03 Ammonia co-firing

Summary

1 Japanese policymakers and utilities have identified ammonia co-firing as a key decarbonisation technology for its power sector and are deploying large sums of capital to commercialise the technology. Our analysis finds these investments are unlikely to help overcome Japan's energy trilemma challenge.

2 On an energy equivalent basis, grey ammonia, which is the cheapest source of ammonia, currently costs around four times that of thermal coal. The cost gap widens even further when considering green ammonia, which is 15 times the cost of coal.

3 At present, 20% co-firing of the cheapest grey ammonia is set to double the fuel costs compared to coal. Co-firing ammonia with coal will only start to make financial sense in 2040, at a carbon price of US$205/t$CO_2$. This results in a LCOE of around US$280/MWh, which is prohibitively expensive.

4 Despite claims, ammonia co-firing does little to reduce emissions. At the current technologically feasible co-firing rate of 20%, the emissions factor remains close to double that of gas-fired combined cycle plants (CCGT), which will need to be replaced or abated by 2035 to be consistent with the IEA's NZE scenario.

5 Due to the carbon and energy intensive nature of conventional methods of ammonia production, unless blue and/or green ammonia is utilised, there is no net emissions reduction from co-firing.

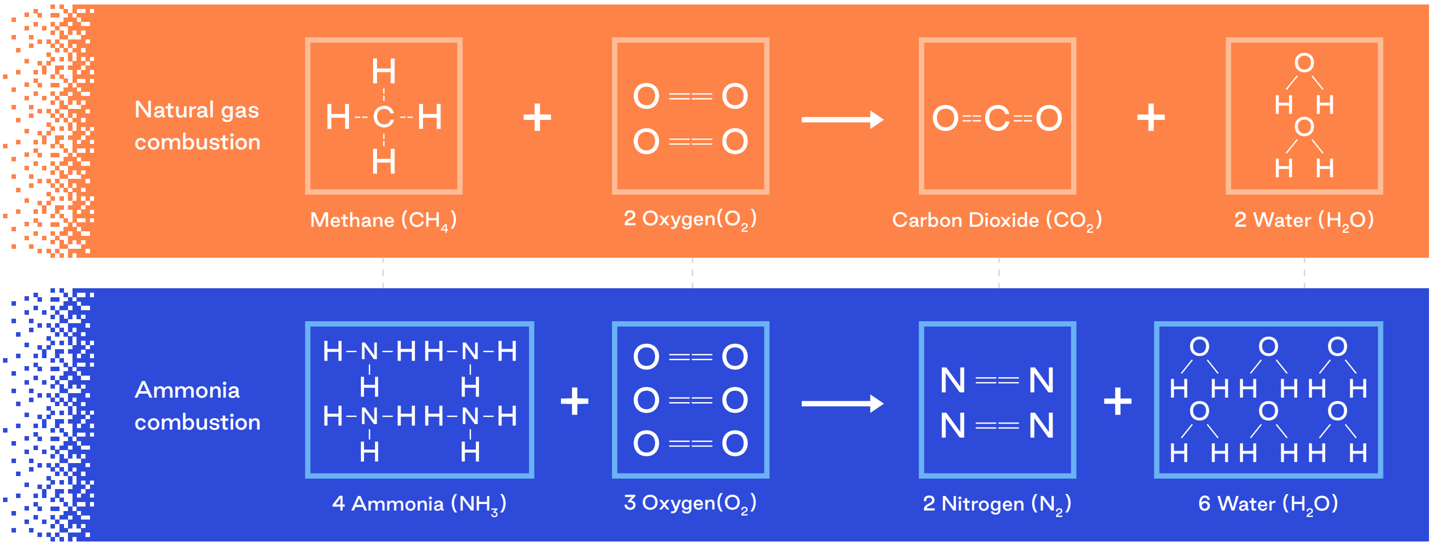
6 The lack of cheap gas as feedstock makes domestically produced ammonia prohibitively costly. This means that Japanese utilities will have to rely on cheaper international imports, further undermining Japan's energy security issues.

7 Despite its poor suitability in the power sector, ammonia has many other uses to support the transition to a zero carbon economy and should be scaled up in hard-to-abate sectors, such as cement and steel.

Background

Ammonia holds similar energy characteristics as fossil fuels, particularly natural gas. Natural gas, consisting primarily of methane, when combusted with oxygen, releases energy through the breaking of carbon-hydrogen bonds, and produces carbon dioxide and water as a by-product. Similarly, the direct combustion of ammonia releases energy through the breaking of nitrogen-hydrogen bonds under heat and produces nitrogen and water as by-products (Figure 2.1).

Figure 2.1 Chemical reactions of natural gas combustion and ammonia combustion



Source: TransitionZero

Ammonia is commonly discussed as a derivative of hydrogen, and as an easy way to capture, store and transport hydrogen to support a zero carbon transition. Its attractiveness stems from its high energy density[2], ability to be stored and transported easily[3] and its well-established supply chain[4]. In recent years, there are also increasing efforts to promote the direct combustion of ammonia as a low-carbon fuel. The combustion of ammonia does not emit any carbon, making it a zero carbon fuel at combustion stage[5]. Furthermore, the relative maturity of the ammonia value chain made it attractive as an interim fuel while the hydrogen economy develops. Hydrogen can be used in its pure form, or through hydrogen carriers such as ammonia etc.

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2 Ammonia has a high energy density (22.5 MJ/kg at HHV), making it a suitable storage medium. In fact, liquid ammonia has a higher energy density (15.6 MJ/L) than liquid hydrogen (9.1 MJ/L).

3 Ammonia can be easily refrigerated at -33°C and stored in liquid form, making it a versatile and easy to store energy medium of hydrogen. In comparison, hydrogen must be cryogenically cooled to -253°C for storage. Similar disparities exist when considering pressurised air storage options. Moreover, compared to hydrogen, it is much less flammable, and thus safer to handle.

4 Ammonia is widely used as fertilizer, raw material feedstock and catalytic reactant, with established international trade and supply chain infrastructure (such as transport vessels, specialized terminals, and storage tanks etc).

5 The production of ammonia may be carbon intensive if fossil fuels are used as feedstock. However, there are zero-carbon alternatives available as well. More on the different production techniques of ammonia is discussed in later segments.

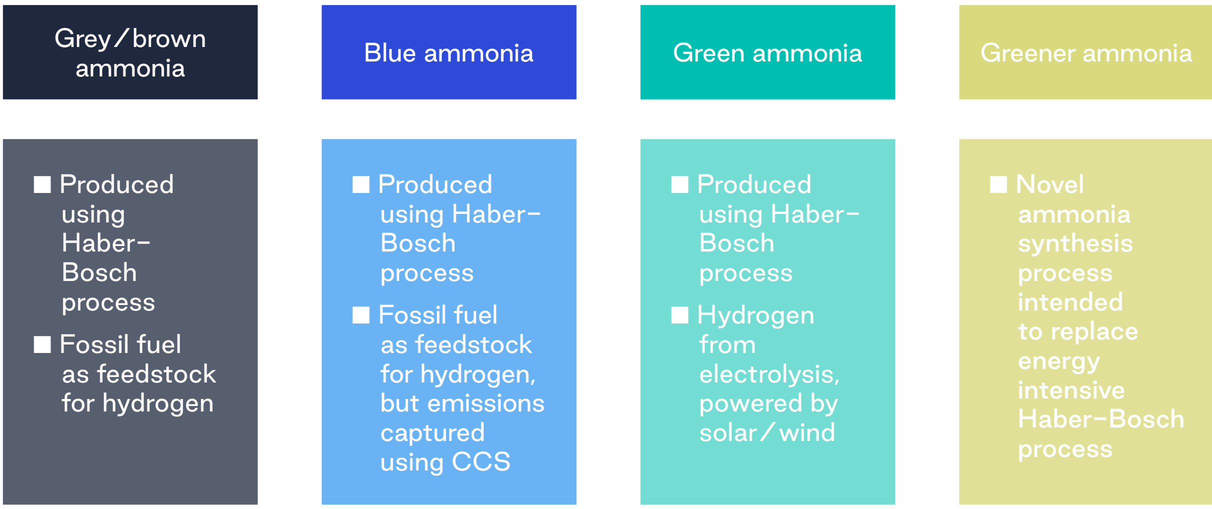
However, the direct use of hydrogen has been hindered by transportation challenges, low energy density and high explosion risk.

As a result, ammonia is often explored as an alternative hydrogen carrier. There are several different forms of ammonia: brown, grey, blue, and green. Grey and brown ammonia are produced using fossil fuels as feedstock, with natural gas used in the former and coal for the later. The bulk of the ammonia produced currently is grey ammonia, which uses steam methane reforming (SMR) to produce hydrogen. SMR is a highly energy intensive process due to the harsh operating environments of 500°C and 250 atmospheric pressure, accounting for 80% of the energy demand in the ammonia production process[6]. As concerns about climate change mount, the production of ammonia from fossil fuels has come under pressure to decarbonise due to the high associated emissions. This has resulted in the emergence of two distinct low-carbon alternatives: blue and green ammonia.

Blue ammonia refers to the use of CCS technologies to reduce emissions from the traditional production of hydrogen using fossil fuel feedstock and the Haber-Bosch process. In the best-case scenario, blue ammonia produces 80-90% less direct emissions than grey/brown ammonia, due to leakages during the CCS process[7]. However, the true climate impact of blue ammonia is unclear. Some studies have highlighted that, after accounting for upstream emissions (including the methane slippages from upstream natural gas production), the lifecycle emissions of blue ammonia may be comparable to natural gas fired power plants[8].

Green ammonia, on the other hand, utilizes the traditional Haber-Bosch process to create ammonia, but gets its hydrogen from water electrolysis, powered by renewable energy sources, such as wind and solar PV. An even greener way of producing ammonia would entail using novel methods of ammonia synthesis, such as through electrochemical process and chemical looping[9]. Though accounting for less than 10% of the market share at present, there are various proposed blue/green ammonia plants in the pipeline, indicating strong interest to decarbonise the ammonia value chain. In fact, estimates place the current green ammonia project pipeline at close to 48 million tonnes[10], equivalent to 25% of the global ammonia market in 2020.

Figure 2.2 Different shades of ammonia



Source: TransitionZero

Note: Only blue and green ammonia can be considered low or zero carbon fuel.

About 96% of the ammonia consumed globally is made through the Haber-Bosch process, using fossil fuels, most commonly natural gas (methane) and coal, and occasionally, oil, as feedstock[11]. This process is highly energy intensive. The use of fossil fuel as feedstock for hydrogen also makes the process carbon intensive as carbon is emitted via both process gas and as combustion emissions[12]. In fact, ammonia production accounts for about 2% and 1.3% of the global energy demand and carbon emissions, respectively[13]. Ammonia synthesis is also considered to be one of the most emissions-intensive chemical industry processes[14]. Therefore, a pivot towards a hydrogen/ammonia economy that is dependent on fossil fuels as feedstock may have no climate benefit, or worse, do more harm than good.

6 The Royal Society (2020)
7 Energy Transitions Commission (2018)
8 Haworth and Jacobson (2021)
9 Smith, Hill and Torrente-Murciano (2020)
10 GCPA (2021)
11 RMI (2020)
12 Energy Transitions Commission (2018)
13 The Royal Society (2020)
14 The Royal Society (2020)

Box 2.1 History of ammonia research and development (R&D) in Japan

Japan first explored the use of hydrogen as an energy carrier back in the 1970s and 1980s, as an alternative energy source to improve energy security. However, interest in hydrogen died down quickly due to the technological and economic hurdles. As part of the broader search for energy alternatives amid large-scale nuclear shutdowns after the Fukushima incident in 2011, the Japanese government revived its research interest in hydrogen with the Energy Carriers technology program. The research covered the three main segments of the hydrogen value chain: production, transportation and utilisation. Under the five-year programme and with US$150 million in government funding, academia, industry leaders and policymakers collaborated to explore the development of a hydrogen value chain, with ammonia being considered as a transport carrier for hydrogen. As part of the programme, a series of tests and demonstrations were conducted to establish the technical viability of coal and ammonia-co-firing.

Laboratory tests

Prior to testing at commercial power plants, a series of laboratory tests were conducted by teams at Osaka University and Central Research Institute of Electric Power Industry (CRIEPI). These initial tests ensured the technical viability of ammonia co-combustion with coal, while also providing key insights on the suppression of NO_x emissions during the process.

Chugoku Electric: 0.6%-0.8% ammonia co-firing

Based on the initial lab test results, Chugoku Electric test-bedded 0.6%-0.8% ammonia co-firing at its 156 MW Mizushima Unit 2 coal plant. The pilot ran for a period of 7 days, from 3 July 2017 to 9 July 2017. Results from the pilot claimed that co-firing coal with 0.6%-0.8% ammonia did not lead to efficiency penalties, nor did it lead to significant increases in NO_x emissions from the plant. In fact, the company claimed that ammonia co-firing with coal is a cheap carbon reduction technology that does not require extensive remodelling of existing coal plants, and thus maximises the use of existing coal fleets[15].

IHI: 20% ammonia co-firing

In December 2017, IHI test-bedded co-firing 20% ammonia at a 10 MW combustion test facility at the Aioi Plant in Hyogo prefecture. This demonstration test was conducted under the Strategic Innovation Promotion Program (SIP) to trial the newly developed coal-ammonia co-firing burner from IHI. This demonstration was the highest level of ammonia co-firing in a practical/commercial setting and paved the way for larger scale demonstrations of ammonia co-firing in Japan.

JERA-IHI: 20% ammonia co-firing with coal at 1 GW Hekinan coal plant

In May 2021, JERA and IHI announced that they are about to embark on the first demonstration project of 20% ammonia co-firing at a commercial coal plant. The demonstration project aims to establish the technological viability of ammonia co-firing at large-scale commercial coal-fired power plants and evaluate both boiler heat absorption and environmental impact characteristics such as exhaust gases. The project will run for approximately four years from June 2021 to March 2025[16], with the test-firing to proceed in 2024/2025.

15 Ammonia Energy Association (2020)

16 Mitsubishi Power (2021)

Cost of ammonia co-firing

While ammonia plays an important role in several industrial processes (see Box 2.2), its use in power generation is likely to be limited. At the current stage, there are no commercial applications of 100% direct ammonia combustion to generate electricity, although large turbine manufacturers and power utilities, such as Mitsubishi[17], IHI[18] and JERA, are investing in research and development of such a clean, carbon-free line. IHI and Mitsubishi Heavy Industries both aim to develop the first 100% ammonia-capable turbine by 2025.

In the meantime, co-firing ammonia with other fuels has been explored as an interim solution. Japan has tested several applications for co-firing ammonia with both coal and gas. Based on current technical constraints, a co-firing ratio of 20% of ammonia with coal (based on energy content) is considered technically feasible. In a scale up of ambitions announced in June 2021, the Japanese government announced that it aims to achieve 50% ammonia co-firing with coal by 2030[19], alongside the goal of importing three million tons of ammonia by the same time frame under their Integrated Innovation Strategy[20].

The Japanese government, with the support of industry players, has strongly pushed ammonia co-firing as a key abatement technology for coal in the power sector. As the co-firing with ammonia does not require major retrofits in the existing coal plants, this strategy is favoured by many Japanese utilities to keep their existing plants running, due to the limited capital outlay. With government backing, a series of demonstration tests were conducted by academia and industry to test the technical and commercial viability of these applications.

The latest among the series of demonstration tests is the 20% ammonia-co-firing at JERA's 1 GW Hekinan power plant. Japan's public research and development arm, the New Energy and Industrial Technology Development Organization (NEDO), has earmarked JPY 110 billion (US$1 billion) for the trial, which is to be conducted at Unit 4 of JERA's Hekinan coal plant[21]. The government funds are expected to contribute to the ammonia procurement, construction of related facilities such as the storage tank and vaporizer, as well as the development of specialised burners for co-firing to be tested at a separate site in Hekinan Unit 5. The tests at Hekinan are Japan's first ammonia co-firing at a commercial plant. If proven commercially and technically viable, Japan aims to progressively refurbish existing facilities for ammonia co-firing from mid to late 2020s, before moving towards higher co-firing/full ammonia combustion by 2050.

IHI has test-bedded co-firing 70% liquid ammonia with natural gas in a 2 MW gas turbine. This demonstration test was conducted between April 2019 and March 2021 and is financed by NEDO. Under this setting, liquid ammonia is sprayed directly into the combustor. The use of liquid ammonia removes the need for a vaporiser, which reduces capital costs. However, this technology is lower on the readiness scale, compared to both ammonia co-firing with coal and hydrogen blending in gas units. Thus, discussions on ammonia's use in the power sector tends to focus on coal-based co-firing. The application of co-firing ammonia with gas has additional challenges due to the corrosive nature of ammonia.


Ammonia in storage tanks

17 Mitsubishi Power (2021)
18 IHI (2021a)
19 Argus Media (2021)
20 Cabinet Office, Government of Japan (2020)
21 NEDO (2021)

Box 2.2 Alternate uses for ammonia

Despite the technical, economic and environmental challenges that ammonia faces in the power sector, it remains an important piece of the wider decarbonisation puzzle. Ammonia is expected to play an important role for decarbonising industrial processes, transport, and to a smaller extent, heating sectors.

Ammonia as feedstock in chemical processes

The use of ammonia as feedstock in the oil refining and petrochemicals industry is considered as one of the key "no regrets" applications, especially since there is currently a lack of zero carbon alternatives in these sectors.

Ammonia in industrial furnaces

Ammonia can also be used in industrial furnaces, through direct combustion. Compared to the power sector, where a variety of alternative power sources are available, decarbonising the industrial sector is considered more difficult, with fewer and often costlier abatement options. Thus, the replacement of fossil fuels by ammonia may be among the best decarbonisation options available, aside from electrification. Potential applications of ammonia co-firing can be explored in the energy intensive iron, steel and cement industries.

Ammonia as a transport fuel

Yet another potential usage of ammonia could be in the replacement of diesel or gasoline in vehicles running on internal combustion engines). Research shows that ammonia-fuelled transport emits less than a third of GHG emissions of a traditional diesel/gasoline vehicle[22]. However, challenges with ignition[23] and safety (with potential ammonia leaks) need to be addressed before the technology can be rolled out widely.

Ammonia in shipping

As emissions standards tighten for the maritime shipping industry, ammonia could emerge as a viable fuel for ships. The benefit of ammonia as a maritime fuel stems from (1) high energy density; (2) safety and (3) low emissions. However, marine engines capable of using ammonia are not yet available. Furthermore, although ammonia is more energy-dense than hydrogen, it pales in comparison to traditional bunker fuels such as diesel and fuel oil. The industry, led by leading engine makers, Wartsila and MAN Energy, is working hard to commercialise ammonia-based engines. Potential challenges ahead for the use of ammonia focuses on emissions (primarily NO_x emissions), corrosion and stability.

Ammonia in aviation

There are also ongoing discussions on the use of ammonia as a jet aviation fuel. The Science and Technology Facilities Council in the United Kingdom has partnered with the private sector to design a prototype that can effectively crack ammonia for use in planes. Following a successful proof of concept, the partners are looking to pilot the technology[24].

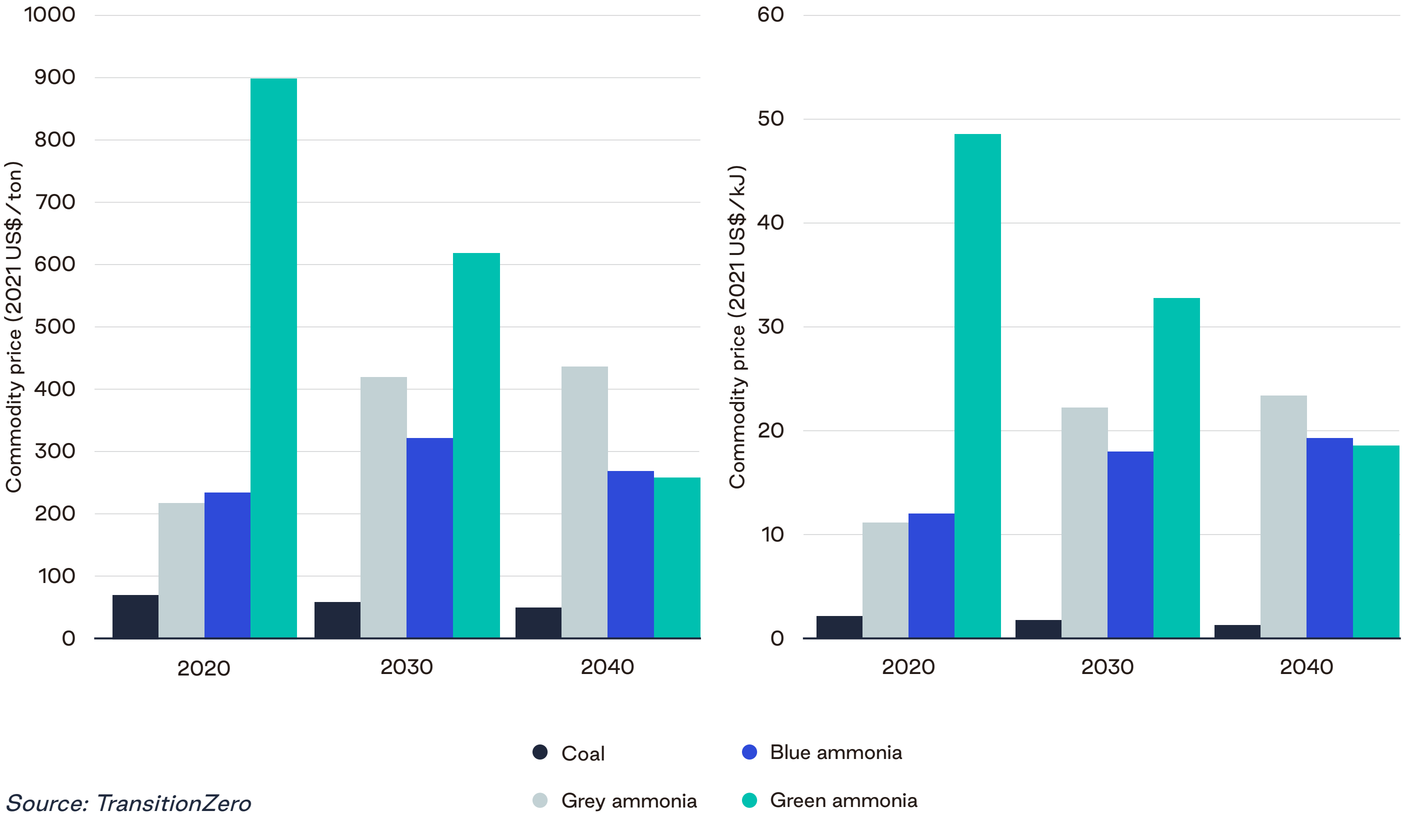
22 Medina et al (2021)
23 Klüssmann et al (2020)
24 UKRI (2020)

Fuel cost assessment

One of the first challenges associated with commercialising ammonia co-firing is cost. On an energy equivalent basis, grey ammonia, which is the cheapest source of ammonia, currently costs around four times that of thermal coal. The cost gap widens even further when considering green ammonia, which is 15 times the cost of coal, on an energy equivalent basis. Assuming carbon prices are instituted globally in line with IEA's NZE scenario, by 2030 the cost of grey ammonia increases substantially, making low-carbon options, such as blue and green ammonia, more competitive.

To support rapid commercialisation of green ammonia, reducing the cost of electrolysers will be a key challenge. Reducing electrolyser costs will depend on breakthroughs in high-temperature electrolysis which reduces electrical energy needs, as well as cost reductions associated with economies of scale and standardisation of system components and plant design. Without these gains, green ammonia may only be competitive in 2040 (Figure 2.3). In addition, on an energy equivalent basis, coal remains the cheapest option, compared to all the shades of ammonia.

Figure 2.3 Ammonia price forecast



Source: TransitionZero

LCOE assessment

Reducing the cost of nascent technologies, such as ammonia co-firing, will be a critical enabler of its adoption. Despite the resurgence of hydrogen related research due to a favourable policy environment, the use of hydrogen in the power sector is being deemphasised compared to other use cases (Table 2.1)[25]. Without widespread international support, ammonia/hydrogen use in power generation is likely to be limited. Other hurdles preventing the uptake of ammonia co-firing stem from the technology itself. The need for customisations for each project limits gains from learning by doing. At the current stage, ammonia co-firing requires the use of specialised burners and stringent control over how and where ammonia is injected into the flame.

Table 2.1 Sectoral priorities of national hydrogen strategies

	Power generation		Industry					Transport		
Country	Power generation	Ancillary service	Iron and Steel	Chemical feedstock	Refining	Others (cement, etc)	Heating	Road transport	Maritime	Aviation
Australia	Low/No	Low/No	Medium	Immediate	Immediate	Low/No	Immediate	Immediate	Medium	Low/No
Japan	Immediate	Low/No	Medium	Immediate	Medium	Low/No	Immediate	Immediate	Low/No	Low/No
South Korea	Immediate	Low/No	Medium	Low/No	Low/No	Low/No	Low/No	Immediate	Low/No	Low/No
EU	Low/No	Low/No	Medium	Immediate	Immediate	Low/No	Medium	Immediate	Medium	Medium
France	Low/No	Low/No	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Low/No	Immediate
Germany	Low/No	Low/No	Immediate	Immediate	Immediate	Low/No	Immediate	Immediate	Medium	Medium
Hungary	Low/No	Medium	Medium	Immediate	Immediate	Medium	Medium	Immediate	Low/No	Low/No
Netherlands	Low/No	Low/No	Immediate	Immediate	Immediate	Low/No	Immediate	Immediate	Low/No	Low/No
Norway	Low/No	Low/No	Medium	Immediate	Medium	Low/No	Low/No	Medium	Immediate	Low/No
Portugal	Low/No	Low/No	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Medium	Medium
Spain	Low/No	Low/No	Medium	Immediate	Immediate	Medium	Low/No	Medium	Low/No	Low/No
Chile	Low/No	Low/No	Low/No	Immediate	Immediate	Low/No	Immediate	Medium	Medium	Medium
Canada	Low/No	Low/No	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Medium	Medium

Source: TransitionZero, adapted from World Energy Council (2021)[26]

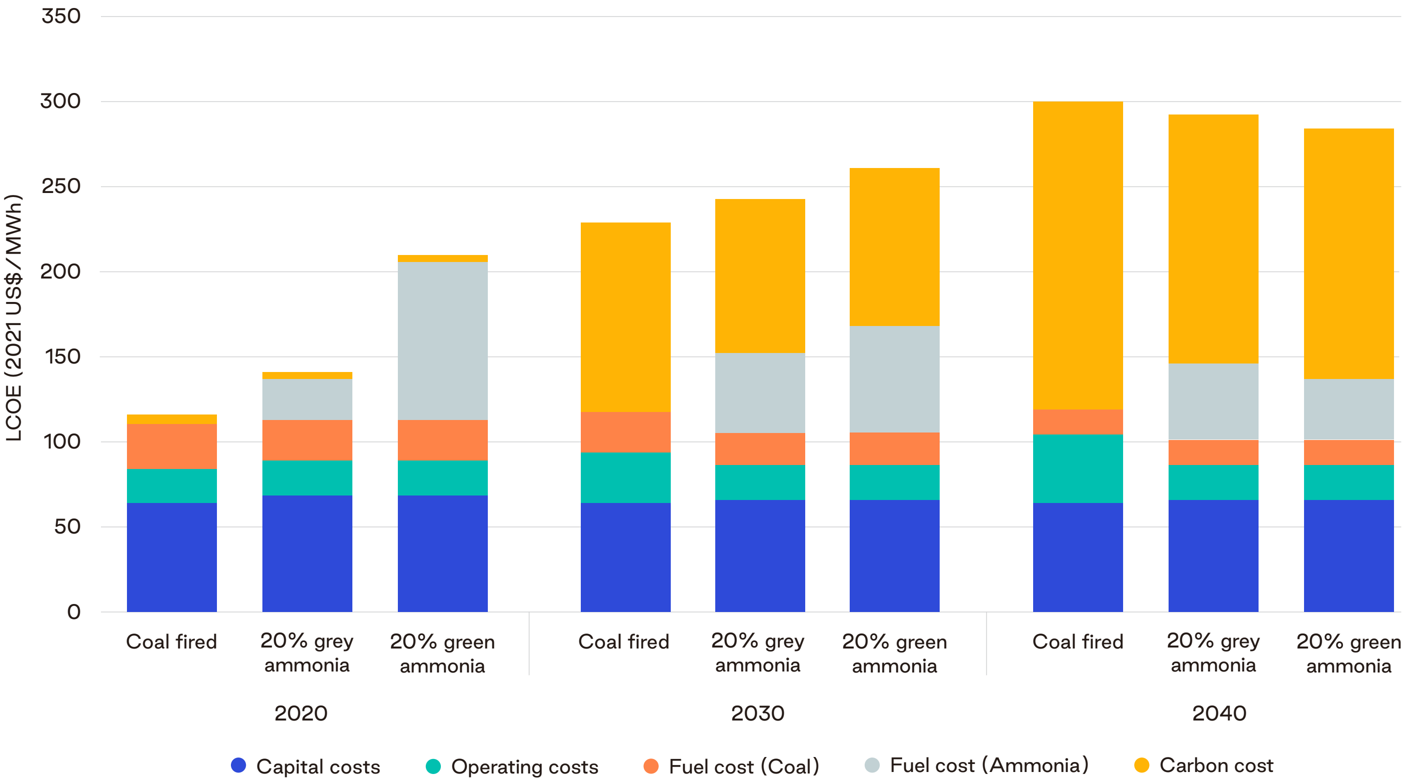
Immediate · Medium · Low/No

25 There has been some discussion on the potential of ammonia as a long-term energy storage option to balance seasonal demand fluctuations. However, the high conversion losses associated with such applications still present technical hurdles for mass deployment. The direct combustion of ammonia in gas turbines as a flexible power generation to support intermittency challenges associated with high RE penetration is also considered. However, its use is hindered by technical challenges with maintaining stable flames due to the slow kinetics of ammonia combustion with air. One potential solution to this is to decompose ammonia into hydrogen and nitrogen and combust hydrogen in the gas turbine. However, the high energy requirements of the cracking process depresses the overall energy efficiency of such applications.

26 World Energy Council (2021)

Even 20% co-firing of the cheapest grey ammonia is set to double the fuel costs compared to coal. The price dynamics shifts slightly in 2030 and 2040 due to the expectation of higher carbon prices being implemented globally. However, due to higher energy equivalent fuel prices, co-blending 20% ammonia triples the total fuel cost, compared to coal. Co-firing ammonia with coal will only start to make financial sense in 2040, at a high carbon price of US$205/t$CO_2$ (Figure 2.4). This results in a LCOE of around US$280/MWh, which is prohibitively expensive.

Figure 2.4 Cost breakdown for ammonia co-firing in power generation



Source: TransitionZero
Note: The carbon cost refers to the carbon costs associated with power generation in Japan, which stands at US$130/t$CO_2$ in 2030 and US$205/t$CO_2$ in 2040, in line with IEA's NZE scenario. The carbon costs associated with upstream production of ammonia, varies according to geography of production sites, and are embedded in the fuel cost component as part of the costs of ammonia. The estimated carbon price ranges between US$15-130/t$CO_2$ and US$35-205/t$CO_2$ in 2030 and 2040, respectively, and are in alignment with IEA's NZE scenario.

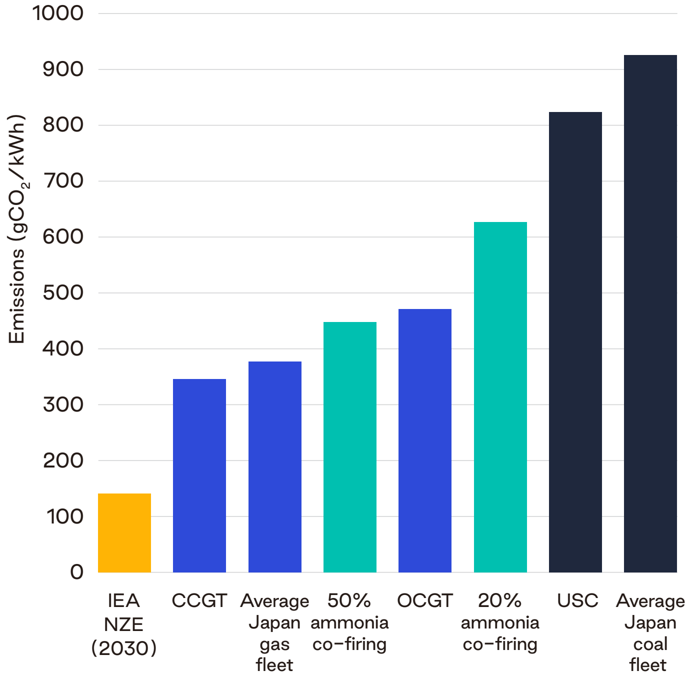
The co-firing of ammonia also comes with additional costs for new plant equipment, such as the supporting ammonia import infrastructure (e.g., storage tanks, pipelines, and vaporisers). The retrofitting and redesigns of existing engines to support ammonia combustion will also contribute to increased capital costs. In the absence of steep increases of carbon costs and/or dramatic cost reductions in electrolysers and CCS technologies, the cost advantage of traditional coal plants over ammonia co-firing plants is expected to last throughout the coming decade.

Carbon reduction potential of ammonia co-firing

Despite claims, ammonia co-firing does little to reduce emissions. At the power generation stage, co-firing ammonia directly displaces emissions associated with coal combustion, with the co-firing rate being a direct proxy for emissions reduction. At the current technologically feasible co-firing rate of 20%, the emissions factor remains close to double that of gas-fired CCGT. A higher co-firing rate of 50% brings the associated emissions per unit of electricity produced close to that of gas generation, which will need to be replaced or abated by 2035 to be consistent with the IEA's NZE scenario[27]. Without significantly higher co-firing rates, ammonia co-firing in coal plants provides only marginal emissions reduction benefits.

> A higher co-firing rate of 50% brings the associated emissions per unit of electricity produced close to that of gas generation, which will need to be replaced or abated by 2035 to be consistent with the IEA's NZE scenario

Figure 2.5 Emissions intensity of different power generation technologies



Source: TransitionZero
Note: IEA NZE refers to the carbon intensity of electricity generation referenced in the IEA Net Zero Roadmap. CCGT and OGCT refers to the emissions factor of combined cycle gas turbines, and open-cycle gas turbines, respectively. Both are gas-based generation technologies. USC refers to the emissions factor of ultra-supercritical coal plants. USC plants are considered to be the most efficient of coal-fired power plants.

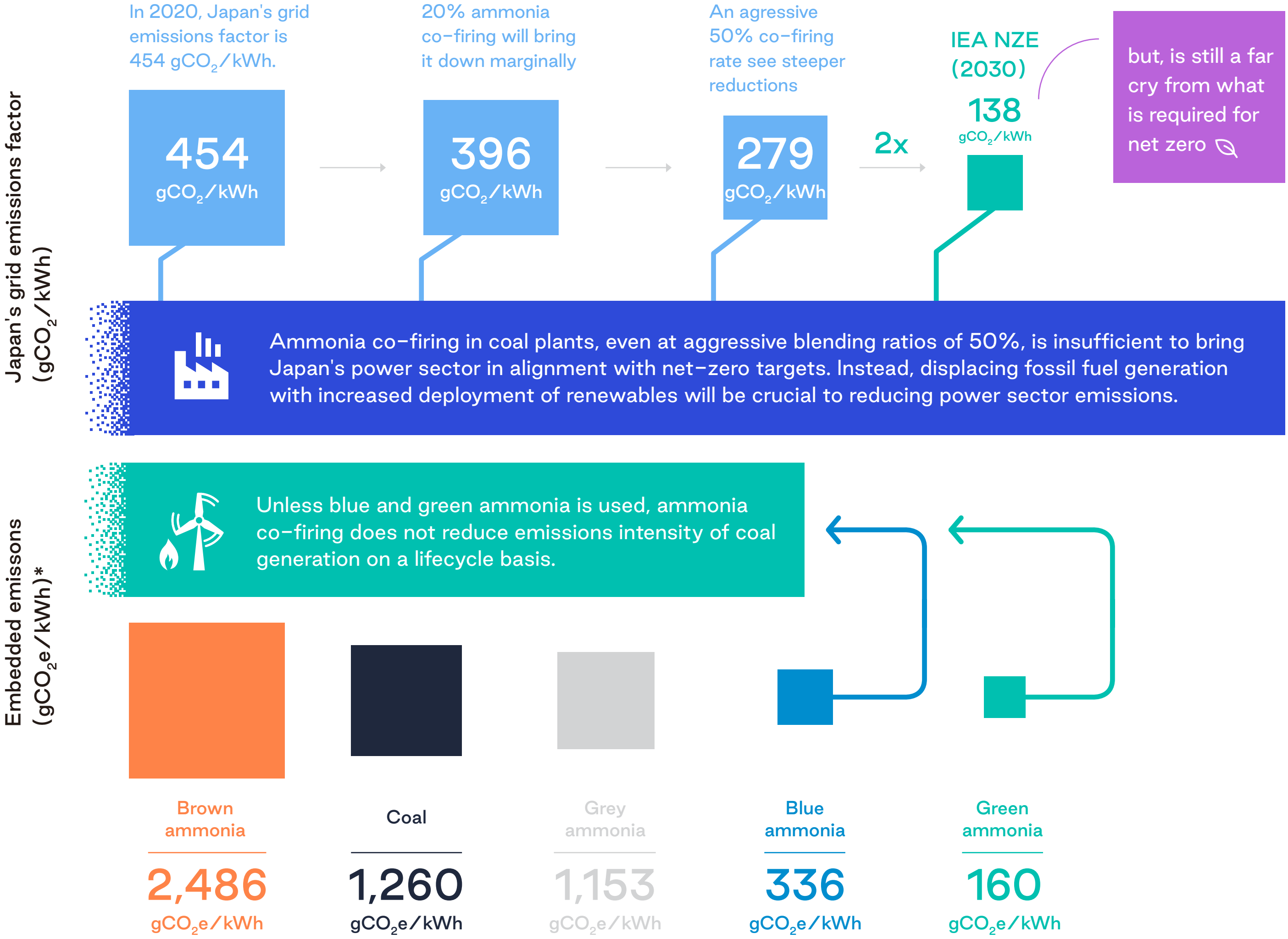
Ammonia is commonly used as a feedstock in the petrochemical industry

27 IEA (2021a)

Based on lifecycle analysis conducted by the IEA, grey ammonia produced using unabated fossil fuel contains embedded emissions of 112–249 gCO_2/MJ (1,090–2,423 gCO_2/kWh)[29]. This is equivalent to double the emissions associated with the direct combustion of coal. Unless blue and/or green ammonia is utilised, there is no net emissions reduction from co-firing. While the use of blue and green ammonia can cut upstream emissions to a minimum, potential emissions may also arise from the use of carbon-intensive transport modes, such as the use of heavy fuel oil as fuel for maritime transport, which adds 3-10 gCO_2/MJ (29-97 gCO_2/kWh) to lifecycle emissions[30].

For ammonia co-firing to be consistent with the IEA's NZE scenario, only blue or green ammonia should be considered. However, since green ammonia has a power-to-power efficiency of 22%[31], close to 80% of the energy is wasted during the conversion process. This steep energy efficiency penalty leads to fundamental questions about the use of green ammonia to produce electricity.

Figure 2.6 Japan's emissions factor and lifecycle emissions comparison between coal and ammonia



Source: TransitionZero

*Note: *The embedded emissions considers both the emissions associated with upstream production, midstream transport and downstream combustion. This estimate also includes non-carbon emissions as well. A thermal efficiency of 37% is used for all plants as there has yet to be consensus on the impact of co-firing ammonia on coal plant efficiency. The net emissions benefit of blue ammonia, specifically when the captured carbon dioxide is utilised for enhanced oil recovery (EOR), which supports further emissions downstream may also be put into question. However, for this piece of analysis, the downstream applications of CCS are not considered.*

29 IEA (2021b)

30 IEA (2021b)

31 IEA (2021b)

Other ammonia co-firing challenges

Technical considerations

There are technical challenges associated with ammonia co-firing. Ammonia has poor flammability, high ignition temperatures, low flame velocity and flame temperature, narrow flammability range and high radiant heat transfer. These challenges make ammonia poorly suited for direct combustion in power plants. Although successful demonstrations have been conducted in a few pilot programmes, the scaling of the technology remains to be seen. Moreover, due to the complexities of coal-fired operations, each power plant is configured differently. As such, the true effect of ammonia co-firing on each plant may be difficult to establish without a wide enough sample pool. Any slight deviation in the power plant set-up may result in high retrofit costs, or lead to efficiency and performance penalties, compromising project economics.

Based on a 20% co-firing rate and an assumed base load operation for the Hekinan plant, we estimate that JERA will need to procure about 500,000 tons of ammonia per year for the demonstration project. However, the company announced that it is only looking to procure 30,000 to 40,000 tonnes for trial at Hekinan Unit 4 and an additional 200 tonnes for the pilot tests at Hekinan Unit 5[32]. This highlights the limited scale of the pilot tests and suggests that the technology is not yet commercially ready.

Air pollution

One of the immediate concerns of ammonia co-firing with coal is air pollution. Due to the presence of nitrogen in ammonia, co-firing ammonia may result in increased NO_x emissions. Simulation studies have shown that NO_x emissions are the highest with low co-firing rates, and gradually decreased with increasing co-firing ratios. However, as a trade-off, unburned ammonia increases once co-firing ratios exceed 40%[33]. The unburned ammonia reacts with NO_x and SO_2 to form secondary PM2.5[34], worsening air pollution. This points to an interesting NO_x-NH_3 dynamic, as ammonia is also often used to control NO_x emissions. Lower flame temperatures and flame instabilities can result in air pollution from NO_x emissions and unburnt carbon in fly ash. While the demonstration plants and test pilots have not seen a significant increase in exhaust gas pollution, the complexities in technical designs of the plant means that there is still a high risk of localised air pollution if care is not taken. While air pollution can be controlled, these technologies are often expensive and reduce the efficiency of the boiler.

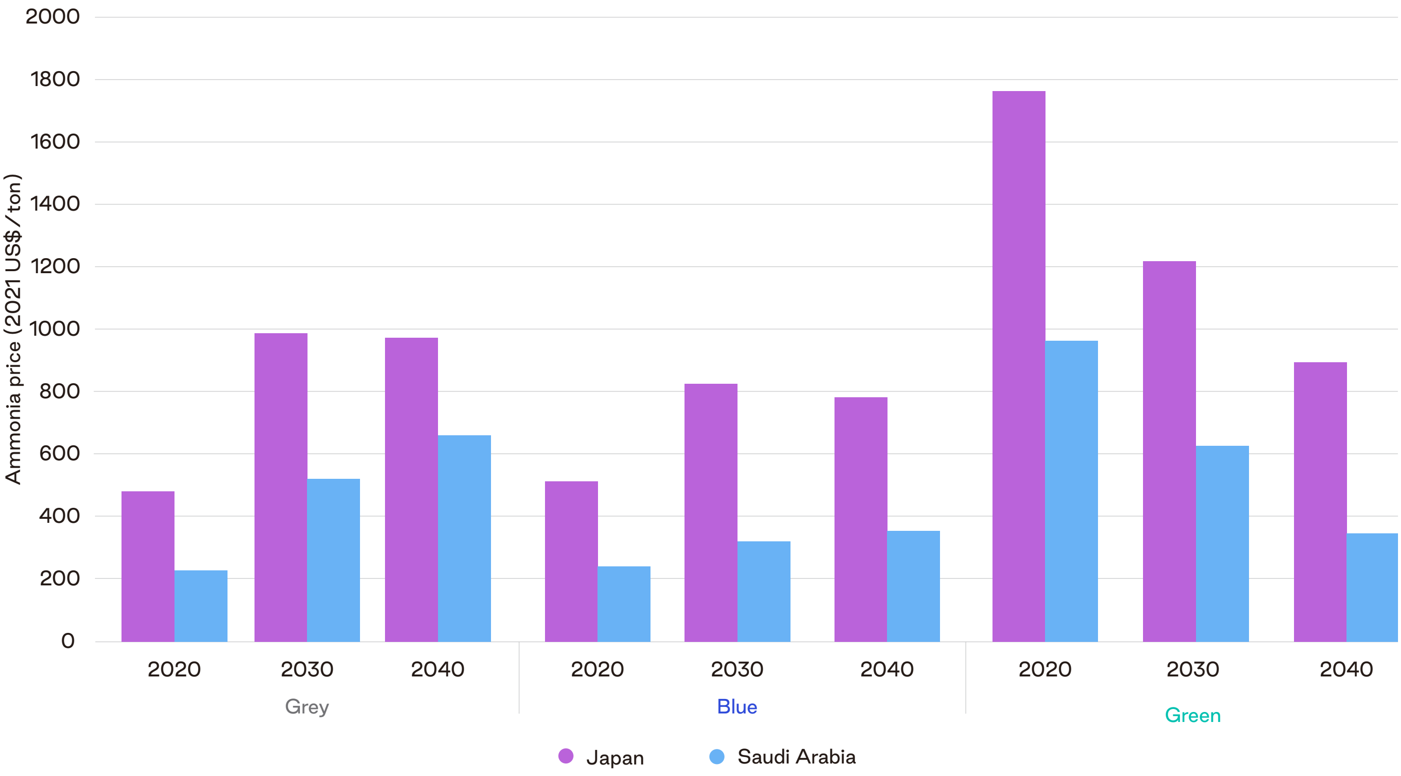
Energy security

Energy security lies at the heart of Japanese energy policy. Japan currently produces about 75% to 80% of its one million tons of ammonia demand domestically. With the growth of the ammonia economy and the increased use of ammonia in power plants, Japan would have to either invest in developing domestic production capacity, or rely on international imports.

Based on our analysis, even accounting for shipping costs, importing from international sources could help Japan save about half of its ammonia costs, across all shades of ammonia. While equipment and other capital expenditure costs are likely to be comparable globally, the presence of cheap natural gas as feedstock and cost-competitive renewable energy is set to widen the pricing gap between domestic production and international imports. The gulf between domestic ammonia and international imports means that Japanese utilities have few options but to rely on cheaper imports.

32 Platts (2021a)
33 Ishihara et al (2020)
34 Oxidised products of NO_x and SO_2 react with NH_3 to form PM2.5 (referred to as secondary PM2.5).

Figure 2.7 Comparison between domestic production versus international imports



Source: TransitionZero
Note: Japan has already imported its first cargo of blue ammonia from Saudi Arabia. The carbon dioxide captured is utilised at a nearby methanol facility, as well as for EOR. Green ammonia production in Saudi Arabia is assumed to be supported by solar PV generation.

This dilemma will worsen Japan's energy security. Assuming a 20% co-firing rate, Japan will require about 20-25 million tons of ammonia every year for use in the power sector, more than 20 times its current demand and about the size of the 2020 globally traded ammonia market. Importing these large volumes of ammonia leaves Japan vulnerable to various sources of uncertainty.

The first source of uncertainty lies in the speed of the energy transition and development of the ammonia market. The rapid scale-up in the global ammonia market will have to be grounded in various transition strategies that are to be determined either at a corporate level or at a national level. If the global economy for low-carbon fuels does not materialise at the speed and scale required, there are significant risks that Japan may be locking itself into obsolete/frontier technologies that remain high cost.

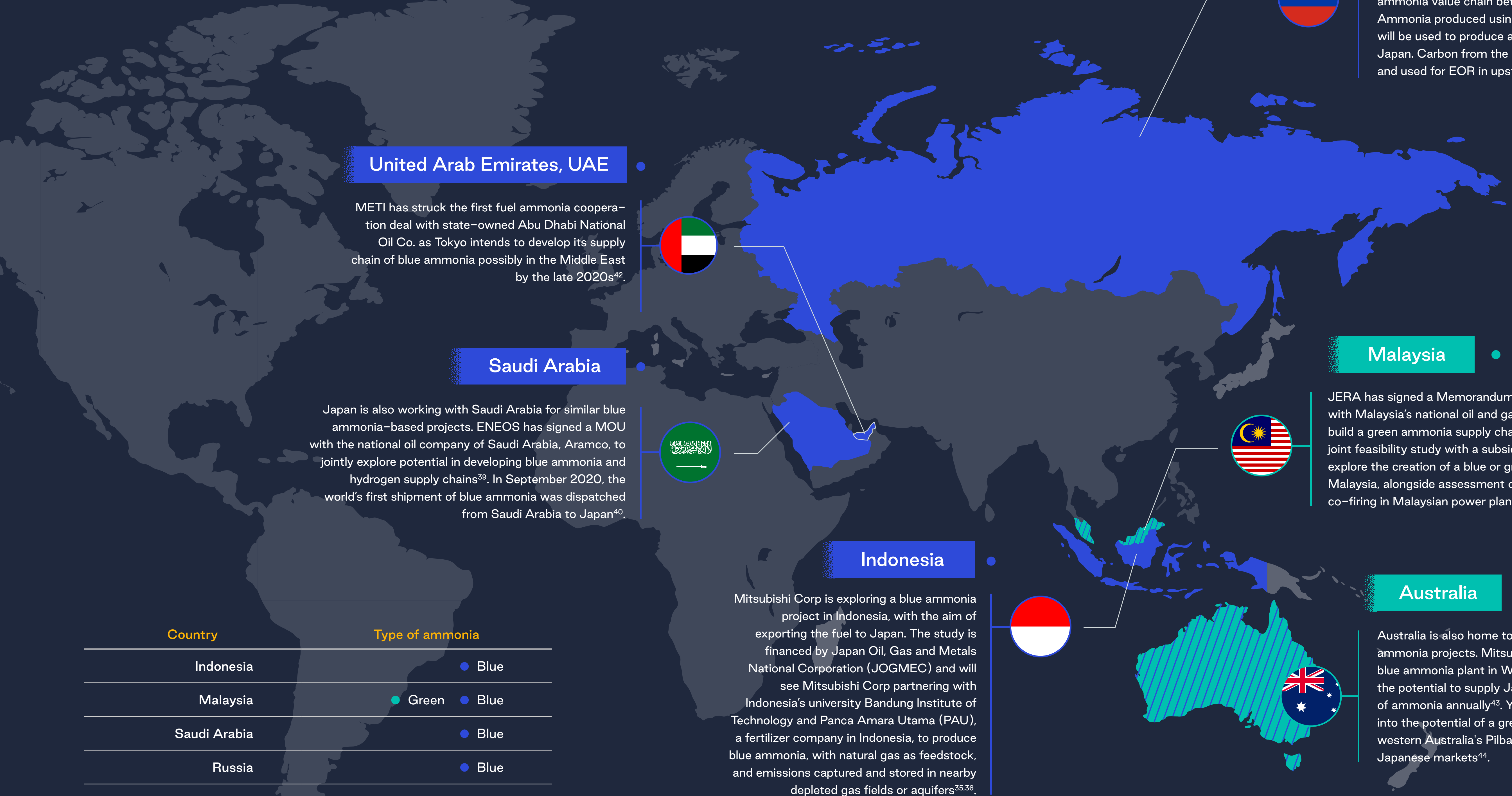
The second degree of uncertainty stems from unanticipated geopolitical shocks across this newly emerging supply chain, leading to concerns surrounding potential price/supply shocks. To mitigate such risks, Japanese companies are looking abroad to develop upstream projects, in a bid to secure dedicated supply for future use. Despite these efforts, it is undeniable that cross-border maritime trade in newly emerging low-carbon fuels such as ammonia and hydrogen, will only serve to increase Japan's energy insecurity.

The last degree of uncertainty arises from the potential sources of ammonia imports. While a diversified group of suppliers may present potential benefits to energy security and resource dependency for Japan, the volatility experienced by gas in 2020/2021 sets up a cautionary tale on how regional and national demand and supply dynamics may introduce unexpected shocks to international markets, to the detriment of resource stability. A high import dependency will leave Japan vulnerable to:

1. uncertainty and price shocks if it relies on the spot market, or
2. pricing premium if Japan chooses to lock in prices for long term stability.

Box 2.3 Map: Japan's ammonia investments globally

Below is a compilation of some of Japan's current partnerships/investments in upstream ammonia supply projects globally.



United Arab Emirates, UAE

METI has struck the first fuel ammonia cooperation deal with state-owned Abu Dhabi National Oil Co. as Tokyo intends to develop its supply chain of blue ammonia possibly in the Middle East by the late 2020s[42].

Saudi Arabia

Japan is also working with Saudi Arabia for similar blue ammonia-based projects. ENEOS has signed a MOU with the national oil company of Saudi Arabia, Aramco, to jointly explore potential in developing blue ammonia and hydrogen supply chains[39]. In September 2020, the world's first shipment of blue ammonia was dispatched from Saudi Arabia to Japan[40].

Indonesia

Mitsubishi Corp is exploring a blue ammonia project in Indonesia, with the aim of exporting the fuel to Japan. The study is financed by Japan Oil, Gas and Metals National Corporation (JOGMEC) and will see Mitsubishi Corp partnering with Indonesia's university Bandung Institute of Technology and Panca Amara Utama (PAU), a fertilizer company in Indonesia, to produce blue ammonia, with natural gas as feedstock, and emissions captured and stored in nearby depleted gas fields or aquifers[35,36].

Russia

Japan's industry ministry signed a memorandum of cooperation (MOC) with Russia's Novatek, Gazprom on hydrogen, ammonia, CCS and CCU. ITOCHU Corporation is also interested in studying the possibilities of establishing a blue ammonia value chain between Eastern Siberia and Japan. Ammonia produced using natural gas from producing oil fields will be used to produce ammonia, which will be transported to Japan. Carbon from the production process will be captured and used for EOR in upstream oil fields[41].

Malaysia

JERA has signed a Memorandum of Understanding (MOU) with Malaysia's national oil and gas company, PETRONAS, to build a green ammonia supply chain[37]. Similarly, IHI also has a joint feasibility study with a subsidiary of PETRONAS to explore the creation of a blue or green ammonia value chain in Malaysia, alongside assessment on the potential ammonia co-firing in Malaysian power plants[38].

Australia

Australia is also home to various proposed upstream ammonia projects. Mitsui & Co. has plans to build a blue ammonia plant in Western Australia, which has the potential to supply Japan with one million tons of ammonia annually[43]. Yara International is looking into the potential of a green ammonia project in western Australia's Pilbara region for export to Japanese markets[44].

Country	Type of ammonia
Indonesia	Blue
Malaysia	Green, Blue
Saudi Arabia	Blue
Russia	Blue
UAE	Blue
Australia	Green, Blue

35 Mitsubishi Corp(2021)
36 Nikkei Asia (2021a)
37 Nikkei Asia (2021b)
38 IHI (2021b)
39 ENEOS (2021)
40 Nikkei Asia (2021c)
41 ITOCHU (2021)
42 Platts (2021b)
43 Nikkei Asia (2021d)
44 Nikkei Asia (2021e)

Conclusion

While the use of ammonia is often cited as a key technology to decarbonise Japan's grid, it currently faces multiple financial, environmental, and technological hurdles. Our analysis shows ammonia will likely remain a prohibitively expensive power generation technology, which will do little to help Japan meet its carbon neutrality ambition. For ammonia to be cost- and climate-effective, there will need to be dramatic cost reductions in electrolysers, technological breakthroughs to allow pure combustion of ammonia in the power sector and the rapid build-up of the globally traded green ammonia market to meet rising demand. There is limited evidence to suggest this will happen in a manner consistent with a 1.5°C outcome. In the absence of a compelling economic and environmental case, the underlying motivation appears to be based on keeping coal plants alive. In doing so, those Japanese utilities who are pursuing ammonia in power generation risk destroying shareholder value unnecessarily.

Ammonia is sometimes transported via trains in tanks

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