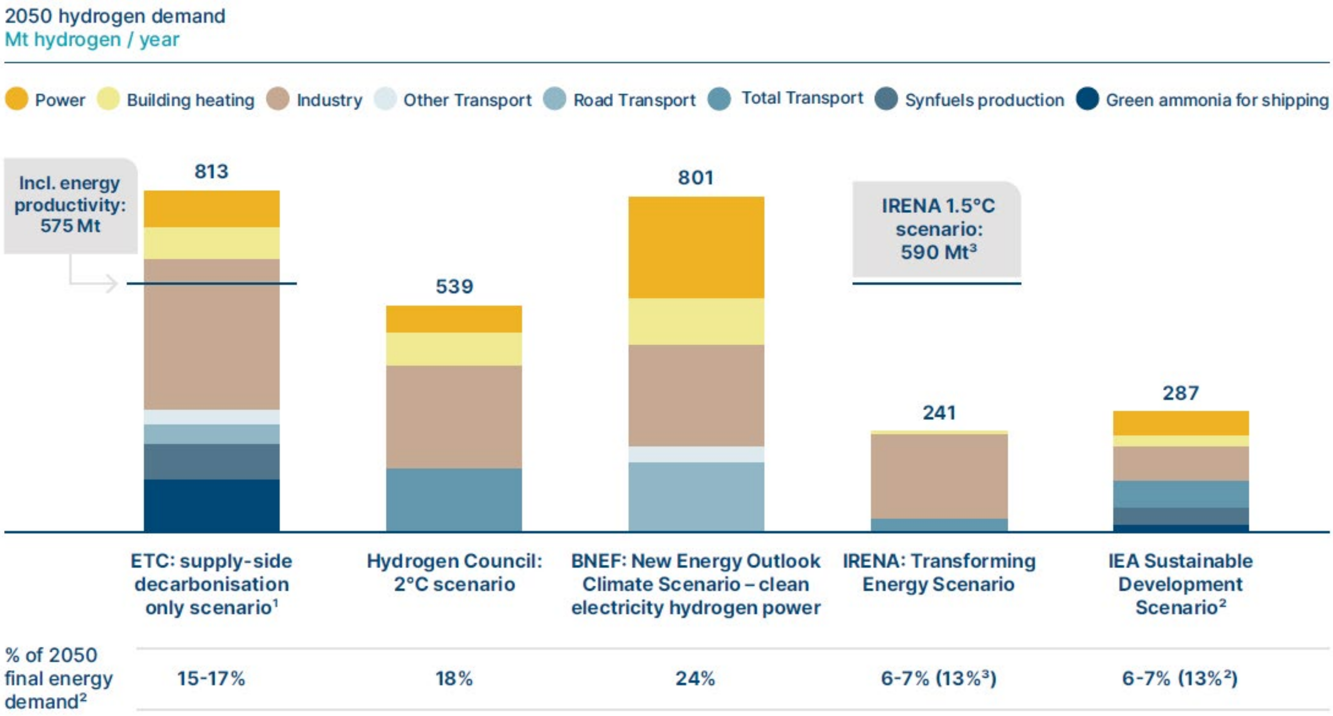
[18] This is Hydrogen Park SA, see HyResource (2021).
[19] ARENA (2021).
[20] Deloitte (2019).
[21] International Energy Agency (2021), pages 75, 109.



NOTES: [1] Illustrative scenario considering 2050 final energy demand without application of energy productivity levers which would reduce energy needs in a net-zero scenario,
[2] Hydrogen reaches 13% of final energy demand by 2070 in IEA SDS, with hydrogen volumes of 520 Mt/year,
[3] IRENA 1.5C scenario does not include split in uses, but represents 13% final energy demand.

SOURCES: SYSTEMIQ analysis for the Energy Transitions Commission (2021); Hydrogen Council (2017), *Hydrogen scaling up – A sustainable pathway for the global energy transition;* BloombergNEF (2020), *New Energy Outlook;* IRENA (2021), *World Energy Transitions Outlook – 1.5C Pathway;* IRENA (2020), *Global Renewables Outlook,* IEA (2019), *The future of hydrogen*

Figure 2: Different perspectives on the size of the global hydrogen industry in 2050, with sector breakdown. SOURCE: Energy Transitions Commission (2021), page 23.

2.1 Recognise the task is large and complex

The hydrogen supply chain has many moving parts, with economic and engineering decisions to be made about large scale investments at multiple points, such as for:

- **Making hydrogen:** Unlike traditional energy sources such as timber, coal, and petroleum products, hydrogen doesn't exist in specific locations in concentrated forms. However, it can be produced via several processes from a wide variety of resources that contain hydrogen. The process most often associated with current discussions about clean hydrogen is to use an electrolyser to make 'green' hydrogen, which requires renewable electricity and water as inputs. However, there is also the opportunity to make 'blue' hydrogen, which is produced via the traditional means of steam methane reforming or coal gasification but capturing and storing the carbon emitted.

Assuming long-term clean hydrogen is green, significant electricity generation capacity will be required. This is on top of the renewable electricity required to replace coal from domestic electricity generation and to electrify light transport. The requirements for new generation capacity grow further if Australia is to meet its hydrogen export objectives. Dr Alan Finkel says that if we were to export as much hydrogen by energy value as the LNG we exported in the year to June 2020 (33 million tonnes) we would need about eight times the total electricity that was generated in Australia in 2019[22] (2200TWh, and Australia generated 265TWh in 2019).[23] He says that if we used solar for that energy, we would need around 75 times Australia's installed solar capacity in 2019 (1000GW capacity, more than the installed solar capacity worldwide).

Adding other export capabilities, such as a new green steel industry, will increase our renewable electricity requirements by further orders of magnitude. For example, BlueScope has calculated that:

> *To replace just 20 per cent of the pulverised coal injection (PCI which is <30% of the fuel/reductant in our Blast Furnace) at Port Kembla Steelworks, for example, with 'green hydrogen' would require 29 x 10MW electrolysers, with each electrolyser having a footprint of 1000m^2. They would consume 290MW of electricity (the Steelworks currently consumes an average of about 100MW).*[24]

If we use this example to calculate what 100 per cent of all fuel/reductant at that one site might consume, this comes to 4.8GW.[25] If the electrolysers are (hypothetically) running at near 100 per cent capacity factor, that gets to 10-20GW of renewable capacity, depending on source (offshore wind, onshore wind, solar). To provide context, under its electricity roadmap NSW plans to instal 12GW for the whole state by 2030.[26]

- **Transporting hydrogen:** Once hydrogen is made, decisions need to be taken about the means for its transportation. This is about both the form of the hydrogen to be transported and the form of hydrogen transport. Hydrogen to be used domestically (and as pure hydrogen) will most likely be in its gas or liquid form, with gas likely to be the better option, at least in current estimates. Liquifying hydrogen requires additional facilities, and transportation at the low temperature required to maintain a liquid form (-253°C) is expensive. Figure 3 shows the view of the Energy Transitions Commission about the better means of transporting hydrogen for different circumstances. The method of transportation for domestic use is most likely to be via pipeline or tube trailer, or potentially between coastal sites via ship.

  Hydrogen for export from Australia will need to be by ship, and this natural constraint on available volume and weight means that a range of options are being considered for the most efficient form for the hydrogen. Current discussions focus most on hydrogen being shipped in a liquid form or via a chemical carrier such as ammonia. However, there are also innovations to ship hydrogen as a compressed gas or as a metal hydride.[27]

- **Using hydrogen:** Hydrogen use can cover many sectors, from applications in industrial processes (such as making ammonia or steel), to replacing liquid fuels for transport uses (the whole spectrum from forklifts to container ships), to replacing natural gas for domestic and commercial heating and cooking. It can also be used in power stations to generate electricity when required.

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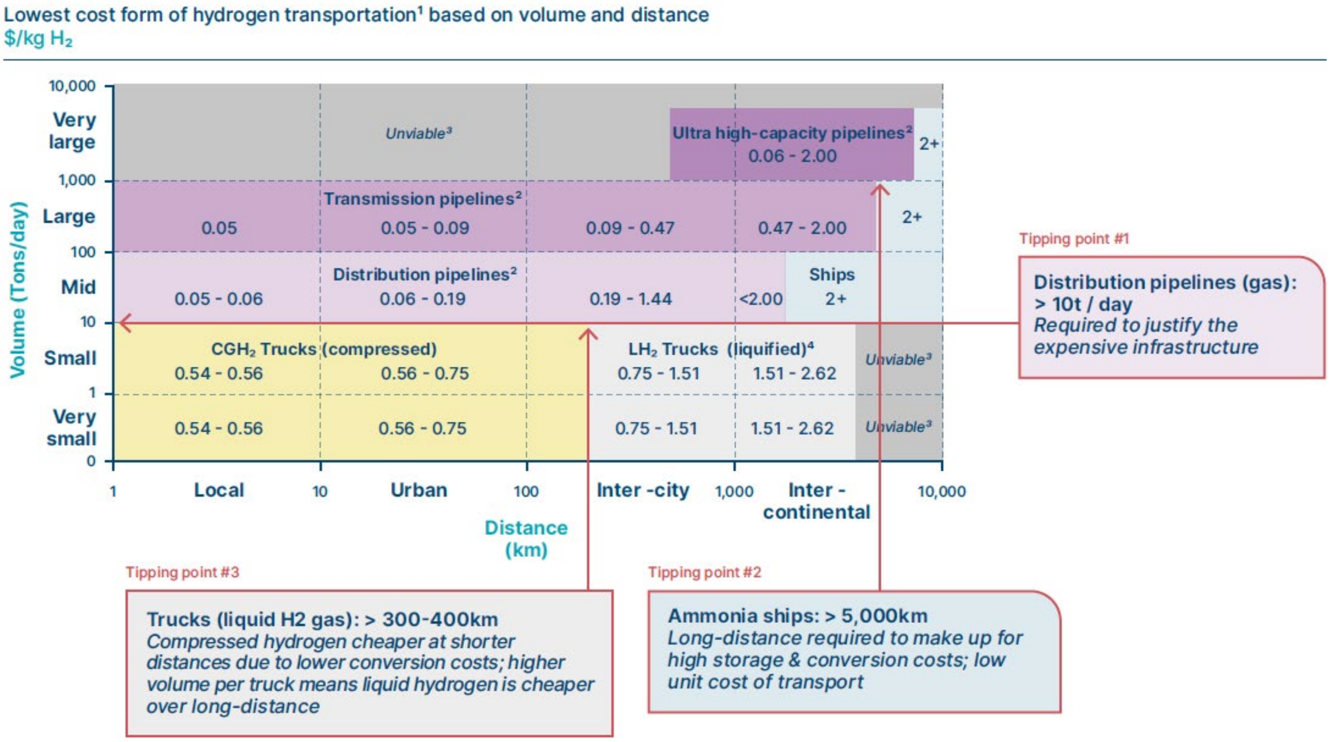
[22] Finkel (2021), pages 66-67.
[23] Australian Government Department of Industry, Science, Energy and Resources (n.d).
[24] BlueScope Steel (2021), page 12.
[25] Where 5x3.3=16.5 times 290MW comes to 4.8GW.
[26] NSW Department of Planning, Industry and Environment (2020), page 30.
[27] See for example, Hydrogen Energy Research Centre (n.d).



Lowest cost form of hydrogen transportation[1] based on volume and distance

$/kg H_2

Tipping point #1

Distribution pipelines (gas): > 10t / day
Required to justify the expensive infrastructure

Tipping point #3

Trucks (liquid H2 gas): > 300-400km
Compressed hydrogen cheaper at shorter distances due to lower conversion costs; higher volume per truck means liquid hydrogen is cheaper over long-distance

Tipping point #2

Ammonia ships: > 5,000km
Long-distance required to make up for high storage & conversion costs; low unit cost of transport

NOTE: [1] Including conversion and storage; [2] Assumes salt cavern storage for pipelines; [3] Ammonia assumed unsuitable at small scale due to its toxicity; [4] While LOHC (liquid organic hydrogen carrier) is cheaper than liquid hydrogen for long distance trucking, it is unlikely to be used as it is not commercially developed.

SOURCE: Adapted from BloombergNEF (2019), *Hydrogen: The Economics of Transport & Delivery*, Guidehouse (2020), *European Hydrogen backbone*

Figure 3: Analysis of lowest costs for hydrogen transport. SOURCE: Energy Transitions Commission (2021), page 38.

We can see that the versatility of hydrogen also brings complexity. Hydrogen allows planners to choose between gas and electricity infrastructure to some degree – it allows ‘sector coupling’, which is a linking of different sectors of the economy, especially different energy sectors, to co-optimise networks and markets. Hydrogen has the potential to become a key technology in this context, bringing the opportunity to create Australian strategic value chains.

An Australian hydrogen industry will require large-scale electrolysers, renewable electricity, hydrogen storage, water and water pipelines, electricity infrastructure, CCS as appropriate, and hydrogen pipelines (which may be repurposed from existing pipelines). Industrial and port facilities will need to be developed to process and export hydrogen and its derivatives, including ammonia. Mineral and chemical companies will invest in new production processes, and transport and logistics companies will procure new vehicle technologies. Refuelling stations will be required to supply hydrogen for vehicles. Households and businesses can convert from gas and oil-based fuels to hydrogen or electricity for heating and mobility.

Each of these elements will have their own costs and dependencies, engineering reality and level of social acceptance, which in turn affects the business case for different means of producing, storing, transporting and using hydrogen.

This also means a variety of timeframes, such as the timing for:

- Building the necessary electricity, gas and refuelling infrastructure.
- Vehicle and vessel design, testing, production and deployment, which can take over seven years.
- Major industrial process changes, such as key sectors planning for and purchasing new equipment that is expected to operate for decades. This can also take several years.
- Very large or 'mega' projects, such as in traditional oil and gas, where the process to go from initial investigation to a final investment decision can be as much as eight years.

It appears that we need to have locked down a great deal within the next year or so if we are to achieve objectives such as the National Hydrogen Strategy's 'Australia as a top three exporter to Asian markets by 2030' or getting hydrogen to less than A$2/kg by then.[28]

Further, the various windows of opportunity need to be aligned as far as possible if we are to get to scale and do so competitively. This is means planning and co-optimising different assets, and timing needs to address a range of different markets.

For example, at a high level there two hydrogen supply pathways:

- **Moving the electrons,** which means limiting the need to transport hydrogen by making it near the end use, and instead taking the renewable electricity (and raw water) to the hydrogen production site.
- **Moving the molecules,** which co-locates the source of renewable electricity (and raw water) with the hydrogen production, and then transporting the hydrogen to its end use.

In each case there will be different economics depending on the proposed project's size, the terrain and available sun and wind, whether the electricity is sourced from the grid or not, and whether the project needs to have port access or not.

Several experts have advocated for common user infrastructure, such as pipelines and ports, as a way of managing some of the complexity and creating efficiencies. This provides an opportunity to share risk among multiple producers and capture efficiencies and allow "users to participate in the hydrogen economy without first mover disadvantage/cost burden".[29]

This is also a key lesson learned from Australia's LNG experience, where a Deloitte[30] survey of LNG leaders found that a lack of forecasting and collaboration between industry players meant that they worked on independent projects in parallel: "In terms of post Final Investment Decision (FID) construction, collaboration among companies was virtually non-existent and this led to a dramatic overbuilding of infrastructure. For example, the three large LNG projects in Queensland don't even share a road". LNG developers were said to race against one other "to build infrastructure at almost any cost".[31]

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[28] While the 'H2 under $2' target does not officially have a date associated with it, AHC believes that it should be 2030. This is because of the messages being sent from our key trading partners Japan and South Korea – meeting their pricing needs would require hydrogen ataround $2 at the point of production.

[29] Advisian (2021), page 16.

[30] Reid and Cann (2016), page 8.

[31] Ibid., page 11.

Researchers from the Grattan Institute explain the need for coordination if we are to compete effectively, using the example of low carbon steel:

> *producing net-zero steel, for example, requires not just a zero-emissions steel smelter, but also a supply of zero-emissions hydrogen for the smelter, which in turn requires zero-emissions electricity.It requires land for hydrogen production and storage. And renewable energy production requires transmission lines from these renewable energy facilities to hydrogen production sites, and so on.*
>
> *When this needs to be repeated for half-a-dozen facilities in the same geographical area, the benefits of coordination become obvious. Achieving scale will be essential for successful transformation. Other countries will be seeking to transform their industrial sectors at the sametime as Australia, and where we are a small producer (for example, of steel, aluminium, or ammonia), individual Australian firms will be well down the queue for equipment suppliers.*[32]

And it's not only about land and infrastructure; vast amounts of construction activity will require workforce planning. Again, there are lessons to be learned from Australia's LNG experience:

> *There is a high probability that undertaking several major capital projects within the same geographic area will create resource scarcities, which in turn will drive up costs to unsustainable levels. Yet, in Australia, this likelihood was largely ignored. As a smaller nation, Australia had inherent resource scarcities, particularly in terms of labour. Additionally, LNG companies did not give a great deal of forethought to how stiff competition among multiple operators would affect local wage rates. This resulted in an 'arms race' of sorts in assuring access to scarce resources, with wage rates soaring to astronomical levels. How high is astronomical? As described by one survey participant, a journeyman carpenter, whose task was to build forms for pouring concrete, commanded AU$250,000 per year at the height of the building activity.*[33]

Impacts on local economies will need to be understood and planned for, to avoid the worst from Australia's previous boom-bust cycles and surges of economic activity. The sheer scale of construction and development will also raise important community (and societal) questions about competing uses for land and water, and priorities for infrastructure for different purposes. There will be a diverse group of stakeholders and connections to be built.

On a related matter, clearly the emerging hydrogen industry will affect several different markets in different timeframes, from now to beyond 2050. This will require a fit-for-purpose regulatory approach with the flexibility to work across sectors and jurisdictions. This means that project planning must also consider and shape regulatory developments.

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[32] Wood, Reeve, and Ha (2021b), page 43.
[33] Reid and Cann (2016), page 10.

2.2 Support co-location of facilities and infrastructure

Australia's National Hydrogen Strategy states the importance of hydrogen 'hubs', which are clusters of demand that share risks and costs:

> *Hubs aggregate various users of hydrogen into one area. Doing so minimises the cost of providing infrastructure – such as powerlines, pipelines, storage tanks, refuelling stations, ports, roads or railway lines – and supports economies of scale in producing and delivering hydrogen to end users. Hubs also help focus efforts for innovation and building a 'hydrogen-ready' workforce.*[34]

Besides co-locating hydrogen users, factors influencing hub site choices include access to hydrogen production (and the necessary land, low-priced electricity, electricity infrastructure, water and relevant storage capacity), access to suitable ports, road and rail infrastructure, and access to gas transmission pipeline easements. Stakeholder and community interest and acceptance is also vital.[35] In work undertaken for the National Hydrogen Strategy, consultant ARUP developed hub criteria as shown in Table 1.

Criteria – level 1	Criteria – level 2
Production (Green)	Renewable source Weather data Backup energy supply
Essential considerations	Transport access Transmission lines Water access Health and safety provisions Environmental considerations Economic and social considerations Land availability
Demand	Population size and density Colocation with industrial ammonia production Colocation with future industrial opportunities Proximity to export hubs
Supply chain to domestic demand	Existing gas networks Gaseous hydrogen storage Refuelling stations

Table 1: Domestic hub assessment framework, adapted from ARUP (2019) page 77.

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[34] COAG (2019), page 34.

[35] Ibid., page 34.

In September 2021, the Australian Government announced that it would support seven hydrogen hubs, with a funding amount of $464 million.[36] Seven locations have been suggested, with a final decision to be made in 2022. Applicants for funding are expected to be consortia of Australian and international industry players, potentially with state and international government backing. Favourable locations will be those with large scale industrial energy demand, a skilled workforce, existing infrastructure that can be utilised, and proximity to energy resources.

Globally, hubs are considered vital to establish scale in clean hydrogen.

The 'hydrogen valley' concept (used in Europe) is similar, where they bring parties together around a common hydrogen supply infrastructure to create a local ecosystem. Hydrogen valleys tend to:

- **Be large in scale,** with project scoping that includes several sub-projects and goes beyond "mere demonstration activities and entails at least a two-digit multi-million EUR investment".
- **Have a clearly defined geographic scope,** with a footprint that "can range from a local or regional focus (e.g. a major port and its hinterland) to a specific national or international region (e.g. a transport corridor along a major European waterway)."
- **Cover the hydrogen value chain,** from hydrogen production to storage and distribution, through to end users.
- **Supply to users from a range of end sectors,** such as hydrogen for industrial use, for transport and for energy supply.[37]

A report for the European Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) advises that the hydrogen valleys across the world have flourished, with estimated investment volume at €250 million in 2017, and growing to more than €18,000 million in 2019.[38] Interest and investment is also shifting from the public and research sector to the private sector, which is said to be a sign of "a maturing market with more and more profitable investment cases".[39] The global hydrogen valleys are also said to be on track to grow in size, number and complexity.

Hydrogen valleys are also apparently aligning with three "archetypical value chain setups", as follows:

- **Archetype 1: Transport focussed smaller-scale producers and consumers of hydrogen** that come together to aggregate consumption volumes from different mobility users and share the means of refuelling vehicles, including hydrogen supply and refuelling stations.
- **Archetype 2: Industrial medium-scale producers and users of hydrogen as a feedstock,** where the demand (off-take) is "on one or more larger off-takers as 'anchor loads', typically from the industry or energy sector (e.g. refineries)" who create a critical mass for initial demand.
- **Archetype 3: Export-focussed large-scale hydrogen producers** "aiming for international, long-distance transport to off-takers abroad". The domestic focus is on off-take from the industry and energy sector "to commercially de-risk the necessary upstream and midstream investments".[40]

See Appendix A for these archetypes and the 'cluster' equivalent from the Energy Transitions Commission.

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[36] Australian Government (2021).
[37] Weichenhain, Kaufmann, Benz, and Matute Gomez (2021), page 13.
[38] Ibid., page 22.
[39] Ibid., page 26.
[40] Ibid.

In the AHC's assessment of our members' plans, we found most have identified multiple key markets for their own involvement in hydrogen.

In May 2021 we asked our members from a range of sectors (consulting, energy, finance, industrial gases, science, technology and transport) which end uses they saw as relevant to their hydrogen ambitions. Figure 4 shows the responses, where we can see road transport and blending into natural gas networks were the most popular. In these responses we can also see industry players shifting into surprising sectors, such as gas networks valuing transport, and transport businesses considering electricity grid stabilisation.

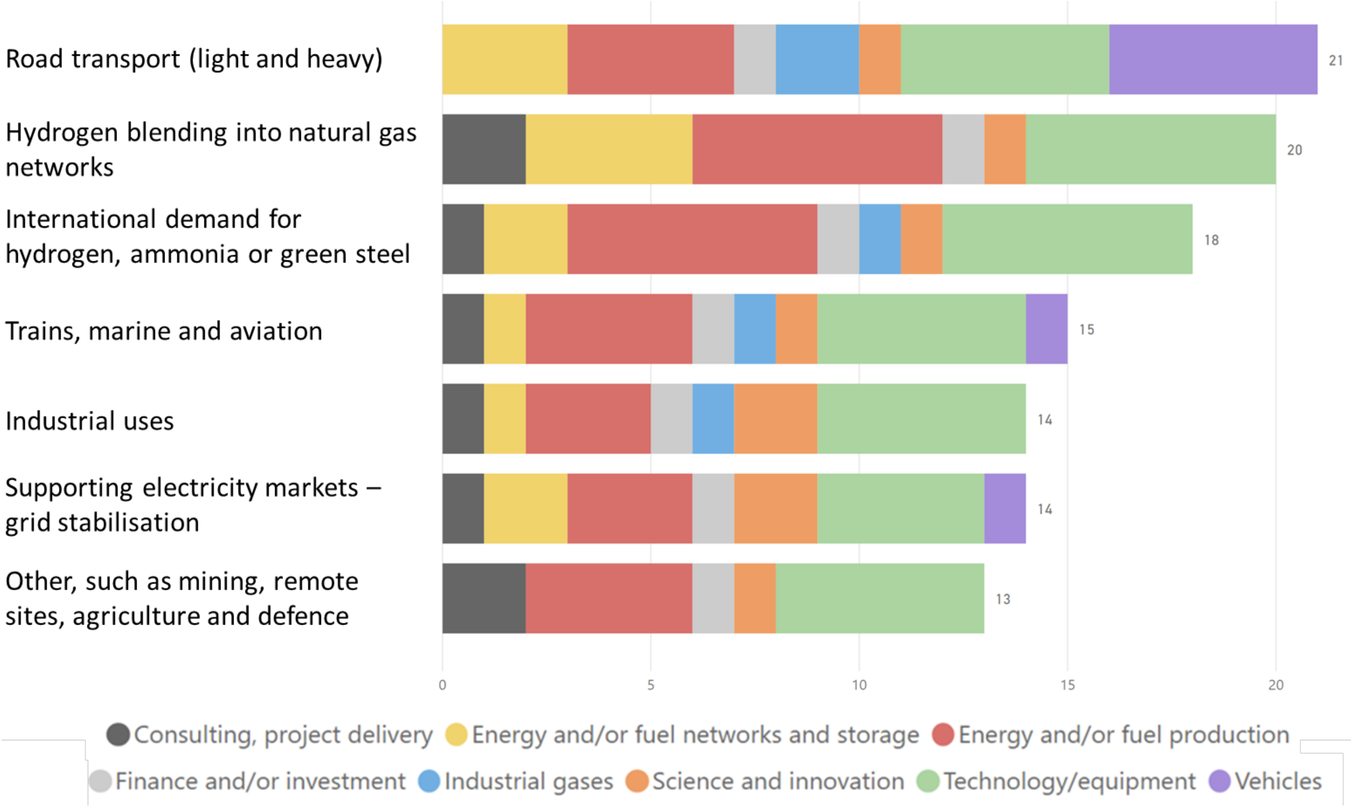

Figure 4: AHC member responses to question about end use markets for their business's interests in hydrogen, May 2021, n=30, AHC internal analysis.

2.3 Provide adequate public funding support to start the markets

Until the industry has reached commercial scale, grant funding is essential. We noted at the start of this chapter that the scale of the electrolysers required to reach scale will be 1GW, and we will need several of these.

It is difficult to estimate the total cost of the various large scale projects that could develop: there are too many unknowns, many variables, and we know the costs of electrolysers and renewable electricity will come down. However, it is likely that the capital investments for production of hydrogen alone could run to the tens of billions of dollars.

For example, using Deloitte's[41] two most ambitious 2030 demand scenarios for the National Hydrogen Strategy (724 kt per year and 1,777 kt per year), we estimate potential hydrogen production costs based on sample project mixes, as shown in Table 2.

We also show how the investment gap (the difference to create a commercial enterprise) might be considered, based on an assumption of 75 per cent government funding required for the near term. Of course, in practice there will be a sliding scale of costs per project per timeframe, with the investment gap varying as well. We might expect that a total of A$21 billion (for example, from column 1) would be spread over several years, and while the government funding to start with would be closer to the 75 per cent, this would reduce to zero over time.

Each scenario has two different mixes of project sizes to illustrate different costs. Columns 1 and 3 reflect relatively more efficient choices than columns 2 and 4 – these have larger projects and show some economies of scale.

H2 production	Electrolyser equivalent	1. Energy of the future Total: 1,777ktpa	2. Energy of the future Total: 1,777ktpa	3. Targeted deployment Total: 724 ktpa	4. Targeted deployment Total: 724 ktpa
1ktpa	10MW	20	700	20	524
10ktpa	100MW	15	60	15	20
50ktpa	500MW	12	10	5	
100ktpa	1GW	10		3	
Total H2 volume (ktpa)		**1,770**	**1,800**	**720**	**724**
Projects		57	770	43	544
Cost (m)		A$21,550	A$42,000	A$10,350	A$20,720
Gap - 2021 75%		A$16,163	A$31,500	A$7,763	A$15,540

Table 2: AHC internal costing for different potential project mixes to align with Deloitte scenarios

We can see from Table 2 that the costs of hydrogen production alone (not including costs of the electricity and water inputs) could be in the range of around A$10 billion (column 3: smaller ambition, more efficient project mix) to A$42 billion (column 2: larger ambition, less efficient project mix).

If all projects received public funding at 75 per cent, funding for production would be at least around $7.7 billion (column 3) and might be expected to be closer to A$15-$20 billion for strong growth and reasonable efficiency. As noted above, the expenditure will of course be over time, and as scale and industry confidence build, we would see a corresponding reduction in public funding over the period.

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[41] Deloitte (2019).

We have addressed the costs of electrolyser projects and now need to add the costs of electrolyser inputs, upgrades to infrastructure, the costs of new assets and equipment, and other usage costs. These costs can also be expected to come to tens of billions of dollars.

Indicative total costs include:

- New wind and solar at large scale could be A$1 million a megawatt,[42] resulting in 10GW installed capacity costing A$10 billion.
- The cost to convert one blast furnace to make green steel has been priced at A$2.8 billion.[43] The capital cost for a new 4Mt/year integrated steelmaking facility is said to be around US$4 billion depending on the jurisdiction.[44]
- Electricity and gas infrastructure costs will also be in the billions: for example, the Dampier to Bunbury pipeline is valued at around A$3 billion,[45] which covers 1,539 kilometres of high pressure pipeline.
- Around A$0.5 million to A$1 million per tonne of hydrogen for storage at scale[46] (more than 20 tonnes).
- One ammonia plant could be over A$700 million,[47] and likely closer to A$1 billion for a 800 ktpa plant, depending on the existing infrastructure and availability of utilities.
- Port upgrades could be hundreds of millions of dollars per port; for example, Townsville's current channel upgrade is reported as costing A$232 million.[48]

Bringing some of these costs together, engineering consultant Hatch has recently developed a case study[49] based on WA iron ore to demonstrate the scale that supply chains will need to reach to displace diesel for transportation in mining. Hatch found that the cost to replace 3,000 ML per year of diesel would be A$28 billion.[50] This is a total cost, not a government funding amount, but we can see that even a small level of government support for a project like this (say 10 per cent) is A$2.8 billion.

Globally, the international Hydrogen Council's 2020 *Path to hydrogen competitiveness* report (supported by McKinsey analysis) estimates that US$70 billion (A$100 billion) of investment in hydrogen is required across the globe by 2030 to meaningfully activate the global hydrogen economy:

> *Reaching the scale required will call for funding an economic gap until a break-even point is reached – an investment to offset the initially higher costs of hydrogen as a fuel and of hydrogen equipment compared to alternatives. Instead of being perceived as costs, this should be seen as an investment to shift the energy system and industry to low-carbon technology.*[51]

BNEF analysis goes further, estimating that US$150 billion (A$214 billion) will be needed globally until 2030 to bridge the cost gap between hydrogen and the cheapest fossil fuels, not just the cheapest low-carbon alternative.[52]

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[42] Solgen (n.d).
[43] BlueScope Steel (2021), page 10.
[44] BHP (2020).
[45] AGIG (2020), page 99.
[46] Ardent Underground Hydrogen Storage (n.d).
[47] Milne (2021).
[48] Hartmann (2021).
[49] Hatch (2021), page 4.
[50] This analysis assumed the total cost of renewable energy generation installed capacity would be A$18 billion for 14GW of solar or A$14 billion for 9GW of wind. The electrolysers for 5.6GW were estimated to be A$10 billion, and there was a need for storage cost of A$2.4 billion for 37 kt of hydrogen.
[51] Hydrogen Council (2020), page 66.
[52] BNEF (2020), pages 4-5.

Recent announcements from overseas provide a further sense of the commitments required. For example:

- The US has allocated US$9.5 billion (~A$13 billion) directly to hydrogen,[53] with further potential multi-billion impacts from other infrastructure coverage. There aren't announced figures for the US hydrogen production targets, but estimates are that the opportunity (not necessarily by 2030) could be to produce up to 40Mt of hydrogen per annum.[54]
- The UK has committed £240 million (~A$452 million) directly, with a further ~£1.3 billion (~A$2.5 billion) for net zero with hydrogen as a priority.[55] This builds on the Prime Minister's 'Ten Point Plan for a Green Industrial Revolution', which aims for 5GW of low carbon hydrogen production capacity by 2030 for use across the economy.
- The European Union has an 'Innovation Fund',[56] expected to provide around €20 billion (~A$32.3 billion) of support over 2020-2030, for the commercial demonstration of innovative low-carbon technologies. For hydrogen, the EU has developed an ambitious plan to reach 2x40 GW of electrolysers by 2030, with 40GW in Europe and 40GW in Europe's neighbourhood with export to the EU.[57] Writing in 2020, the European Commission said:

> *From now to 2030, investments in electrolysers could range between €24 and €42 billion. In addition, over the same period, €220-340 billion would be required to scale up and directly connect 80-120 GW of solar and wind energy production capacity to the electrolysers to provide the necessary electricity. Investments in retrofitting half of the existing plants with carbon capture and storage are estimated at around €11 billion. In addition, investments of €65 billion will be needed for hydrogen transport, distribution and storage, and hydrogen. From now to 2050, investments in production capacities would amount to €180-470 billion in the EU.*[58]

To compare, at this stage with over A$1 billion announced for hydrogen,[59] the Australian Government's financial commitment to hydrogen is significant, but comparatively speaking, it is not where it needs to be if we are to achieve our national objectives. For example, the UK ambition is to produce 5GW of clean hydrogen by 2030, which is around 500 kt per annum. The Deloitte scenarios for the Australian National Hydrogen Strategy (refer to Table 2), are more than this for 2030, with our ambitious hydrogen production figure at three and a half times more than the UK target.

While the figures in this section are approximate, they make clear that meeting our Paris Agreement pledge, and becoming a clean energy exporter to help other countries reach theirs, is a far larger task than we have previously taken on. Playing our part in full decarbonisation is a major increase in ambition. This ambition may be realised over decades, but as noted by the European Commission: "As investment cycles in the clean energy sector run for about 25 years, the time to act is now".[60]

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[53] The whole package is for US$944 billion in total spending over five years, with US$550 billion in new spending. Passed by the US Senate in August 2021, the Infrastructure Investment and Jobs Act: Supports four regional hydrogen hubs, with US$8 billion over 4 years; provides US$500 million over 4 years for hydrogen research, development, and demonstration projects; and provides US$1 billion to fund a grant program to support electrolysis, ideally to reduce the cost of hydrogen produced via electrolysis to less than US$2 per kilogram of hydrogen by 2026. The bill now moves for consideration in the U.S. House of Representatives.

[54] Smith (2021), also Ivanenko (2021).

[55] In August 2021, the UK government launched its hydrogen strategy. The UK policy includes £240 million for government co-investment in production capacity through a Net Zero Hydrogen Fund. It also designates hydrogen as a key priority area a £1 billion fund called the Net Zero Innovation Portfolio, to accelerate commercialisation of low-carbon technologies and systems for net zero. There is a further £315 million Industrial Energy Transformation Fund and £20 million Industrial Fuel Switching Competition.

[56] European Commission (2019).

[57] European Commission (2020), pages 5-6. The strategic objective of the first phase (2020 to 2024) is to install at least 6 GW of electrolysers in the EU and the production of up to 1 million tonnes of renewable hydrogen. The objective of the second phase (2025 to 2030) to install at least 40 GW of renewable hydrogen electrolysers by 2030 and the production of up to 10 million tonnes of renewable hydrogen in the EU.

[58] European Commission (2020), pages 7-8.

[59] As of August 2021, this was at least A$920 million (announced), and some proportion of over A$1.62 billion that will be available for ARENA over the next ten years. See Grubnic (2021), page 7. Australian Government funding was then increased in September 2021 by a further $150 million for hubs, bringing total spend to at least $1.1 billion (see Australian Government, 2021).

[60] European Commission (2020), page 3.

2.4 Recommendations

The transition to net zero energy emissions will require unprecedented rates and complexity of investment in new energy sources, infrastructure and energy use equipment, which will need to be synchronised with an equally unprecedented exit, stranding or repurposing of existing capital stock (e.g. coal-fired power stations, gas networks, oil import supply chains, coal export supply chains).

Those investments will arise from the interplay of policies and programs of federal and state governments, regulatory bodies, a large number of companies in the private sector, energy users from households to major industrial consumers, and governments and companies of our major trading partners.

The scale of the task requires planning, funding, and targeted demand stimulation.

2.4.1 Set up planning and ownership of the task

Comprehensive and published planning information – defined here as projections and assessments of future energy supply and demand pathways – would assist governments, the private sector and the public to make informed decisions about their options and actions. We are suggesting broader net zero planning here rather than for hydrogen alone.

No such planning and reporting information is currently being produced. AEMO's Integrated System Plan (ISP) is the nearest example but it does not cover oil, energy exports, the consumption of electricity and gas off main grids, the full period to 2050, or the achievement of policy and programme goals. So, while the ISP would be important input to a national energy planning document, it serves a different, more specific, and limited purpose.

Our proposal is planning information only in the sense that it is intended to inform the planning of many stakeholders. It would not be a central plan that is intended to be implemented by governments. A close analogy is the International Energy Agency's outlook reports. Indeed, the IEA's reports would be a source of input to a more detailed view of Australia, which would in turn inform the IEA.

The proposed planning information would need to be updated regularly to update supply, demand, technology costs and other parameters that underlie projections. Scenarios would be employed, and subjected to sensitivity analysis, to inform policy, commercial and community decisions rather than advocate preferred directions. Actual results for the relevant parameters would also be reported (e.g. emissions, renewable energy share, vehicle fleet emissions, energy consumption and technology costs) and compared to earlier forecasts and federal and state targets. The impact of policies would be assessed where feasible.

Exports of energy (coal, LNG, hydrogen) and commodities that could be processed with clean energy (e.g. iron ore, steel) would be in scope of forecasting and reporting.

Non-energy indicators of related economic and social impacts (e.g. employment in relevant sectors and regions, energy costs, productivity impacts, land use change due to energy production, air quality and associated health outcomes) would be forecast and reported.

The volume, type and price of offsets could be included in the projections and reporting, as could non-energy emissions.

The development and publication of this planning information:

- Could be undertaken by a body established under statute, with information gathering powers and consultation obligations (with governments, agencies, business and public). It could operate under a Commonwealth-State agreement and legislation adopted nationally. It would need a secure line of funding from general taxation or by a levy on energy production.
- Would be overseen by a Board that is not subject to ministerial direction as to the use of its information powers or its findings. The research would be subject to expert peer review.
- Would cover all sources and uses of energy, and consideration could be given to including non-energy emissions from the outset, or at a later date.

Some transfer of expertise from governments, agencies and academia would be important to provide the required rigour to be achieved as quickly as possible.

A staged approach to expanding the scope (e.g. to non-energy emissions) may be required to make the establishment of the body and its outputs manageable.

Recommendation 1: Plan in the national interest

We recommend that the Australian Government establishes a body to develop an evidence-based approach to planning and coordinating the transition to net zero – including the development of hydrogen infrastructure – and reporting progress. An initial annual budget of approximately A$10 million would be required.

2.4.2 Fund projects and infrastructure

Given the sheer scale of required funding support, and the extended timeline, there should be a specific fund developed to support the emerging hydrogen industry, and early adopters, in managing technology risk. As noted by Wood et al., technology risk is "particularly acute" for Australia's industrial sector because there tend to be only a few facilities per business, amplifying the cost of failed technology.[61] Further:

> *When technology is new, potential users and investors (in this case, large industrial corporations and their shareholders and financiers) will have less confidence about feasibility, viability, and risks, all of which adds to the cost of capital. If this fear persists, it can create a 'risk trap', where the risk remains poorly understood and poorly priced because of lack of experience with the technology, and experience does not develop because of lack of investment.*[62]

We note that hydrogen has a role within a broader net zero policy, and decisions about funding require a national perspective that covers the range of ways to get to net zero. We know that hydrogen has a fundamentally important role and so feel confident that objective and evidence-based decision-making will see and value what this new industry can provide.

Therefore, the AHC recommends that the Australian Government establishes a Net Zero Fund, with an initial allocation of A$10 billion into the fund, with drawdowns to be decided in response to planning and market soundings.

We can expect this kind of public investment will unlock several times its value from the private sector. Assuming all else is equal, figures from ARENA and CEFC suggest that government funding in hydrogen might be expected to unlock at least three times as much private investment.[63]

We recommend that there is a Net Zero Authority created to administer the money allocated from the Net Zero Fund, with power to cover the full spectra from research to commercialisation, and from grants to finance. It will be important to consider ARENA and CEFC in the design, with a view to coordinating or integrating their operations.

We note that the Grattan Institute has recommended the same amount be used for an Industrial Transformation Future Fund, topped up with A$1 billion each year to 2030. Grattan's recommendation fulfils a different role to ARENA and the CEFC, with a "focus on transformation rather than demonstration (unlike ARENA); and…a strong risk appetite without the obligation to pursue returns (unlike CEFC)".[64]

While we are not against this idea, it is not clear how a third body with this remit would work relative to the other agencies. We believe that the funding needs are broader than the coverage suggested by Grattan. For example, while the industry is keen to move ahead, the need for practical demonstration and trial projects remains strong. As discussed in subsequent chapters of this report, there are many uncertainties confronting owners of significant assets, and the industry still needs to develop and share knowledge to grow investor confidence.

We do support the funding amount, although we note this may still not be the funding level required for a country seeking to become a market leader, and the A$10 billion is also not hydrogen specific. The billions of dollars of future GDP envisioned in the National Hydrogen Strategy will only be realised with a significant down payment.

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[61] Wood et al. (2021b) page 39.

[62] Ibid.

[63] De Atholia, Flannigan, Lai (2020). Further, if we take advice from the Hydrogen Council (2020, 2017) across two recent reports, a similar expectation of the ratio of public to private funds emerges: the 2020 report says around US$70 billion is required from government, and in a 2017 report the Council states that 'building the hydrogen economy would require annual investments of [US]$20 to 25 billion for a total of about [US]$280 billion until 2030' (page 66).

[64] Wood et al. (2021b), page 42.

Recommendation 2: Establish a Net Zero Fund

We recommend that the Australian Government establishes a Net Zero Fund, with an initial allocation of A$10 billion and a top up of A$1 billion each year to 2030. Drawdowns should be decided in response to planning and market soundings.

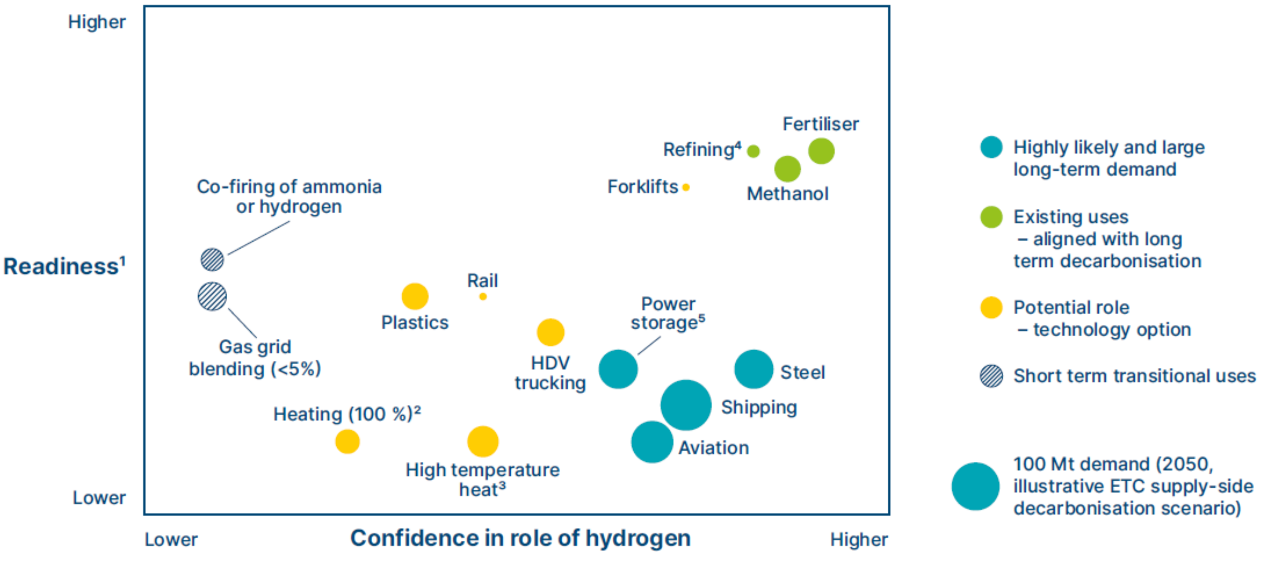
2.4.3 Focus on no regrets demand stimulation

Given the options, the interlinkages, and the need for scale across different markets, the issue for the industry and policymakers is picking where to start when considering potential markets. The AHC encourages prioritising sources of demand – and growing these – to draw through supply.

Figure 5 shows analysis from the Energy Transitions Commission,[65] which plots various end uses for hydrogen by confidence in hydrogen as having a role, and the readiness to use it. This is global analysis and so is not expected to precisely reflect the Australian environment.

We can see from Figure 5 see that the hydrogen uses toward the right along the x-axis reflect stronger confidence, with uses higher up the y-axis reflecting greater readiness. Uses that rate well on both axes relate to where hydrogen already plays a role, such as in the production of fertiliser. Very heavy transport and steel are less ready, but also represent sectors where hydrogen will need to play a role. These are the 'hard to abate' sectors for which direct use of renewable electricity, or use of batteries, is unlikely to be economically or technically feasible.

In work undertaken for the Clean Energy Finance Corporation, consultant Advisian[66] estimated the economic gap between likely delivery price and capacity to pay across 20 industry end use applications in 25 end use sectors. The analysis was for 2020, 2030 and 2050.



NOTES: [1] Readiness refers to a combined metric of technical readiness for clean hydrogen use, economic competitiveness and ease of sector to use clean hydrogen. [2] 'Heating (100%)' refers to building heating with hydrogen boilers via hydrogen distribution grid, [3] 'High temperature heat' refers to industrial heat processes above ca. 800°C [4] Current hydrogen use in refining industry is higher due to greater oil consumption. [5] Long-term energy storage for the power system.

Figure 5: Multiple potential uses of hydrogen in a low carbon economy, some of which can provide early 'off take' for clean hydrogen. SOURCE: Energy Transitions Commission (2021), page 17.

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65 Energy Transitions Commission (2021), page 17.
66 Advisian (2021).

Figure 6 shows the Advisian analysis for 2020, where a more positive figure suggests a higher economic competitiveness for a hydrogen-based technology compared with the incumbent technology. A sizeable negative gap (such as for marine shipping) reflects a hydrogen application that is some way away from being able to effectively compete.

The analysis also shows the extent to which hydrogen applications are likely to be dependent on hydrogen to decarbonise. This shows as a colour scale, where darker green identifies applications that are likely to have a high dependence on hydrogen to decarbonise.

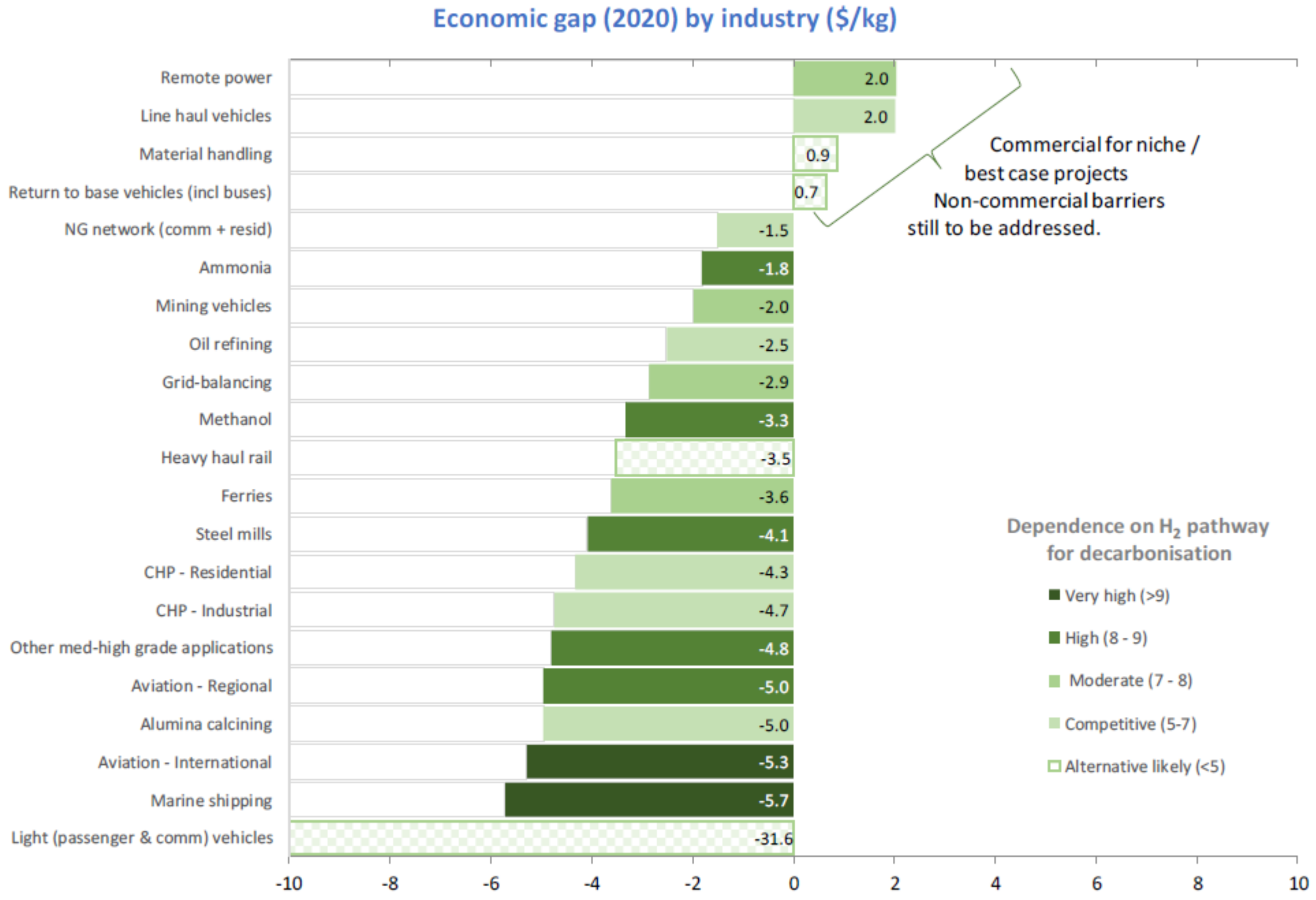

Figure 6: Economic gap (2020) by industry ($/kg), SOURCE: Advisian (2021), page 12.

While the analytical approaches of Advisian (in Figure 6) and the Energy Transitions Commission (in Figure 5) are different, we can see the conclusions are not. The darker green applications from Advisian's analysis are the same sectors as the 'higher confidence' applications from the Energy Transitions Commission. The readiness assessments of the applications are also well aligned.

The AHC is of the view that in the short to medium term it is worth prioritising funding for applications that are more dependent on hydrogen for decarbonisation and have a medium economic gap. If we can close the economic gap (and technology and knowledge gaps in some cases) for applications like ammonia production and heavy transport, we start to see the new hydrogen domestic industry take shape. Further, if we can drive large sources of demand, which again could be ammonia, as well as steel and blending into natural gas networks, we start to see scale and reduced costs.

As noted by the Grattan Institute:

> *risk will be lower where another competitive advantage can be identified (for example Australia's proximity to iron ore, abundant cheap renewable electricity, and proximity to growing Asian markets create a competitive advantage for steel). This is why government assistance to bridge the risk gap should focus on industries where Australia has an advantage – it lessens the call on government funds and develops industries that contribute to ongoing growth.*[67]

Consistent with this, we do need to start thinking about and planning for applications like shipping and aviation that have a high dependence on hydrogen, but these are also applications that are likely to be progressed by other countries, such as for ship building. As a start for Australia, driving scale in fuels that might be used for shipping and aviation (such as ammonia, methanol and synfuels) will have a positive impact. This is all the more important because the world will be looking for the hydrogen, ammonia and methanol to meet international climate goals.[68]

Focussing on building scale and capability on the sectors and applications that will be hard to abate without hydrogen is the best 'no regrets' approach that can be taken in an uncertain environment. This approach should also actively build room for other applications that might value hydrogen at lower prices and with an established (and shared) infrastructure. This is where hubs (and clusters, to use the Australian version, which is about communities of practice) also have an important role to drive collaboration and shared benefit.

The remaining sections of this paper identify the following applications as requiring immediate support:

- hydrogen blending into natural gas networks;
- heavy road transport; and
- manufacturing iron/steel, ammonia, methanol and aluminium/alumina.

Recommendation 3: Prioritise hard to abate and scalable demand sources

We recommend that the Australian Government prioritises project funding to grow demand for hydrogen in the applications that are more likely to require clean hydrogen to decarbonise, and more likely to achieve large scale. Ideally these should demonstrate an ability to open the market to other applications, through knowledge/technology sharing, geographic proximity, and/or cost reduction. Recommendations 6 and 8 provide further information on these priorities.

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[67] Wood et al. (2021b), page 39.

[68] Energy Transitions Commission (2020), page 11.

References

Advisian (2021) *Australian hydrogen market study: Sector analysis summary*, 24 May, for the Clean Energy Finance Corporation, https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf.

AGIG (2020) Five year plan for the Dampier to Bunbury Natural Gas Pipeline, January, https://www.agig.com.au/-/media/files/agig/stakeholder-engagement/agig-dbngp-final-plan-2021-2025.pdf

Ardent Underground Hydrogen Storage (n.d.) website accessed 9 September 2021, https://ardentunderground.com//.

ARENA (2021) 'Over $100 million to build Australia's first large-scale hydrogen plants', media release, 5 May, https://arena.gov.au/news/over-100-million-to-build-australias-first-large-scale-hydrogen-plants/.

ARUP (2019) *Australian Hydrogen Hubs Study: Technical study*, Issue 2, prepared for the COAG Energy Council Hydrogen Working Group, November, https://energyministers.gov.au/publications/reports-support-national-hydrogen-strategy.

Australian Government Department of Industry, Science, Energy and Resources (n.d.) 'Electricity generation', website accessed 12 September 2021, https://www.energy.gov.au/data/electricity-generation#:~:text=Total%20electricity%20generation%20in%20Australia%20in%202019%20was,including%20coal%20%2856%25%29%2C%20gas%20%2821%25%29%20and%20oil%20%282%25%29.

Australian Government (2021) 'Future hydrogen industry to create jobs, lower emissions and boost regional Australia', joint media release from The Hon. Scott Morrison MP, Prime Minister and The Hon. Angus Taylor MP, Minister for Energy and Emissions Reduction, 20 September, https://www.minister.industry.gov.au/ministers/taylor/media-releases/future-hydrogen-industry-create-jobs-lower-emissions-and-boost-regional-australia.

BlueScope Steel (2021) *BlueScope submission to the Standing Committee on State Development's Inquiry into the development of a hydrogen industry in NSW*, 26 February, https://www.parliament.nsw.gov.au/committees/inquiries/Pages/inquiry-details.aspx?pk=2643#tab-submissions.

BNEF (2020) *Hydrogen Economy Outlook: key messages*, March 30, https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

Coady, D., Parry, I., Le, N-P., and B. Shang (2019) *Global Fossil Fuel Subsidies Remain Large: An Update Based on Country-Level Estimates*, IMF Working Paper, Fiscal Affairs Department, WP/19/89, May, https://www.imf.org/en/Publications/WP/Issues/2019/05/02/Global-Fossil-Fuel-Subsidies-Remain-Large-An-Update-Based-on-Country-Level-Estimates-46509.

COAG (2019) *Australia's National Hydrogen Strategy*, November, https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf.

De Atholia, T., Flannigan, G. and S. Lai (2020) 'Renewable energy investment in Australia', Reserve Bank of Australia https://www.rba.gov.au/publications/bulletin/2020/mar/pdf/renewable-energy-investment-in-australia.pdf.

Energy Transitions Commission (2020) *The First Wave: A blueprint for commercial-scale zero-emission shipping pilots*, prepared for the Getting to Zero Coalition, version 1, 11 November, https://www.globalmaritimeforum.org/content/2020/11/The-First-Wave-%E2%80%93-A-blueprint-for-commercial-scale-zero-emission-shipping-pilots.pdf.

Energy Transitions Commission (2021) *Making the Hydrogen Economy Possible – Accelerating Clean Hydrogen in an Electrified Economy*, the Making Mission Possible Series, April, version 1.1, https://www.energy-transitions.org/publications/making-clean-hydrogen-possible/.

European Commission (2020) *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A hydrogen strategy for a climate-neutral Europe*, Brussels, 8 July, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf.

European Commission (n.d.) 'Innovation Fund', website accessed August 2021, https://ec.europa.eu/clima/policies/innovation-fund_en.

Finkel, A. (2021) 'Getting to Net Zero: Australia's energy transition', *Quarterly Essay*, QE81, March, Black Inc: Melbourne.

Grubnic, P. (2021) *A Short Report on Hydrogen Industry Policy Initiatives and the Status of Hydrogen Projects in Australia*, May, https://research.csiro.au/hyresource/wp-content/uploads/sites/378/2021/05/Short-Report-on-Hydrogen-Policy-and-Projects-Status-in-Australia-May-2021-v0.pdf.

Hartmann, I. (2021) Untitled, *Infrastructure Magazine*, https://infrastructuremagazine.com.au/2021/08/04/townsville-ports-channel-upgrade-project-milestone/.

Hatch (2021) *Case study for decarbonising Western Australia's iron ore sector using hydrogen*, prepared for the Green Hydrogen Consortium, August.

Hydrogen Council (2017) *Hydrogen Scaling Up: A Sustainable Pathway for the Global Energy Transition*, November, https://hydrogencouncil.com/en/study-hydrogen-scaling-up/.

Hydrogen Council (2020) *Path to hydrogen competitiveness: a cost perspective*, https://hydrogencouncil.com/en/path-to-hydrogen-competitiveness-a-cost-perspective

Hydrogen Energy Research Centre (n.d.) UNSW Sydney website accessed 29 Aug 2021, https://www.herc.unsw.edu.au/programs/about-hydrogen.

HyResource (n.d.) CSIRO website, accessed 29 August 2021, https://research.csiro.au/hyresource/hydrogen-park-south-australia/.

International Energy Agency (2021) *Net Zero by 2050: A Roadmap for the Global Energy Sector*, May, https://www.iea.org/data-and-statistics/data-product/net-zero-by-2050-scenario.

Ivenenko, I. (2021) 'What Is The Role Of Hydrogen In Biden's Infrastructure Plan?', *Forbes*, 5 August, https://www.forbes.com/sites/forbestechcouncil/2021/08/05/what-is-the-role-of-hydrogen-in-bidens-infrastructure-plan/?sh=381dad372bd3.

Milne (2021) 'Yara plans massive Pilbara green ammonia plant by 2030', 30 June, *Boiling Cold*, https://www.boilingcold.com.au/yara-plans-massive-pilbara-green-ammonia-plant-by-2030/.

NSW Department of Planning, Industry and Environment (2020) *NSW Electricity Infrastructure Roadmap: Building an Energy Superpower*, Overview, November, https://energy.nsw.gov.au/sites/default/files/2020-11/NSW%20Electricity%20Infrastructure%20Roadmap%20-%20Overview_1.pdf.

Reid, S. and Cann, G. (2016) *The good, the bad and the ugly: The changing face of Australia's LNG production*, Deloitte, https://www2.deloitte.com/us/en/pages/energy-and-resources/articles/gx-australian-lng-production.html.

Smith, A. (2021) 'Biden administration and industry alike see hydrogen as "Swiss Army knife" for eliminating emissions', *Washington Examiner*, 15 April, https://www.washingtonexaminer.com/policy/energy/biden-administration-and-industry-alike-see-hydrogen-as-swiss-army-knife-for-eliminating-emissions.

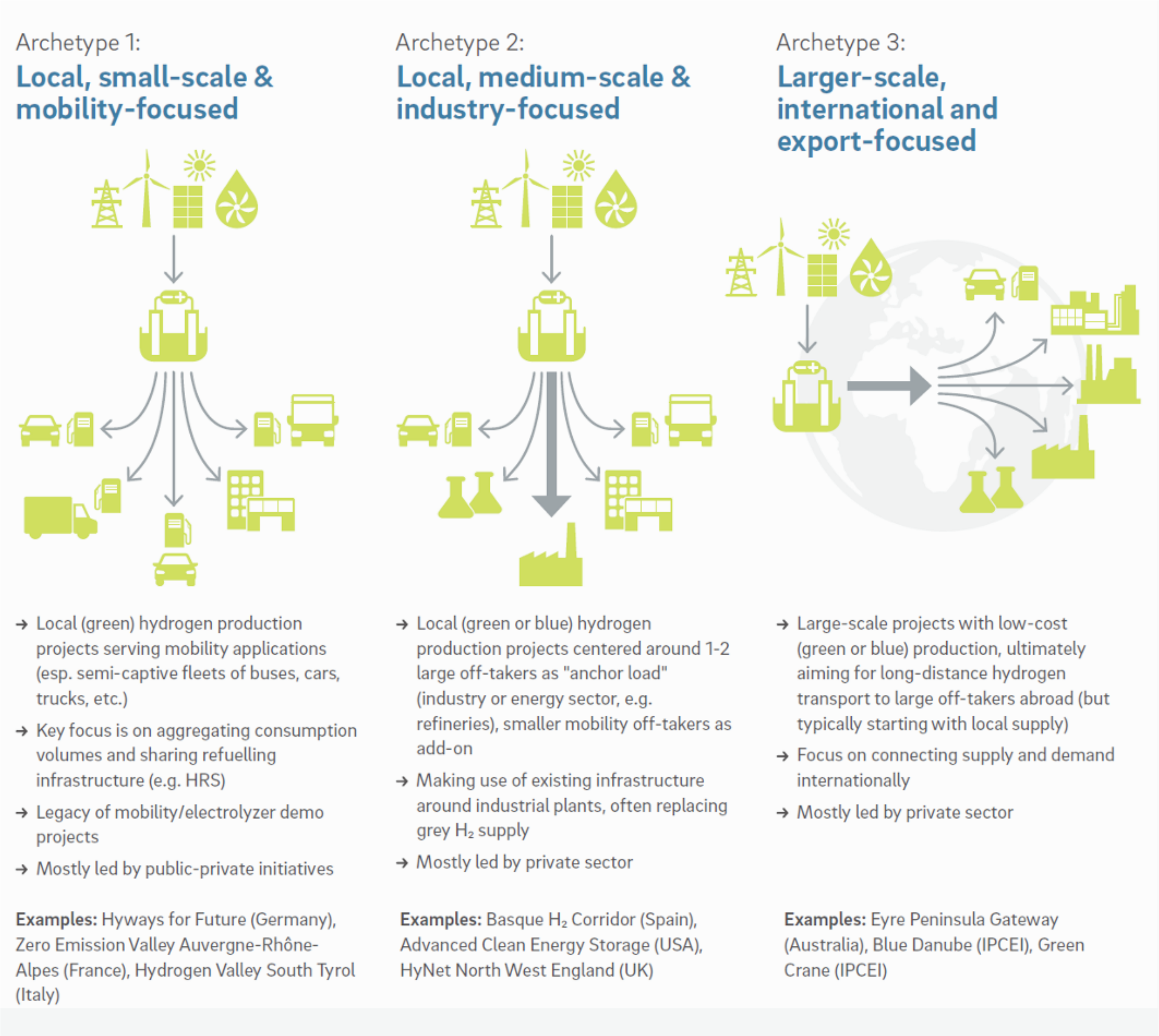
Solgen (n.d) Solgen Energy Group website, accessed 29 August 2021, https://solgen.com.au/solar-power-plant-cost/.

Weichenhain, U., Kaufmann, M., Benz, A., and G. Matute Gomez (2021) *Hydrogen Valleys: Insights into the emerging hydrogen economies around the world*, prepared by Roland Berger and Inycom for the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU), July, https://www.fch.europa.eu/sites/default/files/documents/20210527_Hydrogen_Valleys_final_ONLINE.pdf.

Wood, T., Reeve, A., and Ha, J. (2021b). *Towards net zero: Practical policies to reduce industrial emissions*, Grattan Institute, Report No. 2021-10, August, https://grattan.edu.au/report/towards-net-zero-practical-policies-to-reduce-industrial-emissions/.

Appendix A: Different hub concepts

Hydrogen valleys



Archetype 1:

Local, small-scale & mobility-focused

- → Local (green) hydrogen production projects serving mobility applications (esp. semi-captive fleets of buses, cars, trucks, etc.)
- → Key focus is on aggregating consumption volumes and sharing refuelling infrastructure (e.g. HRS)
- → Legacy of mobility/electrolyzer demo projects
- → Mostly led by public-private initiatives

Examples: Hyways for Future (Germany), Zero Emission Valley Auvergne-Rhône-Alpes (France), Hydrogen Valley South Tyrol (Italy)

Archetype 2:

Local, medium-scale & industry-focused

- → Local (green or blue) hydrogen production projects centered around 1-2 large off-takers as "anchor load" (industry or energy sector, e.g. refineries), smaller mobility off-takers as add-on
- → Making use of existing infrastructure around industrial plants, often replacing grey H_2 supply
- → Mostly led by private sector

Examples: Basque H_2 Corridor (Spain), Advanced Clean Energy Storage (USA), HyNet North West England (UK)

Archetype 3:

Larger-scale, international and export-focused

- → Large-scale projects with low-cost (green or blue) production, ultimately aiming for long-distance hydrogen transport to large off-takers abroad (but typically starting with local supply)
- → Focus on connecting supply and demand internationally
- → Mostly led by private sector

Examples: Eyre Peninsula Gateway (Australia), Blue Danube (IPCEI), Green Crane (IPCEI)

Figure 7: Hydrogen Valley archetypes, SOURCE: Weichenhain et. al (2021, page 28)

Hydrogen clusters

Four archetypes for hydrogen clusters based on “early demand” use cases

1 Port

Ports[1] as infrastructure hubs for import/export of feedstocks and goods.

Core off-taker:

- **Shipping (Ammonia)**

Often co-located with:

- **Refining & Fertiliser**
  Import/export of LNG for these industries
- **Steel**
  Import/export of feedstocks and products
- **Road Transport**
  Container transport
- **Aviation**
  Coastal transport hub
- **Forklifts & Ground Operations**
  Container/goods handling
- **Option for blending** dependant on trade-offs (see Box B)
  Coincide with LNG storage

2 City

Continental cities serve as non-coastal hub for transport and are often well connected to gas grid infrastructure.

Core off-takers:

- **Aviation**
- **Long-haul trucking & buses**
- **Option for low % H_2 blending** into natural gas grid dependant on trade-offs (see Box B)

Often co-located with:

- **Refining & Ammonia**
  As large natural gas demand sites commonly close to gas storage/import sites
- **Forklifts & Ground Operations**
  Heavy transport in mines

3 Refining & Fertiliser

Refineries and fertiliser production are frequently co-located and require large amounts of hydrogen.

Core off-taker:

- **Refining & Fertiliser**

Often co-located with:

- **Ports**
- **Gas storage facilities** – option for low % H_2 blending into natural gas grid dependant on trade-offs (see Box B)

4 Steel

Hydrogen-DRI steel production as major hydrogen off-taker (medium sized steel site requires approximately ~120 kt H_2/year).

Core off-taker:

- **Hydrogen-DRI steel production**

Often co-located with:

- **Ports**

- **Refining, Fertiliser and Steel** offer sufficient off-take to operate on stand-alone basis, but co-location enables shared off-take

- **Road Transport**
  Dependant on long-term role of hydrogen in road transport & hydrogen refuelling infrastructure network requirements

Illustrative cluster size

Port	City	Refining & Fertiliser	Steel
Large to very large (~100- >1000 t/day)	**Small to very large** (~1 - >1000 t/day)	**Medium to Large** (~50-400 t/day)	**Large** (100-300 t/day)

Existing pipeline of projects exemplifies these archetypes:

Port of Amsterdam:

- Partners: Nouryon, Tata Steel
- 100 MW electrolysis
- Oxygen bi-product from electrolysis will be used in steel production

Port of Rotterdam:

- 1.2 Mt clean hydrogen production via green and blue route by 2030
- Wide variety of end-uses targeted in several consortia and pilots including shipping, trucking and aviation

North Sea Port[2]:

- Partners: 500 MW electrolysis
- End-users include refinery, ammonia and steel plant in proximity to port

Aberdeen Hydrogen Hub, Scotland:

- Hydrogen refuelling stations and deployment of hydrogen powered L/M/HDV
- Feasibility study to expand to building heating and industry

Hydrogen Cities, South Korea:

- 4 cities as candidate cities for the hydrogen economy
- Road transport refuelling infrastructure
- Hydrogen grid for building heating/cooling

Liverpool & Manchester, UK:

- Partners: Consortium lead by Cadent and Progressive Energy
- Blue hydrogen for gas grid blending combined with local industry and transport

Puertollano, Spain[3]:

- Partners: Iberdrola and Fertiberia
- 20 MW electrolysis (2021)
- Green hydrogen used to co-feed (10%) into existing ammonia plant

Lingen, Germany[3]:

- Partners: BP and Oersted
- 50 MW electrolysis
- Green hydrogen to replace 20% of grey hydrogen in refinery

Antofagasta, Chile[3]:

- Partners: Engie and Enaex
- 1600 MW electrolysis
- For local ammonium nitrate plant and export market

Large projects such as Australian Renewable Energy Hub[4] and NEOM[5] are in early planning stages

Lulea, Sweden:

- Partners SSAB, Vattenfall, LKAB
- Pioneering hydrogen-direct reduction (DRI) technology
- Commencing early commercial production in 2026

Duisburg, Germany:

- Partners: Thyssenkrupp, RWE
- 100 MW electrolysis
- Co-feed of hydrogen into coal-powered blast-furnace as first step prior to conversion to DRI plants

Dunkirk, France:

- Partners: AcelorMittal, Air Liquide
- Development of hydrogen-DRI and hybrid BF/DRI technology

NOTES: [1] Particular focus on coastal ports due to much bigger size compared to inland ports; [2] Partners: Dow, Yara, Zeeland Refinery, ArcelorMittal, Ørsted and North Sea Port; [3] Early projects only have one-offtaker, but are in principle located in close proximity to additional refinery or fertiliser production facilities; [4] Partners: InterContinental Energy, CWP Energy Asia, Vestas, Pathway Investments. Up to 23 GW electrolysis for ammonia production in early planning stages. [5] Partner: Air Products, ACWA Power, Thyssenkrupp, Haldor Topsøe. Target: 650 t/day H_2 production to produce 1.2 Mt ammonia / year

SOURCES: Port of Amsterdam, "Nouryon, Tata Steel, and Port of Amsterdam partner to develop the largest green hydrogen cluster in Europe", October 18th 2018; Port of Rotterdam, "Port of Rotterdam becomes international hydrogen hub", May 7th 2020; North Sea Port, "Ørsted North Sea Port to develop one of the world's largest sustainable hydrogen plants for Dutch and Belgian industry", April 1st 2021; Aberdeen City Council, "H_2 Aberdeen", retrieved April 2021; FuelCellsWorks, "Korean Government announces its selection of World's first hydrogen cities", January 6th 2020; HyNet North West (2020), "Unlocking net zero for the UK"; Iberdrola, "Iberdrola and Fertiberia launch the largest plant producing green hydrogen for industrial use in Europe", July 24th 2020; Reuters, "BP, Orsted launch green hydrogen project at German oil refinery", November 10th 2020; Power Engineering International, "First green hydrogen projects emerge in Chile", October 5th 2020; The Chemical Engineer, "Australian Government backs renewable energy hub", October 23rd 2020; AirProducts, "Air Products, ACWA Power and NEOM Sign Agreement for $5 Billion Production Facility in NEOM Powered by Renewable Energy for Production and Export of Green Hydrogen to Global Markets", July 7th 2020; Hybrit, "SSAB, LKAB and Vattenfall to begin industrialization of future fossil-free steelmaking by establishing the world's first production plant for fossil-free sponge iron in Gällivare", March 24th 2021; Thyssenkrupp, "Green hydrogen for steel production: RWE and thyssenkrupp plan partnership", June 10th 2020; AcelorMittal, "ArcelorMittal Europe to produce 'green steel' starting in 2020", October 13th 2020.

Figure 8: Energy Transitions Commission perspective on hydrogen hubs. SOURCE: Energy Transitions Commission (2021), page 68.