ERIA Research Project Report FY2025, No. 8

ASEAN Low-carbon Energy Technologies Roadmap (ALERT) – Phase I: ASEAN's Long-term Strategy on Hydrogen and Ammonia

By

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ASEAN Centre for Energy

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Contents

List of Figures

List of Tables

Executive Summary

This report summarises the global hydrogen landscape; highlights the role of hydrogen in ASEAN Member States (AMS); and presents a proposed comprehensive roadmap for the development and deployment of low-carbon hydrogen and ammonia technologies in the ASEAN region, outlining strategic steps until 2050.

As countries all around the world seek ways to decarbonise multiple sectors, hydrogen is a main option, thanks to its abundance in nature, low weight, and high gravimetric energy. Hydrogen can be produced from various methods – through renewable energy such as solar and wind via electrolysis (green hydrogen), steam methane reforming and coal gasification (grey hydrogen), and carbon capture (blue hydrogen) – making it a promising alternative for fuels.

Ammonia is a hydrogen carrier with higher volumetric energy density. Ammonia consists of 17.7% hydrogen in molecular weight and can be stored in simple and cost-effective pressure vessels. Ammonia can be used directly or re-converted by a process called 'cracking', which releases a non-toxic, non-greenhouse gas (GHG), making ammonia (and hydrogen) a valuable option to decarbonise the energy sector and beyond.

Globally, hydrogen and ammonia are increasingly recognised for their potential to decarbonise hard-to-abate sectors such as industry, transport, and energy generation. Currently, hydrogen – which is consumed mainly in industries like oil refining, ammonia production, methanol production, and steel manufacturing – is primarily sourced from fossil fuels. However, a significant shift is underway towards low-carbon blue and green hydrogen production. Blue hydrogen is produced from natural gas using carbon capture and storage (CCS), and green hydrogen is generated through electrolysis utilising renewable energy.

The hydrogen market is witnessing remarkable growth, with numerous green and blue hydrogen projects announced worldwide. Significant investments are being made in electrolysis and infrastructure development as well. Yet despite this momentum, a gap remains between projected production and the levels needed to meet net-zero emissions targets, necessitating accelerated efforts in policy support, technological advancements, and market development.

The ASEAN region stands at a critical juncture in its energy transition, facing rapidly growing energy demand and the pressing need to mitigate climate-change impacts. Hydrogen and ammonia present significant opportunities for AMS to decarbonise their economies, enhance energy security, and support the integration of renewable energy.

Several AMS have set ambitious targets for carbon neutrality and are exploring hydrogen and ammonia as clean-energy carriers. For instance, Indonesia aims for significant GHG emissions reductions by 2060, while Malaysia targets the same for 2050. The region's abundant renewable energy resources position ASEAN well to produce green hydrogen, reducing reliance on fossil fuel imports and potentially becoming a global leader and exporter in the hydrogen economy. Additionally, adopting hydrogen and ammonia technologies can help decarbonise its industrial sectors, improve sustainability, and enhance its competitiveness in global markets focussed on clean energy solutions.

Roadmap for ASEAN's Hydrogen and Ammonia Future

The roadmap provides a structured approach for ASEAN to integrate hydrogen and ammonia into its energy system across three key phases: the short term (2025–2030), medium term (2031–2040), and long term (2041–2050).

Short Term (2025–2030)

1. Enhance regional collaboration and establish the Hydrogen ASEAN Alliance.

By forming the Hydrogen ASEAN Alliance, AMS can foster partnerships amongst key industries and governments to coordinate efforts, share best practices, and pool resources for research and development and infrastructure. This alliance would mirror successful models like the Hydrogen Council and Hydrogen Europe, enabling joint investments and harmonised policies.

2. Attract private investment by de-risking projects.

Implementing mechanisms such as transparency in hydrogen pricing, subsidies, tax incentives, and investment incentives can make hydrogen projects more attractive to private investors by reducing the perceived risks. Governments can also provide financial guarantees and create favourable regulatory environments to encourage investment.

3. Focus on hydrogen deployment in hard-to-abate sectors.

Prioritising the use of hydrogen in sectors like heavy industry, including steelmaking and the oil and gas industries where electrification is challenging, can significantly reduce emissions. Developing sector-specific roadmaps and offering government incentives will support this focus.

4. Establish standards for hydrogen and ammonia handling.

Developing and harmonising regional standards for the safe handling, storage, and transport of hydrogen and ammonia are crucial for facilitating trade and ensuring safety. Aligning with international standards like IEC and ISO will provide consistency and credibility in the global market.

Mid Term (2031–2040)

5. Ramp up low-carbon hydrogen and ammonia production.

Scaling up blue and green hydrogen and ammonia production capacity by investing in carbon capture technologies for accelerating deployment of blue hydrogen and in renewable energy projects and promoting distributed renewable energy generation will increase the supply of green hydrogen. Taking into consideration the production cost difference, the development phase of blue and green hydrogen production in ASEAN will also be affected by the cost of material inputs and capital. Setting clear production targets and enabling policies for the material input and capital costs for hydrogen across AMS will ensure coordinated growth.

6 Expand the focus on hydrogen and ammonia use in the transport and power generation sectors. Extending hydrogen applications to the transport sector (e.g. fuel-cell electric vehicles and public transport) and power generation can further decarbonise the energy system and meet growing energy demands. Pilot projects and governmental incentives will facilitate this expansion.

Long Term (2041–2050)

7 Enhance regional trading of hydrogen and ammonia. Developing a comprehensive regional trading platform and expanding cross-border infrastructure will position ASEAN as a hub for hydrogen and ammonia trade. Establishing standardised systems for pricing, contracts, and logistics will enable efficient cross-border transactions.

8 Expand hydrogen use to process heat. Promoting hydrogen for industrial process heat applications and establishing futures markets will enhance its role in the regional economy. Policies encouraging hydrogen use in high-temperature processes will contribute to decarbonising energy-intensive industries.

9 Establish hydrogen as a building block for energy security. Integrating hydrogen firmly into national energy strategies will reduce reliance on fossil fuel imports, enhance energy security, and support long-term sustainability goals. Governments should set mandatory usage targets and provide support for infrastructure development.

Conclusion

The ASEAN Long-term Strategy on Low-Carbon Hydrogen and Ammonia offers a comprehensive framework for building a sustainable hydrogen economy across the region. It establishes a phased approach, starting with foundational actions such as regional collaboration and pilot projects, scaling hydrogen production and infrastructure in the medium term, and integrating hydrogen as a key part of the energy system by 2050. The roadmap emphasises regional partnerships, investment attraction, and the development of shared standards in supporting the development and deployment of hydrogen and ammonia in ASEAN. Thus, it can ensure the crucial role of both technologies in meeting carbon-neutrality targets in the region, while also ensuring energy security, affordability, and accessibility for all AMS.

Chapter 1

Global Hydrogen and Ammonia Development

Hydrogen is the most abundant chemical element, making up 75% of the universe's mass. The reaction between a molecule of hydrogen and a molecule of oxygen, under an adequate level of activation temperature and pressure, produces water and releases energy in the form of heat or light.

Based on the periodic table, a single atom of hydrogen weighs around 1.01 grams per molecule, lighter than any of the other elements in the table. It possesses a high gravimetric energy density of approximately 120 megajoules (MJ) per kilogram (kg), making it suitable as both a green energy carrier and feedstock in various applications.

Hydrogen production can utilise a variety of resources, including natural gas via steam methane reforming (SMR), nuclear power, biomass through gasification, and renewable power sources like solar and wind via electrolysis. Each production method is unique, making hydrogen a flexible option for use in transport, industrial feedstock, and electricity generation. Hydrogen's uses can span from fuelling vehicles and powering homes to supporting the chemical industry as a raw material.

Despite its benefits, hydrogen's low volumetric density of around 8.49 MJ per litre in liquid form (at –253°C) poses challenges in transport and storage (Chatterjee, Parsapur, Huang, 2021). However, ammonia offers a promising solution as a hydrogen storage medium. Hydrogen stored in the form of ammonia takes up 17.7% of the total molecular weight with an energy density of around 18.6 MJ/kg. Compared to other chemical carriers, such as
toluene-methylcyclohexane (MCH), ammonia has a higher hydrogen density both in volumetric and gravimetric scales (Aziz, Oda, Kashiwagi, 2019).[1] Moreover, ammonia can be stored in simple, cost-effective pressure vessels. When needed, ammonia can be decomposed – through a process called 'cracking' – over a catalyst to release hydrogen and nitrogen, which are non-toxic, non-greenhouse gases (GHGs). Ammonia's unique characteristics also position it as a potential transition fuel, as it can be burned directly in internal combustion engines (ICEs) emitting zero carbon, converted to electricity in alkaline fuel cells, or cracked to provide hydrogen for non-alkaline fuel cells.

Indeed, hydrogen's role in the transition towards a sustainable, carbon-neutral energy future will be paramount. Its applications across various sectors – from transport to industry – promise significant reductions in GHG emissions. It is clear that low-carbon

[1] Hydrogen content in toluene-MCH only takes up around 6.16% of the total molecular weight.

hydrogen production, including green and blue hydrogen,[2] will be pivotal to meet net-zero targets.

Various hydrogen production technologies – including electrolysis, SMR with carbon capture and storage (CCS), and biomass gasification – offer pathways towards blue and green hydrogen production. Electrolysis, especially proton exchange membrane (PEM) and alkaline electrolysis, is gaining prominence due to its high efficiency and purity; several electrolysis projects have been announced in the Asia-Pacific region, Australia, and Europe. However, challenges persist, such as high capital costs and material dependency. Advancements in storage and transport infrastructure are also critical for enabling hydrogen production and adoption.

National hydrogen strategies across the globe vary in priorities and measures yet share the common goals of reducing GHG emissions, integrating renewable energy, and fostering economic growth by ramping up hydrogen production and adoption. Europe leads in public support for green and blue hydrogen development, with momentum growing in Africa, Latin America, and the Middle East. Major industrialised nations, including China, India, Russia, and the United States (US), are poised to release their national hydrogen strategies shortly, reflecting the global momentum towards hydrogen adoption.

Today, the global hydrogen and ammonia landscape is characterised by rapid advancement, driven by the imperative to achieve net-zero emissions targets. Blue and green hydrogen production, associated technological innovation, policy support, and international cooperation, are essential drivers shaping the future of hydrogen. Strategic investments and collaborative efforts are crucial to realising hydrogen's potential as a cornerstone of the clean energy transition, ensuring a sustainable and resilient global energy system.

Hydrogen and Ammonia Use in Achieving Net-zero Emissions Targets

Hydrogen can play a multifaceted role in reaching net-zero emissions targets, offering versatile solutions across various sectors.

Decarbonise industry. Hydrogen can replace fossil fuels in industrial processes such as oil refining, ammonia production, methanol production, and steel production. By transitioning to blue or green hydrogen sources, industries can significantly reduce their GHG emissions.

[2] Green hydrogen is produced through the electrolysis of water, using electricity generated from renewable energy sources. This method does not produce carbon dioxide (CO_2) emissions, making it a highly sustainable option that aligns with global decarbonisation goals. Blue hydrogen is produced from natural gas through SMR or coal/biomass gasification, combined with carbon capture and storage (CCS) technology. This process captures and stores the CO_2 emissions generated during the hydrogen production, significantly reducing its environmental impact compared to traditional hydrogen production methods. However, it still relies on fossil fuels, and the effectiveness of the CCS technology in reducing overall CO_2 emissions can vary.

Act as a clean energy carrier. Hydrogen is a clean energy carrier, particularly in sectors where direct electrification is challenging, such as heavy transport and industrial heating. Hydrogen fuel cells can power vehicles, trains, and ships, providing zero-emissions transport solutions. Moreover, ammonia is a good hydrogen carrier due to its advanced gravimetric and volumetric density.

Store energy. Hydrogen can store surplus renewable energy, addressing the intermittency of wind and solar power. Through electrolysis, excess renewable electricity can be used to produce hydrogen, which can then be stored and later converted back into electricity or utilised as a feedstock for various applications. While methanol has a higher gravimetric energy density than ammonia in liquid form (i.e. 20.1 MJ/kg compared to 18.6 MJ/kg), ammonia stands out as a hydrogen energy storage solution due to its higher gravimetric hydrogen content of 17.8% compared to methanol with only 12.5% (Aziz, Wijayanta, Nandiyanto, 2020).

Generate power. Hydrogen can complement renewable energy sources by providing dispatchable power generation. Power plants equipped with hydrogen combustion or fuel-cell technology can produce electricity with minimal GHG emissions, supporting grid stability and reliability. Indonesia, Japan, and others have piloted co-firing ammonia in thermal power plant generation to reduce coal/natural gas consumption and to decarbonise the power-generation sector (MEMR, 2023).

Heat and cool. Hydrogen can be used as a clean alternative to natural gas for heating and cooling applications in residential, commercial, and industrial buildings. Hydrogen boilers and fuel cells can provide space heating, hot water, and process heat without emitting carbon dioxide (CO_2). Fuel-cell tri-generation using absorption and desorption chillers can be utilised as a cooling mechanism by extracting vapour through condensers, which is then transformed into liquid; evaporators subsequently absorb the heat for evaporation (Yue et al., 2021).

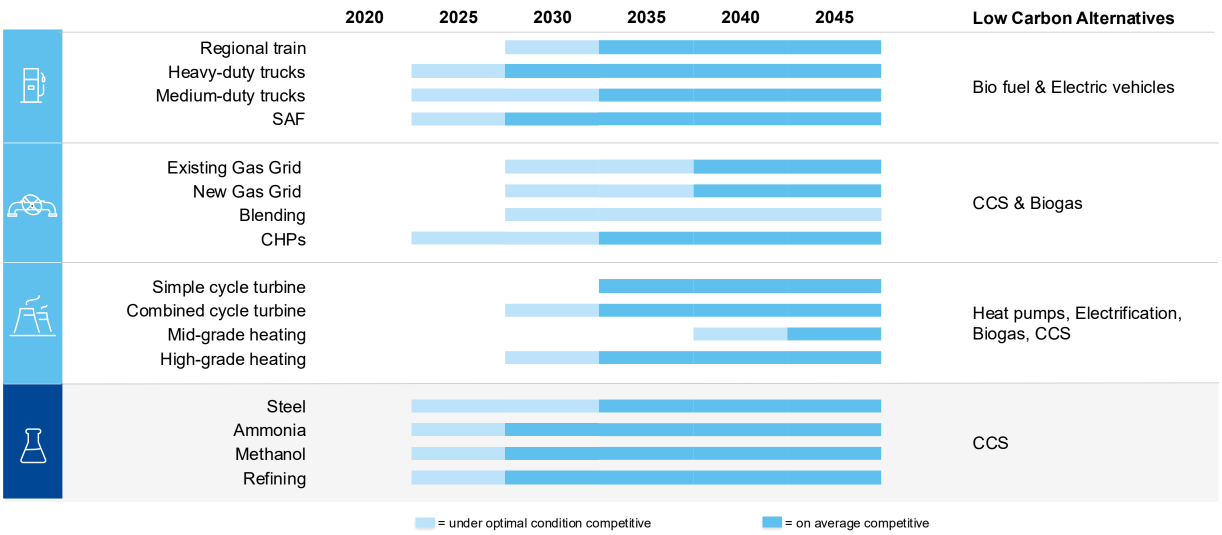
Help abate the fuel industry and aviation. Hydrogen can serve as a feedstock for various industrial processes, including ammonia production, chemical synthesis, and desulphurisation. Additionally, hydrogen-based fuels – like ammonia and synthetic kerosene – have the potential to decarbonise the aviation and shipping sectors, reducing emissions from these hard-to-abate sectors.

As stated, in the transport sector, hydrogen fuel cells are a promising solution for reducing carbon emissions, especially in heavy-duty and long-haul transport. These fuel cells produce electricity through a chemical reaction with water vapour as the only emission, addressing range and payload challenges faced by battery-electric vehicles (BEVs). Enhanced hydrogen refuelling infrastructure and reduced production costs are essential for boosting the competitiveness of hydrogen-powered vehicles, however.

Key players in the transport sector are also developing transport with hydrogen ICEs to complement the adoption of fuel-cell electric vehicles (FCEVs). Huang et al. (2024) examined the combustion characteristics and performance of hydrogen ICEs, demonstrating potential for hydrogen ICEs to decarbonise heavy- and light-duty vehicles; the only problem is that the overall thermal efficiency of hydrogen ICEs is still below that of FCEVs – 31.89% to 35.12%, respectively, depending on the injector configuration.[3] The high heat release rate and heat transfer loss add to the inefficiency of the current state of port fuel injection (Huang et al., 2024).

Figure 1.1 maps out when hydrogen solutions are expected to become economically viable under optimal conditions.[4] For instance, in the transport sector, regional trains and heavy-duty trucks are beginning to transition to hydrogen usage, indicating a shift away from traditional fossil fuels to more sustainable options like biofuels and electric vehicles. In the energy sector, applications such as gas grid blending and combined-cycle turbines are upcoming.

Figure 1.1. Competitiveness of Hydrogen Technologies and Low-carbon Alternatives Worldwide



CCS = carbon capture and storage, CHP = combined heat and power, SAF = sustainable aviation fuel.
Sources: Hydrogen Council and McKinsey & Company (2023), TÜV SÜD (2024c).

Comparing Hydrogen Technologies and Alternatives in Steel Production

One of the most notable applications of hydrogen in industry is occurring in steel production. Traditional steelmaking relies heavily on coking coal, making it a significant source of CO_2 emissions. The most prominent method involving hydrogen is direct reduction of iron using hydrogen, in which hydrogen gas is used as a reducing agent to

3 The conversion efficiency of FCEVs is around 60–65%. See Government of the US, DOE, Alternative Fuels Data Center: Fuel Cell Electric Vehicles, https://afdc.energy.gov/vehicles/fuel-cell

4 The business-as-usual scenario assumes that hydrogen projects without specified commercial operation dates will be built post-2030.

convert iron ore in the form of pellets or lump ore into direct reduced iron (DRI) without undergoing a melting process. This method drastically reduces CO_2 emissions since water vapour is the only by-product of the reaction between hydrogen and iron ore's oxygen.[5]

An alternative to reducing emissions in steel production is using carbon capture, utilisation, and storage (CCUS), which captures CO_2 emissions from blast furnaces and either stores them underground or utilises them in other industrial processes. While CCUS can moderate emissions from conventional steelmaking, it does not eliminate them and involves additional costs and energy for CO_2 capture and storage.

Further, the traditional electric arc furnace process, which relies on recycling scrap steel using electricity, offers a lower carbon footprint compared to primary steelmaking with blast furnaces. Yet its reliance on available scrap steel limits its capacity to fully replace primary steel production methods.

Using biomass as a substitute for coal in the blast furnace process offers another renewable way to produce pure iron ore. Here, the biomass must be gasified to produce hydrogen; then, the hydrogen is used as a reducing agent. However, the scalability of this option is constrained by the availability of sustainable biomass and its impact on land use and biodiversity.

Looking at each steelmaking process, the following can be deduced.

Emissions reduction potential. Hydrogen stands out for its potential to drastically reduce emissions in steel production by nearly 100% (Agora Industry, Wuppertal Institut, Lund University, 2024), offering a pathway to near-zero-emissions steel. In contrast, CCUS reduces but does not eliminate emissions, and its effectiveness depends on the secure and permanent storage of CO_2.

Resource efficiency. The DRI process with green or blue hydrogen as a direct feedstock is more resource-efficient and environmentally friendly compared to using biomass as a feedstock, due to implications for land use and sustainability. The electric arc furnace process is highly efficient but limited by the availability of high-quality scrap steel.

Economic and infrastructure challenges. Transitioning to hydrogen-based steel production involves significant upfront investments in hydrogen production, distribution infrastructure, and process modifications. While CCUS also requires substantial investment, it allows for the continued use of existing blast furnaces, potentially offering a shorter-term solution.

[5] Projects like HYBRIT and H2 Green Steel (now Stegra) in Sweden aim to revolutionise the steel industry through such steel production processes, potentially reducing CO_2 emissions by up to 95% compared to conventional methods.

Comparing Hydrogen Technologies and Alternatives in Refining

Hydrogen is extensively used in refineries for hydroprocessing, which includes hydrodesulphurisation and hydrocracking. Hydroprocessing removes sulphur from crude oil fractions, a necessary step to meet environmental regulations for sulphur content in fuels. Hydrocracking breaks down heavier crude oil molecules into lighter, more valuable products. Currently, most hydrogen used in refineries is 'grey' hydrogen, produced from natural gas through SMR, emitting CO_2 in the process.

Regarding refining practices, the following is noted.

- **Emissions reduction potential.** Transitioning to blue and green hydrogen for refining processes offers a direct path to reducing CO_2 emissions – both from hydrogen production and refinery operations. CCUS also reduces emissions, but it depends on the availability of sequestration sites and the energy source for capture processes.
- **Technology maturity and scalability.** Hydrogen as a feedstock in refining is a well-established practice, but shifting to blue and green hydrogen involves additional technological modifications and infrastructure upgrades. CCUS and electrification are less mature in the context of refining and face scalability challenges due to technological and infrastructure limitations.
- **Economic and infrastructure considerations.** The current cost of the grey hydrogen used for refining is USD0.80–USD5.70/kg through the SMR process (IEA, 2024). The cost of green hydrogen averages USD10.27/kg from onsite solar photovoltaic (PV) electrolysers in ASEAN (Purwanto and Rusli, 2024) and USD62.80/tonne of CO_2 with CCUS technologies (Kimura et al., 2022). Thus, cost remains a significant barrier, requiring policy support and investment to achieve cost competitiveness. Infrastructure for transporting and storing CO_2 or integrating renewable energy into refineries also needs development.

Comparing Hydrogen Technologies and Alternatives in Industrial Heating

Hydrogen can be used as a direct replacement for natural gas and other fossil fuels in industrial boilers and furnaces to generate high-temperature heat (i.e. over 500°C) for processes used in sectors like cement, glass, and metal manufacturing. The main adaptation involves modifying burners and controls to handle hydrogen's different properties, such as its higher flame speed and lower ignition energy. This direct combustion method emits only water vapour, significantly reducing GHG emissions. Developments in burner technology now allow for either 100% hydrogen or a blend with natural gas, offering a transition pathway for industries to gradually shift to hydrogen.[6]

Electric-resistance heating converts electricity directly into heat through resistive elements and is commonly used for lower-temperature processes. Its efficiency and

[6] Bekaert is innovating in this space, developing burners capable of handling these blends, which provide a scalable solution for industries aiming to reduce their carbon footprint incrementally.

simplicity make it a competitive alternative, especially when paired with renewable electricity sources.

Induction and infrared heating offer efficient, controllable heat for specific industrial processes. Induction heating uses electromagnetic fields to heat electrically conductive materials, which is ideal for metals. Infrared heating, emitting radiation absorbed by a material, is suitable for drying, curing, and heating plastics and coatings.

Biomass can serve as a renewable fuel for producing process heat, either directly combusted or gasified to produce syngas. While it is carbon-neutral at the point of use, sustainability concerns regarding land use and biomass sourcing limit its scalability.

For industrial heating, the following points are noted.

Temperature range and scalability. Hydrogen can achieve the higher temperatures necessary for industrial processes like steel or cement production, which alternatives like electric heating may not reach efficiently. In a condition where the fuel and air ratio is 1, hydrogen combustion could produce flames with an adiabatic temperature up to 2,427°C, while natural gas could output up to 2,227°C (Giacomazzi et al., 2023). However, the scalability of hydrogen use in such a manner is contingent upon developing supply chains and infrastructure.

Environmental impact. Direct combustion of hydrogen produces no CO_2 emissions, offering a significant advantage over fossil fuels and even biomass, considering life-cycle emissions. Electric heating methods are clean at the point of use but depend on the grid's carbon intensity for their overall environmental impact.

Cost and infrastructure needs. Current challenges with hydrogen include higher costs (USD10.27/kg) compared to natural gas (USD0.15/kg) and significant investments in storage and distribution infrastructure (Business Insider, 2024; Purwanto and Rusli, 2024). Electric heating methods are limited by electricity costs and grid capacity, while biomass heating must contend with fuel sourcing and potential supply chain issues.

Comparing Hydrogen Technologies and Alternatives in Power Generation and Energy Storage

Hydrogen's integration into the power sector showcases a blend of innovation and potential, especially for generation and storage. Adapting gas turbines to burn hydrogen instead of natural gas is a significant step towards decarbonising electricity generation. These turbines can run on a blend of natural gas and hydrogen or entirely on hydrogen, drastically reducing carbon emissions from the hydrogen-production side. Judging from the upstream production of hydrogen, grey hydrogen emits 12.49 kg of carbon dioxide equivalent (CO_2e)/kg of hydrogen[7] while green hydrogen emits 1.0–3.6 kg of CO_2e/kg of

[7] Including onsite, upstream, and transport emissions.

hydrogen, which equates to a significant drop of around 71.2% (Sayer, Ajanovic, Haas, 2024).

The average 500-megawatt (MW) coal-fired power plant and natural gas-fired power plant emit approximately 11.9 kilotonnes (kt) of CO_2e and 4.9 kt of CO_2e per day, respectively (EPA, 2019). Hydrogen combustion for power generation only emits around 4.5 kt of CO_2e (grey) and 1.29 kt of CO_2e (green), a reduction of 41–76% in carbon emissions. Hydrogen-combustion technology can mirror conventional gas turbines, with various modifications needed to accommodate hydrogen's different combustion characteristics, such as higher flame speed and lower ignition energy.[8]

Fuel cells convert hydrogen directly into electricity and heat through an electrochemical process without combustion, offering a clean, efficient way to generate power. There are several types of fuel cells, but for large-scale power generation, solid oxide fuel cells and PEM fuel cells are particularly relevant. Solid oxide fuel cells operate at high temperatures (i.e. 900°C–1,000°C) (Nnabuife et al., 2023), making them suitable for power and heat generation with high efficiency of 50–60% (Athanasiou et al., 2023). Biogas solid oxide fuel cells at a smaller scale could economically compete with biogas combustion through ICEs, with around a EUR0.35 million difference (10.3%) in net present value (Athanasiou et al., 2023). Thus, solid oxide fuel cells are more economically suitable for both power and heat co-generation.[9] PEM fuel cells, benefiting from lower operating temperatures and quick start-up times, are adaptable for both stationary and mobile applications.

Lithium-ion batteries are the standard for short-term energy storage and an alternative to hydrogen in the power sector, delivering high efficiency and rapid discharge capabilities. They are crucial for grid balancing, peak shaving, and integrating intermittent renewable energy sources. Innovations aim to enhance energy density, reduce costs, and develop alternatives like solid-state batteries for improved safety and performance.

Pumped hydro storage remains the most deployed form of large-scale energy storage, utilising gravitational potential energy by moving water between two reservoirs at different elevations. Its advantages include a long lifespan, large storage capacity, and high round-trip efficiency. However, geographical constraints and environmental considerations limit its expansion.

For power generation and energy storage, the following is reasoned.

> Scalability and flexibility. Hydrogen offers unique advantages in terms of scalability and flexibility for both power generation and energy storage, essential for integrating large shares of renewables into the grid. In contrast, the scalability of battery systems is often constrained by raw material availability and environmental impacts, while pumped hydro storage's scalability is limited by geography.

[8] Siemens Energy and GE are at the forefront of this technology, developing turbines capable of utilising up to 100% hydrogen.

[9] Bloom Energy is a pioneer in solid oxide fuel-cell technology, providing scalable solutions for clean electricity generation.

Energy density and storage duration. Hydrogen's high gravimetric energy density of 120 MJ/kg (equivalent to 33.3 kilowatt-hours [kWh]/kg) and ability to store energy for the long term make it more suitable than lithium-ion batteries (with theoretical gravimetric energy density of around 2.5 kWh/kg) for seasonal storage needs (Xue et al., 2017). However, its low volumetric density means that space is a key concern when storing hydrogen. While pumped hydro storage can also offer long-duration storage, it is limited by geographic constraints.

Efficiency and cost. Direct electricity storage in batteries currently offers higher round-trip efficiency[10] and lower short-term costs compared to converting electricity to hydrogen and back (Hrytsiuk, 2023).[11] However, the cost dynamics could change with advancements in electrolyser and fuel-cell technologies, alongside the decreasing cost of renewable electricity.

Comparing Hydrogen Technologies and Alternatives in Transport

FCEVs, powered by hydrogen fuel cells, convert hydrogen into electricity, driving electric motors to propel vehicles. This technology is particularly advantageous for longer ranges and fast refuelling times, making it ideal for heavy-duty transport such as buses, trucks, and even maritime and aviation applications.

The heavy-duty transport sector stands to benefit significantly from hydrogen. Hydrogen fuel-cell trucks offer a viable alternative to diesel, providing similar range and payload capabilities without the associated emissions. Companies like Hyundai Motor Company, Nikola Corporation, and Toyota are pioneering in this space with hydrogen-powered truck models designed for long-haul transport, where battery-electric solutions face challenges due to battery weight and charging times.

An alternative approach is through modified ICEs designed to burn hydrogen instead of gasoline or diesel. While hydrogen ICEs offer a lower-cost transition strategy by adapting existing engine technologies, they typically do not match the efficiency and emissions benefits of fuel cells.

BEVs, which rely on battery packs for energy storage and electric motors for propulsion, are the primary alternative to hydrogen for light-duty passenger vehicles. Advancements in battery technology have improved the range and reduced the costs of BEVs, making them increasingly popular for personal transport.

Electric road systems, such as overhead lines or embedded road charging, could provide continuous power to electric trucks on designated roads, eliminating range issues. While electric road systems can decarbonise freight transport on major corridors, infrastructure is costly and requires widespread adoption for feasibility.

[10] About 85–95% for lithium-ion batteries, while hydrogen storage is around 30–50%.

[11] The levelised cost of battery storage is USD150–USD200/megawatt-hour (MWh), and hydrogen storage is USD200–USD600/MWh.

Biofuels, produced from organic materials, and synthetic fuels, manufactured using captured CO_2 and hydrogen, offer drop-in replacements for diesel and gasoline. While they can reduce carbon emissions, their sustainability and net emissions benefits depend on the feedstock and energy sources used in production.

Thus, towards hydrogen in transport, the following is noted.

- Range and refuelling. Hydrogen FCEVs provide longer ranges (i.e. around 575 kilometres on average) and faster refuelling times compared to BEVs (i.e. refuelling time from 0 to full tanks for FCEVs takes around 3 minutes on average, while BEVs take around 13 hours on average), making them suitable for heavy-duty and long-distance applications (De Wolf and Smeers, 2023). BEVs, however, are more economically efficient for short to medium ranges due to their lower purchase costs.

- Infrastructure and adoption. Hydrogen-fuelling infrastructure is less developed than electric-charging networks, presenting a challenge for the widespread adoption of FCEVs. However, for heavy-duty trucks and sectors where quick refuelling is crucial, hydrogen may offer a more practical solution than BEVs, given the current limitations of charging infrastructure and battery technology.

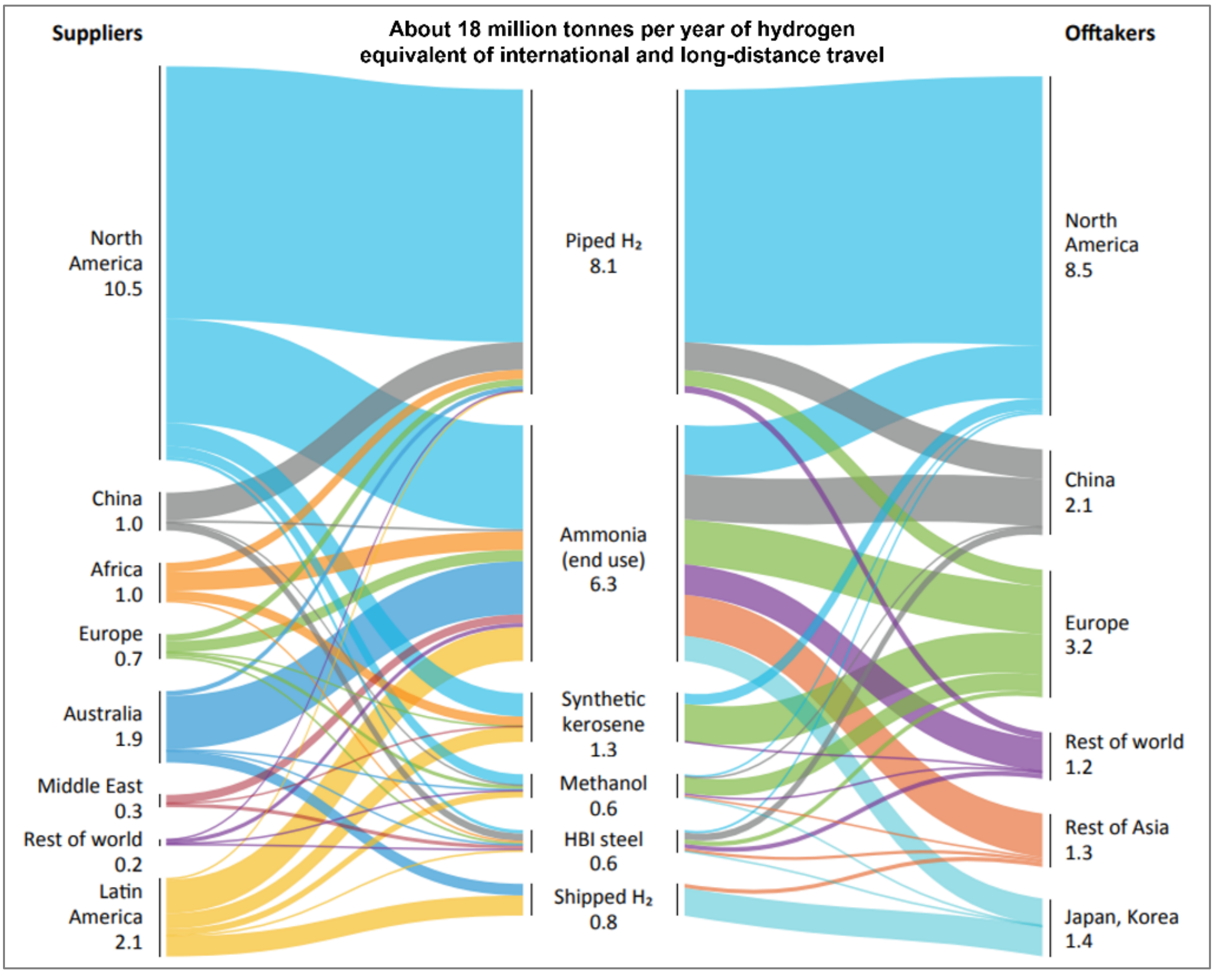
- Emissions and efficiency. Hydrogen, especially when produced from renewable sources, offers a pathway to zero-emissions transport. While BEVs also provide zero tailpipe emissions, their life-cycle emissions depend on the electricity grid's carbon intensity.

Hydrogen and Ammonia Production Costs and Technologies

In 2022, global hydrogen production rose by 3% to nearly 95 million metric tonnes (Mt), mainly fuelled by fossil fuels. Green and blue hydrogen production remained minimal, accounting for less than 1% of production. China led production, followed by the US, the Middle East, India, and Russia (Figure 1.2).

Looking to 2030, numerous green and blue hydrogen projects are underway, with an estimated annual output exceeding 20 Mt. Electrolyser projects dominate, particularly in Europe and Australia, aiming to harness renewable resources for production. Africa, China, Latin America, and the US are also witnessing significant developments in electrolyser projects. This section explores the current state and future developments of the hydrogen market, with a particular focus on demand and supply dynamics.

Figure 1.2. Global Hydrogen Flows, Further Acceleration Scenario



HBI = hot briquetted iron.
Note: Comprises 2030 global clean hydrogen flows for all international trade, including trade between split regions, most notably East and West China, including 65% of domestic production in Australia, Brazil, Canada, Russia, the United States, and West China.
Source: Hydrogen Council and McKinsey & Company (2023).

The hydrogen market is at a pivotal juncture, with future growth underpinned by several key trends:

Policy and regulatory support. Governments worldwide are implementing policies to support hydrogen development, including subsidies, tax incentives, and regulatory frameworks that encourage investment in hydrogen infrastructure and technologies.

Technological advancements. Continuous improvements in hydrogen production, storage, and utilisation technologies are reducing costs and enhancing efficiency, making hydrogen more competitive with traditional energy carriers.

Decarbonisation goals. The pressing need to reduce CO_2 emissions is driving interest in hydrogen as a versatile and clean energy carrier, capable of decarbonising sectors in which direct electrification is challenging.

The supply of hydrogen is expected to diversify significantly by 2030, with green hydrogen production scaling up to meet the growing demand. Electrolysis powered by renewable energy is set to increase, supported by declining costs and the increasing availability of renewable electricity. Additionally, blue hydrogen will play a transitional role in expanding the hydrogen supply while lessening carbon emissions.

1.1.1. Global and ASEAN Ammonia Market Landscape

Although not currently prevalent in energy applications, there is growing anticipation for ammonia to emerge as a significant renewable energy vector in the 21st century, particularly in facilitating the trade of carbon-free energy. Recent years have seen the announcement of various blue and green ammonia production and utilisation projects, gaining substantial momentum since 2020, aligning with commitments towards carbon neutrality by 2050 in multiple regions (IRENA, 2022).

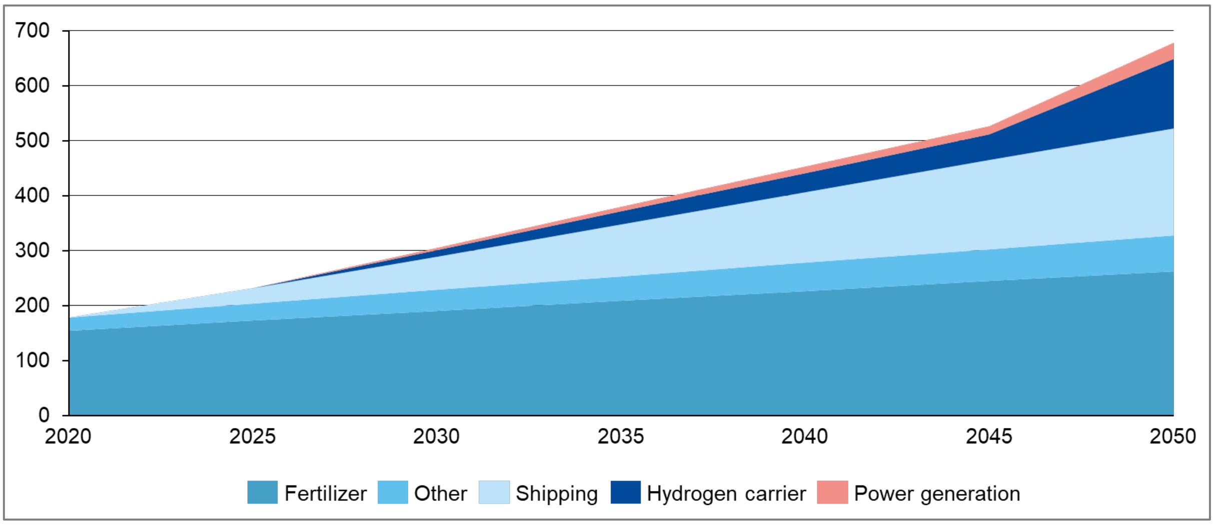
Forecasts indicate a surge in demand for ammonia, projected to reach 688 Mt by 2050 under a 1.5°C scenario, compared to the current demand of 183 Mt (Figure 3). Projections indicate that by 2030, new markets could collectively reach a volume of 300 Mt, with substantial expansion anticipated over the subsequent 2 decades, surpassing current market volume (IRENA, 2022).

Ammonia's significance as a hydrogen carrier is expected to be considerable, with international trade projected to reach 127 Mt by 2050, largely for industrial and chemical purposes. The maritime sector is also expected to see a surge in ammonia usage, with 197 Mt needed by 2050, primarily for international shipping. Additionally, its role in power generation is forecasted to expand to 30 Mt by 2050, predominantly reflecting policies in Japan.[12]

[12] However, note that the precise extent of ammonia's integration into these applications remains uncertain, with projections varying widely across different sources, from 140 Mt to over 1,000 Mt. The degree of adoption will hinge on regulatory frameworks related to climate change and decisions concerning decarbonisation strategies.

Figure 1.3.

(million metric tonnes/year)



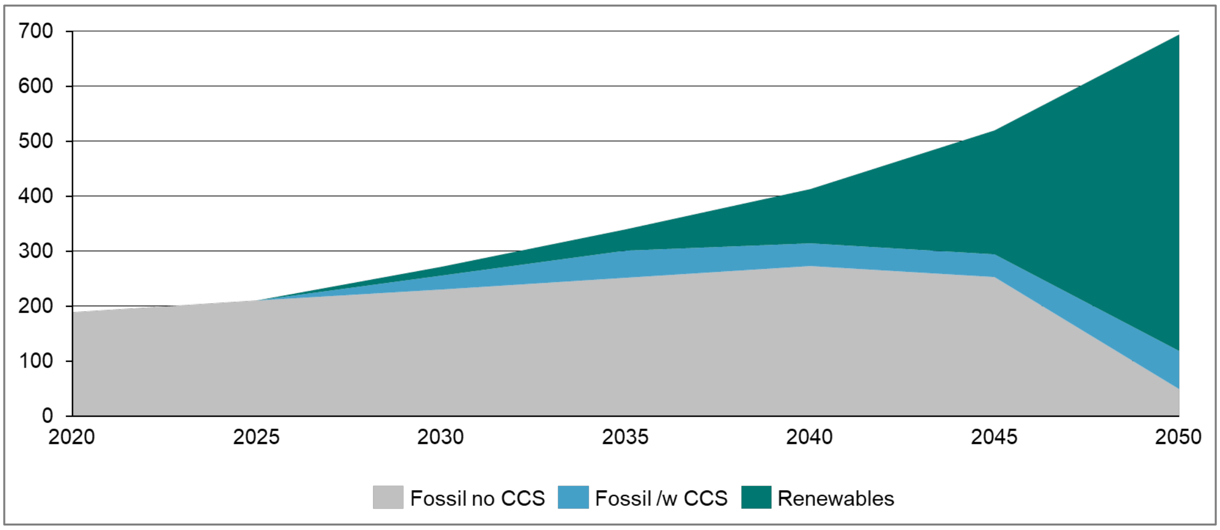
Source: IRENA (2022).

To meet increasing ammonia demand for energy applications, additional production capacity is necessary. However, it is crucial to expand production without jeopardising fertilizer supply and food production. Currently, there is excess capacity of 40–60 Mt of ammonia/year globally, ensuring sufficient ammonia availability in the near term if new ammonia markets do emerge (IRENA, 2022).

Transitioning to low-carbon ammonia production methods is essential to reduce ammonia's carbon footprint. By 2030, the proposed capacity for blue and green ammonia plants will exceed 10% of global production. Under the 1.5°C scenario by 2050, renewable ammonia production would reach 566 Mt annually, comprising over 80% of the total market. Fossil-based production is expected to decline to 122 Mt by 2050, with 71 Mt incorporating CCS (IRENA, 2022).

Figure 1.4. Expected Ammonia Production by Feedstock to 2050 for the 1.5°C Scenario

(million metric tonnes/year)



CCS = carbon capture and storage.

Source: IRENA (2022).

Public perception stands as a crucial determinant in the successful adoption of ammonia. Studies have indicated public openness towards using ammonia as a fuel, provided its cost is comparable to natural gas while offering superior environmental performance. Negative perceptions often arise due to perceived hazards of ammonia, as well as misinformation, underscoring the significance of educational efforts and community involvement. Policymakers increasingly acknowledge the viability of ammonia energy, particularly within the context of the hydrogen economy and renewable energy imports. Indeed, ammonia features prominently in national hydrogen strategies and has been deliberated as a maritime fuel in legislative discussions.

In the ASEAN context, ammonia is widely used in a variety of industries, including agriculture, fertilizers, petrochemicals, and industrial chemicals. The demand is diverse across ASEAN Member States (AMS). Many AMS produce ammonia as a feedstock for fertilizers, in the form of urea, due to their agricultural backgrounds. In 2021, the ASEAN region was a net exporter of urea to the world, with a total export quantity of 4.68 Mt/year.[13] Besides urea, it traded other ammonia-derived products with the world, including anhydrous ammonia with a total export quantity of 2.31 Mt/year, while also importing around 653 kt/year (GIZ, 2024). The ASEAN region also relies on ammonium sulphate imports, totalling around 3.65 Mt/year in 2021. The region also used ammonium sulphate as a nitrogen-based fertilizer (Puengjinda et al. 2024). From the agricultural sector to industrial process, the ASEAN region's demand for ammonia is expected to grow in the coming years (Puengjinda et al. 2024).

[13] Indonesia and Malaysia were the biggest exporters of urea in ASEAN. Malaysia's exports to South-east Asia reached 936.2 kt/year, and Indonesia followed with around 837.1 kt/year.

The ammonia used to produce urea, anhydrous ammonia, and ammonium sulphate is grey, which comes from SMR or through the coal gasification process. In total, the ASEAN region possesses around 30 active plants. Indonesia has the largest total capacity, which can produce around 8.33 Mt/year of grey hydrogen, followed by Malaysia with 4 active plants that can produce around 2.07 Mt/year.

1.1.2. Trends in Hydrogen Production Costs

Recent advancements in hydrogen production technologies – particularly electrolysis – and improvements in renewable energy efficiency may significantly reduce costs in the future. Currently, grey hydrogen via SMR is produced at USD0.80–USD5.70/kg (IEA, 2024). This price is generally cheaper than that for green hydrogen, but natural gas price volatility creates a hurdle for grey hydrogen production. The price of natural gas also accounts for a significant share of the levelised cost of blue hydrogen (i.e. 50–85%), which, based on the natural gas price, is USD2.80–USD3.50/kg (GEP, 2023) – 59% cheaper than that of green hydrogen (Bhashyam, 2023). However, the International Renewable Energy Agency (IRENA) has predicted a potential decrease in the cost of green hydrogen to USD1.00–USD 2.00/kg by 2050, down from the current levels of USD3.00–USD7.50/kg, due to technological advancements and the expected scaling up of production capacities (IEA, 2023).

For ASEAN, the production cost of green hydrogen could be less than USD1.00/kg by 2050 if produced using a PEM electrolyser; it would be slightly higher if produced by alkaline, at USD0.80–USD1.30/kg (Purwanto and Rusli, 2024). For Indonesia, the production cost of hydrogen would be USD3.00–USD12.00/kg, affected by technology and project location choices (Purwanto and Rusli, 2024); the least expensive cost is estimated to be around USD2.00/kg if the technology and location are at their best.

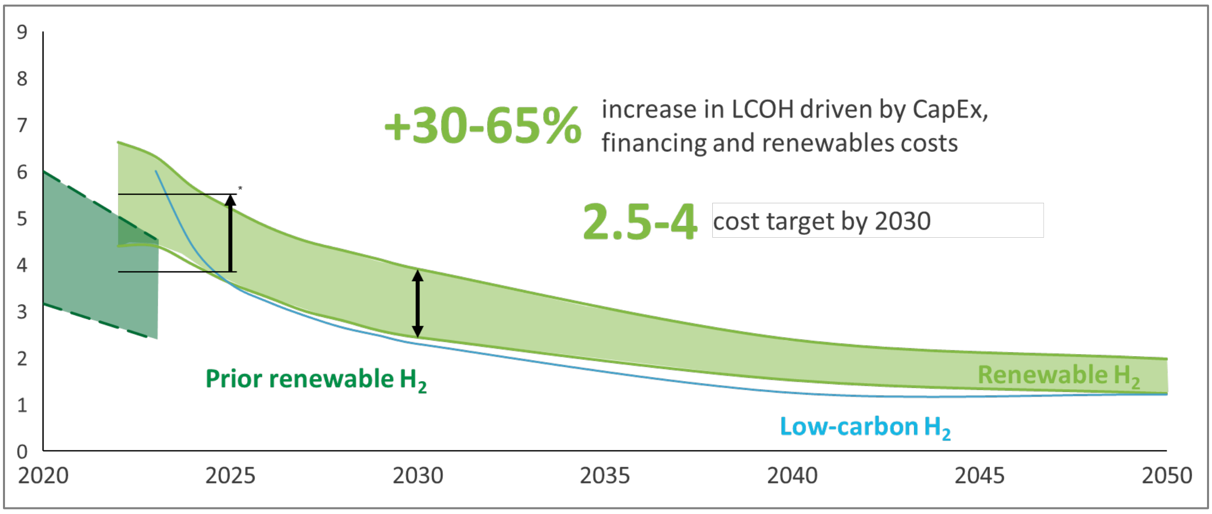
The production cost of green hydrogen, using onsite solar PV electrolysers in industrial plants in ASEAN, may also decrease significantly by 2030 and 2050. The decrease – using alkaline – would be about 47% and 63% of the initial production cost in 2030 and 2050, respectively. Further, the use of onsite solar PV electrolysers in industrial plants in Thailand in 2050 to produce green hydrogen would be the cheaper compared to this occurring in other AMS (i.e. around USD2.67/kg and USD2.72/kg of water, respectively) (Purwanto and Rusli, 2024).

In recent years, the cost of electrolysers globally has surged due to escalating material and labour expenses. The current capital cost for installed electrolysers, including equipment and engineering costs, ranges from USD1,700 per kilowatt (kW) to USD2,000/kW (TÜV SÜD, 2024b). This marks a 9% increase compared to 2021, with certain projects in Europe experiencing inflation rates as high as 40% (Hydrogen Council and McKinsey & Company, 2023). This inflation in capital expenditure (CAPEX) translates into a 30–65% hike in the levelised cost of hydrogen production (Figure 1.5). Moreover, current inflation and rising labour costs have led to upward revisions in initial project estimates. For instance, Saudi Arabia's NEOM Green Hydrogen project saw costs rise from USD5.0

billion to USD8.5 billion due to various factors including inflation and scope enlargement (IEA, 2023).

Looking ahead, however, economies of scale and mass production are expected to drive down capital costs significantly. This reduction could halve the share of CAPEX in the levelised cost of hydrogen, facilitating a more cost-effective transition towards hydrogen-based economies (Figure 1.5).

Figure 1.5. Projection of Hydrogen Production Costs Worldwide until 2050
(USD per kilogram)



CapEx = capital expenditures, LCOH = levelised cost of hydrogen.
Source: Hydrogen Council and McKinsey & Company (2023).

The journey towards lower hydrogen production costs will be influenced by a constellation of factors. The declining cost of renewable energy sources is a pivotal driver, reducing the operational costs associated with electrolysis-based hydrogen production. Concurrently, technological advancements in electrolyser design and materials aim to enhance efficiency and to reduce CAPEX. The growth of constructed hydrogen production facilities and the burgeoning electrolyser industry should leverage economies of scale, further driving down costs. Additionally, government policies – including subsidies and incentives – will be crucial in nurturing the development of the hydrogen economy.

The pace of technological innovation and the scalability of new technologies do remain uncertain factors that could affect cost-reduction trajectories, however. Market development risks – including the need for comprehensive infrastructure and regulatory frameworks, along with international trade agreements – present additional hurdles. Furthermore, the availability and cost of essential inputs, such as renewable energy and water especially in water-scarce regions, could limit the potential for green hydrogen production.

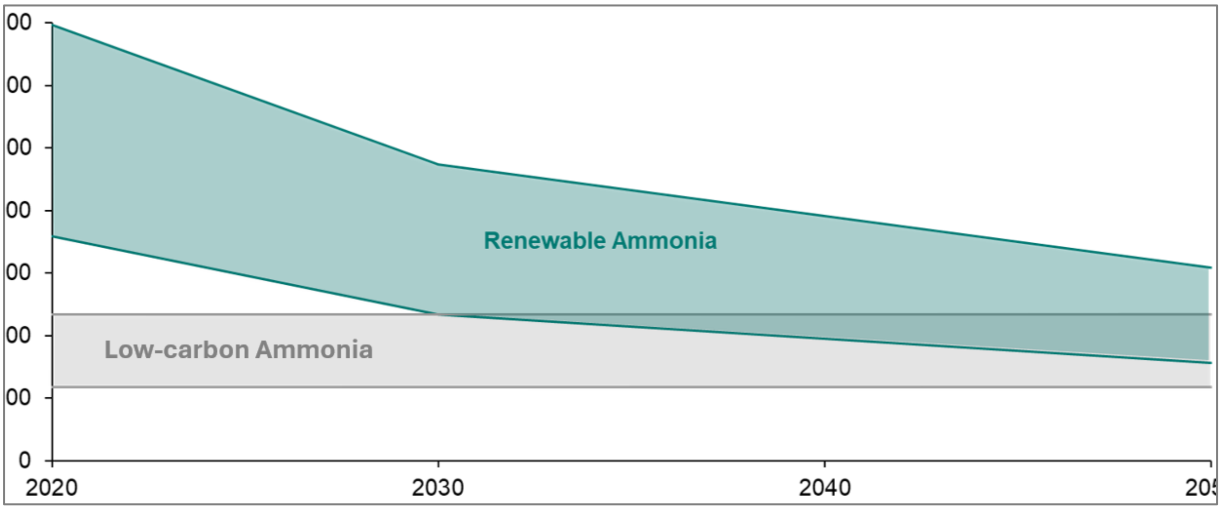
It must be noted that the future of hydrogen production costs is marked by the significant potential for reduction. Strategic investments in research and development, infrastructure, and international cooperation could unlock the opportunities presented by low-cost hydrogen, thereby cementing its role in a sustainable and resilient global energy system.

1.1.3. Trends in Ammonia Production Costs

For blue ammonia, the estimated production cost is around USD381/tonne with the natural gas cost accounting for more than 57% of the total cost. The second-largest cost is CAPEX, with a 15% share (Kobayashi, 2024). Green ammonia costs are predominantly influenced by the price of green hydrogen, which constitutes more than 90% of production expenses. Nitrogen purification and the Haber-Bosch process – although integral – have a relatively minor impact on overall costs. The production cost of green ammonia is estimated to be around USD489/tonne, with the electricity cost accounting for more than 62% and CAPEX accounting for 27% of the total cost in ASEAN (Kobayashi, 2024). To accelerate the deployment of green ammonia, therefore, it is essential to reduce CAPEX and material inputs (i.e. electricity).

There is a notable difference between fossil-based and green ammonia production. While the fuel cost of brown ammonia[14] production takes up the majority of that cost component, the main expense in the production of green ammonia is the investment in renewable energy infrastructure and electrolyser stacks. This upfront investment heavily influences renewable ammonia costs through the weighted average cost of capital. However, green ammonia production can be integrated into existing fossil-based plants, reducing emissions and costs by 2025–2030 (Figure 1.6). Although hybrid production models fall short of full decarbonisation, they do lower emissions and can facilitate prompt investment decisions due to mature technology.

Figure 1.6. Production Costs of Low-carbon and Renewable Ammonia Worldwide
(USD per tonne)

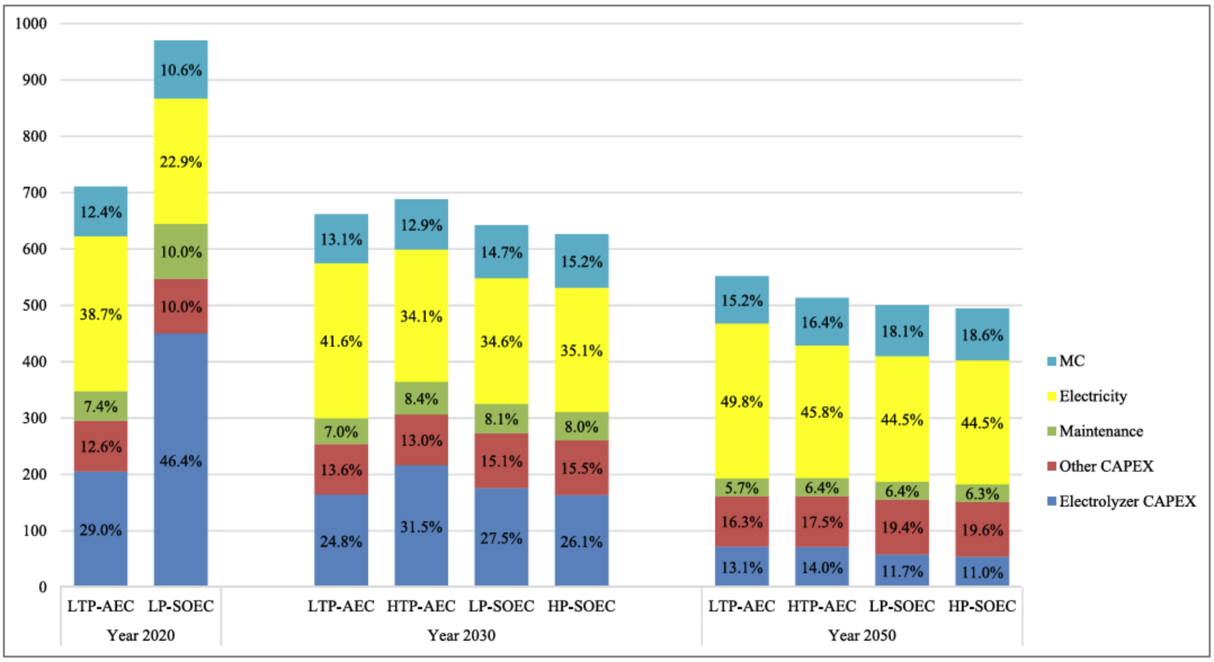


Source: IRENA (2022).

[14] Brown ammonia refers to the ammonia produced from fossil-fuel-derived hydrogen, which relies on coal gasification for the hydrogen production (Hatzell, 2024).

Current ammonia production uses coal gasification and SMR, which could be considered a cheap option, ranging from USD110/tonne to USD 340/tonne; other sources have estimated that the grey ammonia production cost is USD280–USD465/tonne (IRENA, 2022; Nami, Hendriksen, Frandsen, 2024). While it may be less expensive, grey ammonia consumption is responsible for 1.8% of global CO_2 emissions. Grey ammonia production emits 2.4 tonnes of CO_2 per 1.0 tonne of ammonia produced. Blue ammonia comes from fossil fuels (i.e. natural gas) and requires the use of CCS technology, adding USD100–USD150/tonne to the cost, which would total USD210–USD490/tonne of ammonia.

Figure 1.7. Cost Breakdown of Green Ammonia Production via Different Electrolysis Technology
(EUR per tonne)



CAPEX = capital expenditure, HTP-AEC = high-temperature pressurised alkaline electrolysis, HP-SOEC = high-pressure solid oxide electrolysis, MC = manufacturing costs, LTP-AEC = low-temperature pressurised alkaline electrolysis, LP-SOEC = low-pressure solid oxide electrolysis.
Source: Nami, Hendriksen, Frandsen (2024).

Green ammonia production cost USD720–USD1,400/tonne in 2020 (IRENA, 2022); specifically, green ammonia production, through low-temperature pressurised alkaline electrolysis, cost around USD720/tonne (Figure 7). Low-pressure solid-oxide electrolysis was far more expensive at USD980/tonne. Both estimations were made assuming USD30/megawatt-hour (MWh) of the levelised cost of energy (LCOE), 50% of the capacity factor for electrolysers, and current density of 0.5 Ampere per square centimetre (A/cm^2). For both technologies, the electricity price and electrolyser CAPEX took up the largest portion of the cost component, with the electricity price comprising 38.7% and 22.9% of low-temperature pressurised alkaline electrolysis and low-pressure solid-oxide electrolysis, respectively. Electrolyser CAPEX accounted for almost 50% of the cost component of low-pressure solid-oxide electrolysis and only 29% in low-temperature pressurised alkaline electrolysis.

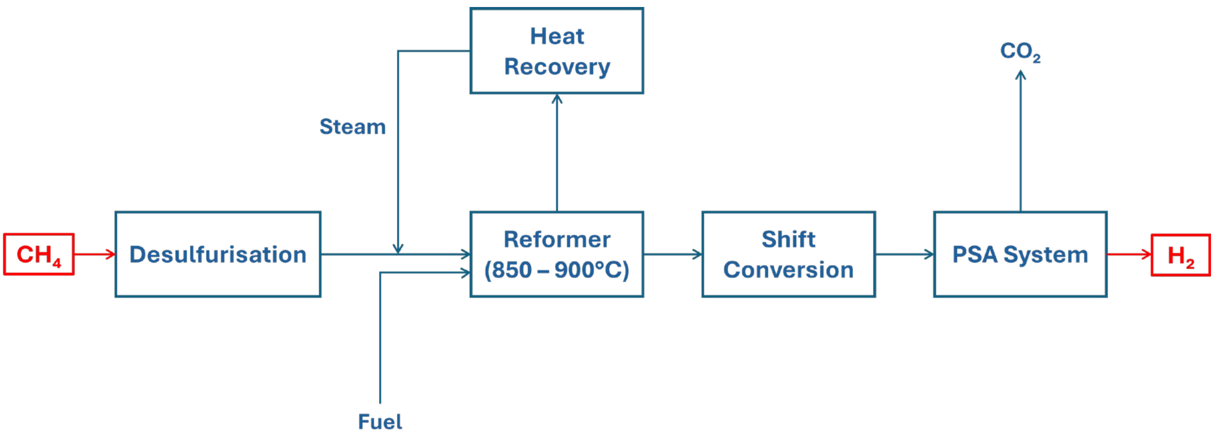
It is expected that the cost of green ammonia will eventually decline, reaching as low as USD510–USD560/tonne by 2050, due to technology maturity and economy of scale (IRENA, 2022; Nami, Hendriksen, Frandsen, 2024). Moreover, it is forecasted that the price of blue ammonia will depend on the technological advancement of various carbon-capture technologies, reaching USD360–USD550/tonne by 2050, assuming that the natural gas price stays at USD10–USD30/MWh without the addition of a carbon tax. Imposing a carbon tax policy and taking into account the volatility of natural gas prices may make green ammonia more favourable in the future.

1.1.4. Hydrogen and Ammonia Production Technologies

Steam Methane Reforming

As previously mentioned, SMR is a widely used industrial process for producing hydrogen gas from natural gas – primarily methane and steam. It is the most common method for large-scale hydrogen production globally due to its low cost of operations, which is USD0.50–USD2.00/kg of hydrogen. Besides the low operational cost, the typical efficiency of SMR is quite high, 75–85% (Nnabuife et al., 2023). Figure 8 shows the SMR process.

Figure 1.8. The Steam Methane Reforming Process



PSA = pressure swing absorption.
Source: Authors based on Nikolaidis and Poullikkas (2017).

The working mechanism of SMR is detailed below.

Feedstock preparation. The process begins with the preparation of the feedstock, which typically involves pre-treating natural gas to remove impurities such as sulphur compounds, as sulphur deactivates the catalysts used in subsequent steps. This ensures that the reaction proceeds smoothly without 'catalyst poisoning'. Sulphur removal requires catalytic hydrogenation to convert sulphur compounds in the feedstocks into gaseous hydrogen sulphide (i.e. hydrodesulphurisation and hydrotreating):

$$H_2\,(g) + RSH \rightarrow RH + H_2S\,(g)$$

Hydrogen sulphide is absorbed and removed by passing it through beds of zinc oxide, where it is converted to solid zinc sulphide:

$$H_2S\,(g) + ZnO\,(s) \rightarrow ZnS\,(s) + H_2O\,(g) \qquad \Delta H = -70.3\ \text{kJ/mol}$$

Steam reforming. In the reforming reactor, natural gas and steam are introduced at high temperatures (i.e. 700–1,100°C) and moderate pressures (10–25 bar) over a catalyst bed, usually composed of nickel-based catalysts supported on alumina. The main reaction occurring is an endothermic reaction known as the steam-reforming reaction:

$$CH_4\,(g) + H_2O\,(l) \rightarrow CO\,(g) + 3H_2\,(g) \qquad \Delta H = +206.2\ \text{kJ/mol}$$

This reaction produces carbon monoxide and hydrogen gas. It is important to maintain the right steam–methane ratio for optimal conversion and to prevent the formation of carbonaceous deposits (i.e. carbon buildup), which can deactivate the catalyst.

Water-gas shift reaction. The product stream from the steam reformer contains a mixture of hydrogen, carbon monoxide, CO_2, and unreacted methane. To further increase the hydrogen yield and to reduce the carbon monoxide content, the stream is passed through a water-gas shift reactor. In this reactor, water vapour reacts with carbon monoxide to produce additional hydrogen and CO_2:

$$CO\,(g) + H_2O\,(g) \rightarrow CO_2\,(g) + H_2\,(g) \qquad \Delta H = -41.0\ \text{kJ/mol}$$

This reaction is exothermic and is usually carried out at lower temperatures compared to steam reforming. Since the exothermic reaction dissipates heat, the water-gas shift reaction may also be beneficial for heat recovery, which may increase system efficiency in general.

CO_2 removal. The resulting gas mixture now contains mainly hydrogen, CO_2, and traces of methane and other gases. To obtain high-purity hydrogen, the CO_2 is removed through processes such as pressure swing absorption or membrane separation.

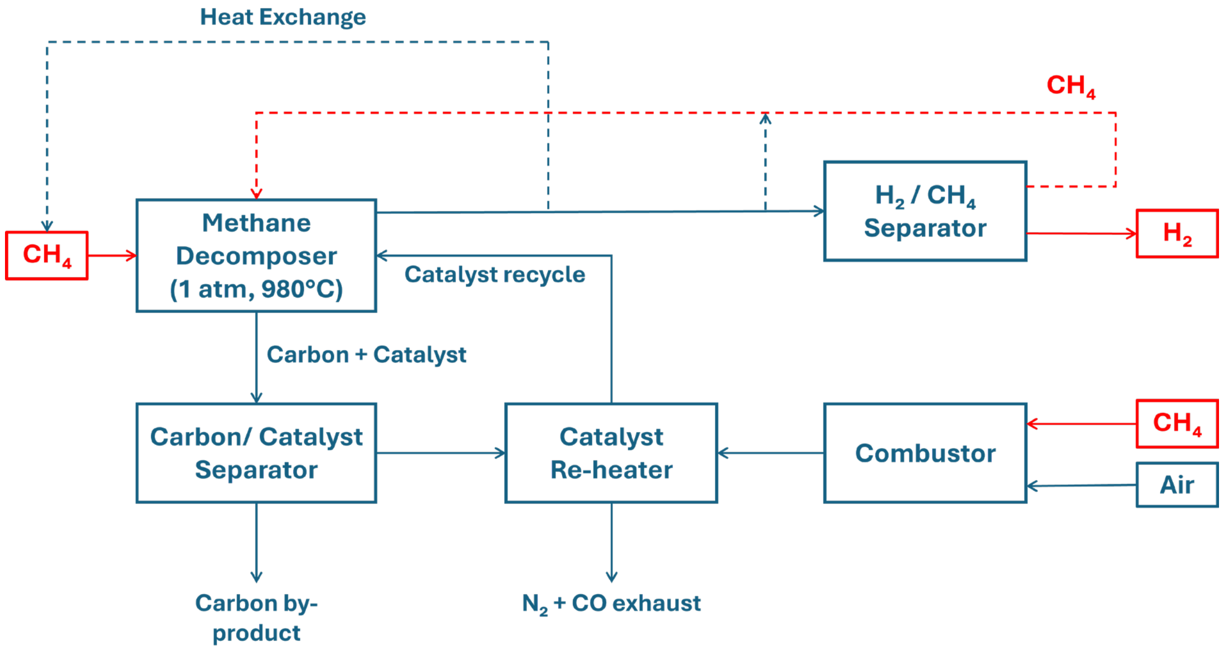
Product purification. The final step involves purifying the hydrogen gas to remove any remaining impurities, such as trace amounts of carbon monoxide and CO_2, as well as moisture. This can be achieved through additional purification processes like pressure swing adsorption or membrane separation.

Overall, SMR is a highly efficient and established process for large-scale hydrogen production, but it does produce CO_2 emissions as a by-product (Mohd Yunus et al., 2024). Advancements – such as integrating CCS technologies with SMR – can mitigate these emissions, paving the way for blue and green hydrogen production.

Pyrolysis

Pyrolysis of methane to hydrogen involves breaking down methane molecules into simpler compounds, primarily hydrogen gas, through a high-temperature thermal decomposition process (Figure 1.9). Overall, pyrolysis offers a potential pathway for producing hydrogen gas from abundant methane resources. While this process requires high temperatures and energy input, it provides a means of generating hydrogen with reduced CO_2 emissions compared to traditional methods such as SMR. However, further research and development are needed to optimise the process, improve efficiency, and address challenges such as carbon by-product management and process economics.

Figure 1.9. Methane Pyrolysis



Source: Authors based on Nikolaidis and Poullikkas (2017).

Pyrolysis of methane to hydrogen occurs as follows.

Feedstock preparation. The process begins with the preparation of methane, which is typically obtained from natural gas sources. Methane is a hydrocarbon gas consisting of one carbon atom bonded to four hydrogen atoms.

Heating. Methane is subjected to high temperatures ranging from 700°C to 1,200°C (i.e. an endothermic reaction) in the presence of a suitable catalyst or in the absence of oxygen (i.e. anaerobic conditions). This high temperature is necessary to initiate the thermal decomposition of methane molecules.

Thermal decomposition (pyrolysis). As the methane is heated, it undergoes pyrolysis, a process where the chemical bonds within the methane molecules break, leading to the formation of simpler compounds. The primary reaction involved in methane pyrolysis is (Uehara, Asahara, Miyasaka, 2024):

$$CH_4\ (g) \longrightarrow 2H_2\ (g) + C\ (s) \qquad \Delta H = +75\ \text{kJ/mol at } 25°C$$

This reaction results in the decomposition of methane into hydrogen gas and solid carbon, commonly referred to as 'carbon black' or soot. The carbon produced in this reaction can be captured and utilised or disposed of, depending on the application.

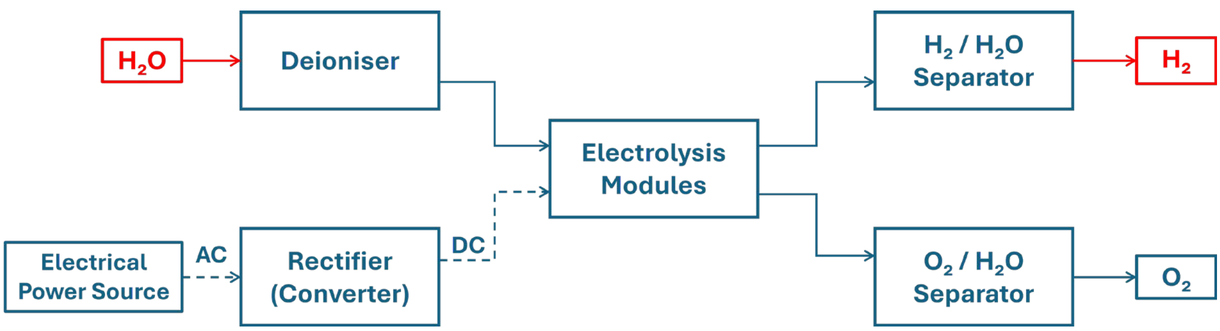
Hydrogen collection. The hydrogen gas produced during pyrolysis is collected and separated from the other reaction products, such as carbon and any residual methane. This separation can be achieved through processes such as cooling, condensation, and purification.

Process optimisation. The efficiency of pyrolysis varies based on the catalysts used in the process but is typically around 58%. Various parameters – including temperature, residence time, catalyst type, and reactor design – can be optimised to control the pyrolysis process and to maximise the yield and purity of the hydrogen gas. For instance, catalytic methane pyrolysis using nickel and silicon oxide boosts the hydrogen yield by 53% to 73% compared to using iron catalysts under similar conditions (Sánchez-Bastardo, Schlögl, Ruland, 2021). Additionally, process integration with downstream purification and separation steps may be employed to enhance the efficiency and economics of the hydrogen production.

Electrolysis

Electrolysis represents a cornerstone for green hydrogen production, with its feasibility tightly intertwined with the source of electricity (Figure 1.10).

Figure 1.10. Water Electrolyser Process



Source: Authors based on Nikolaidis and Poullikkas, (2017).

Three types are described below and summarised in Table 1.1.

PEM electrolysis. PEM electrolysis is lauded for its high efficiency – it is capable of achieving 70–80% efficiency when using renewable energy sources – and high purity (i.e. 99%) in hydrogen production (Nnabuife et al., 2023). It is particularly suited for dynamic energy sources, thanks to its rapid response to fluctuations in electricity supply. Despite its advantages, the reliance on precious metals, such as platinum and iridium, as catalysts presents cost challenges, highlighting a need for innovation in materials science to reduce dependency on scarce resources.

Alkaline electrolysis. This is characterised by its cost-effectiveness due to the use of non-precious metal catalysts, offering a lower-efficiency alternative that has been the backbone of industrial hydrogen production for decades. The low-efficiency characteristics of alkaline electrolysers are mainly due to the gas bubbles formed in the electrolyte, which can obstruct the active sides of the electrodes, leading to reduced efficiency of the electrochemical reactions. Its slower response to power supply changes – compared to PEM electrolysis – makes it less ideal for direct coupling with variable renewable energy sources but remains a viable option for steady power supply scenarios. The current density of alkaline electrolysers is around 0.2–0.4 A/cm^2, while the PEM electrolyser is 0.6–2.0 A/cm^2 (Nnabuife et al., 2023).

Solid oxide electrolysis. This is a high-efficiency technology, particularly at elevated temperatures, capable of directly utilising steam to produce hydrogen. This technology's efficiency advantage, however, is offset by higher costs associated with the materials capable of withstanding operational temperatures, signifying an area ripe for technological breakthroughs. The current density of solid oxide electrolysers is 0.3–1.0 A/cm^2, higher than that of the alkaline electrolysers (Nnabuife et al., 2023).

Table 1.1. Comparison of Electrolysis Technologies Technical Specifications

Technical Specification(s)		Low-temperature Electrolysis		High-temperature Electrolysis
		Alkaline (ALK)	Proton Exchange Membrane (PEM)	Solid Oxide Electrolysis (SOE)
System efficiency (% LHV)		51–60	70–80	76–81
Hydrogen purity (% LHV)		99	99	99
Stack lifetime (hours)		60,000–120,000	20,000–100,000	8,000–20,000
Current density (A/m^2)		2,000–8,000	0–20,000	0–20,000
Stack capital costs (USD/kW)	Minimum 1 MW	270	400	>2,000
	Minimum 10 MW	500–1,000	700–1,400	

LHV = lower heating value, kW = kilowatt, m^2 = square metres, MW = megawatt.
Sources: Authors based on Elrhoul, Naveiro, Romero Gómez (2024); Nnabuife et al. (2023).

Biomass Gasification

Biomass gasification offers a renewable pathway to hydrogen production, with its sustainability contingent upon the sources of biomass and the emissions associated with its life cycle. The efficiency of biomass gasification is 40.0–69.6% of the input biomass, with 0.0154–0.165 kg of hydrogen biomass and hydrogen purity of 99.9% upon going through the pressure swing absorption process in which the hydrogen is separated from the resulting mixture of gases (Tavares Borges et al., 2024). Through the process, it is estimated that the levelised cost of hydrogen from biomass gasification is around USD5.37/kg (Tavares Borges et al., 2024).

Ammonia Production

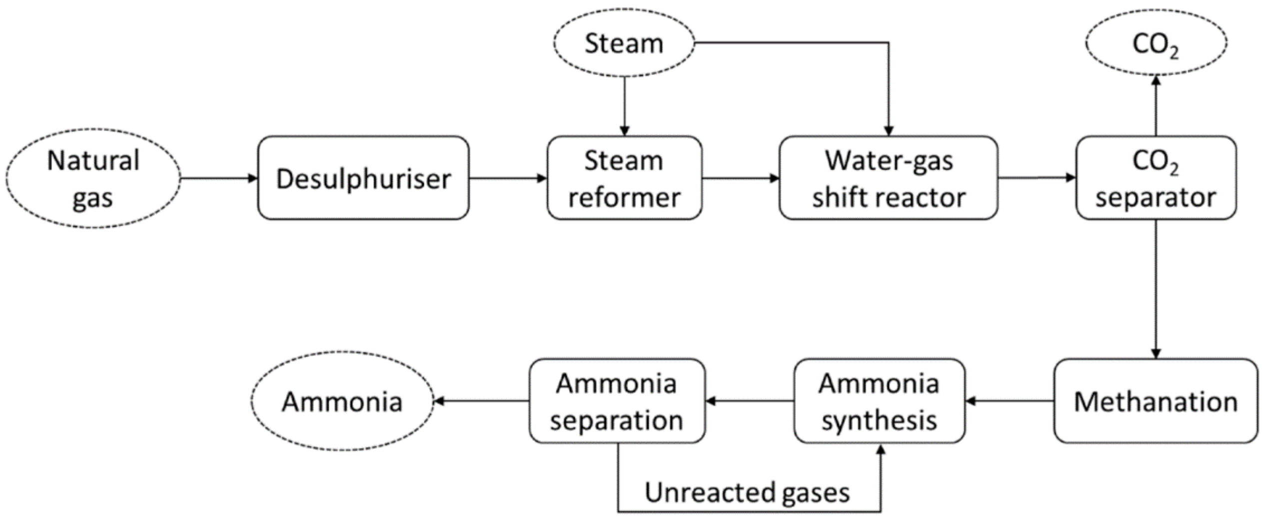
Ammonia production from hydrogen relies on the Haber-Bosch process, a fundamental chemical reaction in industrial chemistry. In this process, nitrogen gas from the air and hydrogen gas derived from natural gas or water are combined to form synthesis gas, comprising a mixture of nitrogen and hydrogen. This mixture undergoes ammonia synthesis within a high-pressure reactor containing an iron-based catalyst. The reaction, operating at elevated pressure (i.e. 100–300 bar) and temperature (400–500°C), facilitates the transformation of nitrogen and hydrogen molecules into ammonia according to this reversible equation:

$$N_2\,(g) + 3H_2\,(g) \rightleftharpoons 2NH_3\,(g) \qquad \Delta H = -92.28\ \text{kJ/mol at } 25°C$$

The presence of the catalyst enhances the reaction rate and yield of ammonia. After synthesis, the resulting mixture is cooled and depressurised to condense ammonia into a liquid phase, which is then separated from unreacted gases. The unreacted gases are recycled, while the purified liquid ammonia undergoes further purification for various industrial uses, notably fertilizer production.

While the Haber-Bosch process is critical for global agriculture and various industrial sectors – driving the production of essential nitrogen-based compounds – ongoing research aims to optimise the process for improved efficiency and sustainability.

Figure 1.11. Conventional Ammonia Production: Haber-Bosch



Source: Aziz, Wijayanta, Nandiyanto (2020).

Each process step is explained in the order of the production process shown in Figure 1.11.

Desulphurisation. Natural gas – primarily methane – is first desulphurised to remove sulphur compounds, which can poison the catalysts used in later steps. This purified natural gas serves as a hydrogen source in the ammonia synthesis process, setting the foundation for efficient hydrogen production.

Steam reforming. In the steam reformer, natural gas reacts with high-temperature steam to produce a mixture of hydrogen and carbon monoxide, known as synthesis gas. This reaction is endothermic, requiring substantial heat, and is a crucial step in obtaining hydrogen, which will later react with nitrogen to form ammonia.

Water-gas shift reaction. The synthesis gas undergoes a water-gas shift reaction, where carbon monoxide reacts with additional steam to produce CO_2 and more hydrogen. This step not only increases the hydrogen yield but also helps reduce carbon monoxide levels, optimising the gas mixture for ammonia synthesis.

CO_2 separation. The gas mixture is then directed through a CO_2 separator to remove CO_2, ensuring that the remaining gas stream is primarily composed of hydrogen and nitrogen. This step is essential as it minimises impurities in the synthesis gas, making it suitable for the high-pressure ammonia synthesis reaction.

Methanation. To eliminate any trace amounts of carbon oxides left in the gas stream, methanation is used to convert them into methane. This process further purifies the synthesis gas by removing potential contaminants that could impact the efficiency of ammonia synthesis.

Ammonia synthesis. The purified hydrogen and nitrogen gas mixture is then introduced into a high-pressure reactor, where it reacts over an iron-based catalyst at high temperature (i.e. 400–500°C) and pressure (100–300 bar) to form ammonia. This exothermic reaction, $N_2 + 3H_2 \rightleftharpoons 2NH_3$, is facilitated by the catalyst, which enhances the rate and yield of ammonia production.

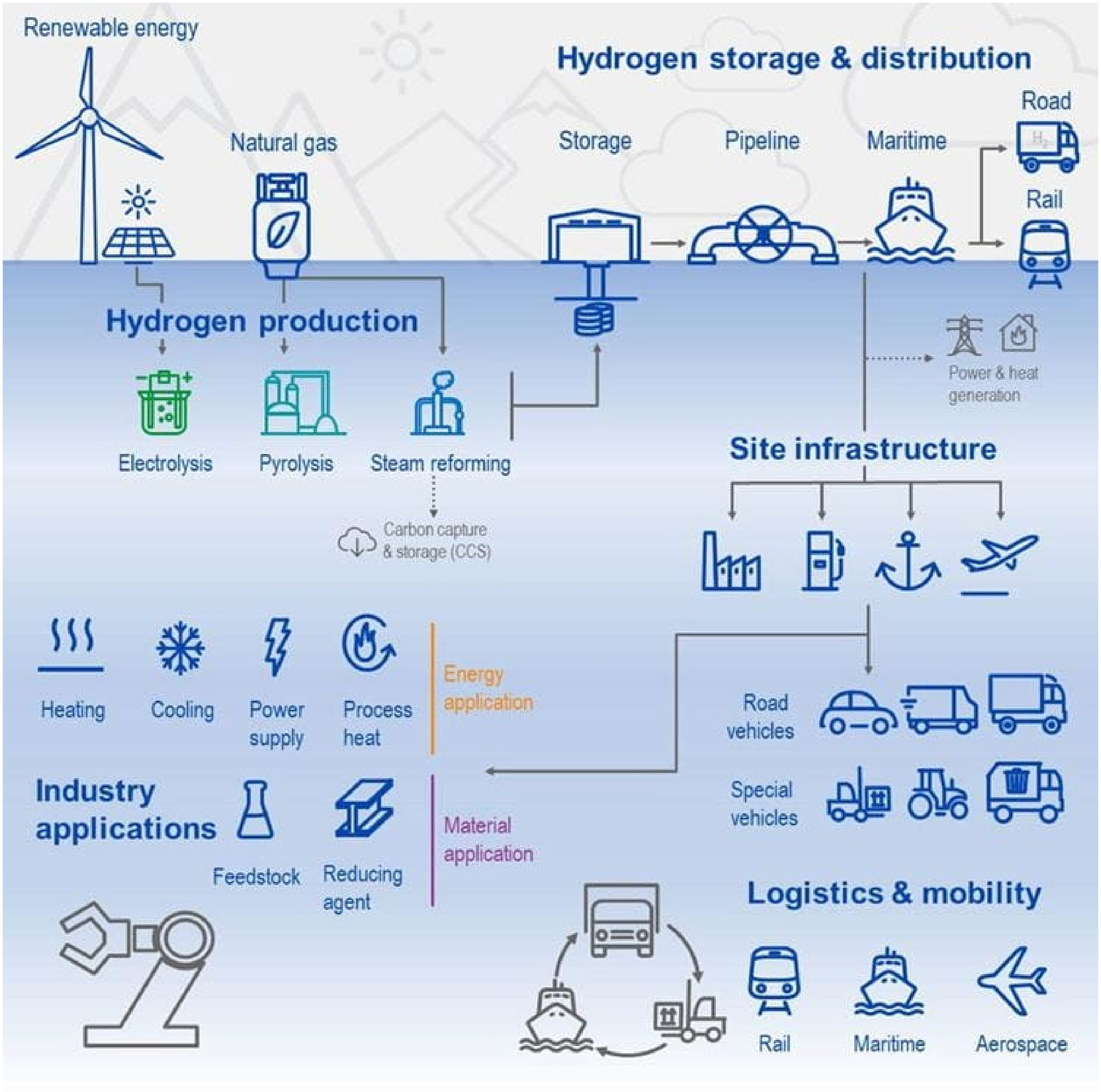
Ammonia separation. After synthesis, the ammonia-rich gas mixture is cooled and depressurised, causing the ammonia to condense into a liquid. This liquid ammonia is then separated from the unreacted hydrogen and nitrogen gases, which are recycled back into the reactor to maximise production efficiency and to reduce waste.

Hydrogen and Ammonia Transport and Storage Technologies

This section examines state-of-the-art hydrogen production, transport, and storage technologies, drawing upon recent advancements, efficiency benchmarks, and cost considerations.

The hydrogen value chain is typically split into production, storage and distribution, site infrastructure, and consumption in industrial applications as well as logistics and transport (Figure 1.12).

Figure 1.12. The Hydrogen Value Chain



Source: Authors.

There are different ways to produce hydrogen as explained in the previous section. Further processing of hydrogen to remove impurities may be necessary depending on the target application.

Hydrogen can be transmitted or stored in liquid or gaseous form depending on transmission pipelines as well as maritime and road distribution. Hydrogen can be provided at the point of use via pipeline, storage, or filling stations/systems.

Gaseous hydrogen can be distributed to the point of use either in high-pressure containers or via pipelines. The transport of high-pressure containers faces similar challenges as storage in high-pressure vessels and can be facilitated using road, rail, or ships. This makes this solution flexible and suited to any destination without the need for new infrastructure.

Transmission of hydrogen via pipelines is a good solution if large quantities of hydrogen need to be distributed. Gas pipelines can transport high amounts of energy at a lower cost than electricity transmission on overhead power lines. The existing gas pipeline infrastructure in countries like Germany can be used to transport hydrogen with few adaptions.

Theoretically, a methane pipeline could transport nearly the same amount of energy using hydrogen, although the existing pipeline infrastructure may risk embrittlement due to the reactive nature of hydrogen. Further adaption, using coating, is required to reduce the risk. It is also possible to mix hydrogen with natural gas to mitigate such a risk and to decrease the required adaptions to the pipeline. However, if the share of hydrogen exceeds 30% of the mix, parts like compressors and turbines likely need to be exchanged to cope with the higher volume flow of hydrogen (EPA, 2023).

Ammonia, as a type of hydrogen carrier, provides an alternative way to transport hydrogen and to use it in various sectors. Ammonia can be used to transport hydrogen energy for utilisation through gas distribution pipelines or shipping. Shipping hydrogen energy in ammonia can occur in both gaseous and liquid forms. Shipping ammonia in its liquid state is more cost-effective compared to liquified hydrogen, with liquified ammonia costs around USD61–USD80/MWh and liquified hydrogen costs USD60–USD105/MWh. This is due to the conversion process of hydrogen; liquefying hydrogen requires an energy-intensive process to cool and to maintain the state of the hydrogen (i.e. lower than –252.7°C) (Negro, Noussan, Chiaramonti, 2023).

1.1.5. Transport and Infrastructure

The transport of hydrogen from production sites to places of use is a critical aspect of the hydrogen supply chain. Effective transport methods are vital for the widespread adoption of hydrogen as a key energy carrier in the transition to a low-carbon economy. This section provides a detailed technological overview of hydrogen transport via trucks, pipelines, and ships, comparing their positive and negative aspects to offer insights into the most efficient and sustainable practices.

<u>Trucks</u>

Transporting hydrogen by truck involves compressed hydrogen gas in high-pressure tanks or liquid hydrogen in cryogenic tankers. Compressed hydrogen is typically stored at pressures up to 700 bar, while liquid hydrogen is kept at –253°C to maintain its liquid state.

	Pros		Cons
Pros	**Flexibility**. Trucks can deliver hydrogen to various locations not connected by pipelines, making this method highly versatile. **Speed of implementation**. Utilising trucks for hydrogen transport does not require significant infrastructure development, allowing for rapid deployment.	Cons	**Cost**. High operational costs are incurred due to fuel consumption, vehicle maintenance, and the need for specialised tankers to handle high-pressure or cryogenic conditions. **Scalability**. This is limited by cargo capacity and the frequency of trips, making it less suitable for large-scale hydrogen distribution.

<u>Pipelines</u>

Pipeline transport involves the continuous flow of hydrogen gas through dedicated pipeline systems. This method can be considered for large-scale hydrogen distribution over short to medium distances.

	Pros		Cons
Pros	**Economic efficiency**. For substantial volumes, pipelines offer a cost-effective solution compared to road transport, especially over long distances. **Continuous supply**. Pipelines can provide a steady flow of hydrogen, essential for industrial processes requiring consistent hydrogen input.	Cons	**Infrastructure investment**. The initial CAPEX for pipeline construction is high, requiring significant investment and planning. **Geographical limitations**. The feasibility is restricted by terrain and the necessity to avoid densely populated areas, which may limit route options.

Another point to consider regarding pipelines is hydrogen embrittlement. Prolonged exposure to hydrogen can cause certain metals to become brittle and to crack, compromising the integrity of pipelines and storage vessels. Thus, developing pipeline materials that can withstand hydrogen exposure without degradation is essential.

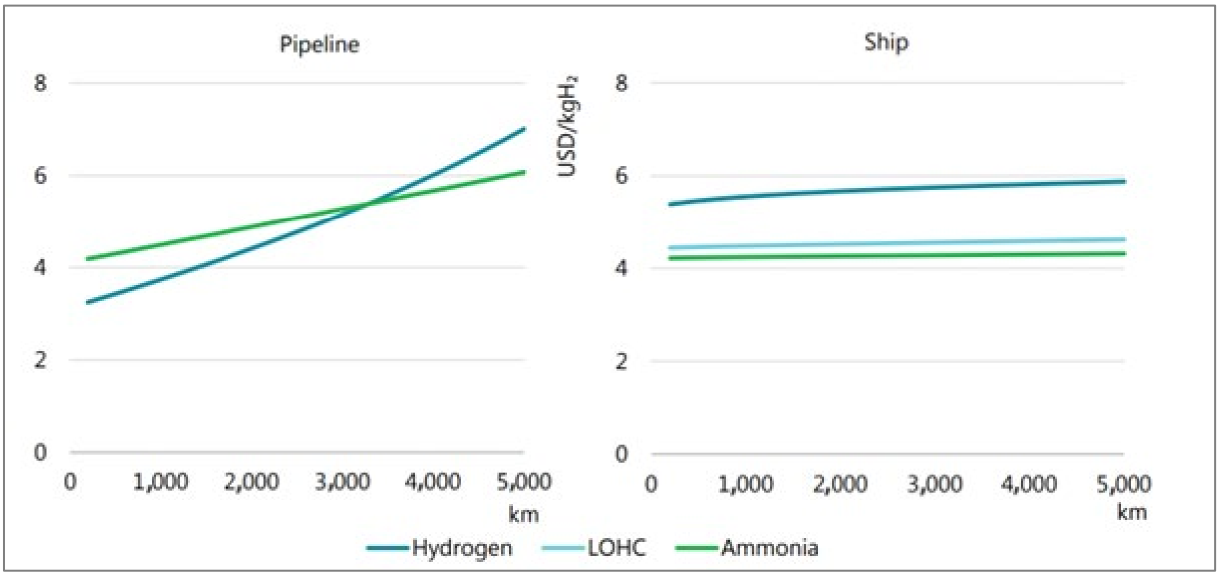
Moreover, energy infrastructure projects generally tend to have long lead times, averaging 6–12 years for natural gas pipelines, port terminals, and underground gas storage facilities (IEA, 2024). Gas (and hydrogen) infrastructure projects are large civil engineering projects, often spanning several jurisdictions, which often entail delays due to permitting issues and a lack of sociopolitical support, creating a hurdle in developing hydrogen pipelines for distribution in ASEAN. It is therefore critical to start infrastructure planning well in advance – even before production and demand are fully established.

Ships

To transport hydrogen over long distances where pipeline transmission is not feasible, or in regions without suitable geological conditions for underground storage, hydrogen must be converted into denser forms to be transported via shipping. Liquefied hydrogen and other chemical carriers such as ammonia, MCH, and liquid organic hydrogen carriers (LOHCs) are promising options for transporting hydrogen in a denser form. The idea was proven through the commencement of the AHEAD project where MCH is used to transport around 210 tonnes of hydrogen per year from Brunei Darussalam to Kawasaki, Japan via shipping (AHEAD, 2019). However, while the conversion of hydrogen to ammonia for use as ammonia is already well established, if conversion back to hydrogen is needed, the technologies required are not yet available on a commercial scale; thus, more pilot projects are needed to ensure the viability of commercial shipping for hydrogen.

Pros	Cons
Large volume transport. Ships can transport large quantities of hydrogen, making them suitable for international trade and supply chains. Flexibility in source location. This enables the import and export of hydrogen, connecting regions with surplus renewable energy resources to those with high demand.	Technological challenges. Specialised vessels are required for cryogenic or high-pressure conditions, entailing high costs and operational complexities. Conversion losses. Transporting hydrogen as ammonia or LOHCs involves conversion processes that incur energy losses and additional costs.

Figure 1.13. Average Costs of Hydrogen and Ammonia Transport by Pipelines and Ships Worldwide
(USD per kilogram)

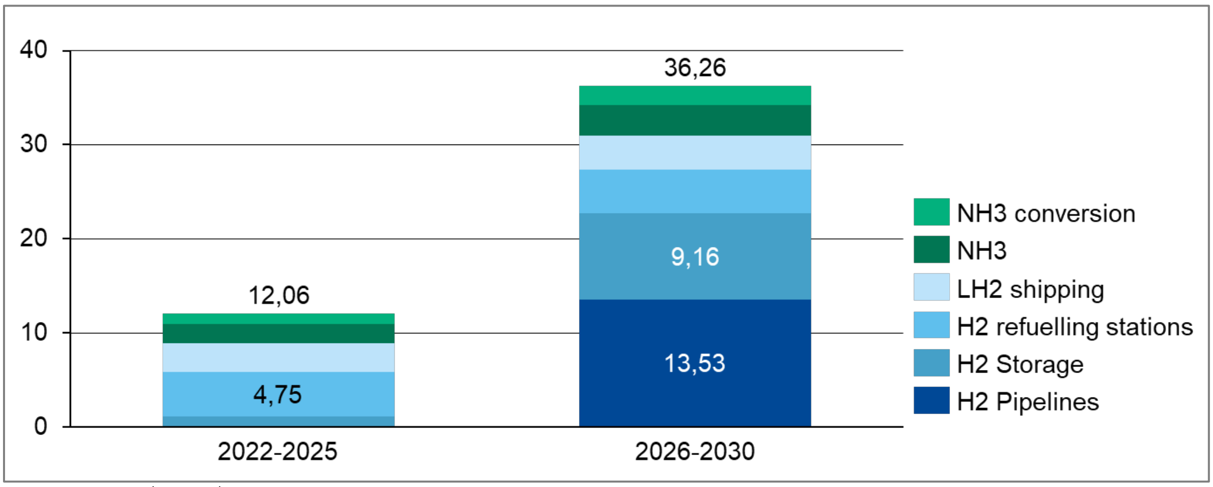


km = kilometre, LOHC = liquid organic hydrogen carrier.
Source: IEA (2019).

The choice of transport method depends on several factors, including distance, volume, cost considerations, and infrastructure availability. While truck transport offers flexibility and quick deployment, it is less economically viable for large volumes and long distances. Pipelines, though capital-intensive, provide an efficient solution for bulk transport over land. However, geographical constraints may limit their applicability. Maritime transport opens avenues for international hydrogen trade, bridging distant markets, but faces challenges related to technology, costs, and energy losses in conversion processes.

The development of effective hydrogen transport infrastructure is crucial for harnessing hydrogen's potential as a clean energy carrier. Each transport method has unique advantages and challenges, requiring careful consideration based on specific use cases and regional needs. The figure below shows the projected global annual investment for hydrogen infrastructure.

Figure 1.14. Global Annual Investment in Infrastructure in the Net-zero Emissions Scenario
(USD billion)



Source: IEA (2019).

Following the national pledges for net-zero emissions, both countries and private players are planning to provide investments to establish hydrogen infrastructure in support of carbon emissions reduction targets. Hydrogen pipelines and storage facilities have become two of the most favoured technologies, with investments projected to grow from USD5 billion by 2022–2025 to USD22.69 billion by the end of 2030. Advances in technology, combined with strategic investments and policy support, will be essential in overcoming the barriers to efficient hydrogen transport, paving the way for a sustainable energy future.

1.1.6. Storage

Efficient storage solutions are pivotal for integrating hydrogen into the energy system, balancing supply and demand, and ensuring the reliability of hydrogen as an energy carrier. This section delves into the technological aspects of storing hydrogen, focussing on pressure tanks, cryogenic tanks, and underground storage methods, comparing their advantages and disadvantages to highlight their roles in comprehensive hydrogen infrastructure.

<u>Pressure Tanks</u>

Pressure tanks for hydrogen storage employ either Type I steel tanks or more advanced composite materials (i.e. Types II–IV) to withstand high pressures, typically up to 700 bar. These tanks are used for both stationary storage at hydrogen production sites and mobile applications in vehicles. Tanks are best for applications where weight is less critical, and high purity, fast discharge, and rapid refuelling are prioritised (e.g. fuelling stations and certain industrial processes)

Pros		Cons	
Pros	**Scalability**. Pressure tanks are easily scalable by adding additional tanks, making them suitable for various applications from small-scale industrial use to larger fuelling stations. **Flexibility**. Highly versatile, pressure tanks can be installed in multiple locations, including urban areas, without significant spatial constraints.	Cons	**High costs**. Advanced composite materials used in higher-type tanks are expensive, increasing the cost of storage solutions. **Energy-intensive**. Compressing hydrogen to high pressures requires significant energy, reducing the overall efficiency of hydrogen as an energy carrier.

Cryogenic Tanks

Liquid hydrogen requires specialised cryogenic tanks that are vacuum insulated to minimise evaporation and to house redundant pressure-relief devices as a precaution to prevent overpressurisation. Liquid hydrogen tanks typically operate at pressures up to 850 kilopascals (i.e. about 123 pounds per square inch [psi]). With a volume of around 1/800 gaseous hydrogen, almost 100% pure, not necessarily refined, and directly injected into fuel cells, liquid hydrogen has the perfect compatibility to transport a large amount of hydrogen across nations without losing efficiency (Kimura and Li, 2019). It is suitable for large-scale storage or applications where weight is a priority but where liquefaction infrastructure is feasible (e.g. aerospace and long-distance hydrogen transport).

Pros	**High energy density.** Liquid hydrogen offers a much higher energy density by volume compared to compressed hydrogen gas. This enables cryogenic tanks to store larger amounts of hydrogen in a smaller space. **Lower operating pressure.** Operating at lower pressures reduces the risk of rupture compared to high-pressure gas storage.	Cons	**High energy cost.** Converting hydrogen gas to liquid (in cryogenic temperatures) impacts the overall cost and efficiency of the hydrogen supply chain (58% for liquefying hydrogen gas, and 55–60% for the regasification). Conversion into liquified hydrogen requires around 10–13 kWh/kg of liquid hydrogen (Aziz, Oda, Kashiwagi, 2019; Gardiner and Satyapal, 2009). **Complex insulation requirements.** To minimise boil-off, cryogenic tanks require multilayer, high-performance insulation systems, often with vacuum insulation.

Liquid Organic Hydrogen Carriers

MCH is a promising candidate for hydrogen storage, particularly for applications requiring high energy density and ease of transport (Kimura and Li, 2019). It is an LOHC; it has a chemical structure that can easily release hydrogen when needed and can be re-hydrogenated back to its original form. The storage system involves two primary chemicals: toluene and MCH. Toluene can be hydrogenated to form MCH, which effectively stores the hydrogen. When hydrogen is needed, MCH is dehydrogenated back to toluene, releasing the hydrogen for use.

It is ideal for long-distance hydrogen transport and storage in centralised locations, such as hydrogen distribution hubs or large-scale storage facilities. LOHCs are also being explored for maritime fuel and large-scale renewable energy storage applications.

Pros	Cons
High energy density. MCH has a high hydrogen storage density, making it suitable for applications where space and weight are critical factors, such as in transport or portable power sources. **Safety.** Liquids like MCH are generally safer and more manageable compared to high-pressure gas storage, reducing risks associated with hydrogen storage and transport.	**Energy and cost requirements.** The hydrogenation and dehydrogenation processes are energy intensive. They require expensive catalysts and considerable amounts of heat, which can offset the energy benefits gained from hydrogen storage. **Efficiency.** There can be significant energy losses during the hydrogenation and dehydrogenation processes, impacting the overall efficiency of the hydrogen storage and retrieval cycle.

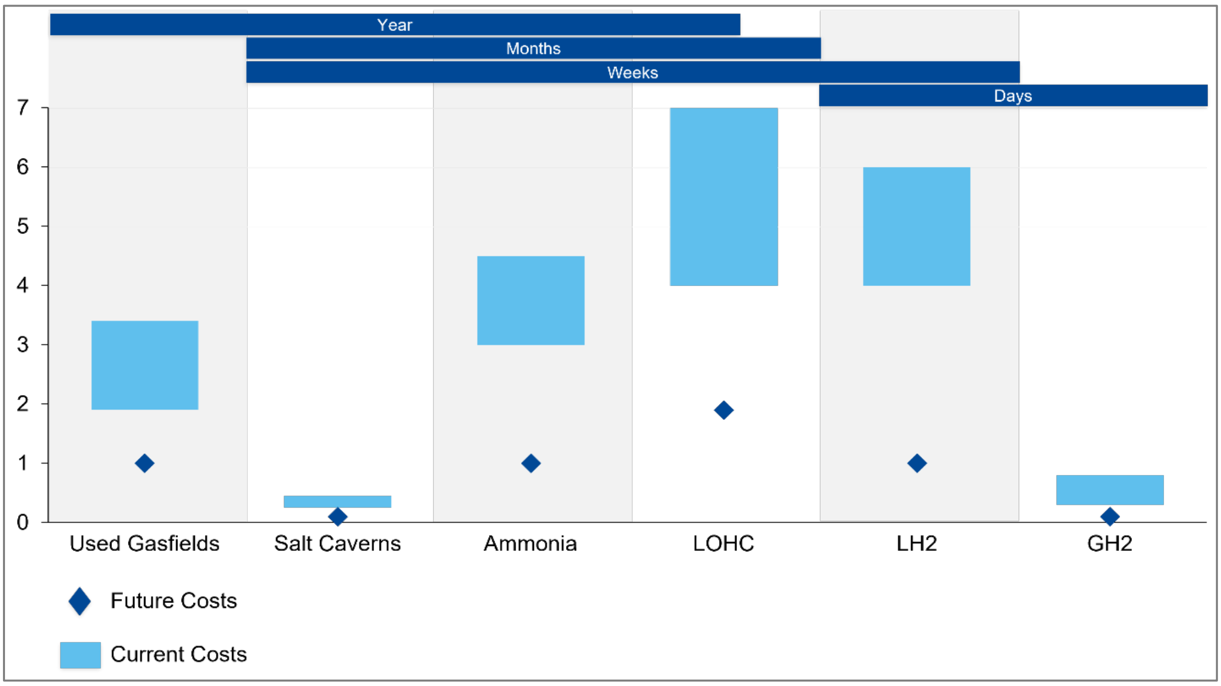
Underground Storage

Underground hydrogen storage involves storing hydrogen in geological formations, such as salt caverns, depleted oil or gas fields, or aquifers. This method leverages the natural barriers provided by geology to safely and efficiently store large volumes of hydrogen.

Pros		Cons	
	Large-scale storage. This method can store vast quantities of hydrogen, making it ideal for balancing seasonal supply and demand variations. **Low-cost at scale**. Beyond the initial development and injection costs, underground storage can be more economical, especially for long-term and large-volume storage needs.		**Geographical limitations**. Feasibility is highly dependent on suitable geological formations being available near hydrogen production or usage sites. **Regulatory and safety concerns**. careful monitoring and management are required to prevent leaks and to ensure safety, potentially complicating regulatory approvals.

Each hydrogen storage method has unique advantages and trade-offs, with specific applications that align with its characteristics. Compressed and liquid hydrogen are best suited for applications needing rapid release and high purity, especially in transport and industrial processes. LOHCs offer promises of safe, large-scale storage and transport, utilising existing infrastructure, although efficiency improvements are still needed. Finally, underground storage presents a solution for massive-scale, long-term storage needs, albeit with geographical and regulatory constraints. The choice ultimately depends on the balance of energy density, safety, weight, and cost-effectiveness requirements for the intended use case.

Figure 1.15. Hydrogen Storage Costs Worldwide
(EUR per kilogram)



LOHC = liquid organic hydrogen carrier.
Source: Authors based on Agora Energiewende and AFRY Management Consulting (2021).

From Figure 1.15, it is evident that hydrogen storage using salt caverns outperforms the other methods in terms of costs. This is due to geological formations occurring naturally, making such a method inexpensive and incurring no construction expenses. However, exploring potential geological formations is a challenge and may be costly, thus the rarity of utilisation at the current stage of hydrogen deployment in ASEAN.

Developing versatile and efficient hydrogen storage infrastructure is crucial to leveraging hydrogen's full potential as a sustainable energy resource. Both pressure tanks and underground storage play essential roles within this infrastructure, catering to different storage needs across the hydrogen value chain. Advances in technology and materials science, alongside strategic planning and regulatory frameworks, will be key to optimising hydrogen storage solutions, making hydrogen a cornerstone of the clean energy transition.

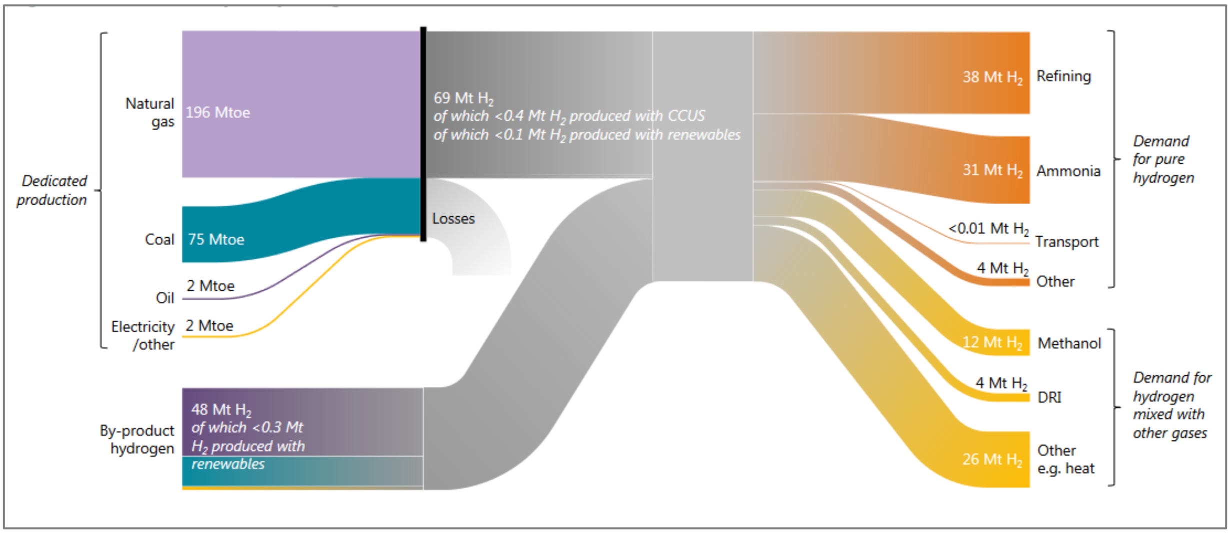
Global Demand and Supply of Hydrogen and Derivatives

This section outlines the current status of hydrogen and ammonia utilisation, development of hydrogen and ammonia technology, and policies that support hydrogen and ammonia utilisation and development globally.

Today, most hydrogen production is reliant on fossil fuels, with about 60% produced in facilities specifically dedicated to its production, primarily from natural gas and, to a lesser extent, coal. A small portion of hydrogen is also produced through water electrolysis.

Additionally, about one-third of the global hydrogen supply is obtained as a by-product from processes originally intended for other production, requiring purification before it can be used. In terms of usage, around 70 Mt of hydrogen/year are needed in forms requiring high purity, mainly for oil refining and ammonia production for fertilizers. There is also a significant demand – about 45 Mt – for hydrogen mixed with other gases, which is used predominantly for methanol production and steel manufacturing. While a considerable portion of hydrogen is linked to the transport sector – particularly for refineries and as a component of vehicle fuel – the direct utilisation of pure hydrogen in FCEVs remains extremely low, with less than 0.01 Mt used per year (Figure 1.16).

Figure 1.16. Status of Hydrogen Production and Utilisation Globally, 2018



CCUS = carbon capture, usage, and storage; DRI = direct reduced iron; Mt = metric tonnes; Mtoe = million tonnes of oil equivalent.
Source: IEA (2019).

Production tends to be localised, with most hydrogen generated close to where it is ultimately used, using resources extracted from the same country. This approach helps minimise the logistical challenges associated with transporting hydrogen. Less than 1% of global hydrogen production is currently produced by water electrolysis and accounts for blue or green hydrogen (IEA, 2019).

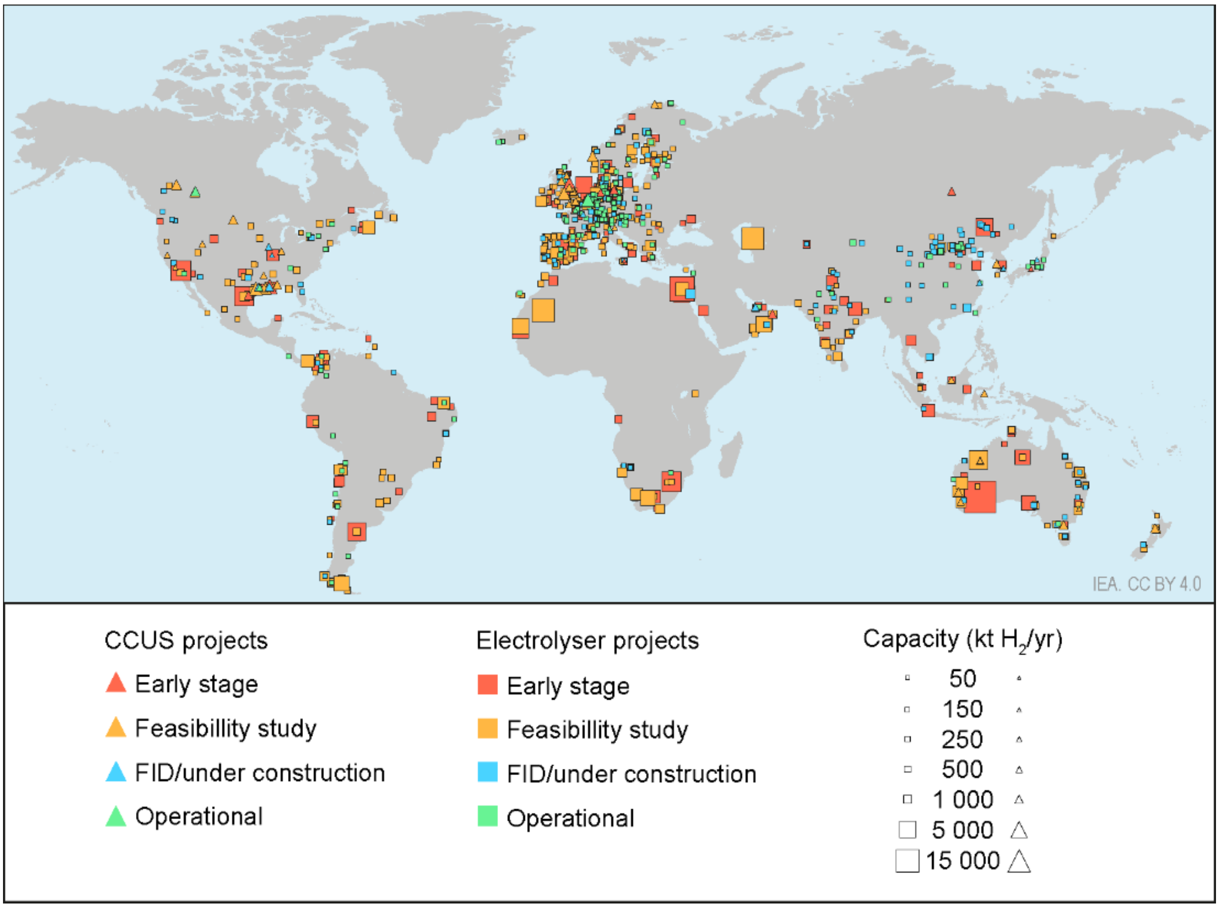
Current hydrogen consumption varies widely across different regions, reflecting each area's unique economic, technological, and policy environments. In 2022, China was at the forefront of global hydrogen use, contributing to 29.0% of worldwide consumption, primarily for chemical production and refining. North America was next, using 17.0% of the global total, followed by the Middle East, which accounted for 13.0%. India and Europe utilised 9.0% and 8.0% of the global total, respectively. The remaining 24.0% was used by other regions around the world (IEA, 2023). In the ASEAN region, current hydrogen demand is around 3.74 Mt/year, mostly for the petrochemical industry (Purwanto and

Rusli, 2024). This number only constituted around 3.3% of the worldwide demand for hydrogen in 2023 (IEA, 2024).

Demand for ammonia and methanol is expected to increase over the next few years due to a greater need for fertiliser and methanol as a maritime fuel. In the long term, steel production and other high-temperature industries can also benefit from using hydrogen to decarbonise the industry. However, due to the technological complexity and high amounts of clean energy needed, this endeavour requires political support and low renewable electricity prices (IRENA, 2022; IEA, 2023; WEC, 2024).

Due to the potentially high offtake, the number of announced projects for green and blue hydrogen production is therefore rapidly expanding (Figure 17). Annual production of hydrogen could reach 38 Mt in 2030 if all announced projects are realised, although 17 Mt would come from projects at early stages of development. Only 4% of these potential projects have made a final investment decision, double since last year in absolute terms reaching nearly 2 Mt. Of the total, 27 Mt are based on electrolysis and low-emissions electricity and 10 Mt on fossil fuels with CCUS (IEA, 2023).

Figure 1.17. Map of Announced Low-emissions Hydrogen Production Projects



CCUS = carbon capture, usage, and storage; FID = final investment decision.
Source: IEA (2023).

The private sector has also begun adopting green and blue hydrogen, driven by various factors including compliance with decarbonisation policies, government signals favouring hydrogen adoption, public reputation considerations, and strategic decisions to lead in technology development and new markets. As a result, many companies have begun agreements to utilise hydrogen and hydrogen-based fuels. Most are still in the preliminary stages – often in the form of memoranda of understanding or letters of intent. More than 2 Mt of green and blue hydrogen demand can be unlocked by 2030 from these agreements, even if only around half of that demand comes from realised deals.

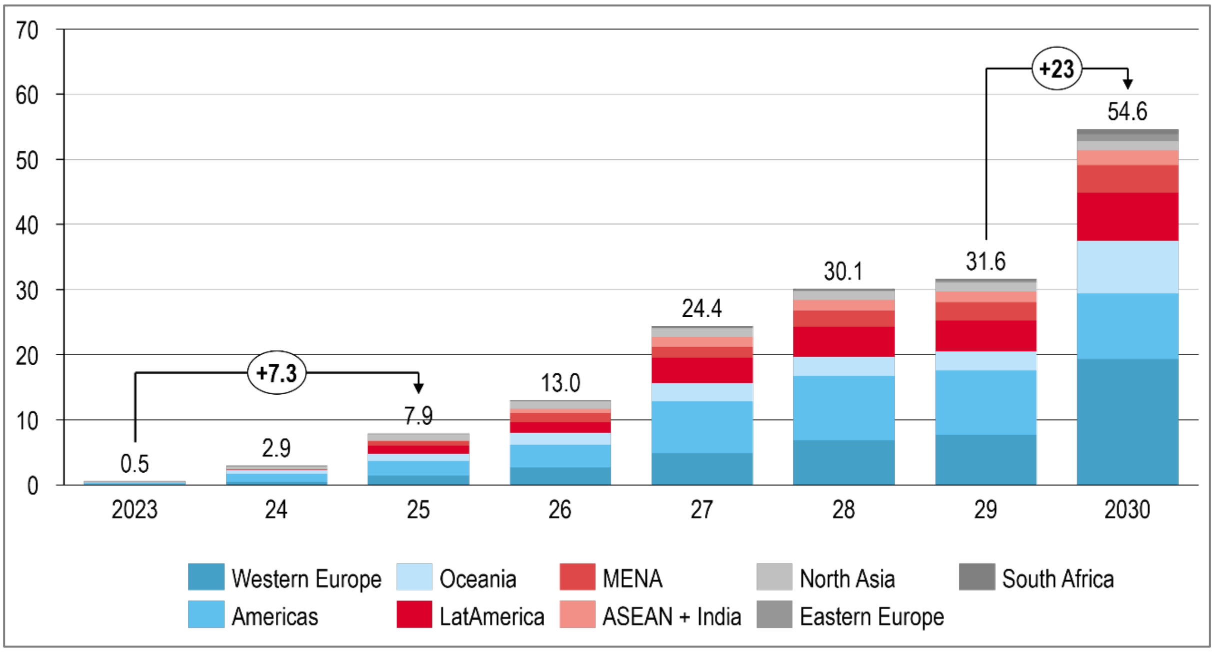
The hydrogen market's growth trajectory must therefore be supported by a confluence of policy initiatives, technological progress, and a collective commitment to decarbonisation. As the market evolves, strategic investments and international cooperation will be critical to realise hydrogen's potential as a cornerstone of the global energy transition, ensuring a balanced and sustainable demand-supply dynamic.

Europe is leading in policy support and investment in hydrogen technologies, aiming to become a global hydrogen hub by leveraging its renewable energy capacity and technological expertise. The Asia-Pacific region has a significant opportunity here as well, with Japan and South Korea prioritising hydrogen in their energy strategies to achieve carbon neutrality. North America's hydrogen market has been buoyed by policy incentives such as the Inflation Reduction Act in the US, which aims to accelerate the deployment of clean hydrogen technologies. The Middle East is positioning itself as a key player in the global hydrogen export market, capitalising on its vast renewable energy resources and existing energy infrastructure.

ASEAN upholds great potential to become a low-carbon (i.e. blue and green) hydrogen exporter, considering its abundance of renewable energy. Most AMS are promoting the use of hydrogen in decarbonising various sectors through their national hydrogen strategies and incorporating hydrogen into their national energy policies. The rest of the world is gradually embracing hydrogen, with initiatives underway to explore its potential in local energy systems and transport sectors.

Figure 1.18. Estimated Supply of Hydrogen by Region Based on Current Project Pipeline

(millions of metric tonnes per year)



Americas = North and South America, MENA = Middle East and North Africa.

Source: Hydrogen Council and McKinsey & Company (2023).

Figure 1.18 illustrates the expected increase in worldwide hydrogen output. It is anticipated that production capacity will grow by a factor of 10 from 2024 to 2030. The regions with the highest production capacity in 2030 are expected to be the Americas and Western Europe, followed by Oceania and the Middle East and North Africa. The data emphasise a rapid growth trajectory, with production capacity rising from a minimal base in 2021 to a projected 55 Mt by 2030.

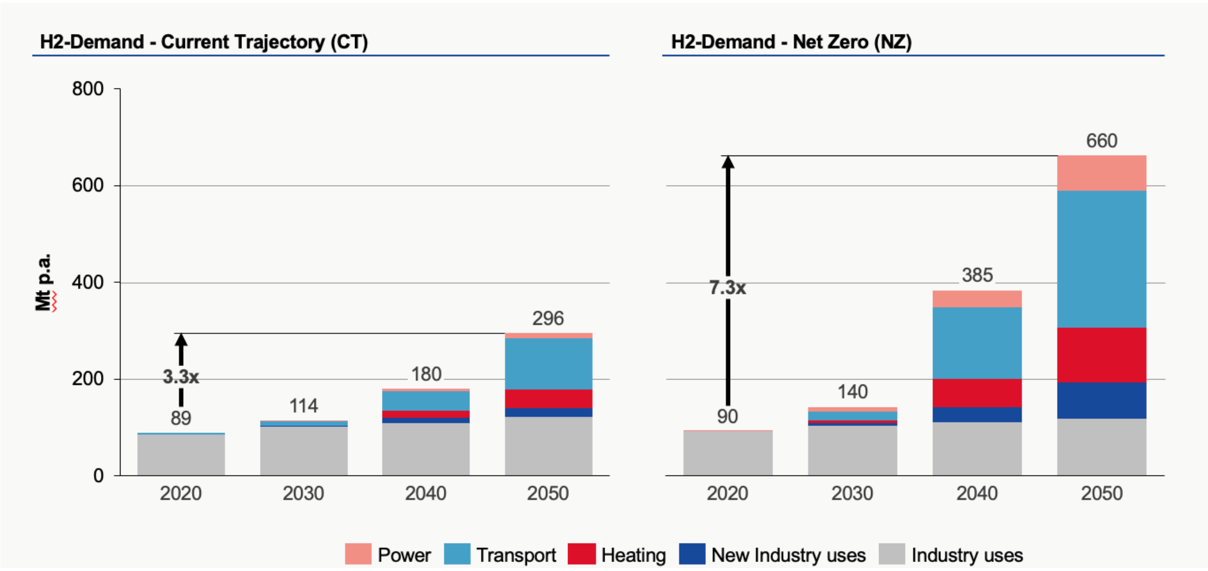
From the announced projects, hydrogen capacity growth would mainly be due to renewable sources, such as solar and wind. By 2025, there will be an additional of 4.5 Mt/year of green hydrogen; 25.6 Mt/year will be developed by 2030, compared to the 2023 level. North America is planning to increase its blue hydrogen capabilities, announcing the production of 1.96 Mt/year of blue hydrogen by 2025. China's hydrogen capacity will mainly be sourced from renewable energy through electrolysers, as it has announced a goal of 3.6 gigawatts of electrolysers by 2030 (Hydrogen Council and McKinsey & Company, 2023).

While hydrogen is promising for its wide range of applications, its widespread adoption has been hindered by competitiveness challenges against incumbent fossil fuels and other
low-emissions technologies as well as the immaturity of end-use technologies. However, efforts towards decarbonisation are expected to spur increased hydrogen utilisation, especially in sectors struggling with emissions reduction where alternative low-emissions technologies are scarce.

Traditional applications – including refining; utilisation as a feedstock for ammonia, methanol, and various chemicals; and its role as a reducing agent in DRI production – currently account for a hydrogen demand of 90 Mt/year. This demand is projected to increase to 120 Mt/year by 2050. Additionally, these applications have use in sectors such as electronics, glassmaking, and metal processing, amounting to 1 Mt/year (IRENA, 2022).

Potential new applications – including 100% hydrogen DRI, transport, fuel production (e.g. ammonia or synthetic hydrocarbons), biofuel upgrading, high-temperature industrial heating, and electricity storage and power generation – present a wide range of new demand volumes influenced by the market penetration of different carbon-neutral technologies and policy implementations. Under the current trajectory scenario, an estimated demand of 180 Mt/year of hydrogen is anticipated due to such new applications, with the transport sector constituting the bulk. Under the net-zero emissions scenario, a demand of 540 Mt/year has been estimated, driven further by these emerging demand sectors (Hydrogen Council and McKinsey & Company, 2023). Figure 1.19 demonstrates the increasing demand over time. It is evident that demand rises under both the current trajectory and the net-zero emissions scenario from 2030 onwards.

Figure 1.19. Hydrogen Demand Scenarios
(million tonnes per year)



Notes:

1. Current Trend (CT) – The ongoing decline in renewable energy costs persists, yet existing policies are insufficient to meet 2030 objectives. Developed regions are on track to achieve 2050 targets, while long-term cost reduction trends endure. This trajectory anticipates a global temperature rise of 1.9–2.9°C.
2. Net Zero (NZ) – From an industry standpoint, this approach quantifies the necessary deployment of hydrogen to attain a net-zero emissions pathway, with an emphasis on meeting 2030 targets. It underscores hydrogen's potential role in the energy landscape and decarbonisation efforts, projecting a global temperature increase of 1.5–1.8°C.

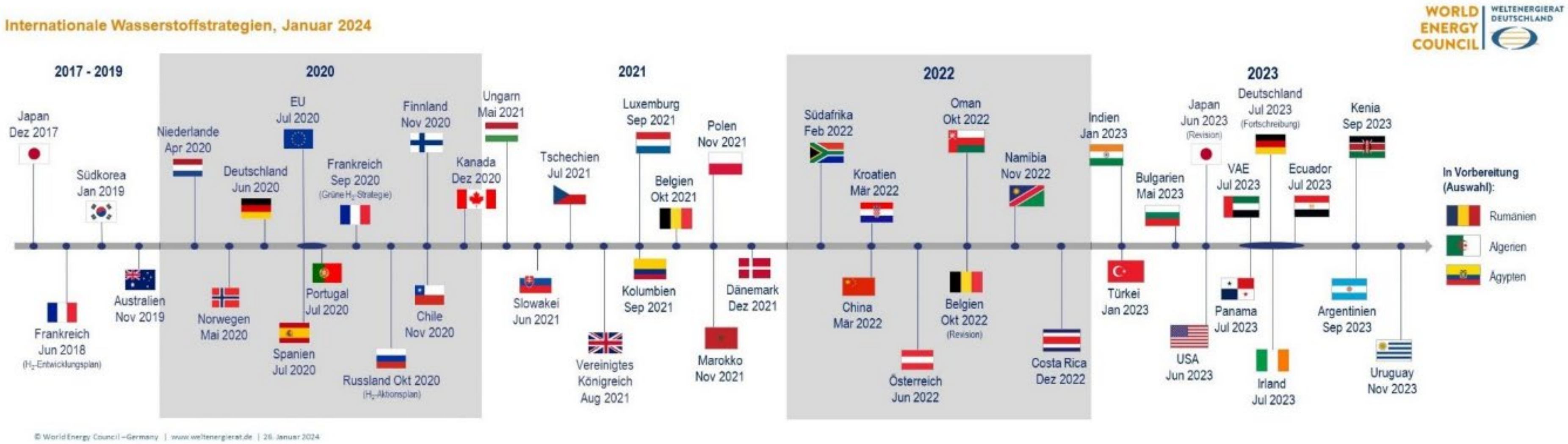
Source: Hydrogen Council and McKinsey & Company (2023).

With the anticipated surge in demand across various sectors, policymakers must prioritise supportive regulations and incentives to facilitate the deployment of carbon-capture technologies and the expansion of renewable energy sources essential for electrolytic hydrogen production. To achieve a sustainable energy transition and to meet future hydrogen demand projections, it is crucial to foster international cooperation, bolster investments in technology development, and ensure a strategic alignment of policy frameworks globally.

Comparison of National Hydrogen Strategies Globally

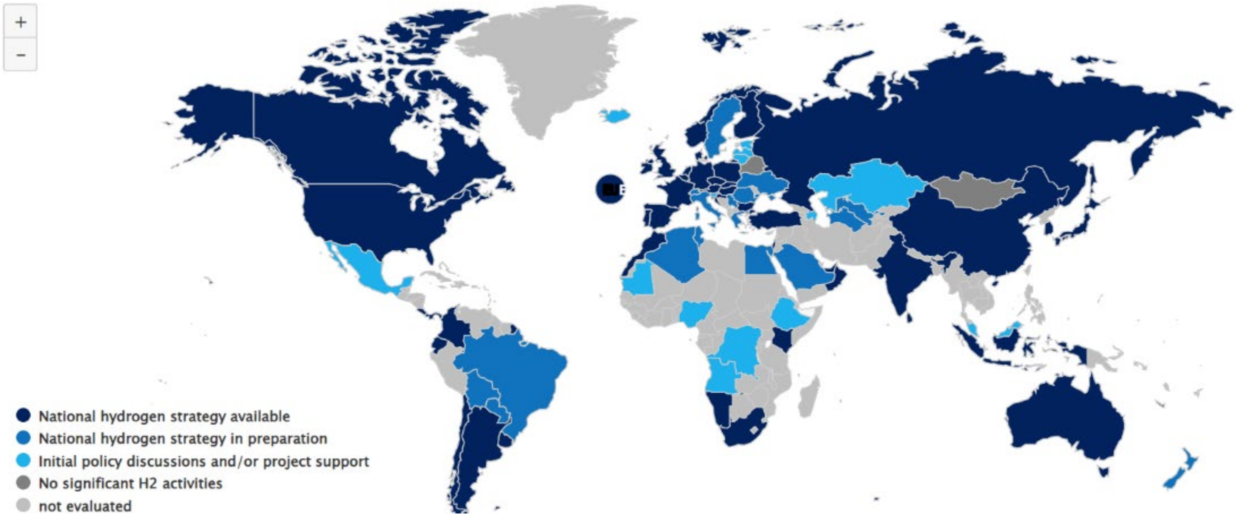
National hydrogen strategies differ in terms of their priorities and measures. However, the motivation to create a hydrogen strategy is often similar – reducing national GHG emissions, increasing the integration of renewable energies, and diversifying energy sources. Through these strategies, many countries are also highlighting opportunities for economic growth, such as through job creation, technological developments, and additional revenue from hydrogen and technology exports. Developed nations hope that a domestic hydrogen economy will help them become global competitors. There are now 41 national hydrogen strategy documents and 4 revisions or updates at the government level in the world. Countries representing over 80% of global gross domestic product are expected to have their own hydrogen strategies by 2025 (WEC, 2024).

Figure 1.20. Published and Updated Hydrogen Strategies in Chronological Order



Source: WEC (2024).

Figure 1.21. Countries with Available or Announced Hydrogen Strategies



Source: Authors based on WEC (2022).

An effective hydrogen strategy, analysed across various national approaches, should incorporate these four key points:

Production and infrastructure development. Specific targets should be established for hydrogen production capacity (e.g. X gigawatts of electrolysis capacity by 2030) and infrastructure rollout, ensuring that these goals are measurable and achievable within a set time frame.

Technological innovation and cost reduction. Clear, quantifiable objectives should be set for technology advancement and cost reduction (e.g. reduce green hydrogen production costs to USDX/kg by 2025), emphasising the relevance of these goals to the strategy's success.

Market creation and sectoral integration. Specific sectors (e.g. transport, industry, power generation) should be identified for hydrogen integration, with measurable targets for hydrogen adoption (e.g. X% of city buses powered by hydrogen by 2030), making these goals achievable through supportive policies.

International cooperation and standards. Governments should commit to establishing or participating in international partnerships or agreements by a certain date to secure hydrogen supply chains and to develop global standards, ensuring that these efforts are relevant to enhancing the strategy's effectiveness and are time-bound.

Moreover, the development and deployment of hydrogen must be supported by targeted financial mechanisms. Japan's Green Innovation Fund, for example, demonstrates how subsidies and grants can lower green hydrogen production costs, thereby encouraging adoption across various sectors. In the US, the Inflation Reduction Act uses tax incentives to make clean hydrogen production financially attractive, promoting a shift away from fossil fuels. The European Investment Bank is facilitating such a transition by offering low-interest loans for hydrogen projects, easing the financial burden for developers. Further, public-private partnerships, like Australia's Hydrogen Energy Supply Chain project, illustrate the effectiveness of collaborative investments in establishing hydrogen infrastructure. Meanwhile, the European Union's Emissions Trading System incentivises cleaner energy alternatives through carbon pricing, thereby increasing demand for green hydrogen.

The United Kingdom's Hydrogen Production Business Model, Germany's Carbon Contracts for Difference, and a similar scheme forthcoming from Japan aim to incentivise low-emissions hydrogen usage. Canada and the European Commission are also considering similar programmes. Denmark, India, and the Netherlands offer direct payments for hydrogen production over specified periods through competitive bidding schemes.

Box 1.1. Germany's National Hydrogen Strategy

Germany's *National Hydrogen Strategy* (NHS) aims to integrate hydrogen technology into the nation's energy, industrial, and transport sectors as a key component of its transition to a climate-neutral economy by 2045. The strategy outlines ambitious targets for 2030, which include doubling the national target for electrolyser capacity to at least 10 gigawatts and ensuring the development of an efficient hydrogen infrastructure and market. These goals underscore Germany's commitment to becoming a global leader in hydrogen technology by fostering a competitive and secure supply chain for hydrogen production and use.

Germany's approach to fostering hydrogen technology involves a comprehensive array of policy and funding instruments:

IPCEI funding. Germany participates in the Important Projects of Common European Interest (IPCEI) initiative to support the development of hydrogen technologies, emphasising
large-scale projects and international collaboration.

Regulatory framework. The strategy outlines measures to streamline planning and approval processes and to establish uniform standards and certifications for hydrogen technologies.

Financial incentives. Germany provides significant financial support for hydrogen projects through national funding programmes and European Union initiatives, focussing on both domestic production and the import of hydrogen.

Research and innovation. The strategy emphasises strengthening research, innovation, and training of professionals to maintain technological leadership and to support industry transformation.

The governance of the NHS involves several committees and platforms:

National Hydrogen Council. The council provides advisory support to the federal government, monitoring the implementation of the NHS and suggesting adjustments as necessary.

European and international collaboration. Germany actively engages in European and global fora to promote international standards and collaboration, ensuring the integration of the NHS with broader international efforts.

Sector-specific committees. These committees oversee the application of hydrogen technologies in various sectors, including industry, transport, and energy, to ensure that each sector contributes effectively to the overarching goals of the NHS.

The NHS is a forward-looking plan that integrates innovative funding models, regulatory frameworks, and international cooperation to establish Germany as a leader in hydrogen technology. The strategy not only focusses on technological and economic aspects but also emphasises sustainability and security, aligning with global energy transition goals. By setting a robust framework for hydrogen adoption, Germany aims to significantly contribute to global efforts towards achieving climate neutrality and enhancing energy security.

Source: BMWK (2023).

Box 1.2. Japan's Basic Hydrogen Strategy

Japan's hydrogen strategy, formalised in the *Basic Hydrogen Strategy*, sets a multifaceted goal to transition to a hydrogen-based society by harnessing hydrogen's potential for energy security, economic growth, and environmental sustainability. The strategy emphasises the need for a stable, inexpensive, and blue and green hydrogen supply, aiming to significantly increase Japan's hydrogen intake to 3 million tonnes/year by 2030 and 20 million tonnes/year by 2050. This ambitious target supports Japan's broader vision for carbon neutrality by 2050, promoting hydrogen as a key pillar in its energy and industrial policies.

To achieve these targets, Japan has developed the following policy measures and funding instruments:

Green Innovation Fund. Launched alongside the 2050 Carbon Neutrality Declaration, the fund allocates substantial resources (approximately JPY800 billion) specifically for hydrogen-related technologies. This includes development and demonstration projects aimed at reducing costs and enhancing the production and utilisation of hydrogen.

Regulatory support. Japan has enacted policies that favour the development of a domestic and international hydrogen supply chain. Initiatives include tax incentives, direct subsidies, and regulatory adjustments designed to foster market environments conducive to hydrogen adoption.

International collaboration. Japan emphasises strengthening its international partnerships, engaging in multinational frameworks, and contributing to the setting of global standards for hydrogen technologies and safety.

The governance of Japan's hydrogen strategy involves several key committees and frameworks:

Ministerial Council on Renewable Energy, Hydrogen and Related Issues. This council oversees the implementation of the hydrogen strategy, coordinating various government bodies and stakeholders.

Strategic Road Map for Hydrogen and Fuel Cells. Updated periodically, this strategic document outlines specific steps for technology development, regulatory changes, and market creation strategies. It serves as a guide for both public and private sector activities related to hydrogen.

International partnerships and standardisation efforts. Japan actively participates in international bodies focussed on energy policies and hydrogen technologies. It leads and collaborates on efforts to develop international standards, which is crucial for the global trade and application of hydrogen technologies.

Japan's hydrogen strategy exemplifies a comprehensive approach to integrating hydrogen into its national energy and economic framework. By setting clear targets, establishing supportive policies, and actively engaging in international collaborations, Japan has positioned itself as a leader in the transition towards a sustainable, hydrogen-based global economy. The strategy's focus on innovation, safety, and international competitiveness highlights its role as a blueprint for other nations aiming to realise similar transformations.

Source: Ministerial Council on Renewable Energy, Hydrogen and Related Issues (2023).

Comparing the available strategies, common goals, differences, and synergies are highlighted below.

Common Goals

Decarbonisation. All strategies aim to reduce carbon emissions and to transition towards cleaner energy systems.

Technology development. All strategies emphasise the development and deployment of hydrogen technologies, such as electrolysis, fuel cells, and hydrogen infrastructure.

Market development. Efforts are focussed on creating markets for hydrogen across various sectors, including industry, transport, and power generation.

International collaboration. Many strategies emphasise collaboration with other countries and international organisations to share knowledge, resources, and best practices in hydrogen development.

Differences

Resource availability. Strategies vary in their approaches based on the availability of renewable energy resources and existing infrastructure in a country. For example, countries with abundant renewable energy prioritise green hydrogen production, while others focus on blue hydrogen using fossil fuels with CCS.

Sectoral focus. Strategies differ in their emphasis on specific sectors for hydrogen deployment. Some prioritise transport, while others focus on industrial applications or power generation.

Policy instruments. There are differences in the policy instruments used to support hydrogen development, including subsidies, incentives, regulations, and targets. Some strategies rely more on market mechanisms, while others emphasise governmental intervention.

Scale and ambition. Strategies vary in their scale and ambition, with some countries setting more ambitious targets for hydrogen production, deployment, and investment.

Synergies

Research and innovation. Many strategies highlight the importance of research and innovation in advancing hydrogen technologies and reducing costs. Collaborative research programmes and technology demonstrations facilitate knowledge sharing and accelerate technology development.

Infrastructure development. Collaboration on infrastructure development, such as hydrogen production, storage, and distribution facilities, help create a more interconnected and efficient hydrogen market.

Policy alignment. Harmonising policies, regulations, and standards across countries creates a conducive environment for investment and market growth. Sharing policy best practices and lessons learned facilitates alignment and coordination.

Potential Trade-offs

Research availability. Countries rich in renewable energy resources, such as wind or solar (e.g. Australia and Morocco), prioritise green hydrogen, which is produced using renewable electricity. Others with abundant natural gas reserves (e.g. Russia and the US) lean towards blue hydrogen. These choices impact global GHG emissions and influence the cost and scalability of hydrogen. The trade-off here lies in balancing cleaner but potentially more expensive green hydrogen versus more affordable but carbon-intensive blue hydrogen.

Sectoral focus. Countries prioritise sectors that align with their economic strengths. For instance, Germany has a strong focus on heavy industry and emphasises hydrogen for steel production and manufacturing. Japan, with a focus on energy imports and automotive innovation, prioritises hydrogen for transport and power. This sectoral focus leads to trade-offs in investment, as countries fund hydrogen projects beneficial to certain sectors at the expense of others, potentially fragmenting global progress.

Policy approaches. Some countries or regions emphasise heavy governmental support for hydrogen infrastructure (e.g. the European Union's Hydrogen Strategy), while others take a market-driven approach, relying on private investment. This results in different levels of hydrogen adoption speed and infrastructure development. For instance, strong governmental support can expedite adoption but may create dependency on subsidies, while a market-driven approach may limit rapid scaling up.

Overall, while there are differences amongst published national hydrogen strategies, there are also significant synergies and opportunities for collaboration to accelerate the global transition to a hydrogen-based economy and to achieve common decarbonisation goals.

Chapter 2

The Hydrogen and Ammonia Landscape in the ASEAN Region

The ASEAN region stands at the crossroads of a pivotal energy transition. This transition is not only a shift from fossil-based to renewable energy sources but represents a profound transformation in the way that energy is produced, distributed, and consumed across the 10 AMS. At the heart of this transformation is the dual imperatives of climate-change mitigation and the drive for sustainable development. ASEAN's energy transition is underpinned by the collective recognition of the region's vulnerability to climate-change impacts, such as rising sea levels, extreme weather events, and disruptions to biodiversity and ecosystems. These challenges are compounded by the region's rapid economic growth, urbanisation, and increasing energy demand. As a result, the energy transition in ASEAN is not only an environmental but also an economic and social one.

ASEAN economic ministers endorsed the *ASEAN Strategy for Carbon Neutrality* on 19 August 2023, a visionary strategy that helps unlock this huge economic opportunity in the region by promoting renewable energy integration, CCUS, and hydrogen production and use technologies and emphasising key sectors like power generation, industry, and transport (ASEAN Secretariat, 2023). The strategy outlines eight critical strategies to bolster regional cooperation in achieving ASEAN's carbon-neutrality goal and promoting sustainable growth and environmental stewardship across the region.

Accelerate green value chain integration. The development and adoption of green products across the region must be sped up.

Promote regional circular economy supply chains. The use of recycled materials and sustainable practices must be encouraged to reduce waste.

Connect green infrastructure and markets. Cross-border infrastructure must be developed for electric, hydrogen, and flex-fuel vehicles across AMS to support renewable energy integration and to enable regional power trading across ASEAN.

Enhance interoperable carbon markets. A unified carbon trading system must be created that allows emissions trading across AMS.

Foster credible and common standards. Consistent, rigorous standards must be developed and enforced for environmental performance across various sectors.

Attract and deploy green capital. Financial investments must be secured for green projects to drive the economic transition towards sustainability.

Promote green talent development. Education and workforce development in green technologies and practices must be supported, facilitating knowledge exchange and mobility within ASEAN.

Share green best practices. Successful policies and technologies must be shared amongst AMS to enhance regional environmental strategies.

Given each AMS's energy mix and varied potential to introduce renewable energy, covering all additional electricity demand in the ASEAN region with renewable energy is unrealistic. Thus, it is important to pursue credible, greener pathways in line with supply and demand as well as each AMS's energy demands, especially for power generation, transport, and industrial processes. Amongst such pathways, blue and green hydrogen and ammonia have the potential to contribute significantly to the decarbonisation of ASEAN's energy systems by offering a practical, carbon-free hydrogen storage and transport vector as well as a green fuel.

This chapter explores AMS ambition to reach energy transition and carbon-neutrality targets. The role of hydrogen and ammonia in fostering these targets in AMS is analysed, and the current policies and research and development status of hydrogen and ammonia production and use in AMS are also examined.

3.1. Overview of Energy Transition and Carbon-neutrality Targets

ASEAN's approach to energy transition is characterised by a blend of regional frameworks and country-specific initiatives. The *ASEAN Plan of Action for Energy Cooperation* serves as a blueprint for energy cooperation from 2016 to 2025, aiming to increase renewable energy in the energy mix to 23% by 2025 (ACE, 2021). This target is supported by strategies to enhance energy connectivity and market integration, promoting the advancement of renewable and alternative energy sources across AMS.

In addition, as noted previously, the *ASEAN Strategy for Carbon Neutrality* outlines eight strategies that will deliver four key outcomes for the region: (i) development of green industries, (ii) interoperability within ASEAN, (iii) globally credible standards, and (iv) development of green capabilities. Furthermore, individual AMS have set various carbon-neutrality/net-zero and energy transition targets (Table 2.1).

Table 2.1. ASEAN Member States' Energy Transition and Climate Targets

	Target Year	Greenhouse Gas Reduction Targets	Energy Transition Targets
Brunei Darussalam	2050	By 2030: Reduce national GHG by 20% from the BAU level. By 2035: Reduce GHG to more than 50% in comparison to the BAU. By 2050: At the COP26, Brunei expressed interest in reaching net-zero emissions by 2050.	By 2025: Increase its share of renewable energy, particularly from PV to 200 MW. By 2030: Increase the share of power generation from renewable energy accounts to at least 30% of the total capacity in the power generation mix using mainly solar PV. To support the development of renewable energy sources, the government plans to introduce renewable energy policy and regulatory frameworks.
Cambodia	2050	Long-Term Strategy for Carbon Neutrality: By 2050: The strategy aims to guide Cambodia towards a carbon-neutral economy by 2050.	Power Development Plan 2022–2040: By 2040: Have 3,155 MW of solar capacity and 3,000 MW of hydropower capacity. Although Cambodia has issued policies and regulations in the energy sector, the government has not yet set a national target for renewable energy utilisation.
Indonesia	2060	By 2060: A roadmap for energy transition aims to help Indonesia achieve its carbon-neutral target by 2060. The government has prepared four strategies to reduce carbon emissions.	Goals for the share of renewable energy of the total energy mix: By 2025, 17–19%; by 2030, 19–21%; by 2040, 38–41%; by 2060, 70–72%.
Lao People' s Democratic Republic	2050	Nationally Determined Contribution: By 2030: Unconditional emissions reduction target of 60% relative to BAU.	Renewable Energy Development Strategy (2011): By 2025: Achieve 30% of total energy consumption from renewable sources as well as ensure 10% of total transport energy uses biofuels.

	Target Year	Greenhouse Gas Reduction Targets	Energy Transition Targets
Malaysia	2050	By 2030: Reduce GHG emissions by 45%. By 2050: Achieve carbon neutrality as part of the Twelfth Malaysia Plan.	In August 2023, Malaysia revised its target of renewable energy installed capacity with a focus on solar panel installation of: By 2040: 40% By 2050: 70%
Myanmar		By 2030: Reduce 244.52 million tonnes of CO_2e unconditionally and a total of 414.75 million tonnes of CO_2e subject to conditions of international finance and technical support.	By 2030: 30% renewable energy in rural electrification and 12% renewable energy in the national energy mix.
Philippines		By 2030: Cut GHG emissions by 75% (2.71% unconditional and 72.29% subject to international support).	By 2030: Achieve a 35% share of renewable energy in its power generation mix. By 2040: Reach a 50% share of renewable energy.
Singapore	2050	Reduce emissions to around 60 million tonnes CO_2e in 2030 after peaking emissions earlier.	By 2030: Deploy at least 2 GW of solar energy. By 2035: Import 4 GW of low-carbon electricity.
Thailand	2065	By 2030: Reduce GHG emissions by 30%.	The share of renewable electricity generation will be at least 50% of new power generation capacity. By 2037: Solar energy projected comprises over 80% of the planned renewable energy mix.
Viet Nam	2050	By 2030: Reduce total national GHG emissions by 43.5% compared to BAU. By 2050: Total national GHG emissions reach the net emission level of zero.	Developing new energy production to serve domestic and export demand.

BAU = business as usual, CO_2e = carbon dioxide equivalent, GW = gigawatt, GHG = greenhouse gas, MW = megawatt, PV = photovoltaic.
Source: Authors based on ACE.

The energy transition in ASEAN is not without its challenges, however. Financial constraints, technological barriers, and infrastructure needs pose significant hurdles. Yet these challenges also present opportunities for innovation, regional cooperation, and the development of a green economy. Investment in renewable energy technologies, coupled with policies that encourage energy efficiency and conservation, can drive economic growth while ensuring environmental sustainability.

The role of international partnerships and funding mechanisms in ASEAN's energy transition cannot be overstated. Financial and technical support from global institutions and developed nations is crucial to helping AMS achieve their energy and climate targets.

Emphasis on the energy and transport sectors is also key to achieving carbon neutrality throughout ASEAN. As of 2024, around 77% of the GHG emissions in ASEAN were generated from energy, industrial, and land-use processes, including land-use change and forestry, while the global energy sector recorded around 75% of total GHG emissions (ACE, 2024a). Hydrogen and ammonia are emerging as key players in 'greening' these sectors, particularly in replacing traditional fossil fuels and reducing carbon footprints. Moreover, in transport, the adoption of hydrogen and ammonia can significantly decrease GHG emissions, especially in heavy industries and public transit systems.

2.2. Role of Hydrogen in Energy Transition and Carbon Neutrality

This section delves into the strategic importance of blue and green hydrogen in the energy transition efforts of AMS, highlighting its potential to bridge the gap between renewable energy production and the diverse energy needs of various AMS.

Blue and green hydrogen can play a multifactor role in ASEAN's energy ecosystem, from decarbonising hard-to-abate sectors such as heavy industry and transport to facilitating energy storage and enhancing grid stability. The urgency for ASEAN to incorporate blue and green hydrogen into its energy transition strategies is underscored by the region's growing energy demand, its commitment to the Paris Agreement, and the collective aspiration to achieve carbon neutrality. Indeed, the strategic deployment of blue and green hydrogen technologies could significantly reduce GHG emissions, decrease dependency on imported fossil fuels, and catalyse the development of a regional low-carbon economy.

In addition, blue and green hydrogen development can bolster energy security in a region heavily dependent on imported fossil fuels. By diversifying the energy mix with blue and green hydrogen that can be produced locally from renewable sources, the region can reduce its vulnerability to the geopolitical risks affecting global energy prices. Blue and green hydrogen not only provide a sustainable alternative to conventional energy sources but also support the creation of resilient local energy networks that can sustain economic growth and environmental objectives.

Furthermore, as countries in the region ramp up their renewable energy capacities, the intermittent nature of sources like solar and wind necessitates innovative solutions for energy storage and management. Blue and green hydrogen emerge as compelling options, serving as clean energy carriers as well as means to store surplus renewable energy, thereby enhancing grid reliability and facilitating a higher penetration of renewables.

To summarise, the use of hydrogen in the industry, transport, and power sectors can certainly propel the energy transition and reaching carbon-neutrality targets:

Industrial sector. Heavy industries – such as steel, cement, and chemicals – are amongst the hardest to decarbonise due to their reliance on high-temperature processes and the lack of viable electric alternatives. Blue and green hydrogen can serve as a clean fuel for high-temperature heat and as a feedstock for green chemicals and materials, significantly reducing industrial carbon emissions.

Transport sector. ASEAN's transport sector, a significant contributor to regional GHG emissions with around 37.8% of the total emissions in 2023 (ACE, 2024a), can benefit from hydrogen fuel-cell technologies. From buses and trucks to marine and even aviation applications, hydrogen offers a path towards zero-emissions transport, with several AMS exploring hydrogen-powered public transport pilot projects.

Power generation sector. Hydrogen helps decarbonise power generation, particularly in conjunction with natural gas in gas turbines to lower the carbon intensity of electricity. Additionally, hydrogen can serve as a long-duration energy storage solution, balancing supply and demand over varying time frames.

As of 2024, 4 out of 10 AMS have published a hydrogen strategy, with different focusses for the end-use of hydrogen (Figure 2.1). Others have created plans of action to adopt hydrogen in the future. Table 2.2 provides an overview of these strategies with a focus on the hydrogen/ammonia value chain.

Figure 2.1. Timeline of the Release of ASEAN Member States' Hydrogen Strategies

Source: ACE (2024c).

Table 2.2. ASEAN Member States with Hydrogen Strategies and Focus Areas

Country	Hydrogen Strategy	End-use			Value Chain		
		Transport	Power Generation	Industry	Export	Production	Technology
Indonesia	Blue and green hydrogen are set to replace fossil fuels in all industries and power generation and to become one of the main fuels in the transport sector by 2060. The country is aiming to ensure energy security, develop the domestic hydrogen market, and export hydrogen and ammonia.						
Malaysia	Malaysia is actively pursuing a hydrogen economy as part of its commitment to a blue and green future. The government aims to achieve a target income of MYR12 billion by 2030 through the hydrogen economy.						

Country	Hydrogen Strategy	End-use: Transport	End-use: Power Generation	End-use: Industry	Value Chain: Export	Value Chain: Production	Value Chain: Technology
Singapore	Singapore is focussing on technology leadership and workforce training. Hydrogen can play a major role in decarbonising the Singapore energy sector by 2050 with potential electricity generation from hydrogen.	low focus	high focus	medium focus	no focus	no focus	high focus
Viet Nam	By 2030, Viet Nam aims to produce blue and green hydrogen of around 0.1 million–0.5 million tonnes/year and to develop the hydrogen energy market in line with the fuel transition roadmap in various sectors of the economy. By 2050, it aims to 10 million–20 million tonnes/year by 2050 and to promote the application of green hydrogen energy and hydrogen-derived fuels in all energy sectors	low focus	medium focus	high focus	high focus	medium focus	low focus

= no focus; = low focus; = medium focus; = high focus

Sources: Authors based on TÜV SÜD (2024a), MTI (2022), MOSTI (2023), MEMR (2024), Purwanto and Rusli (2024), Agora Energiewiende and AFRY Management Consulting (2024).

The hydrogen strategies of Indonesia and Malaysia focus on the transport sector, while this sector plays a subordinate role in the strategies of Viet Nam and Singapore. The industrial sector is addressed by all strategies, with Viet Nam focussing on it the most; Viet Nam stands out for its desire to become an export nation for blue and green hydrogen. In other strategies, however, export is only considered tangentially. Except for Singapore, all surveyed AMS address hydrogen production in the future. Singapore focusses on technology leadership and workforce training in relation to hydrogen. All seem to recognise the opportunities that arise from the use of hydrogen or ammonia as a carrier.

Policy and Regulation Support for Hydrogen and Ammonia

As previously stated, several AMS have developed national strategies and roadmaps specifically tailored to the integration of hydrogen and ammonia into their energy systems. These strategic documents often set clear targets for hydrogen production and use; outline priority sectors; and propose frameworks for research, development, and commercialisation. Recognising the potential of blue and green hydrogen, several AMS have initiated policies and strategies to support their development.

In general, creating a cohesive national hydrogen strategy begins with focussed research and development to lay the foundational knowledge and technological groundwork for hydrogen applications in a country. This phase involves funding research projects; supporting innovations in hydrogen production, storage, and usage; and fostering collaborations with academia and industry. Next, vision documents and preliminary roadmaps outline hydrogen's potential roles and sets initial goals. These documents should engage stakeholders and the public to gather support and input, detailing a clear vision aligned with national energy and environmental goals. The third step is comprehensive strategic planning, where a detailed national hydrogen strategy is drafted. This includes setting specific targets; outlining policy measures such as incentives and regulatory reforms; and planning the necessary infrastructure development for hydrogen transport, storage, and distribution. The final phase involves implementing the strategy, rolling out pilot projects, building infrastructure, and enacting policies. Continuous monitoring and adjustments must ensure that the strategy remains effective and adaptable to technological advances and market developments over the years (IRENA, 2022; Hydrogen Council and McKinsey & Company, 2021).

Various key policies designed to foster the development and integration of blue and green hydrogen across various sectors should be integrated into a cohesive strategy to accelerate a hydrogen economy (Hydrogen Council and McKinsey & Company, 2021). One policy is an emissions trading scheme, which caps and trades carbon emissions to internalise the cost of carbon, making low-carbon technologies more competitive. Complementing this, a carbon tax directly levies a fee on emissions from economic activities, with the goal of pushing the market away from carbon-intensive solutions. Currently, Singapore and Indonesia are the only AMS with established carbon-pricing policies. However, Brunei Darussalam's pioneering initiatives, the ongoing journeys of Cambodia and Viet Nam, and the plans of Malaysia and Thailand to explore carbon taxes and emission trading systems demonstrate that other AMS are actively considering carbon-pricing policies and a range of approaches and ambitions.

To enhance the economic viability of hydrogen, alternative revenue streams can also be introduced, such as payments for grid services that hydrogen storage can provide, offering a financial boost beyond primary business models. Simultaneously, direct support mechanisms like contracts-for-difference and feed-in tariffs may ensure higher revenue or reduced operational costs, thereby de-risking investments and encouraging new entrants. These initiatives should be supported by regional cooperation frameworks that aim to share knowledge, harmonise standards, and attract investments in hydrogen technologies.

Box 2.1. European Hydrogen Bank

The European Hydrogen Bank (EHB) offers a clear and effective model for ASEAN to follow in ramping up its hydrogen and ammonia markets. Launched by the European Commission, the EHB was designed to address two key challenges: de-risking investments in hydrogen production and bridging the cost gap between renewable hydrogen and fossil fuels.

One of its most notable features is the auction-as-a-service mechanism. This allows member states to allocate national funds to projects that participated in European Union-level auctions but were not selected due to budget constraints. This avoids the need for separate national auctions, reducing administrative burdens and speeding up the funding process. ASEAN could benefit greatly from adopting this strategy, as it allows for more efficient allocation of resources across the region, avoiding duplicated efforts.

The funding mechanism is straightforward yet highly effective. The EHB provides a fixed premium per kilogram of renewable hydrogen produced, covering up to 10 years of operation. This financial support allows producers to confidently invest in large-scale hydrogen production without worrying about fluctuating market prices. This kind of stability is essential for ASEAN, where high initial capital costs and uncertain future demand may deter potential investors.

Additionally, the EHB enhances market transparency, providing critical data on supply, demand, and pricing for renewable hydrogen. ASEAN could replicate this approach to establish a clear view of the region's hydrogen market, which would attract more investors and foster greater regional cooperation.

Financial support mechanisms play a crucial role in the EHB, as governments offer grants and loans to reduce the capital intensity of pioneering hydrogen projects. Similarly, guaranteed offtake agreements provide long-term revenue certainty through fixed-price purchase commitments, enhancing the financial attractiveness of hydrogen initiatives. ASEAN Member States have likewise introduced various support mechanisms, including grants for research and development and subsidies for hydrogen infrastructure development. Singapore has set up a funding programme for energy research. To further mitigate investment risks, investment de-risking mechanisms such as debt guarantees and equity injections are provided, safeguarding against financial losses. Removing economic distortions, the phasing out of fossil fuel subsidies makes hydrogen solutions more economically competitive by levelling the playing field.

Governmental involvement is also deepened through the EHB's public procurement policies, which mandate or prioritise hydrogen solutions in public contracts, thereby creating reliable demand. Return-on-investment de-risking policies, like regulated asset base models, offer financial stability, encouraging deeper capital deployment to hydrogen infrastructure. Quotas and targets mandate specific thresholds for hydrogen use within industries, propelling demand and supporting the growth of the hydrogen market. Finally, the implementation of standards and certifications ensures that all hydrogen products meet rigorous safety and performance criteria, fostering trust and facilitating market acceptance.

Source: EC, European Hydrogen Bank, https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen/european-hydrogen-bank_en

Table 2.3. Hydrogen Policies and Funding Programmes of ASEAN Member States

Country	Hydrogen Policies	Funding Programmes
Indonesia	The National Energy Policy supports renewable energy integration, including hydrogen. It also provides an adequate tariff policy on electricity tariff for hydrogen production units.	Investments are occurring in green energy projects, including hydrogen. Specific volumes for hydrogen are under development.
Malaysia	The *Green Technology Master Plan 2017–2030* supports sustainable energy technologies and establishes the National Hydrogen Economy and Technology Steering Committee.	The National Hydrogen Fund has been established for hydrogen-related projects and technology. Subsidises and incentives for various economic sectors will help them generate and adopt hydrogen.
Singapore	Singapore has the *Green Plan 2030,* Low-carbon Energy Research Funding Initiative, and a strategic focus on hydrogen as part of its energy transition.	SGD55 million has been allocated for blue and green energy research, including hydrogen, while SGD49 million has been committed to energy storage and low-carbon alternatives.
Viet Nam	The country is developing regulations on renewable energy policies, including hydrogen, in the Electricity Law. It is reviewing and supplementing national standards and regulations in accordance with international standards.	

Sources: Authors based on TÜV SÜD (2024a), Agora Energiewiende and AFRY Management Consulting (2024), Purwanto and Rusli (2024), MEMR (2023), MOIT (2024), MOSTI (2023), MTI (2022).

Despite these initiatives, ASEAN faces challenges and policy gaps that need to be addressed to fully unleash the potential of hydrogen and ammonia in the region and globally. These challenges include:

Varied technological readiness. Production, storage, transport, and utilisation technologies for hydrogen are in various stages of maturity and commercial readiness throughout the ASEAN region. Scaling up these technologies while ensuring safety and efficiency remains a hurdle.

Limited infrastructure development. Establishing the necessary infrastructure for hydrogen, including production facilities, pipelines, refuelling stations, and storage, requires substantial investment and strategic planning. As the hydrogen value chain is still under development, this infrastructure often needs to be created from scratch.

Uncertain economic viability. The current cost of blue and green hydrogen production is relatively high compared to conventional fuels and even other renewable energy sources. Thus, achieving cost-competitiveness through technological advancements and economies of scale is crucial (Hydrogen Council and McKinsey & Company, 2023; IEA, 2024).

Lack of policy and regulatory frameworks. Developing comprehensive policies and regulations that support the development of the hydrogen economy – including incentives, safety standards, and market mechanisms – is essential for creating a conducive environment for hydrogen investments.

Overview of Research and Pilot Project Status

The next section provides an overview of current hydrogen and ammonia pilot projects and research and development activities in the ASEAN region.

ASEAN governmental investment in the research and development of hydrogen technologies increased in 2022. This represents a continuation of the trend observed since the mid-2010s, which has accelerated further in the past 2 years. Below are the selected governmental programmes or pilot projects that include support for hydrogen technology demonstration projects since 2020. The pilot project information is based on the limited information available.

Table 2.4. Hydrogen Initiatives by ASEAN Member States

Country	Pilot Projects and Developments
Brunei Darussalam	Japan's Advanced Hydrogen Energy Chain Association for Technology Development has launched a demonstration project for a supply chain of by-product hydrogen shipped using liquid organic hydrogen carriers between Brunei Darussalam and Japan. The first shipment was completed in April 2020.
Cambodia	Cambodia's *Long-Term Strategy for Carbon Neutrality* announced some hydrogen-related measures, including studies and allocation of a budget for research and development.
Indonesia	PT Pertamina is looking to invest USD11 billion to help accelerate its clean energy transition, including developing hydrogen. Mitsubishi is planning a brownfield blue ammonia project, converting an existing 338-tonne/day hydrogen production plant to serve an ammonia plant in Central Sulawesi.
Malaysia	Sarawak Energy has developed a pilot hydrogen electrolysis plant and refuelling station and hydrogen-fuelled buses. Sarawak also plans a fuel-cell light rail transit system by 2024. H_2biscus is a project developed by South Korean and Malaysian companies for the production of green and blue hydrogen, ammonia and methanol for export to South Korea. PETRONAS and ENEOS of Japan are developing feasibility studies for the production of blue and green hydrogen and the transport of 50 kilotonnes/year of hydrogen in toluene.
Philippines	The Department of Energy conducted a study in 2023 to develop a national hydrogen-ammonia policy framework and roadmap. From this study, it issued Department Circular No. DC 2024-01-0001, providing a national policy and general framework, roadmap, and guidelines for hydrogen development and use in the energy sector. Hydrogen is also incorporated in the *Philippines Energy Plan 2023–2050.* Moreover, several memoranda of understanding between the government and the private sector were procured to explore the use of hydrogen for power generation.
Singapore	Multiple memoranda of understanding are being signed by Singapore with governments worldwide (e.g. Australia, Chile, and New Zealand) to collaborate on hydrogen technologies.

Country	Pilot Projects and Developments
Thailand	Under the *Alternative Energy Development Plan*, hydrogen is included as part of the Alternative Fuels category with a set target goal of 10.0 kilotonnes of oil equivalent (3.5 kilotonnes of hydrogen) consumed by 2036. The Energy Regulatory Commission has included hydrogen in the definition of 'renewable energy' to be purchased by provincial or metropolitan electricity authorities and the Electricity Generating Authority of Thailand.
Viet Nam	Germany's TGS Green Hydrogen is planning a green hydrogen production plant (24 kilotonnes/year of hydrogen and 150 kilotonnes/year of ammonia) in the Mekong Delta with a total investment of USD847.8 million. Hydrogen is also mentioned in Viet Nam's *Power Development Plan 8* as a technology to be developed.

Sources: Authors based on IRENA (2022), Purwanto and Rusli (2024), Agora Energiewiende and AFRY Management Consulting (2024), ACE (2023), DOE (2023).

The activities of these AMS demonstrate initial steps towards expanding knowledge in the hydrogen value chain. This development must now be followed by clear, reliable legal frameworks to accelerate momentum and to provide investment security for the private sector.

The ASEAN region would benefit from a cooperative approach as well, where knowledge regarding the establishment of hydrogen and ammonia production and infrastructure, as well as political measures, is shared amongst AMS. As hydrogen technologies have essentially reached a high technical readiness level, the focus should now be on a hydrogen market ramp-up, where both the supply and demand sides are jointly developed through political instruments. It is thus essential for each AMS to develop a hydrogen strategy and to establish a continuous process to drive the implementation of these strategies. Recommendations for driving the hydrogen economy and associated pilot projects in ASEAN are as follows:

- **Develop a clear hydrogen technology utilisation strategy**. ASEAN should formulate a comprehensive strategy that details how hydrogen technology will be integrated across various sectors. This includes establishing objectives, timelines, and action plans to guide the deployment of hydrogen technologies.
- **Identify priority sector(s) for hydrogen technology.** Key industries in AMS where hydrogen technology can be most effectively utilised must be discerned. These sectors likely would have a high impact on decarbonisation efforts and could benefit significantly from hydrogen as an alternative energy source.
- **Increase the regional capacity of hydrogen technology and supply chains**. The region should focus on expanding its capabilities in hydrogen production, storage, and

distribution. This includes investing in infrastructure, research, and development to bolster the entire hydrogen supply chain.

Initiate more hydrogen pilot projects and demonstrations. To validate the viability and efficiency of hydrogen technologies, AMS should launch more pilot projects and demonstration initiatives. These projects would serve as a practical testbed for understanding the real-world application of hydrogen technology and fine-tuning strategies for broader deployment.

Box 2.2. Indonesia's National Hydrogen Strategy

Indonesia's *National Hydrogen Strategy* outlines a clear pathway towards integrating hydrogen as a key component of the country's energy matrix. The strategy aims to develop a robust hydrogen economy by focussing initially on blue hydrogen production, with a transition to green hydrogen as it becomes economically viable. The strategy sets ambitious targets for hydrogen to become a major contributor to Indonesia's energy needs and to significantly reduce its carbon footprint by replacing fossil fuels across multiple sectors, including transport and industry.

Indonesia's approach to developing its hydrogen sector includes a variety of policy instruments and funding initiatives:

Pilot projects and research initiatives. The strategy emphasises the importance of pilot projects and research, particularly in cooperation with international partners, to develop and to refine technologies for hydrogen production, storage, and utilisation.

Regulatory framework. Despite the current lack of formal regulations specific to hydrogen, Indonesia recognises the need for such policies and is working towards establishing a regulatory environment that supports hydrogen development.

Investment in infrastructure. Significant investments are planned to build the necessary infrastructure for hydrogen production and distribution, including facilities for hydrogen fuel-cell hybrid power plants.

Indonesia's hydrogen strategy involves multiple stakeholders across government and industry:

National committees and working groups. These bodies are tasked with overseeing the implementation of the strategy, coordinating between different sectors such as energy, transport, and industry.

While Indonesia’s hydrogen strategy is comprehensive in many respects, there are notable gaps that could impact its efficacy:

Vague regulatory policies. The strategy currently lacks specific regulatory measures and standards for hydrogen production and use, which are crucial for attracting investment and ensuring safety and environmental protection.

Unspecified financial incentives. Although pilot projects are mentioned, the strategy does not specify the financial incentives nor support mechanisms that will be available to businesses and researchers in the hydrogen sector.

Unclear long-term market creation. There is a need for clearer policies on market creation and support, ensuring that there is a domestic and international demand for the hydrogen produced in Indonesia.

Indonesia's *National Hydrogen Strategy* presents a forward-looking approach to establishing hydrogen as a cornerstone of the country's energy and industrial sectors. By focussing on both domestic use and potential exports, the strategy aims to position Indonesia as a leader in the global hydrogen economy. However, to fully realise this potential, the strategy must address its current gaps, particularly in regulatory and financial areas, to ensure a conducive environment for the growth of the hydrogen sector.

Source: MEMR (2023).

Box 2.3. Malaysian Hydrogen Economy and Technology Roadmap

The *Malaysian Hydrogen Economy and Technology Roadmap* aims to establish hydrogen as a cornerstone of the country's new energy economy by 2050. This initiative seeks to integrate hydrogen into various sectors, enhancing the share of clean energy in the national energy mix and promoting energy security through technological innovation and sustainable practices. Key initiatives in the strategy include:

Regulation and standards. The strategy emphasises the development of blue and green hydrogen standards and regulations, including a domestic guarantee of origin certification to meet international standards and to streamline the permitting process for hydrogen projects.

Technology development. Research and development in electrolyser technologies are to be promoted within local universities and the private sector to reduce costs and to enhance production efficiency.

Cost reduction and market development. Hydrogen hubs will be established to optimise the economics of blue and green hydrogen production and incentives for the development of hydrogen-refuelling infrastructure and vehicle uptake.

The strategy also outlines the creation of governance frameworks involving multiple stakeholders across government and industry to ensure the effective implementation of the roadmap. These include strategic partnerships and collaborations with both domestic and international entities to foster a comprehensive hydrogen ecosystem.

While Malaysia's hydrogen strategy is robust in several areas, certain gaps could potentially hinder its progress:

Imprecise implementation timeline. There is a need for a more detailed timeline and specific milestones for transitioning from blue to green hydrogen to provide clarity and direction for stakeholders.

Technological and infrastructure challenges. The challenges related to the current technological immaturity of hydrogen production and usage in the country, and the need for substantial infrastructure development, must be addressed.

Uncertain economic viability and incentives. While the strategy includes financial incentives, more detailed information on economic models and additional incentives could help accelerate the adoption and scalability of hydrogen technologies.

The *Malaysian Hydrogen Economy and Technology Roadmap* presents a forward-looking framework aimed at integrating hydrogen as a key component of the country's energy future. It emphasises sustainability, technological advancement, and international cooperation. However, addressing the outlined gaps will be crucial in ensuring that the strategy delivers on its promise of transforming Malaysia into a leader in the hydrogen economy by 2050.

Source: MOSTI (2023).

Box 2.4. Viet Nam's National Hydrogen Strategy

Viet Nam's national hydrogen strategy, initiated after the Prime Minister's commitment at the 2021 United Nations Climate Change Conference, aims to establish a robust hydrogen ecosystem in Viet Nam. The strategy seeks to integrate hydrogen into the national energy mix, focussing on both renewable sources and carbon-capture technologies to facilitate a transition to a low-carbon economy. By 2030, Viet Nam plans to produce 100,000–500,000 tonnes of green hydrogen annually, escalating to 10 million–20 million tonnes by 2050.

The government has outlined several key mechanisms and policies under its hydrogen strategy to ensure successful implementation:

Technology and innovation. It emphasises deploying technologies for green hydrogen production and carbon capture, supporting both current energy sources and renewable energies.

Infrastructure development. It contains plans to enhance infrastructure for hydrogen production, storage, distribution, and usage on a scale that aligns with global trends.

Investment and financial incentives. The strategy aims to diversify investment sources, involving both state and non-state sectors, to boost the hydrogen economy. This includes attracting foreign investment and utilising international support for green technologies.

Implementation and oversight of the strategy involve coordination amongst various ministries and local agencies, tasked with integrating hydrogen-related objectives into national and provincial planning and adjusting policies to encourage hydrogen use.

While Viet Nam's hydrogen strategy is comprehensive, there are areas that could be improved:

Unclear regulatory framework. The strategy could benefit from more detailed and specific regulations tailored to hydrogen production and use, which would help create a more conducive environment for investors and developers.

Poor public awareness and education: There is a need to increase public awareness and education regarding the benefits of hydrogen energy, which could help garner broader support for hydrogen initiatives.

Lack of technological partnerships. More emphasis on international technological partnerships could accelerate the adoption of advanced technologies necessary for a robust hydrogen economy.

Viet Nam's strategy represents a forward-looking approach to integrating hydrogen as a component of its energy transition efforts. The strategy's focus on technology, infrastructure, and investment aims to position Viet Nam as a leader in hydrogen energy in the region. However, addressing the outlined gaps – especially in regulatory development and public engagement – will be crucial for achieving its long-term goals.

Source: MOIT (2024).

Box 2.5. Singapore's National Hydrogen Strategy

Singapore's *National Hydrogen Strategy*, launched in October 2022, is designed to integrate hydrogen significantly into the nation's energy mix by 2050, potentially meeting up to half of its power needs. The strategy emphasises hydrogen's role in decarbonising the power, maritime, and aviation sectors, leveraging Singapore's strategic position as a global hub.

Key elements of the strategy include:

Innovation and experimentation. Singapore is prioritising the deployment of advanced hydrogen technologies through pilot projects. These projects are aimed at testing the commercial viability of technologies like ammonia for power generation.

Research and development. The strategy includes substantial investment in research and development, with SGD129 million allocated for low-carbon energy research, focussing on hydrogen.

International collaboration. The strategy underscores the importance of international partnerships to establish a viable low-carbon hydrogen supply chain.

Infrastructure and workforce development. Plans are in place for long-term infrastructure development and workforce training to support the emerging hydrogen economy.

The implementation of the strategy will involve collaboration across multiple governmental and industry sectors, focussing on aligning national efforts with international developments and standards.

While comprehensive, the strategy could benefit from clearer details regarding:

Specific targets and timelines. More specific milestones and timelines could help track progress and adjust policies as needed.

Detailed regulatory frameworks. As the hydrogen market evolves, detailed regulatory frameworks will be essential to ensure safety, efficiency, and compatibility with international standards.

Public awareness and engagement. Increased efforts towards public engagement and awareness could help build a more supportive environment for hydrogen adoption.

Singapore's *National Hydrogen Strategy* positions the country at the forefront of the shift towards
low-carbon energy solutions, aligning with its broader goals for sustainability and energy security. By addressing the identified gaps, Singapore can enhance the strategy's effectiveness and ensure it meets its ambitious long-term goals.

Source: MTI (2022).

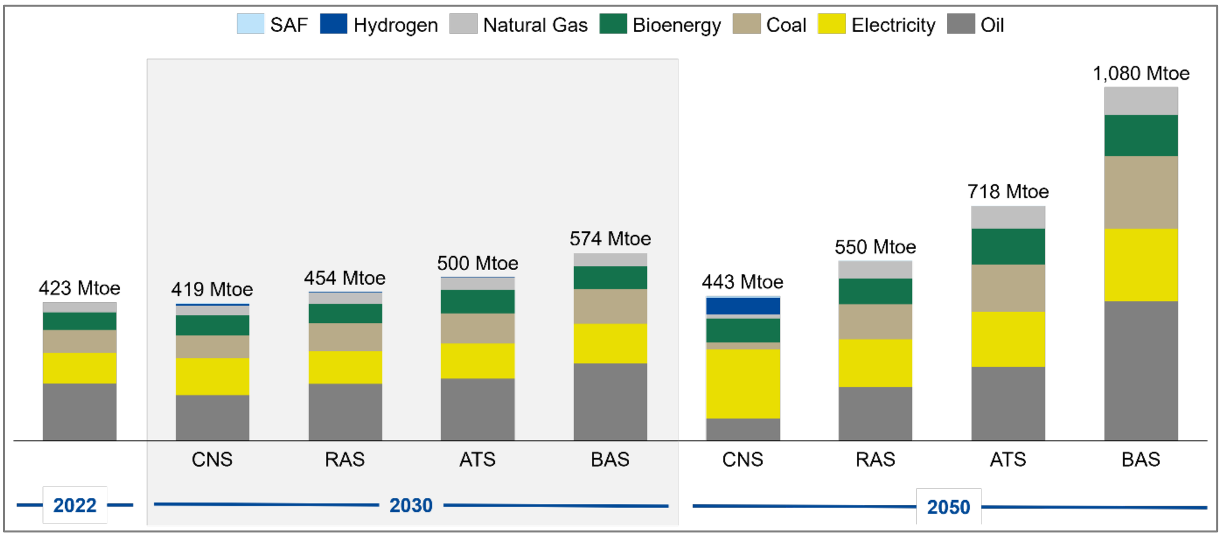
Chapter 3

Opportunities in Developing Low-carbon Hydrogen and Ammonia Technology

As AMS navigate the challenges of increasing energy demand and environmental sustainability, hydrogen technology is emerging as a crucial component for achieving deep decarbonisation and enhancing energy security. This chapter explores the opportunities and potential for developing low-carbon hydrogen technology within the ASEAN region as part of a long-term decarbonisation strategy.

Currently, the ASEAN region exhibits a diverse energy landscape with significant reliance on fossil fuels, particularly oil and coal (Figure 3.1). This reliance underscores the urgent need for alternative energy solutions. In the short term, there is an ongoing, growing shift towards electrification and renewable energy sources, such as bioenergy and biofuels, driven by economic growth, urbanisation, and policy interventions.

Figure 3.1. Total Final Energy Consumption in ASEAN



ATS = ASEAN Member States' target scenario, BAS = baseline scenario, CNS = carbon neutrality scenario, Mtoe = million tonnes of oil equivalent, RAS = regional aspiration scenario, SAF = sustainable aviation fuel.
Source: ACE (2024a).

Figure 3.1 describes the total final energy consumption in the ASEAN region across multiple fuel types for various scenarios. The carbon neutrality scenario (CNS) represents the pathway to reach the various carbon neutrality pledges set by most AMS. The AMS target scenario (ATS) demonstrates the region's energy consumption with the attainment of current national policy objectives. The regional aspiration scenario (RAS) explores the enhancement of the ATS by escalating the national energy efficiency and renewable targets. Finally, the baseline scenario (BAS) follows the historical energy trend of AMS. The figure demonstrates the following.

Sustainable aviation fuel and hydrogen. Under the CNS, sustainable aviation fuel and hydrogen use would see significant growth by 2050, with hydrogen reaching about 17 Mt/year. However, in the RAS and ATS, hydrogen use would remain limited, indicating that while adoption would be underway, it would not be optimal without enhanced renewable energy generation specifically for hydrogen production.

Natural gas and oil. Natural gas consumption would drop significantly in the CNS, suggesting hydrogen and electrification efforts would replace natural gas. Natural gas and oil consumption would remain higher in the RAS, ATS, and BAS, underscoring the need for more aggressive hydrogen integration to replace these fuels.

Electricity. Electricity consumption would grow sharply under the ATS and CNS, showing optimal electrification efforts. In the BAS, coal and oil would still dominate, highlighting the need for further renewable energy integration and hydrogen deployment.

Coal. Under the CNS, coal usage would plummet, reflecting a strong shift towards clean energy. In contrast, coal consumption would more than double in the BAS, stressing the need for AMS to focus on hydrogen and electricity to reduce fossil fuel reliance.

Bioenergy. Bioenergy would grow steadily across all scenarios, especially the ATS and BAS. However, without enhanced efforts for hydrogen adoption, bioenergy and natural gas would continue to dominate the total final energy consumption, limiting the full decarbonisation potential.

Also, regarding Figure 3.1, analysis of fuel types reveals distinct shifts towards cleaner energy sources, and examining how these transitions impact key sectors – industry, transport, residential, and commercial – illustrates varying levels of electrification and hydrogen integration under the different scenarios as follows.

Industry sector. Electrification efforts would progress well, especially under the CNS. Hydrogen would show strong potential to replace natural gas and oil, particularly in the CNS.

Transport sector. Electricity consumption would increase significantly in the CNS and ATS, indicating a strong shift towards electrification. Hydrogen adoption would grow, particularly in the CNS and ATS, where it could replace a significant share of oil and natural gas by 2050.

Residential sector. Electrification in the residential sector would show modest growth under all scenarios. Hydrogen adoption would remain minimal in this sector, indicating that renewables and electrification would likely be the primary focus for decarbonisation.

Commercial sector. Electrification efforts would be notable in all scenarios, especially in the CNS and ATS, with electricity consumption rising steadily through 2050. Hydrogen adoption would be minimal, but there is potential to replace natural gas and oil in the long term with greater investments in hydrogen technologies.

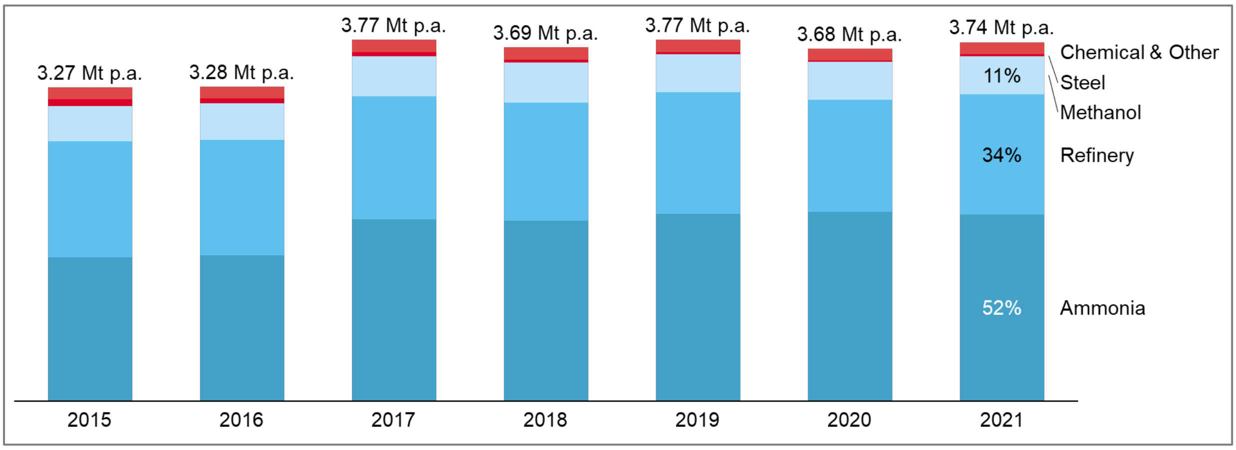
ASEAN's reliance on fossil fuels – particularly oil and coal as seen in the BAS – highlights the urgent need to adopt alternative energy solutions. The CNS shows that with increased investment in renewable energy and hydrogen production, the ASEAN region could significantly reduce its dependence on fossil fuels while achieving deep decarbonisation and enhancing energy security, especially in sectors like transport and industry where hydrogen has the potential to replace natural gas and oil.

Current Hydrogen Demand in the ASEAN Region

Currently, hydrogen demand in the ASEAN region is primarily driven by the chemical industry, refineries, and ammonia production. Indonesia, Malaysia, and Singapore lead in production capacity due to their advanced industrial infrastructure and favourable policies. However, as demand is projected to rise exponentially – driven by decarbonisation goals and sustainable energy initiatives – a significant opportunity exists for AMS to expand their supply capabilities.

Most hydrogen demand in ASEAN is met by captive on-site production – approximately 86.5% in 2021 – indicating that almost all hydrogen produced can be classified as grey hydrogen. The current hydrogen supply in ASEAN increased from approximately 3.27 Mt/year in 2015 to about 3.74 Mt/year in 2021, with a compound annual growth rate of 2.3% (Figure 3.2). The methanol industry was the fastest-growing sector, followed closely by significant growth in the ammonia sector, while hydrogen demand in the oil-refining industry remained stable.

Figure 3.2. Current Hydrogen Demand in ASEAN by Sector



Mt p.a. = million tonnes per year.

Source: Purwanto and Rusli (2024).

Key trends indicate that current hydrogen demand is concentrated in industrial applications with high energy and environmental compliae requirements, and hydrogen is mainly used as a feedstock. Future hydrogen demand in the ASEAN region is expected to grow exponentially across various sectors, driven by the need for decarbonisation and sustainable energy solutions.

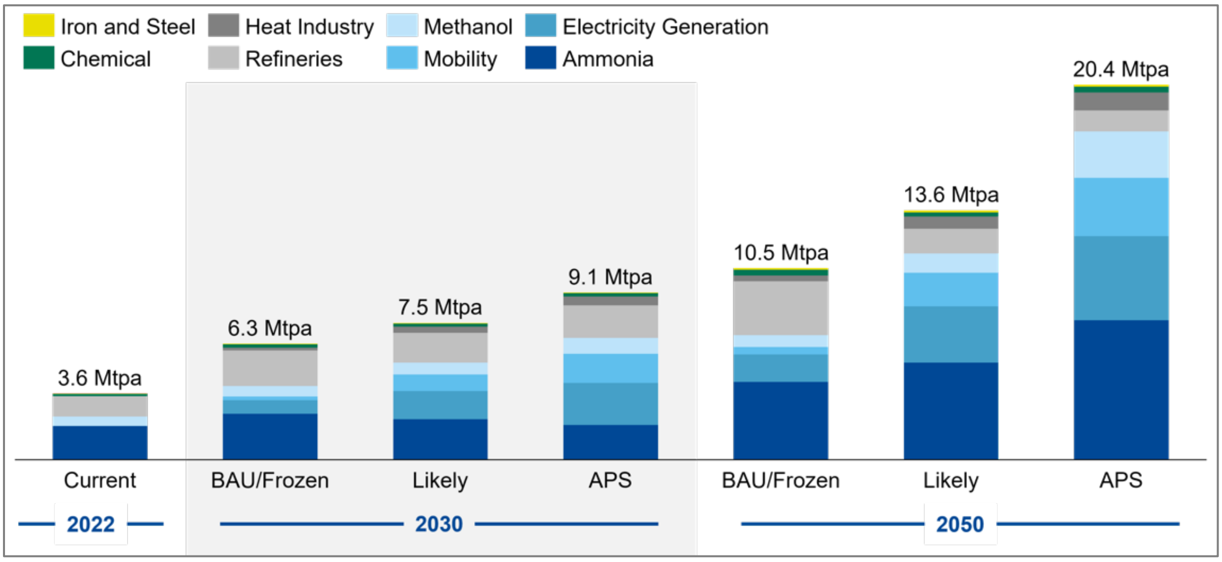
Based on current demands in ASEAN, three scenarios were developed regarding hydrogen demand development in the future for industry sectors (Purwanto and Rusli, 2024). A forecast for hydrogen usage for electricity generation and transport was also used (Kimura and Li, 2019).

In the BAU scenario, the hydrogen demand and supply trends from 2015 to 2020 would continue unchanged. AMS would maintain a business-as-usual approach without setting new CO_2, renewable energy, or energy-efficiency targets. Policies from the 2015–2020 period would remain unaffected, and the future demand and supply of hydrogen would grow at the same average rate. Supply would meet demand using the existing supply structure.

The announced pledges scenario (APS) scenario, based on that of the International Energy Agency, assumes that all government targets would be met fully and on time. It highlights global efforts to tackle climate change and to meet the Sustainable Development Goals and nationally determined contribution targets. It also addresses the 'implementation gap' (e.g. the remaining carbon emissions reduction and/or needed renewable energy capacity) that needs to be closed for countries to achieve announced decarbonisation targets. Specific targets for AMS include carbon neutrality by 2060 for most, with variable dates for Indonesia, Malaysia, and Viet Nam.

As Figure 3.3 demonstrates, regarding ammonia production, Indonesia, Malaysia, and Viet Nam would see a substantial rise in hydrogen demand, driven by agricultural needs and industrial applications, under both scenarios. By 2050, Indonesia's demand for hydrogen in this sector could exceed 4.9 Mt, highlighting the sector's critical role in future hydrogen consumption. The transport sector would be poised for transformative growth, with hydrogen FCEVs becoming increasingly prevalent. Indonesia and Malaysia would lead this shift, with projected demand reaching over 1.5 Mt by 2050 in Indonesia under the APS. Electricity generation would also grow, with hydrogen being used for grid stability and integrating renewable energy sources. In Indonesia, hydrogen demand for electricity generation could surge to over 2.0 Mt by 2050, reflecting the sector's strategic importance in future energy systems.

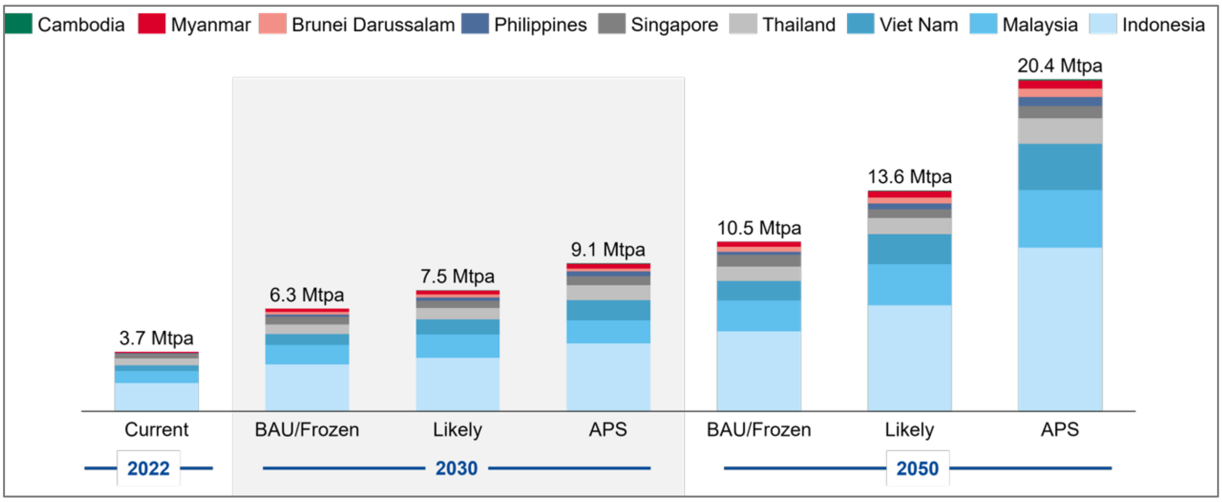
Figure 3.3. Future Hydrogen Demand by Scenario and Sector



APS = announced pledges scenario, BAU = business as usual scenario, Mt p.a. = million tonnes per year.

Source: Purwanto and Rusli (2024).

Figure 3.4. Future Hydrogen Demand by Country and Scenario



APS = announced pledges scenario, BAU = business as usual scenario, Mt p.a. = million tonnes per year.

Source: Purwanto and Rusli (2024).

Hydrogen demand would remain varied across AMS, with Indonesia, Malaysia, and Viet Nam emerging as the key players (Figure 3.4). Indonesia would lead in hydrogen consumption across multiple sectors, driven by its large industrial base and ambitious decarbonisation targets. The country's demand for hydrogen in ammonia production, methanol, and electricity generation would grow substantially, with the APS indicating a potential rise to over 4.9 Mt for ammonia alone by 2050.

Indonesia. Indonesia's hydrogen demand in 2015 was notable for refineries (i.e. 260 kt/year) and chemicals (i.e. 30 kt/year), with significant contributions from the ammonia production and methanol sectors. By 2030, under the APS, demand in ammonia production would rise significantly to 1,435 kt/year and methanol production to 268 kt/year. By 2050, the APS projects that hydrogen demand for ammonia production would soar to 4,956 kt/year and for methanol production to 782 kt/year. The electricity generation sector would see hydrogen demand reach 2,023 kt/year. These trends would be driven by strong policy interventions, technological advancements, and growth in industrial sectors, particularly ammonia and methanol production, and an increasing focus on decarbonising the electricity generation sector.

Malaysia. Hydrogen demand in 2015 was significant for refineries (312 kt/year) and chemicals (34 kt/year), with ammonia production also contributing. By 2030, hydrogen demand in ammonia production would reach 432 kt/year under the APS, while demand in methanol production would be 237 kt/year. By 2050, the APS forecasts ammonia production demand to grow to 1,097 kt/year and methanol production to 691 kt/year. The electricity generation sector would see hydrogen demand rise to 593 kt/year. These trends would be supported by Malaysia's strategic focus on industrial development and a clean energy transition, driven by strong policy measures and technological innovations.

Viet Nam. Hydrogen demand in 2015 was primarily in the chemicals sector (4 kt/year) and for ammonia production. By 2030, the APS projects hydrogen demand in ammonia production to reach 291 kt/year and in chemicals to 6 kt/year. By 2050, hydrogen demand in ammonia production would grow to 1,005 kt/year and in chemicals to 11 kt/year. The electricity generation sector would also see a significant increase in hydrogen demand, reaching 1,116 kt/year. These trends would be driven by industrial growth, particularly in ammonia production and chemicals, supported by governmental policies promoting hydrogen adoption and decarbonisation.

Thailand. Hydrogen demand in 2015 was notable for refineries (281 kt/year) and chemicals (37 kt/year). By 2030, under the APS, demand in methanol production would reach 169 kt/year, and in chemicals, 31 kt/year. By 2050, the APS forecasts hydrogen demand in methanol production to grow to 494 kt/year and in chemicals to 57 kt/year. The electricity generation sector would see a rise in hydrogen demand to 244 kt/year. These trends reflect Thailand's policy support for hydrogen technology and clean energy, alongside industrial expansion and decarbonisation efforts in key sectors like chemicals and methanol production.

Singapore. Hydrogen demand in 2015 was primarily for refineries (191 kt/year) and chemicals (15 kt/year). By 2030, hydrogen demand in chemicals is projected to reach 25 kt/year under the APS. By 2050, the APS forecasts hydrogen demand in chemicals to grow to 47 kt/year. The electricity generation sector would see a rise in hydrogen demand to 104 kt/year. These trends would be driven by technological advancements and policy measures supporting hydrogen adoption, alongside growth in industrial applications, particularly in the chemicals sector.

Philippines. The country saw modest hydrogen demand in 2015, mainly for refineries (20 kt/year) and chemicals (5 kt/year). By 2030, under the APS, hydrogen demand in methanol production would reach 24 kt/year. By 2050, the APS forecasts hydrogen demand in methanol production to grow to 69 kt/year and in chemicals to 15 kt/year. The electricity generation sector would see an increase in hydrogen demand to 314,041 tonnes. These trends would be driven by policy initiatives and industrial growth, alongside an increasing focus on clean energy and decarbonisation.

Myanmar. Hydrogen demand in 2015 was primarily for refineries (36.0 kt/year) and chemicals (0.3 kt/year). By 2030, hydrogen demand in chemicals would reach 9,440 tonnes under the APS. By 2050, the APS forecasts hydrogen demand in chemicals to grow to 17 kt/year. The electricity generation sector would see a rise in hydrogen demand to 105 kt/year. These trends would be driven by industrial development and policy support for hydrogen adoption, alongside efforts to decarbonise key sectors like chemicals and electricity generation.

Brunei Darussalam. Hydrogen demand in 2015 was modest, with notable demand for chemicals (0.2 kt/year). By 2030, under the APS, hydrogen demand for ammonia production would reach 133 kt/year. By 2050, the APS forecasts hydrogen demand for ammonia production to grow to 457 kt/year and for chemicals to 3 kt/year. The electricity generation sector would see a rise in hydrogen demand to 349 kt/year. These trends would be driven by policy measures supporting hydrogen technology, alongside industrial expansion and efforts to integrate hydrogen into energy systems.

Lao People's Democratic Republic. Hydrogen demand here in recent years has not been as significant as other sources of conventional fuels. In 2017, hydrogen as final energy consumption in the Lao People's Democratic Republic (Lao PDR) was lower than 0.01 million tonnes of oil equivalent. However, there is potential demand for hydrogen consumption in the Lao PDR for rare earth mineral mining, cement production, and co-firing technologies for industrial heat. In the mining sector, the Lao PDR possesses approximately 600 kt of rare earth deposits in Xiangkhouang and Houaphanh provinces, which require around 10 tonnes of ammonium sulphate (consisting of 0.611 tonne of hydrogen) to leachate the initial processing phase (Han and Phongsavath, 2024). This would mean that to fully extract these rare earth deposits, the country requires around 3.7 kt of hydrogen in the future.

Cambodia. The country has yet to incorporate hydrogen into its energy consumption mix. While there is no exact quantity of hydrogen being imported into the country, Cambodia reported USD840 worth of hydrogen imported from Thailand or approximately 420 kg of grey hydrogen, assuming the price for grey hydrogen is around USD2/kg (World Bank, 2022).

Hydrogen demand in the ASEAN region is set to grow exponentially, driven by the chemical industry, refineries, and ammonia production. Indonesia, Malaysia, and Viet Nam are poised to lead this transformation, particularly under the APS, due to significant increases in the ammonia production, methanol, and transport sectors. Key drivers include industrial growth, environmental regulations, and policy support. The data underscore hydrogen's critical role in decarbonising industries and supporting sustainable energy solutions, emphasising the need for robust policies, technological advancements, and regional cooperation to achieve energy security and environmental goals.

Hydrogen Supply and Potential in ASEAN Member States

As the region accelerates its transition towards cleaner energy sources, understanding the supply dynamics of hydrogen and ammonia is imperative. Currently, the production of hydrogen and ammonia is primarily driven by industrial needs, particularly for refineries, chemical manufacturing, and fertilizer production.

Today, about 3.74 Mt/year hydrogen is produced in ASEAN. Of this, 84.7% – grey hydrogen – is produced at the site of consumption (Purwanto and Rusli, 2024). As green and blue hydrogen technologies evolve, they will compete with future carbon-neutral solutions. Utilising green and blue hydrogen in sectors currently dependent on grey hydrogen presents an opportunity. Policy measures should focus on phasing out grey hydrogen and replacing it with blue and green hydrogen. Additionally, any expansion in these sectors should prioritise the use of green hydrogen to ensure future sustainability and alignment with carbon reduction goals.

The ASEAN region is actively participating in the global hydrogen supply chain. Based on data collected from the World Bank, the ASEAN region exported a total of 1.58 million cubic metres of hydrogen, about 130.73 tonnes/year in 2022. Judging by the trade flow, ASEAN exports occur mainly within the region, with around 67.8% of the exports transported to other AMS. Singapore's potential as the region's hub for hydrogen is becoming more apparent due to its strategic geographical location, enabling a total export of around 35.09 tonnes/year to other AMS and the other 55.12 tonnes/year globally. Indonesia and Thailand each have the potential to become the leading hydrogen exporter in the region, based on historical trade data (World Bank, 2022).

The hydrogen production potential of each AMS needs to be acknowledged. To understand this potential, the technical renewable energy potential of each AMS and the conversion rate of its electrolysers in breaking down water molecules into hydrogen must be known. To produce 1 kg of green hydrogen using low-temperature electrolysis, around 55–60 kWh of electricity is required. High-temperature electrolysis is more efficient, consuming only around 40–45 kWh of electricity in the process (Franco and Giovannini, 2023).

A technical paper from the National Renewable Energy Laboratory was used to analyse the technical potential of renewable energy in South-east Asia (Lee et al., 2020). The data were obtained through satellite imaging, examining the available land area and taking into account the LCOEs within the area based on the solar irradiance (for solar power plants) and wind speed (for wind power plants). Then, through the gathered data, the technical potential for renewable energy in the available land area with LCOEs below

USD150/MWh[15] was measured and taken as potential opportunities for additional installed capacity (Table 3.1).

Table 3.1. Data Used for the Assumed Hydrogen Production Capacity

Country	Total Installed Capacity (MW)	Potential Supply Capacity by Renewable Sources (MW)	Excess/ Remaining Capacity for Hydrogen* (MW)	Total Hydrogen Production Capacity** (Mt/year)
Brunei Darussalam	1,322	16.02	0	0
Cambodia	3,465	3,267.00	2,920.5	25.58
Indonesia	83,802	1,102.00	0	0
Lao PDR	11,017	1,291.00	189.3	1.66
Malaysia	33,128	1,967.00	0	0
Myanmar	7,291	8,199.00	7,469.9	65.44
Philippines	28,932	2,127.00	0	0
Singapore	12,344	2.00	0	0
Thailand	53,352	10,538.00	5,202.8	45.58
Viet Nam	75,665	2,847.00	0	0

Lao PDR = Lao People's Democratic Republic, MW = megawatt, Mt = million tonnes.
*Assuming the potential supply capacity is used to satisfy 10% of the country's electricity generation capacity.
**Assuming the electrolysers run for 8,760 hours per year.
Source: ACE (2024c).

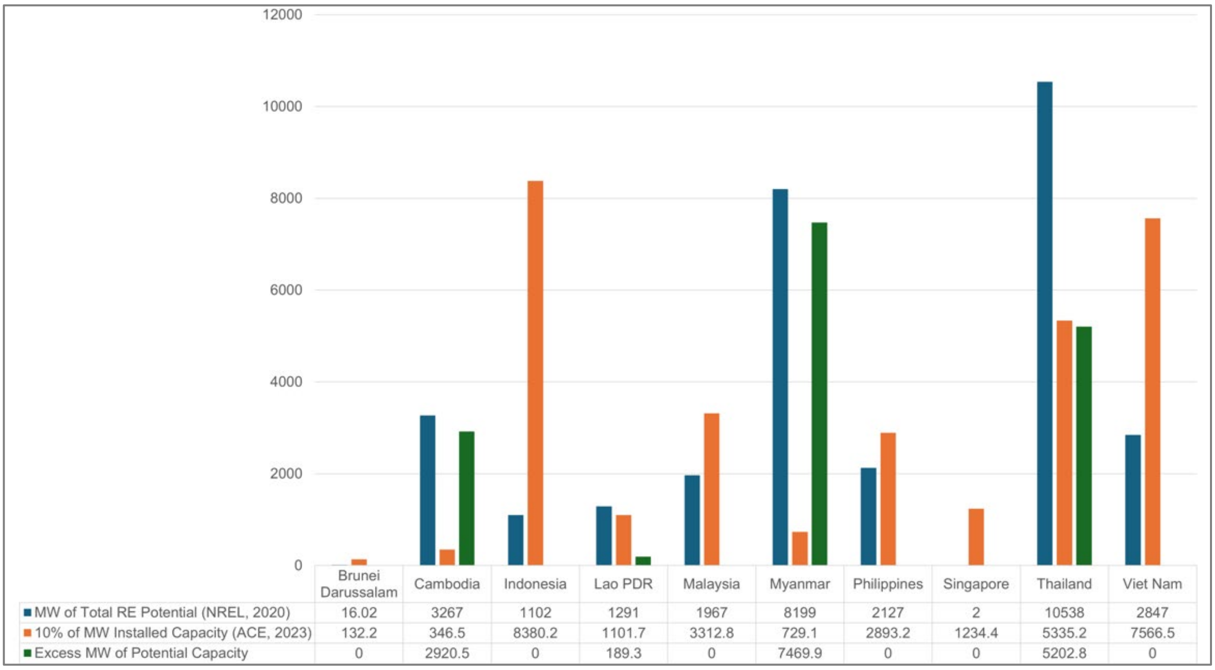
Assuming the renewable electricity potential is utilised to fulfil 10% of the country's electricity supply based on the existing installed capacity – and the excess capacity for hydrogen production is used through electrolysis – calculations reveal significant hydrogen capacity across some AMS, driven by their huge renewable energy capacities (ACE, 2023; Lee et al., 2020). The calculation also assumes that the electrolysers would be working every hour of the year.

Using low-temperature electrolysis, Myanmar would have the highest potential hydrogen production capacity of 1,148 Mt/year. Thailand follows with around 799 Mt/year, and

[15] The potential with LCOEs below USD150/MWh were chosen due to the solar LCOEs ranging from USD99/MWh to USD200/MWh and the wind LCOEs around USD150/MWh; thus, the areas with LCOEs of less than USD150/MWh would provide better options than the existing solar and wind power generation plants.

Cambodia with 448 Mt/year of green hydrogen. Lao PDR would only have around 29 Mt/year of hydrogen production capacity. Higher-temperature electrolysis would harness higher hydrogen production, with around 35.7% of additional hydrogen for each AMS. Note that the estimated amounts exclusively include green hydrogen.

Figure 3.5. Hydrogen Production Potential by Country Based on Economical Viable Wind and Solar Energy
(megawatts)



	Brunei Darussalam	Cambodia	Indonesia	Lao PDR	Malaysia	Myanmar	Philippines	Singapore	Thailand	Viet Nam
MW of Total RE Potential (NREL, 2020)	16.02	3267	1102	1291	1967	8199	2127	2	10538	2847
10% of MW Installed Capacity (ACE, 2023)	132.2	346.5	8380.2	1101.7	3312.8	729.1	2893.2	1234.4	5335.2	7566.5
Excess MW of Potential Capacity	0	2920.5	0	189.3	0	7469.9	0	0	5202.8	0

Lao PDR = Lao People's Democratic Republic, MW = megawatt, RE = renewable energy.
Source: Lee et al. (2020).

The production volume for blue hydrogen largely depends on the availability of CO_2 storage formations like deep saline aquifers, depleted oil or gas reservoirs, and basins. Generally, it should be noted that the potential for blue hydrogen is based on the availability of natural gas and CO_2 storage, which is difficult to estimate accurately.[16] Based on actual storage volume, however, the maximum hydrogen production potential for blue hydrogen can be estimated (Table 3.2).

[16] The limitation lies in the unclear technical and economic feasibility of developing these storage sites. Additionally, it must be assumed that these storage sites cannot be exclusively used for blue hydrogen production, as they will likely serve multiple purposes, further constraining the available capacity for blue hydrogen initiatives.

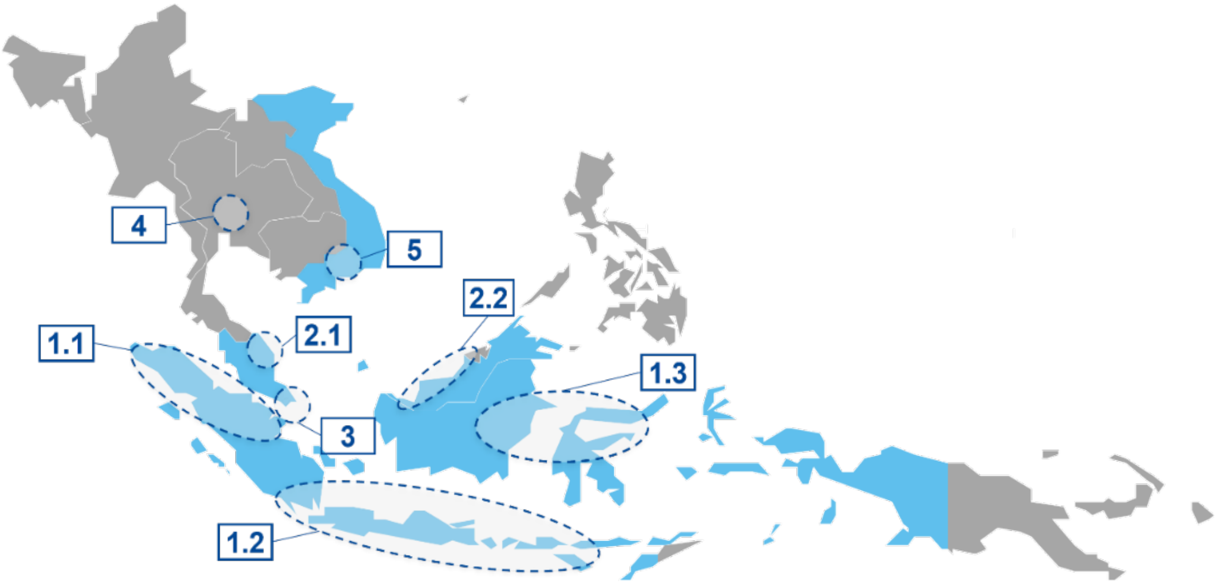
Table 3.2. Carbon Capture, Usage, and Storage Potential for Blue Hydrogen in ASEAN

Country	Type of Storage	Estimated CO_2 Storage Volume (gigatonnes)	Max. Blue Hydrogen Production (million tonnes)
Brunei Darussalam	Oil and gas fields	0.6	60
Indonesia	South Sumatra Basin	7.7	765
	Java Basin (deep saline layers)	0.4	40
	Tarakan Basin	0.1	13
	Central Sumatra Basin	0.2	23
Malaysia	Malay Basin	80.0	8,000
Philippines	Saline aquifers	22.0	2,200
	Gas fields	0.3	30
Thailand	Saline formation in the Greater Chao Praya Basin and Pattani Basin	8.9	890
	Gas and oil fields	1.4	140
Viet Nam	Deep saline reservoirs	10.4	1,040
	Depleted oil and gas fields	1.4	140

Source: Calculations based on IEA (2021).

When considering current developments in blue or green hydrogen production, it is evident that AMS are at different stages of developing and implementing hydrogen supply projects, with each exhibiting different approaches and progress. A map showing the location of these hydrogen projects is provided in Figure 3.6.

Figure 3.6. Current Hydrogen Supply Projects in ASEAN



Notes:

1. The numbers on the map indicate the numbering in Table 3.3.
2. Blue countries have already published a hydrogen strategy.

Source: IEA (2023).

Table3.3 lists the projects in the regions by project name, technology, production capacity, status, and commissioning year. Most of the announced projects are in the concept phase or in the feasibility study phase. Individual small-scale projects are already in operation. In addition to the projects mentioned here, the International Energy Agency announced a total of 25 hydrogen projects in AMS.

Table 3.3. Operational and Announced Projects to Produce Low-emissions Hydrogen in ASEAN

	No	Project Name	Production Capacity	Status	COD	End-use
Indonesia	1.1	MOU TOYO-PT Pupuk Indonesia Holding Company		Concept		Ammonia
		MOU GGGI, Samsung, and Hyundai		Concept		Ammonia
		MOU ReNu Energy, Countrywide Hydrogen, and Anantara Energy Holdings	10 MW 2 kt/yr	Feasibility	2025	
	1.2	Ulubelu geothermal plant	0.21 MW <0.01 kt/yr	FID	2023	Refining

No	Project Name	Production Capacity	Status	COD	End-use
	ACWA Power hydrogen and ammonia project	173 MW 30 kt/yr	Feasibility	2027	Ammonia
	ACWA Power large-scale hydrogen project	5,000 MW 866 kt/yr	Concept		Industry
	Renewstable Sumba		Concept		Power
1.3	Balikpapan refinery		Feasibility		Refining
	Danish nuclear in Indonesia	1,000 MW 205 kt/yr	Concept	2028	Ammonia
	PT Panca Amara Utama Banggai ammonia plant, Luwuk Central Sulawesi	126 kt/yr	Feasibility	2028	Ammonia
2.1	MOU Petronas-ENEOS	289 MW 50 kt/yr	Concept	2027	
2.2	H_2biscus	108 kt/yr	Feasibility		Ammonia
	Sumitomo Malaysia		Feasibility		
	Sarawak Energy	0.3 MW	Operational	2019	Transport
3	Jurong Island hydrogen	9 MW 2 kt/yr	Feasibility	2024	
	E-methanol plant in Singapore	110 MW 19 kt/yr	Concept	2024	Transport
4	MOU PTT, EGAT, and ACWA Power	2,494 MW 432 kt/yr	Concept		Ammonia
	Lam Takhong Wind Hydrogen Hybrid Project, EGAT	1 MW 0.1 kt/yr	Operational	2018	Power
5	Ben Tre Project, phase 2	775 MW 134 kt/yr	Concept		Ammonia

FID = final investment decision, kt = kilotonne, MOU = memorandum of understanding, MW = megawatt.
Source: IEA (2023).

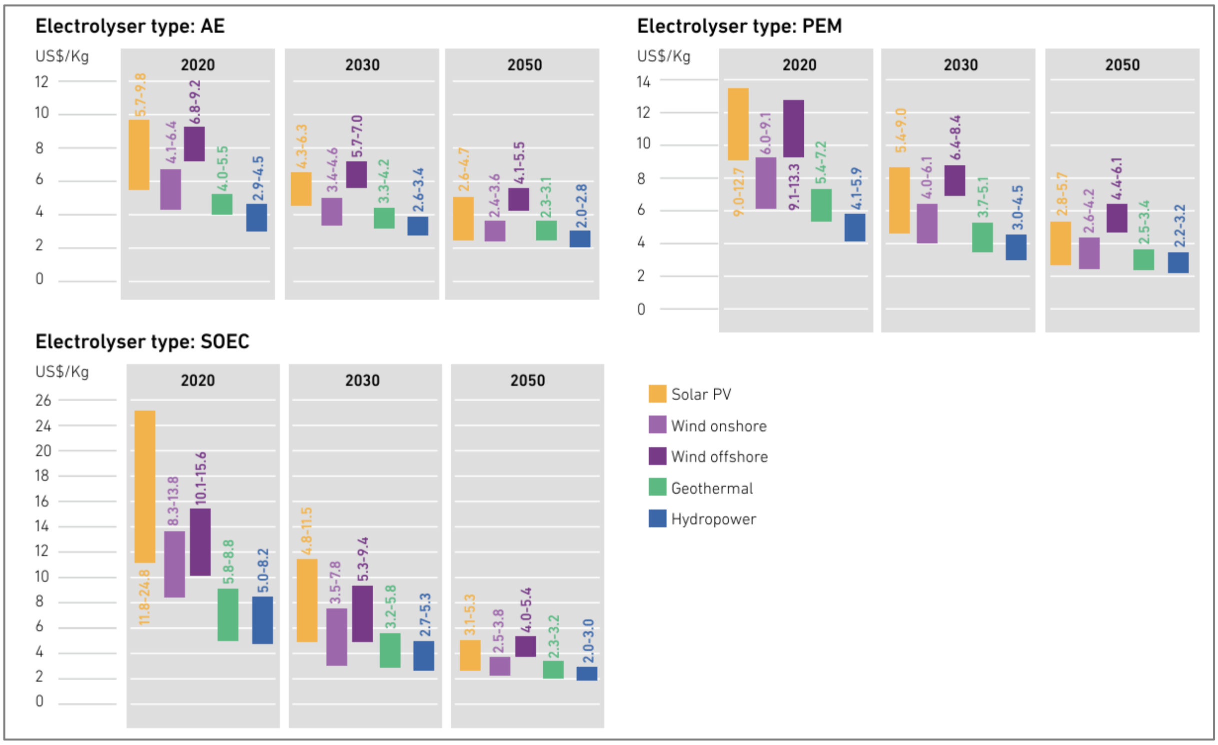
Overall, the ASEAN region is making strides in hydrogen development through national policies, pilot projects, and international cooperation. It is poised to become a significant player in the global hydrogen economy. The current production landscape, dominated by grey hydrogen, underscores the urgent need for a transition to greener alternatives. The substantial renewable energy capacities in AMS highlight potential for green hydrogen production, which could far exceed future demand. However, to ensure renewable energy is used effectively for hydrogen production, countries must prioritise the use of renewable energy where CO_2 reduction potential is highest. If renewable energy is allocated for hydrogen production, the additionality of renewable energy sources becomes critical, ensuring that new capacity is built specifically for this purpose. Moreover, leveraging CO_2 storage capabilities for blue hydrogen production offers additional pathways to sustainability.

Economic Assessment of Low-carbon Hydrogen and Ammonia Production in ASEAN

The biggest challenge in adopting low-carbon (i.e. green and blue) hydrogen in the ASEAN region is the cost of production, which is influenced by the equipment cost and electricity price as implied in Figure 3.7. Hydrogen produced from the SMR process is the most utilised form, due to its low production cost, which is USD0.70–USD1.60/kg (IEA, 2024). The reason green hydrogen production cost is not as competitive as grey hydrogen is because of the high electricity cost, which is used as the feedstock for electrolysis, as well as the expensive cost of electrolyser technologies.[17] Since the electrolyser stack cost heavily influences the price of hydrogen production, technological advancements in hydrogen technologies are needed to help bring down the cost of green hydrogen production.

[17] As of 2024, the cost of an electrolyser stack is USD1,700–USD2,000/kW, with a potential reduction to around USD200–USD300/kW by 2030 (IEA, 2024).

Figure 3.7. Green Hydrogen Production Costs



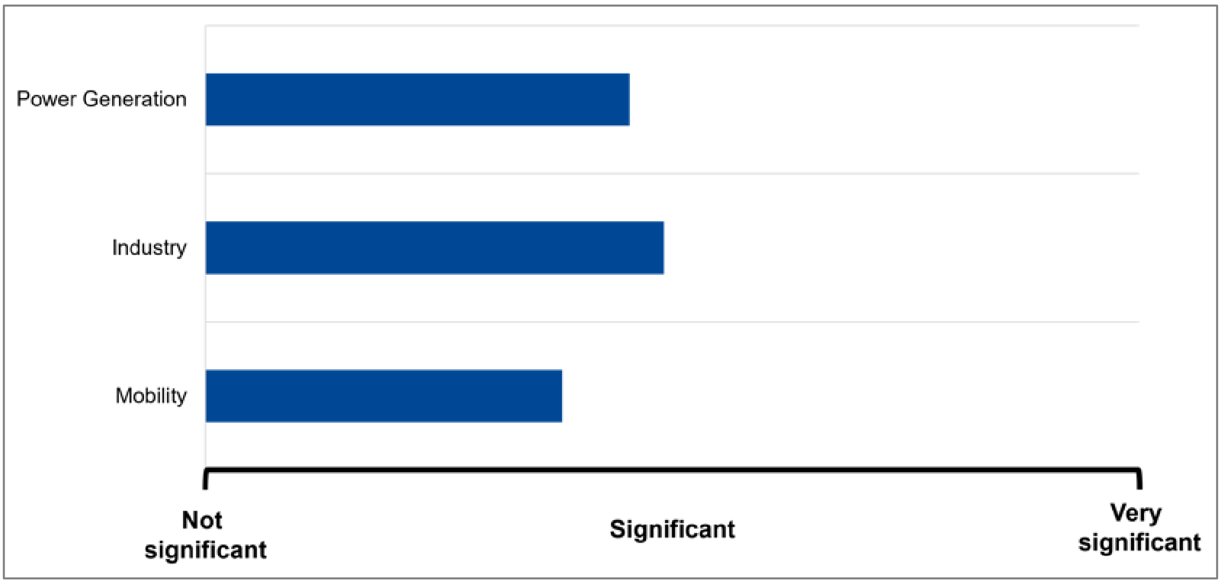
AE = alkaline electrolysis, kg = kilogram, PEM = proton exchange membrane, PV = photovoltaic, SOEC = solid oxide electrolyser cell.
Source: Purwanto and Rusli (2024).

The ASEAN Centre for Energy conducted a survey amongst key hydrogen stakeholders in the ASEAN region, which includes energy policymakers, power utilities, and state-owned oil and gas enterprises. The survey conveyed that the desirable cost of producing green or blue hydrogen is USD1.00–USD7.00/kg, averaging USD5.20/kg depending on the country's resources (ACE, 2024c). Thailand, with an abundant resource potential of renewable energy, argued that green hydrogen production costs of around USD4.00–USD5.00/kg would create a more level playing field for green hydrogen to compete with grey hydrogen in the industrial sector.

Such perspectives are in line with the report made by Institute for Essential Services Reform in 2022, which projected a cost reduction of green hydrogen through various means of production (Purwanto and Rusli, 2024). Green hydrogen production costs would fall to USD5.40–USD9.00/kg by 2030 using solar PV technology, while the use of wind power would bring it further down to USD3.00–USD4.50/kg (Sayer, Ajanovic, Haas, 2024). Longer operation hours create an economic advantage for hydrogen production using electricity from wind power plants compared to solar PV plants that rely on sunlight.

Given the relatively high production cost, the adoption of green hydrogen in the ASEAN region should consider available resources, sectoral demand for hydrogen, and the economic feasibility of hydrogen utilisation.

Figure 3.8. ASEAN Member States' Priority Sectors for Hydrogen Adoption



Source: ACE (2024b).

Figure 3.8 describes the perspectives of AMS for adopting low-carbon hydrogen. From the survey results, low-carbon hydrogen – considered a cleaner alternative energy source for the growing ASEAN demand – remains a low priority in the ASEAN region despite its versatility. This may be related to the high production cost of low-carbon hydrogen and availability of necessary infrastructure that hinders AMS in using hydrogen in various sectors. AMS highlighted that the industrial sector remains the top priority for low-carbon hydrogen utilisation, noting the current utilisation of grey hydrogen in the ASEAN region as a feedstock in the fertilizer industry and in the oil-refining process.

The power generation sector follows as the second-most prioritised sector for hydrogen utilisation. While AMS consider the power sector as a top sector for low-carbon hydrogen adoption, power generation from green hydrogen using the power-to-hydrogen-to-power scheme would be inefficient considering the conversion efficiency of electrolyser technology. As previously mentioned, the levelised cost of green hydrogen reaches USD9.00–USD12.00/kg using PEM electrolysers (Purwanto and Rusli, 2024); converting the hydrogen for transport would add another USD1.00–USD3.00/kg depending on the technology. Hydrogen pipeline investment costs would be 110–150% of those for existing natural gas pipelines, while retrofitting the pipelines would add an additional 10–25% to the investment costs (Risco-Bravo et al., 2024). It is estimated that using the power-to-hydrogen-to-power scheme for electricity supply would output 8.5–11.2% of the input electricity, taking into account the conversion efficiency of electrolysis, conversion for shipping/transport, and the re-electrification process through thermal combustion (Boretti, 2024; Risco-Bravo et al., 2024). Highlighting the current costs of producing green hydrogen in the power sector, re-electrifying green hydrogen to supply electricity is inefficient unless the electricity used for producing green hydrogen comes from excess renewable electricity. Thus, from a cost-comparative advantage and the availability of infrastructure, deployment of low-carbon hydrogen in ASEAN needs to be aligned or prioritised with each AMS's comparative advantage.

Potential Market Players in ASEAN Member States

The ASEAN region is increasingly becoming a focal point for the hydrogen economy, with a diverse range of stakeholders. These stakeholders include industry players, investors and financial institutions, research and academic institutions, and governmental bodies. Each group has distinct roles and goals, collectively driving the hydrogen agenda forward. A table of all identified stakeholders can be found in the Annex.

Industry players are the backbone of the hydrogen economy, responsible for the production, distribution, and technological advancements in hydrogen technology. Key industry players in the ASEAN region include AMEA Power (Dubai); PETRONAS (Malaysia); PT Pertamina (Indonesia); PTT (Thailand); Sarawak Energy (Malaysia); and international companies like Fortescue Metals Group, Mitsubishi, and Siemens. These companies are involved in various stages of the hydrogen value chain, from producing hydrogen to developing the necessary infrastructure for storage and distribution. The primary goals of these industry players are to transition from fossil fuels to hydrogen to meet global sustainability goals, expand market share, and capitalise on new economic opportunities presented by the hydrogen economy. They also aim to develop and to deploy advanced hydrogen technologies to improve production efficiency and to reduce costs.

Investors and financial institutions provide the crucial capital needed to fund hydrogen projects. Major players include Asian Development Bank, European Investment Bank, International Finance Corporation, Japan Bank for International Cooperation, and Mitsubishi UFJ Financial Group (MUFG). These entities finance infrastructure projects, research and development, and the scaling up of hydrogen production and distribution networks. For example, MUFG is involved in financing hydrogen infrastructure projects across Asia, including ASEAN, to support low-carbon technologies. The European Investment Bank backs large-scale green hydrogen hubs, promoting sustainable energy solutions in the region. Goals include diversifying investment portfolios by including hydrogen projects, achieving long-term financial returns by investing in clean-energy technologies, and facilitating the development and commercialisation of hydrogen technologies through strategic investments.

Research and academic institutions are also critical for advancing hydrogen technologies and providing data-driven insights. Notable institutions include the ASEAN Centre for Energy, Bandung Institute of Technology (Indonesia), Chulalongkorn University (Thailand), National University of Singapore, and University of Malaya (Malaysia). These institutions conduct cutting-edge research on hydrogen production methods, storage solutions, and applications in various sectors. The goals of these institutions are to develop new and efficient hydrogen technologies; provide data, analysis, and strategic insights to policymakers and industry stakeholders; and train the next generation of scientists and engineers in hydrogen technologies.

Further, governmental bodies in the ASEAN region play a vital role in shaping policies, providing incentives, and fostering an enabling environment for the hydrogen economy. Key government stakeholders include the ministries of energy, environment, and industry across AMS, regulatory authorities, and intergovernmental organisations. Governments are responsible for creating regulatory frameworks that support hydrogen production and use, offering financial incentives, and facilitating international collaborations. For instance, the *ASEAN Plan of Action for Energy Cooperation (APAEC) Phase II: 2021–2025* includes measures to promote hydrogen storage and use. Goals include establishing supportive policies and regulations to accelerate hydrogen adoption, enhancing the region's competitiveness in the global hydrogen market, and achieving national and regional sustainability goals by promoting clean energy sources.

The primary consumers of hydrogen in the ASEAN region span various sectors including transport, industrial processes, and power generation. These consumers are integrating hydrogen into their operations such as by replacing the coal and natural gas in power plants, fertilizer plants, and other industrial consumers, including the potential of blending hydrogen into natural gas to enhance sustainability, reduce carbon emissions, and improve energy efficiency.

Hydrogen FCVs are gaining traction in countries like Malaysia, Singapore, and Thailand. For instance, Sarawak Energy has been involved in projects to supply hydrogen for public transport, including hydrogen-powered buses in Kuching, Malaysia (MIDA, 2024). Additionally, Thailand's PTT is exploring hydrogen use in transport as part of its broader strategy to promote low-carbon technologies (Akin Gump, 2021).

Hoa Phat Group in Viet Nam is integrating hydrogen into its steel production processes. Hydrogen is used to replace coke and coal, significantly reducing carbon emissions and enhancing the sustainability of steel manufacturing (Purwanto and Rusli, 2024). Pupuk Indonesia utilises hydrogen for ammonia synthesis, a critical component in fertilizer production. This use of hydrogen not only supports agricultural productivity but also contributes to the decarbonisation of the chemical industry (ACE, 2024b). PLN in Indonesia is exploring hydrogen as a backup power source and for stabilising the grid. Hydrogen can be used to store excess energy generated from renewable sources like solar and wind, ensuring a reliable power supply and enhancing grid resilience (ACE, 2024b). Brunei LNG is leveraging its established infrastructure to develop hydrogen export capabilities. By producing liquefied hydrogen, it aims to supply international markets, particularly Japan, thus playing a crucial role in the global hydrogen supply chain (ACE, 2024b). Companies like AEDP Power in Thailand and Fortescue Metals Group from Australia are also investing in large-scale green hydrogen projects in the ASEAN region.

Chapter 4

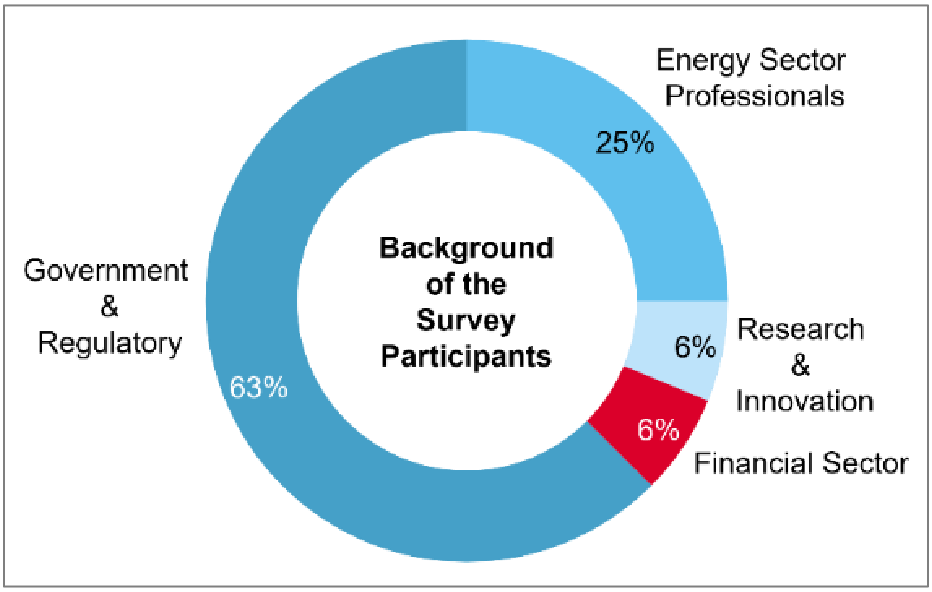
Analysis of Hydrogen and Ammonia's Role in the ASEAN Energy Sector

This chapter analyses the role of hydrogen and ammonia that are particularly aligned with the region's carbon-neutrality targets by 2050 and outlines a strategic roadmap for the development and integration of hydrogen and ammonia technologies in the ASEAN region. It addresses three critical questions: (i) how ASEAN's carbon-neutrality goals should shape hydrogen and ammonia development across different timelines; (ii) how AMS can select suitable technologies of hydrogen and ammonia based on their unique resource profiles; and (iii) how to structure policies that drive market growth while minimising investment risks for the private sector in developing and deploying both technologies in ASEAN.

The roadmap for hydrogen and ammonia development in the ASEAN region reflects the growing recognition of hydrogen's potential in supporting energy transitions and meeting decarbonisation targets. AMS, like much of the world, face the challenge of transitioning from fossil fuels to cleaner, renewable energy sources. Several AMS have set ambitious goals for carbon neutrality, and hydrogen offers a promising solution, particularly for hard-to-decarbonise sectors such as industry, transport, and power generation. As the ASEAN region strives to meet its rising energy demands while reducing carbon emissions, hydrogen has emerged as a key focus, aligning with the global shift towards cleaner energy sources.

To validate the findings of this report, two workshops were held with participants from AMS in June 2024 and October 2024. In addition, a survey was distributed to all attendees to capture current perspectives on the region (ACE, 2024c). About 63% of the participants were from government and regulatory agencies, 25% were energy sector professionals, and 6% were from the financial sector and research and innovation (Figure 4.1).

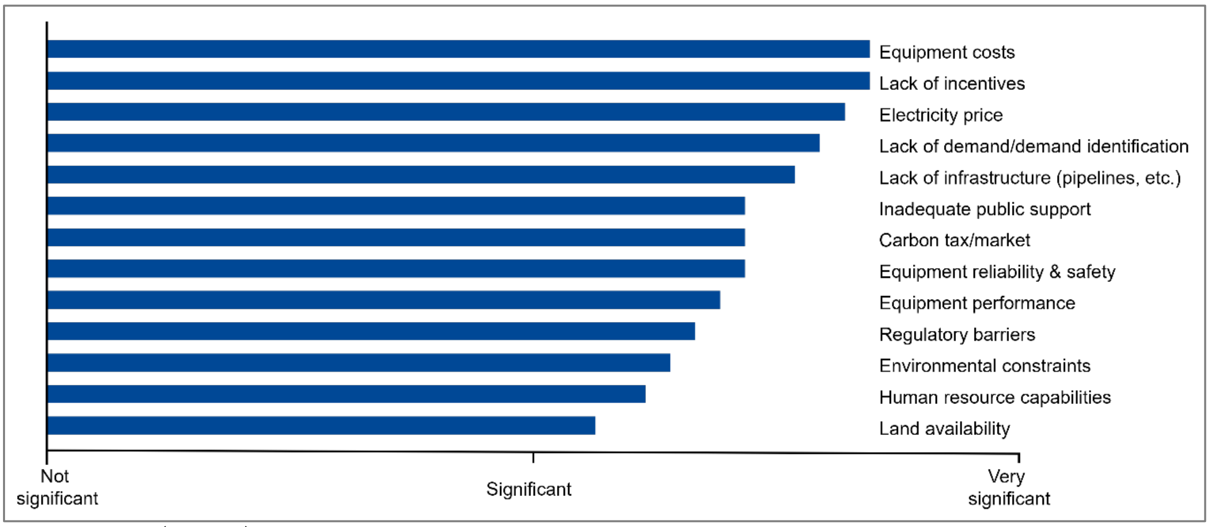
Figure 4.1. Participants of the Survey



Source: ACE (2024c).

Most respondents recognised the significant role that hydrogen will play in decarbonising their country's energy sectors, particularly in hard-to-abate industries. However, many AMS are still in the early stages of strategy development, with Myanmar and the Lao PDR reporting minimal activity or infrastructure for hydrogen and ammonia production and use. Technological advancements, particularly related to cost reduction in hydrogen production (e.g. electrolysis efficiency and CCS) are seen as key enablers. Adding to this, regulatory barriers, lack of infrastructure, and insufficient governmental incentives also need to be tackled (Figure 4.2).

Figure 4.2. Survey Results – Significant Barriers to the Development of a Hydrogen Market in ASEAN



Source: ACE (2024c).

The five highest-ranked barriers are as follows.

Prohibitive equipment costs. The high capital expenditure associated with hydrogen technology is a significant barrier to hydrogen market expansion in the ASEAN region. Electrolysers for green hydrogen production, fuel cells, and specialised storage systems are expensive due to the limited manufacturing scale and technological complexities. These costs make hydrogen less competitive compared to traditional energy sources and even other renewables. Additionally, the lack of local manufacturing capabilities often necessitates importing equipment, further escalating expenses due to tariffs and logistics. Without substantial cost reductions or financial support mechanisms, these equipment costs impede widespread adoption and hinder the development of a robust hydrogen market in the region.

Limited incentives. Incentives such as subsidies, tax credits, or feed-in tariffs are crucial for offsetting initial investment risks and encouraging private sector participation. Currently, policy frameworks supporting hydrogen are either weak or non-existent, leading to uncertainty amongst investors and developers. This lack of policy support also means insufficient funding for research and development, which is essential for technological advancement and cost reduction. Without proactive governmental intervention to create a favourable investment climate, the hydrogen market will continue to struggle to gain the necessary momentum for expansion.

High electricity prices. High electricity prices present a significant challenge for hydrogen production in the ASEAN region, particularly for green hydrogen generated through electrolysis. Electricity costs constitute a substantial portion of hydrogen production expenses, making the product less competitive against fossil fuels and other energy carriers. In many AMS, electricity prices are elevated due to reliance on imported fuels or inadequate energy infrastructure, such as grid infrastructure. Comparing renewable energy and fossil-fuel-based electricity costs in ASEAN using 2020 prices, the wind electricity cost was found to be highest amongst hydropower, wood biomass, and solar PV (Purwanto and Rusli, 2024). This economic barrier discourages investment in electrolyser technology and hampers the scalability of hydrogen projects. Lowering electricity costs through renewable energy integration or policy reforms is essential to make hydrogen production economically viable.

Lack of infrastructure. Insufficient infrastructure for hydrogen production, storage, distribution, and utilisation is a major obstacle in the ASEAN region. Developing a hydrogen economy requires significant investments in specialised facilities like refuelling stations, pipelines, and storage units capable of handling hydrogen's low density and high diffusivity. Currently, the region lacks a coherent network to support these needs, leading to logistical challenges and higher operational costs. This infrastructural gap also raises safety concerns, as inadequate facilities may not meet the stringent requirements for handling hydrogen. Addressing this barrier necessitates coordinated efforts between government and the private sector to invest in and develop the necessary infrastructure.

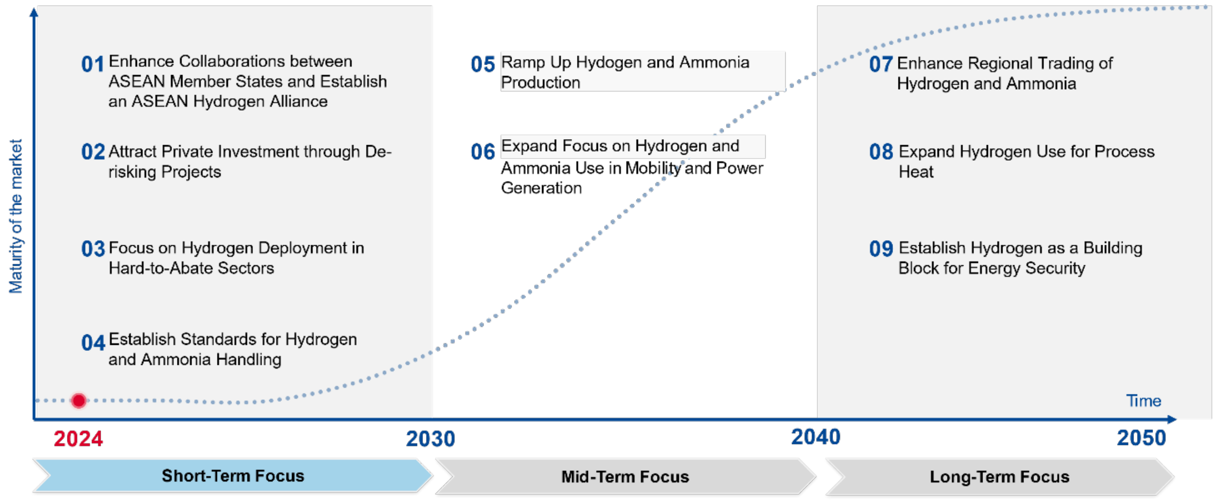
Lack of demand. A limited market demand for hydrogen has impeded its market ramp-up in the ASEAN region. Industries and consumers have yet to adopt hydrogen on a scale that justifies large-scale production and infrastructure investment. This hesitation stems from a lack of awareness, the dominance of established energy sources, and concerns over costs and reliability. Without sufficient demand signals, investors are reluctant to fund hydrogen projects, creating a cyclical barrier to market growth. Stimulating demand through pilot projects, public-private partnerships, and demonstrating the practical applications of hydrogen can help overcome this hurdle and encourage broader market acceptance.

Most respondents recognise hydrogen as a critical part of the future energy mix, especially in the decarbonisation of hard-to-abate sectors. The overall outlook on hydrogen is positive across ASEAN, with many AMSs noting its potential to reduce carbon emissions and to contribute to energy diversification.

Ammonia is also seen as an important energy carrier and a key element in decarbonisation strategies, particularly for co-firing in existing coal power plants. In the Philippines, ammonia is being explored as a way to reduce emissions from coal-fired power generation, while Thailand and Malaysia are also investigating its role in the industrial and transport sectors. The survey shows that, like hydrogen, ammonia is still in the early stages of development across the region, with many countries conducting feasibility studies and pilot projects.

The following roadmap outlines ASEAN's strategic plan to develop hydrogen and ammonia as central components of its future energy system. It provides a structured approach to achieving this goal across three key phases: the short term (2025–2030), medium term (2031–2040), and long term (2041–2050). It emphasises the need for regional collaboration through the creation of the Hydrogen ASEAN Alliance, fostering partnerships between key industries like oil and gas, transport, energy utilities, and governments. It also identifies critical steps to attract private investment; enhance cross-border trade; and deploy hydrogen in sectors such as transport, power generation, and industrial processes. By following these recommendations, ASEAN aims to position hydrogen as a cornerstone of its energy security and decarbonisation efforts, while building a competitive and sustainable hydrogen market in the region.

Figure 4.3. ASEAN's Long-term Strategy on Low-carbon Hydrogen and Ammonia



Source: ACE (2024c).

<u>Short Term (2025–2030)</u>

Short-term steps lay the groundwork for more extensive development. They focus on immediate actions like pilot projects, initial investments, and policy frameworks.

1. Enhance Regional Collaborations amongst ASEAN Member States and Establish the ASEAN Hydrogen Alliance

AMS have diverse energy profiles, with Indonesia and Malaysia being large producers of natural gas and coal, while Viet Nam and the Philippines are working on expanding their renewable energy capacities. Hydrogen can act as a unifying framework for energy collaboration, complementing this diversity by allowing AMS with abundant renewable resources to export hydrogen to those with higher energy demands. To ensure the success of this vision, ASEAN must prioritise enhancing regional collaborations to facilitate the shared development of hydrogen and ammonia projects.

One crucial step is the establishment of the Hydrogen ASEAN Alliance – a hydrogen task force – to connect key stakeholders across the value chain, including those involved in oil and gas, energy utilities, shipping and pipeline transport, infrastructure, and governments as well as regulators. The goal is to foster collaboration across industries and borders, ensuring that hydrogen and ammonia technologies are developed efficiently with least-cost production, the risks of early market stages are shared, and regional carbon neutrality targets are aligned.

Examples from around the world highlight the importance of such an initiative. The Hydrogen Council, a global coalition of over 120 companies, brings together industry and governments to advance hydrogen adoption globally. In Europe, Hydrogen Europe aligns policy with industrial needs, ensuring the commercialisation of hydrogen technologies. The MENA Hydrogen Alliance in the Middle East and North Africa accelerates hydrogen economies by fostering partnerships amongst energy producers, regulators, and researchers, while Hydrogen Africa connects renewable energy producers with hydrogen export markets in Africa. These alliances have proven that coordinated efforts across sectors can significantly reduce development time and costs, while also attracting investments and fostering innovation.

The Hydrogen ASEAN Alliance would deliver similar benefits to the region. By pooling resources and expertise, AMS could accelerate research and development, share best practices, and develop cost-effective infrastructure. Joint research and development initiatives could drive technological advancements in hydrogen production, storage, and distribution, enabling ASEAN to stay competitive on the global stage. Furthermore, by harmonising regulations and policies, the alliance could facilitate cross-border hydrogen trade and ensure infrastructure compatibility, crucial for building an integrated regional hydrogen network. A formal alliance would also help establish shared infrastructure projects, such as pipelines, hydrogen transport systems, and port facilities, enabling AMS to transport surplus hydrogen to those with higher energy demands. This would enhance energy security across the region, ensuring that ASEAN collectively meets its energy transition goals. Lastly, such an alliance would make ASEAN more attractive to global investors. By presenting a unified, large-scale hydrogen strategy, the region could unlock significant international investment, driving the development of hydrogen hubs and innovation clusters that would position ASEAN as a leader in the global hydrogen economy.

One key finding from the final workshop with the AMS representatives was the importance of collaboration amongst AMS through such a task force. Currently, ASEAN lacks the hydrogen pipelines, port facilities, and refuelling stations to support a large-scale hydrogen economy. Storing and transporting hydrogen requires cryogenic tanks or high-pressure containment, which are technically challenging and costly. Due to hydrogen's low energy density, it must be compressed to high pressures or liquefied at extremely low temperatures, requiring specialised infrastructure that does not yet exist on a large scale in ASEAN. Building these facilities across multiple AMS would require significant investment and regional coordination, complicating implementation timelines and budgets. Therefore, having a hydrogen production location concentrated in higher potential AMS could be also become a regional collaboration to be discussed. It brings about reduction of the investment needed, including the capital cost of hydrogen production.

2. Attract Private Investment by De-risking Projects

Hydrogen and ammonia projects involve significant CAPEX. Producing green hydrogen requires electricity from renewable energy, while blue hydrogen requires natural gas, which takes up more than half of the cost component in producing each hydrogen. This would create a risky investment for hydrogen development that hinders state-owned enterprises and the private sector from investing in low-carbon hydrogen projects. Due to the limited capacity of public funds to cover all necessary investments for hydrogen and ammonia, private sector investment is needed. Yet private investors often need help funding these projects due to the perceived high risks, such as the fluctuating price of natural gas and changing policies in AMS. This is further challenged by the uncertainty of hydrogen demand in the ASEAN market. Therefore, de-risking mechanisms can help lower financial barriers, making it more attractive for private capital to flow into these projects.

In de-risking hydrogen and ammonia projects, policymakers can develop supporting policies for renewable energy and hydrogen projects through feed-in tariffs and tax breaks for renewable energy project development. According to the final workshop with AMS representatives, current regulations and incentives are insufficient to drive down these costs to competitive levels. To push the availability of energy sources for producing green hydrogen, feed-in tariffs are a policy that AMS could provide. Feed-in tariffs provide a competitive price incentive for renewable energy projects to be developed. Tax breaks, such as exemption on taxes for imports of renewable energy technology/electrolyser stacks and special corporate tax rates, would also help alleviate the burden of the private sector in developing renewable energy and hydrogen projects. Department Circular No. DC2024-01-0001 of the Department of Energy of the Philippines is an example that reflects supporting policies for hydrogen development. Additionally, one of the ways to de-risk the uncertainty of demand is through the establishment of offtake agreements that enable the project developer to obtain a stable revenue stream to boost productivity of hydrogen production and to push more hydrogen development in the country/region.

AMS representatives during the final workshop stated that ASEAN can also provide additional financial support through direct funding, subsidies, and grants to stimulate hydrogen and ammonia development. These financial instruments would be aimed at reducing CAPEX and operational expenditure for pilot projects and early-stage hydrogen infrastructure, such as electrolysis plants, hydrogen pipelines, and hydrogen storage facilities. By reducing ongoing costs, CAPEX and operational expenditure funds would make hydrogen and ammonia more competitive with traditional fossil fuels. This financial support can encourage industries and power plants to switch to hydrogen and ammonia, accelerating adoption across the region. ASEAN can also utilise the growing momentum of the carbon-pricing discussion in the region by linking it with existing tax incentive schemes to reduce the production cost of hydrogen and ammonia in the region.

Moreover, funding mechanisms for hydrogen projects, such as hydrogen banks and financing facilities, are some other ideas that could be implemented to induce hydrogen investments in the ASEAN region. As previously mentioned, the European Hydrogen Bank was designed to de-risk investments in hydrogen production by giving a fixed premium per kg of green renewable energy produced, which will cover up to 10 years of a plant's operation. This scheme lifts the burden of risk associated with hydrogen projects so that producers can confidently invest in large-scale hydrogen production with fewer effects from fluctuating market prices.

AMS can also take steps to increase transparency regarding hydrogen pricing. Increasing transparency regarding hydrogen pricing across the region as well as a regional transparency framework, which includes regular publication of hydrogen and ammonia prices alongside government-backed financial guarantees, will be vital in driving investment in these sectors.

3. Focus on Hydrogen Deployment in Hard-to-abate Sectors

Focussing on hydrogen deployment in hard-to-abate sectors is essential for ASEAN's hydrogen development due to these industries' unique challenges and opportunities. Hard-to-abate sectors include heavy industries (i.e. steel, cement, and chemicals), aviation, maritime shipping, and long-haul transport, which have limited options for direct electrification. Hard-to-abate sectors are an important field for hydrogen deployment considering the energy-intensive nature and high GHG emissions. As hydrogen does not emit carbon when combusted, hydrogen utilisation as a feedstock for high-temperature heating and as a reducing agent for steelmaking becomes crucial for AMS decarbonisation efforts, which directly support AMS nationally determined contributions.

Given the significant challenges and opportunities, ASEAN should prioritise expanding hydrogen use in these areas, which are already integral to its operations. Sectoral mandates for GHG emissions reduction could be implemented at the national level by giving quotas and penalties for emitted GHGs, which would drive the sectoral players to adopt hydrogen. The development of sector-specific roadmaps is another way to introduce sectoral mandates in the country. The introduction of sectoral mandates could induce growth for hydrogen offtake since industrial players would shift towards cleaner alternative energy utilisation to comply with the regulation. Such mandates would also incentivise the development of hydrogen pilot projects in the industrial sector, which would help industrial players acknowledge the technical, economic, and environmental benefits of hydrogen adoption in the hard-to-abate sector.

ASEAN could also link carbon-pricing policies (e.g. a carbon tax or emissions trading scheme) with hydrogen and ammonia development in the region. An emissions trading system and the carbon market would present benefits to green industry players by giving them carbon emissions rights that can be traded in the market. These green policies would encourage hard-to-abate sectors to utilise cleaner hydrogen. The timing of linking carbon-pricing policies into hydrogen and ammonia development in ASEAN is also relevant to the European Cross-border Adjustment Mechanism (CBAM), which will affect the competitiveness of some ASEAN industries in trading with the European Union. However, the crucial step related to carbon pricing in ASEAN is that revenue allocation needs to be designed or linked with incentive schemes for key priority sectors related to ASEAN's carbon neutrality, including hydrogen and ammonia development. AMS can utilise this support to leverage their infrastructure and expertise to achieve substantial emissions reductions by prioritising hydrogen in hard-to-abate sectors.

4. Establish Standards for Hydrogen and Ammonia Handling

To support the deployment of hydrogen and ammonia technologies, ASEAN must develop shared standards for handling, storage, and transport. A regional framework – whether by adopting international standards or creating new region-specific guidelines – would ensure uniformity and facilitate cross-border trade. These standards would provide stability for investors and stakeholders, reduce risks, and create market certainty. A dedicated regional standards committee should be established to align ASEAN's guidelines with global safety and technical standards, such as IEC 60079 and ISO 80079, which address explosion protection and explosive atmospheres. The adoption of standards like the American Society of Mechanical Engineers B31.12 for hydrogen pipelines, designed to mitigate hydrogen embrittlement, would help ensure safe distribution across the region. Accelerating the development of high-pressure hydrogen testing methods will also be essential.

Additionally, a clear, internationally aligned definition of green hydrogen, based on renewable energy sources and its GHG reduction potential, is necessary. Without this, ASEAN risks inconsistent market development and inaccurate GHG reduction calculations. Adoption of standards like those from ISO Technical Committee 197 for classifying green hydrogen will create a level playing field, helping foster international investment and market confidence. ASEAN should build on systems like IECEx, extending them across the value chain to ensure compliance with safety, performance, and sustainability standards, creating consistency and credibility in hydrogen markets.

Medium Term (2031–2040)

To support hydrogen and ammonia development in the medium term, ASEAN should adopt a range of strategies that balance immediate feasibility with long-term potential. The medium-term strategies build on initial successes, expanding hydrogen production and use and scaling up infrastructure. This phase often includes more significant investments and broader policy.

5. Ramp up Hydrogen and Ammonia Production

As ASEAN moves into the medium term, the focus should shift towards significantly increasing hydrogen and ammonia production. Setting clear and common production targets across AMS would ensure a coordinated scale-up that meets regional energy and decarbonisation needs.

As of November 2024, only Singapore, Malaysia, Indonesia, and Viet Nam have created national hydrogen strategies, while only Malaysia and Viet Nam have laid out tangible production targets for low-carbon hydrogen and ammonia. By setting a clear and tangible targets for hydrogen production, AMS could develop a step-by-step path towards the goals, providing clarity on the roles of each sector in utilising hydrogen. National hydrogen strategies help AMS focus on the development of hydrogen and its derivatives in a certain area/sector, noting resource availability and the country's energy priorities. As Malaysia and Indonesia did, potential renewable resources that the country possesses should be mapped out so that industry players, international organisations, and policymakers can acknowledge the potential resources that could be harnessed to achieve renewable hydrogen production targets.

Besides laying out national directives, promoting hydrogen project development is an integral part of ramping up low-carbon hydrogen and ammonia production. This point correlates with the short-term focus on attracting investment for renewable energy projects since scaling up hydrogen and ammonia production requires abundant renewable energy. Promoting the development of green hydrogen projects can be done by various key players in the hydrogen market. From the government's point of view, providing dedicated funding and direct funding mechanisms for hydrogen project implementation, such as the Inflation Reduction Act in the US, enables the private sector, utilities, and project developers to implement green hydrogen projects. While a direct funding mechanism seems attractive, AMS need to have enough fiscal flexibility to fulfil such policies. Therefore, governments may need to engage with the private sector to fund hydrogen projects through blended financing or other types of financing mechanisms that de-risk investing in a green hydrogen project. These efforts should be supported by a regulatory framework that incentivises the construction of large-scale production facilities, providing the necessary backing for projects that contribute to these shared goals.

6. Expand the Focus on Hydrogen and Ammonia Use in the Transport and Power Generation Sectors

AMS should broaden the application of hydrogen and ammonia beyond the industrial sector to include the transport and power generation sectors. As the transport sector was the top energy-consuming sector in 2022, growing demand enables hydrogen to be adopted. Transport modes, such as aviation and shipping, are potential markets available for hydrogen-derived fuels like ammonia and synthetic fuels to reduce carbon emissions over long distances where battery technologies are insufficient. Japan and South Korea are the front-runners in the development of FCEVs, which induce the growth of hydrogen demand in the region. Heavy-duty vehicles, trucks, and buses would become the ideal implementation area for hydrogen-derived fuels.

Although it may seem inefficient for green hydrogen and its derivatives to be used in the power generation sector, hydrogen adoption in the power sector can help the region reduce reliance on imports and secure electricity production, which can enhance energy security in ASEAN. Green hydrogen adoption via fuel-cell technology is mainly relevant to supplying electricity to remote areas, especially on islands with high solar irradiance. The hydrogen production and storage could act as a buffer for excess electricity to be stored in the form of hydrogen, which will later be harnessed using a fuel cell.

To support this, pilot projects and demonstration plants should be implemented to showcase the viability of hydrogen in power generation and FCEVs. By now, governments could further support this expansion by establishing dedicated funding mechanisms for research and development in fuel-cell technologies, attracting research institutes and the private sector to support the deployment of fuel-cell technologies in the transport and power generation sector. In later years, the introduction of a carbon tax and carbon market would further increase the adoption of hydrogen-powered public transport and hydrogen-based power generation plants, making the production cost more competitive with other conventional technologies.

Long Term (2041–2050)

This phase ensures that hydrogen becomes a stable and reliable part of the energy mix. The strategy aims for full-scale deployment, integration into the energy system, and achieving sustainability targets.

7. Enhance Regional Trading of Hydrogen and Ammonia

In the long term, ASEAN should focus on strengthening the regional market for hydrogen and ammonia by enhancing trading mechanisms and positioning itself as a hub for these commodities. Developing a comprehensive regional trading platform, along with expanding the necessary cross-border infrastructure, will be critical for establishing ASEAN as a leader in hydrogen and ammonia commerce. This platform should include standardised systems for pricing, contracts, and logistics, ensuring that hydrogen and ammonia can be traded efficiently across the region.

A regional trading platform for hydrogen and ammonia in ASEAN offers several benefits, including enhanced coordination, cost reduction through shared infrastructure, and unified standards that facilitate efficient cross-border trade. This platform would also promote market stability by balancing supply and demand across the region. The trading of green hydrogen should go beyond the ASEAN border as well. Highlighting the rapid demand growth for hydrogen in East Asia (i.e. Japan and South Korea), AMS could leverage the growth to produce and to export renewable hydrogen there. AMS have a unique economic and geographical advantage in supplying green hydrogen to East Asia due to the abundant renewable resources, which, in turn, could produce cheap green hydrogen.

To set up such a market mechanism, a regional hydrogen cooperation framework should be developed to ensure the seamless implementation and transparency of regional trading of hydrogen. An agreement or memorandum of understanding amongst AMS is pivotal in shaping the understanding of each country to align the visions to utilise hydrogen as a medium for enhancing greater energy security. The development of the proposed regional cooperation framework on hydrogen should ensure the sovereignty of each AMS and that market participation should be on a voluntary basis. Upon the creation of this regional cooperation framework, a hydrogen market institution should be formed to oversee trading, avoiding any misconduct in regional market activities.

8. Expand Hydrogen Use to Process Heat

Along with its stage of development and deployment, hydrogen can be also expanded to be utilised in high-temperature industrial processes. Promoting hydrogen for process heat applications will not only increase its value in the regional economy but also contribute to decarbonising energy-intensive industries. The steel manufacturing industry – as one of the most energy-intensive industries – would benefit from the use of hydrogen as the reducing agent in producing steel. The low-carbon nature of hydrogen combustion and utilisation would make hydrogen usage useful in fulfilling the demand for heat in industrial processes. Enabling policies should be implemented to encourage the use of hydrogen in these areas, supported by financial incentives and technology demonstrations. Additionally, establishing futures markets for hydrogen in the region could stabilise prices and provide long-term contracts for industrial users, further embedding hydrogen in ASEAN's economic landscape.

9. Establish Hydrogen as a Building Block for Energy Security in the Region

At this time, it is expected that ASEAN has entered the mature market phase of hydrogen and ammonia in the region. Under this phase, hydrogen could be utilised further as an energy security source in the region. This would involve ensuring that hydrogen forms a substantial part of the region's energy mix, supported by investments in domestic production capabilities. Reducing reliance on imported fossil fuels through increased hydrogen production would be key to achieving energy security. This would require the inclusion of hydrogen in ASEAN energy security frameworks and setting mandatory usage targets in downstream sectors (i.e. hard-to-abate industries, transport, and power) in the region. Moreover, it would also be timely in regard to the development of the next phase of ASEAN Plan of Action for Energy Cooperation.

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Annex

Hydrogen Stakeholders in ASEAN

Stakeholder Type	Name	Description
Industry Players	PETRONAS	Exploring green hydrogen production and leveraging existing natural gas infrastructure for blue hydrogen projects.
	PT Pertamina	Targeting 10 gigawatts of clean power capacity by 2026, focussing on blue hydrogen with carbon capture and storage technology.
	PTT	Promoting hydrogen as a key energy source through the Hydrogen Thailand Group, investing in blue and green hydrogen projects.
	Sarawak Energy	Developing hydrogen production facilities using water resources to supply hydrogen fuel, particularly for transport.
	AMEA Power	Developing large-scale green hydrogen projects across the Asia-Pacific region.
	PT Pupuk Indonesia	Producing hydrogen for ammonia synthesis, supporting agricultural productivity, and reducing carbon emissions.
	PT Perusahaan Listrik Negara (PLN)	Exploring hydrogen for grid stabilisation and backup power, integrating renewable energy sources.
	Hoa Phat Group	Integrating hydrogen into steel manufacturing processes to reduce carbon emissions.
	HDF Energy	Developing hydrogen infrastructure projects in ASEAN to decarbonise the power generation and transport sectors.
	Philippine National Oil Company Gas	Exploring hydrogen production from natural gas and renewable sources to diversify the energy mix of the Philippines.

Stakeholder Type	Name	Description
	Petrovietnam	Investing in blue and green hydrogen projects to support Viet Nam's low-carbon economy transition.
	Brunei LNG	Developing liquefied hydrogen export capabilities to supply international markets, particularly Japan.
	AEDP Power	Integrating renewable energy sources with hydrogen production in Thailand.
	Fortescue	Investing in green hydrogen projects in the ASEAN region, leveraging expertise in large-scale industrial operations.
	Siemens	Providing advanced electrolysis technology for hydrogen production.
	Mitsubishi	Involved in hydrogen infrastructure projects across Asia, focussing on distribution and technological solutions.
Investors and Financial Institutions	MUFG	Financing hydrogen infrastructure projects to support low-carbon technologies and net-zero emissions goals.
	Japan Bank for International Cooperation (JBIC)	Providing financial support for the development and commercialisation of hydrogen technologies, both domestically and internationally.
	European Investment Bank	Backing large-scale green hydrogen hubs and projects to promote sustainable energy solutions.
	Asian Development Bank	Investing in renewable energy and hydrogen projects to support decarbonisation and to enhance energy security in ASEAN.
	International Finance Corporation	Promoting private sector investment in hydrogen and renewable energy projects to drive sustainable development and innovation.
Research and Academic Institutions	Economic Research Institute for ASEAN and	Conducting comprehensive research and providing strategic insights into energy policies and technologies, including hydrogen.

Stakeholder Type	Name	Description
	East Asia (ERIA)	
	National University of Singapore	Leading research on advanced hydrogen production technologies, storage solutions, and fuel cells, and collaborating with industry partners.
	Chulalongkorn University	Researching sustainable energy technologies and integrating hydrogen into Thailand's energy system, offering policy recommendations.
	Universiti Malaya	Focussing on hydrogen production, storage, and utilisation research, collaborating with national and international partners.
	Bandung Institute of Technology	Developing efficient hydrogen production methods, exploring storage solutions, and integrating hydrogen into Indonesia's energy infrastructure.
Government Bodies	ASEAN Member State Ministries	Shaping policies, providing incentives, and fostering an enabling environment for the hydrogen economy.
	ASEAN Centre for Energy (ACE)	Representing ASEAN Member States' interests in the energy sector, conducting studies, and offering policy recommendations to promote hydrogen adoption.
	Regulatory Authorities	Ensuring safety standards, regulatory compliance, and market regulation to support hydrogen development and integration.