SINGAPORE'S NATIONAL HYDROGEN STRATEGY

EXECUTIVE SUMMARY

Global developments in hydrogen are at an inflection point, with increased investments from countries and companies globally to develop new technologies and establish supply chains for low-carbon hydrogen. Given these significant developments, Singapore believes that low-carbon hydrogen has the potential to be a major decarbonisation pathway to support Singapore's accelerated transition towards net zero by 2050, while strengthening our energy security and resilience.

Low-carbon hydrogen can play an important role to decarbonise our power sector, given our limited ability to generate renewable energy domestically. Utility-scale Combined Cycle Gas Turbines (CCGTs) that can combust a blend of hydrogen and natural gas are already available, while CCGTs able to run fully on hydrogen are expected to become available in around 2030. If technology continues to advance and international efforts remain strong, we assess that hydrogen could meet up to 50% of our projected electricity demand by 2050.

Low-carbon hydrogen is also a pathway for mitigating industrial emissions and enabling sustainable p roduction. As a feedstock for multiple industrial processes, demand for low-carbon hydrogen is expected to increase as companies decarbonise and transition towards the making of sustainable products such as biofuels and synthetic fuels. Low-carbon hydrogen also presents an option for the industry to decarbonise heat, power and steam generation by replacing fossil fuels in burners and co-generation plants.

Besides reducing domestic emissions, low-carbon hydrogen can be a key decarbonisation solution for the maritime and aviation sectors. As a global shipping and air hub, Singapore can play an important role in supporting this transition. In the maritime sector, hydrogen-based fuels such as ammonia are expected to play a prominent role in the sector's multi-fuel transition, and we are working with industry and international partners to study ammonia's potential as a marine fuel. On the aviation front, low-carbon hydrogen can contribute to the production of Sustainable Aviation Fuels, be used in fuel cells for airside ground vehicles and aircrafts, and in the longer term possibly directly as a fuel.

Recognising both the potential as well as continued uncertainties surrounding low-carbon hydrogen, Singapore will pace its hydrogen deployment and infrastructure development, in line with technological and global progress.

We will focus on progressively building capabilities in industry, workers and the Government in areas that are critical to unlocking hydrogen adoption in Singapore, and will organise our efforts around five key thrusts:

1. Experimenting with the us of advanced hydrogen technologies at the cusp of commercial readiness through pathfinder projects,

2. Investing in research and development to unlock key technological bottlenecks,

3. Pursuing international collaborations to enable supply chains for low-carbon hydrogen,

4. Undertake long-term land and infrastructure planning, and

5. Supporting workforce training and development of our broader hydrogen economy.

Singapore looks forward to working closely with our industry and international partners, to realise low-carbon hydrogen's potential for Singapore as well as the world.

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INTRODUCTION

INTRODUCTION

Two years into this decade, the world has already witnessed the acceleration of two major shifts in the global energy situation. First, there has been a marked increase in recognition of the urgency of our climate crisis, in no small part due to more frequent and extreme weather patterns faced by countries across the world.

The search for a more sustainable way to power our economies and lifestyles has never been more pressing. Second, the Russia-Ukraine war has sent shockwaves around the global gas market. Countries that depend significantly on natural gas are faced with a significant increase in energy prices, which has in turn fuelled broad-based inflation.

The world cannot overcome either challenge without a substantial scale-up in the generation, trade, and deployment of low-carbon energy sources. According to the International Energy Agency (IEA), around 29% of the world's 2020 electricity generation was met by renewable sources[1], and this figure needs to rise to 90% for the world to reach net zero by 2050[2] .

However, renewable energy alone cannot go sufficiently far in decarbonising the world. First, there is a large variance in countries' access to renewable energy; those that are not naturally endowed will need to find means to import low-carbon energy. Second, hard-to-electrify sectors, many of which are critical to the global economy, will need to continue to rely on fuel energy until significant breakthroughs in electrification technology materialise. These include heavy industries such as chemicals, steel and cement, as well as long-range aviation and maritime transportation.

[1] *Global Energy Review 2021, IEA. April 2021.*

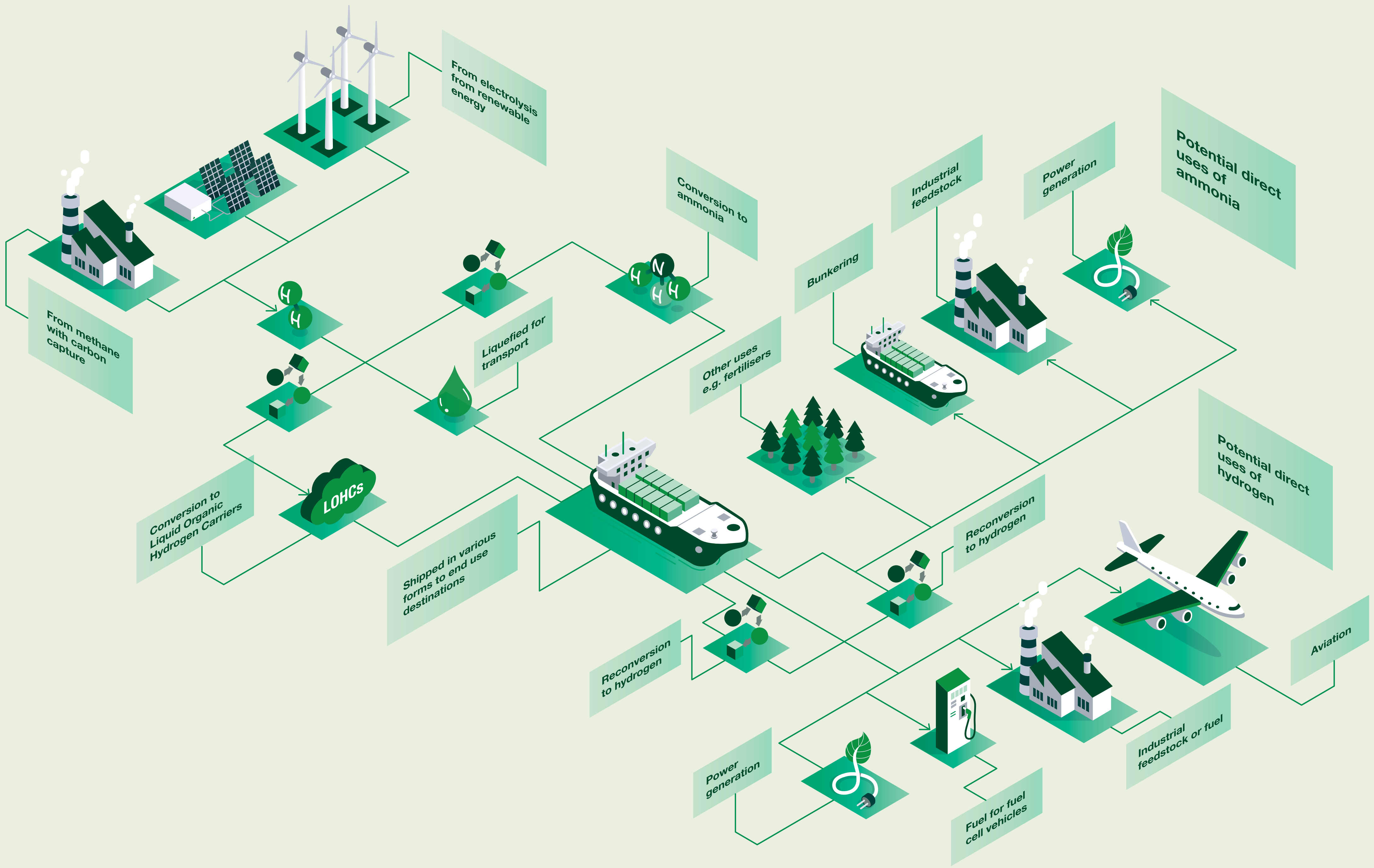
[2] *Net Zero by 2050, IEA. May 2021.*

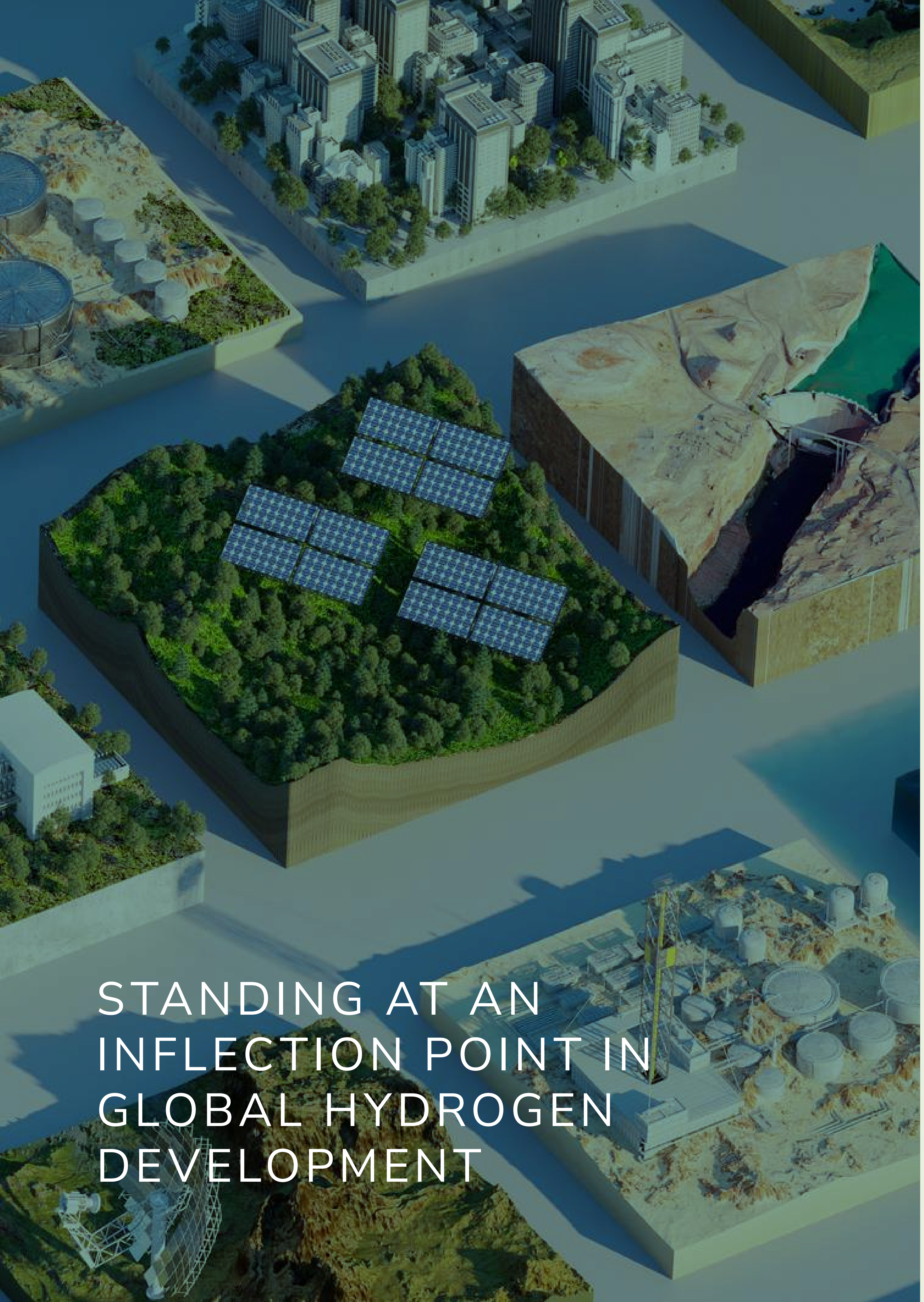
HYDROGEN AS A LOW-CARBON SOLUTION FOR THE WORLD

This is where hydrogen comes into the picture. Low-carbon hydrogen is widely recognised by industry experts and international organisations – such as IEA, International Renewable Energy Agency (IRENA), and the World Economic Forum to name a few – as a sustainable alternative to fossil fuels and a major pathway to address climate change. Hydrogen, when used as a low-carbon fuel, is especially valued for its ability to decarbonise sectors that are difficult to abate through renewable energy. For a city-state like Singapore that has very limited access to in-situ renewable energy, hydrogen is also an attractive decarbonisation pathway because it presents a scalable way to transport clean energy from countries around the world.

Low-carbon hydrogen can be produced either from the electrolysis of water using renewable/low-carbon energy or from fossil fuels with carbon removal technologies applied. Due to its low volumetric energy density, hydrogen needs to be transformed into a more easily transportable form, typically through liquefaction or the conversion into a “hydrogen carrier” before it can be shipped across long distances. Hydrogen carriers include ammonia or liquid organic hydrogen carriers such as methylcyclohexane (MCH) and dibenzyltoluene (DBT).

Upon arrival at its destination, the hydrogen can then be regasified or extracted to be used as either a fuel or a feedstock for a variety of applications, including power generation, industrial processes, and transport. In certain use cases, hydrogen carriers, such as ammonia, can be used directly without the need to extract the hydrogen, which presents cost savings to the end-user by skipping the (usually) energy-intensive extraction process.





STANDING AT AN INFLECTION POINT IN GLOBAL HYDROGEN DEVELOPMENT

The world is currently at an inflection point of global hydrogen development, and we are not the only country that thinks so. 40 countries have announced their hydrogen strategies, and committed significant resources to building up their hydrogen value chains[3].

This has had a rallying effect on global hydrogen production and supply chains. The IEA estimated that if all announced pipeline projects for low-carbon hydrogen materialise, the production of low-carbon hydrogen could reach up to 24 million tons per annum (mtpa) by 2030, an exponential increase from less than 1 mtpa in 2021[4].

We are also starting to witness the importance of hydrogen trade in enabling this global supply chain. The IRENA reported that the cumulative number of announcements of agreements for hydrogen trade had increased progressively from early-2018 to May 2021 to over 40, but doubled in the nine months from May 2021 to Feb 2022 to about 90[5].

In addition, there are growing industry activities surrounding technologies along the hydrogen value chain. These include continued efforts to improve electrolyser efficiency and scale, the world's first shipment of liquefied hydrogen, and the promising development of 100% hydrogen- and ammonia-fired power generation gas turbines and ammonia-fuelled ship engines, just to name a few. IEA reported in its Global Hydrogen Review 2022 that there are more than 100 pilot and demonstration projects involving the use of hydrogen and its carrier forms in shipping, while more than 3.5 GW of power generation capacity through the use of hydrogen and ammonia by 2030 have been announced.

Given the significant progress, we believe it is timely to more closely examine hydrogen's potential for Singapore, and assess our next steps to establish a domestic hydrogen supply chain.

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[3] *Hydrogen Insights 2022. Hydrogen Council and McKinsey & Company. September 2022.*

[4] *Global Hydrogen Review 2022. IEA (2022).*

[5] *Global Hydrogen Trade to Meet the 1.5OC Climate Goal: Trade Outlook for 2050 and Way Forward. IRENA (2022).*

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HYDROGEN IN SINGAPORE'S JOURNEY TOWARDS NET ZERO

Singapore has committed to achieving net zero emissions by 2050, as part of our contribution to global climate action. As a small and densely populated city-state, Singapore faces significant limitations in harnessing alternative energies. We have limited land for solar deployment, and do not have access to wind and hydropower at a meaningful scale.

Nevertheless, this has not stopped us from making an ambitious effort to lower our carbon footprint and develop more sustainably.

POWER

Contributes to 39.8% of our primary emissions. We have already transitioned away from fuel oil to rely almost fully on natural gas, the cleanest burning fossil fuel. In addition, we are maximising solar deployment on all available spaces, scaling up energy efficiency solutions, and leveraging regional power grids to access cleaner electricity.

INDUSTRY

Contributes to 44.4% of our primary emissions. We have implemented energy efficiency and resource optimisation measures to reduce the sector's carbon footprint, and continue to explore low-carbon technologies such as carbon capture, utilisation and storage, and low-carbon hydrogen.

TRANSPORT

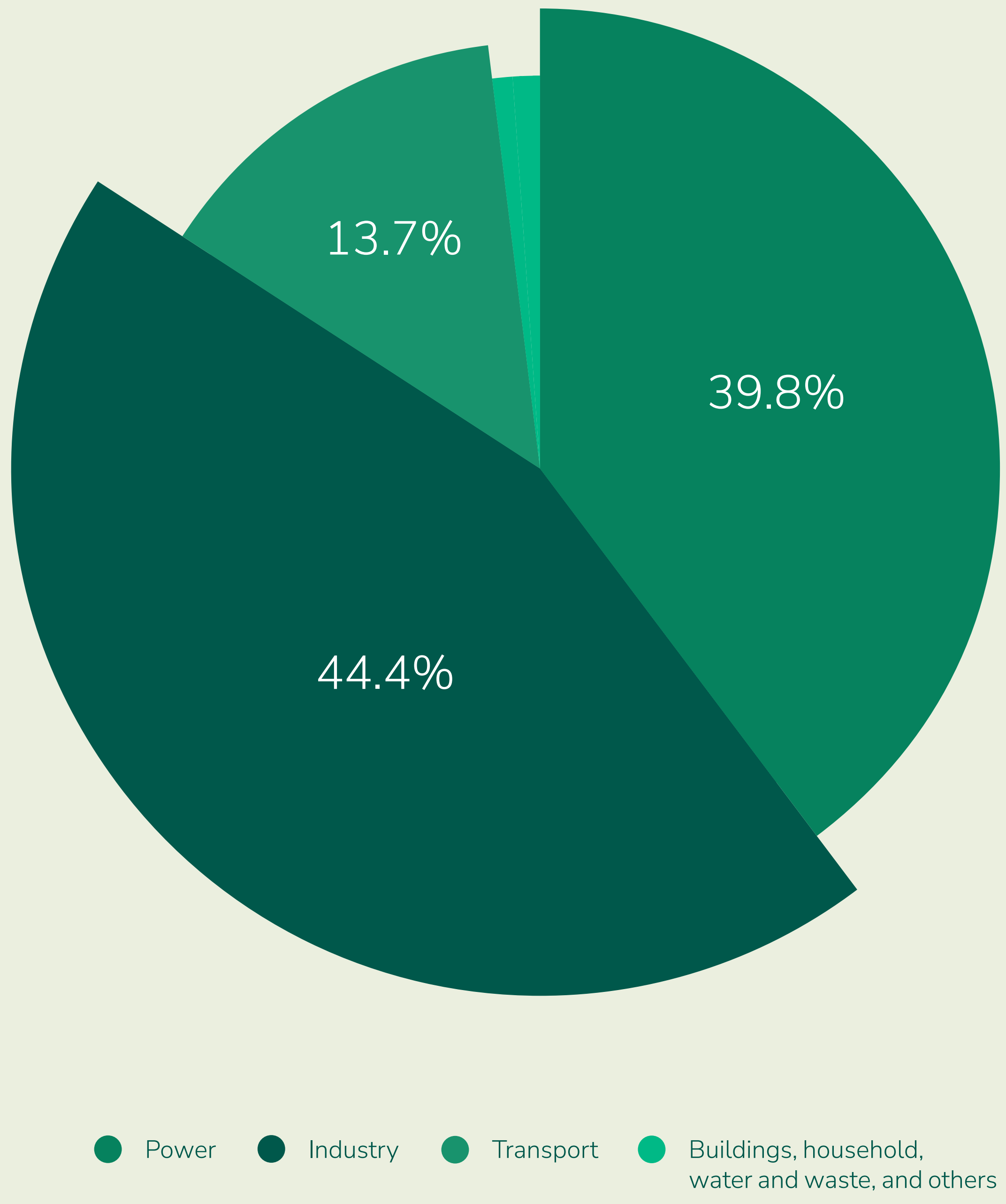
Contributes to 13.7% of our primary emissions. For land transport, we envisage a system where walking, cycling and riding public transport are the preferred modes of commute. We also aim to have all vehicles run on cleaner energy by 2040.

However, these measures will not be sufficient for Singapore to bring our emissions down to zero. Effective international cooperation and the maturing of key decarbonisation technologies will be needed to help us overcome our resource constraints.

Low-carbon hydrogen is one such technological pathway. Hydrogen does not release any greenhouse gases when combusted. When produced through low-emission methods such as the electrolysis of water using renewable energy, it can have low to zero emissions. As it can be shipped over long distances and stored to some extent, it can also help strengthen our energy security and resilience given our increasing reliance on domestic renewable sources and electricity imports.

PRIMARY EMISSIONS PROFILE (2020)[6]

EMISSION 49.7 $MtCO_2e$



[6] *The emissions profile above excludes estimated hydrofluorocarbons (HFCs) emissions of around 3.1 $MtCO_2e$ from the Refrigeration and Air-conditioning (RAC) sector in 2020. When more robust estimates are established, the national emissions profile will be updated in accordance with the United Nations Framework Convention on Climate Change (UNFCCC) and Intergovernmental Panel on Climate Change (IPCC) guidelines on continual improvement of national GHG inventories.*

POWER

The power sector currently accounts for about 40% of Singapore's primary greenhouse gas emissions. Decarbonising power generation is therefore instrumental in enabling Singapore to achieve net zero emissions by 2050.

In 2019, we announced the Singapore Energy Story, and laid out the plans to decarbonise the power sector and help Singapore achieve its climate commitments while ensuring that our power system remains secure and reliable. Four supply "switches" were identified to transform our fuel mix – natural gas, solar paired with Energy Storage Systems (ESS), regional power grids, and low-carbon alternatives.

Low-carbon hydrogen is a promising technology under the last pillar. In March 2022, the Energy 2050 Committee, a group of industry experts commissioned by the Energy Market Authority (EMA) to make recommendations on how Singapore can decarbonise the power sector, stated in its report that hydrogen is a promising low-carbon solution that can be scaled up and contribute to power sector's zero emissions target by 2050. The findings noted that hydrogen could be a major component of Singapore's 2050 fuel mix, depending on technological developments and the extent of international cooperation in the low-carbon energy trade.

Singapore will work towards achieving a diversified supply of low-carbon energy to meet our 2050 demand.

Solar is our most viable source of renewable energy, and we will need to maximise solar deployment in all available spaces. In the update of the solar photovoltaic roadmap by the Solar Energy Research Institute of Singapore, the maximum technical potential for solar deployment was estimated to be around 8.6 Gigawatt peak, meeting about 10% of our projected electricity demand in 2050 if it materialises. Electricity imports are estimated to meet about 30% of our projected electricity demand by 2035, and we may consider more imports if doing so can meet our holistic needs.

Beyond solar and electricity imports, we will need to invest in other nascent low-carbon alternatives such as geothermal and hydrogen to fully decarbonise the power sector in the long term. Given recent developments in the global energy market and further acceleration in momentum behind hydrogen, we assess that hydrogen has the potential to supply up to 50% of our projected electricity demand by 2050. The eventual fuel mix is not fixed and will depend on the development of technologies over time.

FOUR SWITCHES TO POWER SINGAPORE'S FUTURE

NATURAL GAS

Natural gas has allowed us to significantly reduce emissions by switching away from fuel oil, and will remain a key source of fuel in the decades to come. We will continue to diversify our natural gas sources and improve the efficiency of power generation.

SOLAR

We will maximise solar deployment paired with the use of Energy Storage Systems.

REGIONAL POWER GRIDS

Regional power grids will allow Singapore to import cleaner electricity from neighbouring countries and promote the development of renewable energy in the region.

LOW-CARBON ALTERNATIVES

The remaining supply could be met by Low-carbon alternatives such as hydrogen to bring the power sector to net zero. Carbon Capture, Utilisation and Storage (CCUS) and geothermal are also being explored as potential solutions.

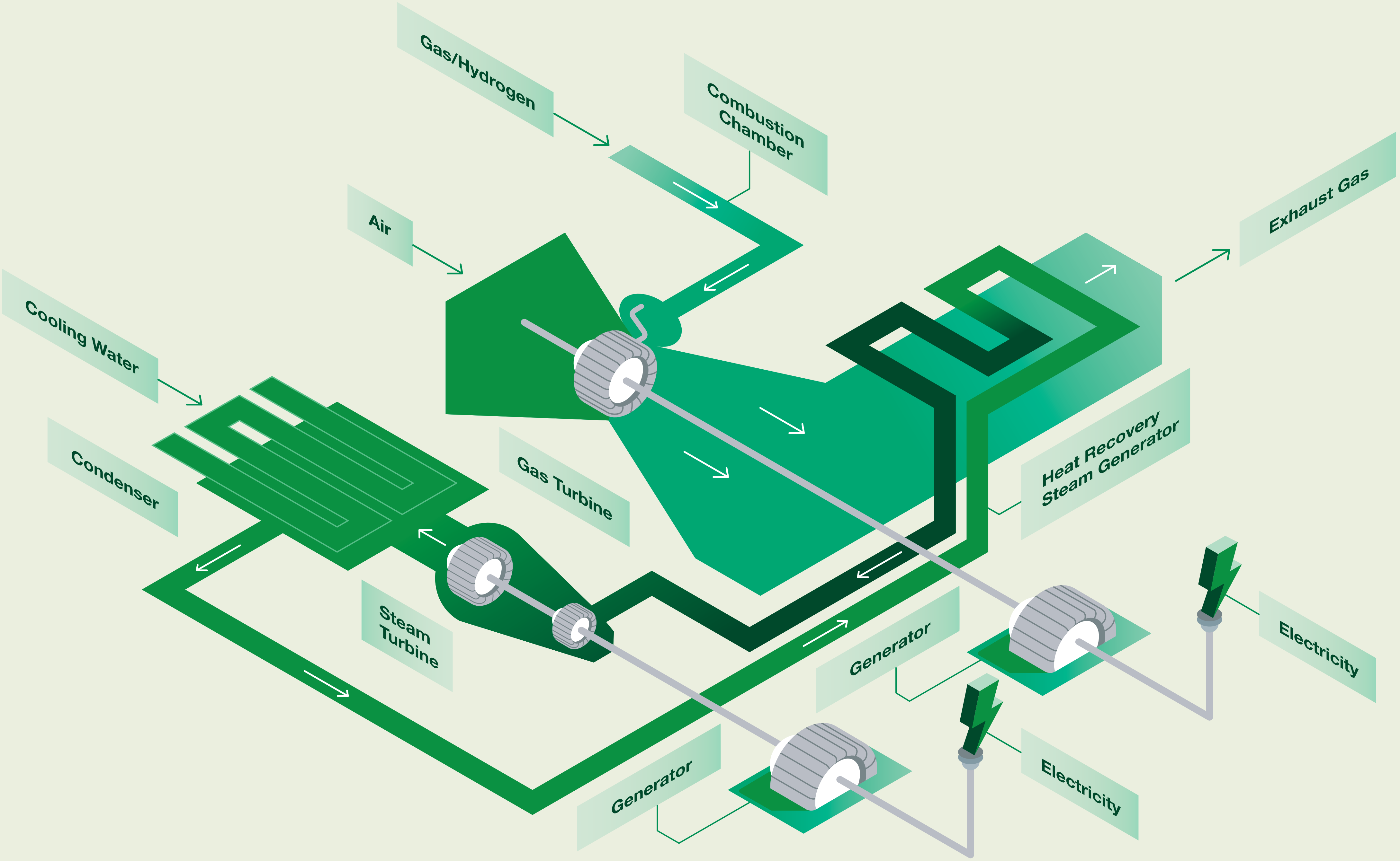
HYDROGEN-TO-POWER

Hydrogen-to-power applications, whilst nascent compared to natural gas power generation technology, are already commercially available. There are two main pathways to convert hydrogen to electricity.

First, it can be used in fuel cells, which generate electricity through electrochemical reactions. Second, similar to natural gas, hydrogen can be combusted in gas turbines. The advantage of fuel cells is that they are more energy-efficient than gas turbines in converting hydrogen to electricity. However, they are significantly more expensive to produce, require high-purity hydrogen, and are more land-intensive when deployed at scale based on current technology. Therefore, while they can be a good solution for decarbonising microgrids, they are currently not suitable for utility-scale power generation until design and technology improve. Nonetheless, we will continue to explore hydrogen fuel cell applications for decentralised power generation to augment existing grid infrastructure and complement conventional power plant operations.

On the other hand, utility-scale natural gas-fired Combined Cycle Gas Turbines (CCGTs) that can combust a blend of up to 30 – 50% of hydrogen by volume are already commercially available.

The Original Equipment Manufacturers are developing 100% hydrogen-compatible CCGTs, targeted for commercial availability in around 2030. The transition from partial to 100% hydrogen-fuelled gas turbines is expected to only require limited retrofits, which offers power generation companies a more certain pathway to start reducing their emissions.



HYDROGEN IMPORT, STORAGE FACILITIES AND DISTRIBUTION NETWORK

Beyond end-use applications for power generation, hydrogen will need to be stored and distributed to off-takers. This will require the development of suitable import and storage facilities, as well as a distribution network.

Hydrogen can be distributed directly in pure hydrogen pipelines, or blended with natural gas in existing pipelines. Based on current literature studies, natural gas pipelines may be able to accommodate up to 10% blend of hydrogen by volume. However, blending into the existing natural gas network will impact all consumers, and the needs of all gas network users will need to be considered. Therefore, there may be a need to consider the distribution of hydrogen via dedicated pipelines, and for blending with natural gas to take place onsite to tailor to the individual needs of off takers.

The development of a distribution network, whether via dedicated pipelines or through blending into the current natural gas network, will have to be built up progressively, taking into consideration a myriad of factors such as the pace and eventual extent of hydrogen demand in the power sector, the type of carrier used, safety considerations and availability of overground and underground space for the new pipelines. Singapore will continue to study the methods to transport hydrogen effectively, safely and efficiently.

INDUSTRIAL

The manufacturing sector is a significant contributor to Singapore's economy, comprising about 21% of our Gross Domestic Product (GDP). The sector employs about 450,000 people, or approximately 12% of our workforce, and provides good paying jobs with median wages about 10% higher than the economy-wide median. Singapore's manufacturing sector is also globally competitive, and was ranked second in the world for manufacturing value-add in the 2020 Bloomberg innovation index. At the same time, the manufacturing sector is the largest contributor to Singapore's carbon emissions, at around 44% of total emissions in 2020.

Decarbonising our manufacturing sector will be important to our net zero efforts, and to improve our competitiveness in a low-carbon future. In this regard, low-carbon hydrogen is one of the key pathways in bringing down industrial emissions, enabling sustainable production and supporting the manufacturing of sustainable products. It can be used as both (i) feedstock for industrial processes and (ii) fuel for heat, power, and steam generation. The adoption of hydrogen also contributes to end-users and consumers' sustainability efforts. For this reason, the adoption of low-carbon hydrogen was identified to be one of the key initiatives under Singapore's Sustainable Jurong Island plans, to support the transformation of our Energy & Chemicals sector.

HYDROGEN AS FEEDSTOCK

Hydrogen is used as feedstock in multiple industrial processes – in manufacturing plants such as semiconductor wafer fabrication, food manufacturing as well as refineries and chemical plants. Demand for low-carbon hydrogen is expected to increase as companies decarbonise their operations, grow the base of advanced semiconductor wafer fabrication, and transit towards the production of sustainable products such as biofuels and synthetic fuels (e.g. e-methanol, e-kerosene). Hydrogen is also used to produce sustainable chemicals such as methionine, a feed additive that allows for more sustainable livestock production.

Today, the hydrogen used in these plants is produced through steam methane reforming, partial oxidation of refinery bottoms, or as a by-product of chemical processes, which are emissions-intensive processes. We are exploring options to decarbonise hydrogen production, including through pairing hydrogen production assets with carbon removal technologies, or switching to imported low-carbon hydrogen at the end of life of these assets.

HYDROGEN AS FUEL

Low-carbon hydrogen also presents an option for the industry to decarbonise heat, power and steam generation. This is achieved through the partial or complete replacement of fossil fuels such as natural gas in burners and co-generation plants, thus avoiding carbon emissions from fossil fuel combustion. We expect that the use of low-carbon hydrogen as fuel, alongside carbon removal technologies, will play a key role in decarbonising fuel use in the manufacturing sector as part of our transition towards net zero emissions by 2050.

The adoption of low-carbon hydrogen in the industrial sector can have synergies with hydrogen adoption in other sectors such as power generation. For example, both end-use sectors can share key infrastructure to import and distribute hydrogen and/or its carrier forms (such as ammonia).

MARITIME

The Port of Singapore is currently the world's busiest container transhipment port, with ship arrival tonnage exceeding 2.8 billion gross tonnage in 2021. Singapore is also the world's largest bunkering hub, supplying close to 50 million tonnes of marine bunker fuel to vessels that plied international shipping routes in 2021.

As a major global maritime hub, Singapore can play an important role in the sector's decarbonisation, especially through transitioning to lower-carbon fuels. To this end, we unveiled our Maritime Singapore Decarbonisation Blueprint in March 2022, which outlined our approach towards the maritime green transition, and will update this progressively to reflect the concrete steps that we are taking to enable decarbonisation both within and beyond our shores.

SUPPORTING INTERNATIONAL MARITIME DECARBONISATION

The international maritime sector is undergoing a green transition that will span the next few decades. Engine manufacturers have made progress on developing engines that can directly combust ammonia or methanol fuel, and large global shipping lines have ordered new fleets built to be run on these engines. These developments are reflected in the latest industry projections for maritime fuel transition, which estimate that ammonia and hydrogen onboard fuel technologies could be available well before the end of the decade.

Singapore believes that the international shipping sector is headed for a multi-fuel transition. The more prominent low-carbon marine fuels in the near term include biofuels, methanol and ammonia, with liquefied hydrogen potentially playing a role in the longer-term. Liquefied natural gas (LNG) is also expected to be a transition fuel for ship liners that want to move off marine gas oil and do not wish to wait for newer marine fuel technologies to mature. Each of these fuels has its respective advantages and disadvantages, and we expect ship liners to adopt a portfolio approach to meet the needs of different vessels' operating profiles.

Industry experts share this view. For example, DNV projects that various alternative fuels (including biofuels, synthetic fuels and ammonia) will all feature strongly in the 2050 fuel mix[7]. Actual uptake of the different fuels will be contingent on a multitude of factors, such as fuel availability and prices, suitability for different vessel-operating profiles, additional demand for onboard vessel storage, safety and regulations, global acceptance of status as a low-carbon fuel, availability of global bunkering infrastructure, and extent of capital investment.

Notwithstanding these uncertainties, ammonia continues to be considered as one of the most promising zero-carbon marine fuels. In several projected scenarios, DNV expected ammonia to contribute to a significant proportion of the world's maritime energy mix to decarbonise the world's fleet by 2050, while IEA estimated ammonia to meet 45% of international shipping fuel demand to achieve global net zero in 2050[8].

[7] DNV Maritime Forecast 2022
[8] Global Hydrogen Review, International Energy Agency, 2021.

The Maritime and Port Authority of Singapore (MPA) has already taken early steps to ensure that Singapore can be an early mover in the transition towards ammonia bunkering. First, it is working directly with various industry consortia to study the feasibility of ammonia as a bunkering fuel, and to accelerate its deployment in international shipping. Second, it is collaborating with stakeholders to define safety and operational envelopes that will be used to facilitate a regulatory sandbox for ammonia bunkering trials.

MPA is also investing in industry enablers that can help build up capabilities in the maritime sector and facilitate its transition to a low-carbon future, and studying the support infrastructure to train seafarers. In addition, it is building a network of like-minded ports and countries, to establish green and digital shipping corridors and realise sustainable vessel sailing.

We will continue to monitor key signposts in low-carbon fuel development, and work with the industry to develop new standards and regulations on bunkering of such fuels, as part of our long-term strategy to build a sustainable maritime industry and to strengthen our position as a leading global port and bunkering hub. As a leading global hub port, bunkering hub and shipping registry, Singapore will continue to advance strong, credible and inclusive climate action at the International Maritime Organization (IMO) and international fora.

EFFORTS TO ADVANCE AMMONIA BUNKERING

- Work with industry consortia to accelerate the operational deployment of ammonia-fuelled vessels and build up the supply chain for ammonia bunkering
- Co-develop ammonia bunkering standards with industry, class societies, research institutes and academics
- Set up the Global Centre for Maritime Decarbonisation (GCMD), together with six other founding partners, as a non-profit organisation based in Singapore to advance maritime decarbonisation
- Establish green and digital corridors with like-minded ports and countries to build low-carbon marine fuel supply chains, conduct joint bunkering pilots and trials, and develop bunkering infrastructure

DECARBONISING PORT OPERATIONS & THE DOMESTIC HARBOUR CRAFT FLEET

On the domestic front, Singapore will focus on decarbonising port operations and transitioning the domestic harbour craft fleet towards full-electric propulsion and net zero fuels. PSA Corporation is taking the lead by developing Tuas Port with sustainability as a key focus area. By 2050, PSA Corporation's container handling operations will be electrified, supplemented by low-carbon energy sources such as hydrogen. We envisage that all licensed harbour craft will operate on full-electric propulsion or net zero fuels, consistent with our international climate commitment to achieve net zero emissions by 2050.

AVIATION

Sustainability will be a key priority for Singapore's aviation sector in the coming years, as it revives air travel and rebuilds the Singapore air hub. At the same time, Singapore will also play its part and contribute to the decarbonisation of global aviation.

SUPPORTING INTERNATIONAL AVIATION DECARBONISATION

At the recent 41st International Civil Aviation Organisation (ICAO) Assembly held in September and October 2022, ICAO adopted a long-term aspirational goal (LTAG) for international aviation to achieve net zero carbon emissions by 2050. This is an important breakthrough, and its successful attainment will require the scaling up of a combination of low-carbon solutions. By industry estimates, including studies and scenarios laid out in the ICAO LTAG report and Air Transport Action Group (ATAG) Waypoint 2050 report, Sustainable Aviation Fuels (SAF) are expected to play the largest role in decarbonising aviation, although short-haul flights could potentially also utilise electric and hydrogen technologies to reduce emissions.

Singapore has started making the transition to green its aviation sector. In July 2022, the Civil Aviation Authority of Singapore (CAAS), Singapore Airlines (SIA) and Temasek embarked on a pilot where blended SAF was uplifted onto SIA and Scoot departing flights at Changi Airport for the first time. Come 2023, Singapore will also be home to the world's largest production plant for SAF, a Neste facility that boasts an annual production capacity of 1 million tonnes.

Low-carbon hydrogen will be an important part of this transition. In the near-term, we expect that low-carbon hydrogen can start playing a role in supporting the production of SAFs, amongst other sustainable fuels and chemicals. In the medium-term, hydrogen fuel cells could be used for airside ground vehicles and aircraft propulsion, with liquefied hydrogen as a potential fuel source for hydrogen-powered aircraft in the long-term. However, the latter will require several key challenges to be addressed, such as on-board storage, safety, cost of fuel production and airport infrastructure.

We have already begun preparing for these longer-term but promising technologies. In February 2022, CAAS signed a Cooperation Agreement with Airbus, Changi Airport Group, and Linde to study the development of hydrogen supply and infrastructure for aviation. Under the Cooperation Agreement, the four parties will collaborate to conduct market analysis on the projected aviation demand and supply for hydrogen, as well as regional readiness and commercial feasibility for the adoption of hydrogen. The parties will also evaluate the infrastructure requirements for a hydrogen airport hub and the electrification of airport operations using hydrogen fuel cells.. Where deemed suitable, the parties are open to pursuing industry trials.

EFFORTS TO DECARBONISE AIRPORT OPERATIONS

In addition to exploring the use of hydrogen fuel cells in airport operations, our airport stakeholders are progressively taking steps to enhance their energy efficiency, reduce energy consumption, and shift towards renewables, including through infrastructure upgrades, equipment replacement, and electrification of airside vehicles. As part of the International Advisory Panel (IAP) on Sustainable Air Hub recommendations, which was published in Sep 2022, the airport community will continue to advance such efforts. This includes working to transition all airside vehicles towards cleaner energy options, exploring the deployment of solar panels on airfield, in addition to conventional rooftop panels, and studying the adoption of waste-to-energy initiatives.

LAND TRANSPORT

Singapore aims to develop a greener and more sustainable domestic transport sector. The Land Transport Master Plan 2040 envisages a land transport system that is convenient, well-connected and fast, using "Walk, Cycle or Ride" transport options, and making them the preferred way to commute. In addition, we aim to electrify our vehicle population, which will help Singapore achieve our vision of 100% cleaner energy vehicles by 2040.

While encouraging the adoption of electric vehicles, we continue to monitor developments in other clean energy alternatives that can support the development of a more sustainable land transport sector. We expect that hydrogen fuel cells may have a role to play in decarbonising vehicle segments that require higher power and mileage. The Government will continue to work with industries and the research community to understand and monitor such developments.

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ADVANCING THE TRANSITION

Singapore believes in the potential of low-carbon hydrogen as a broad-based decarbonisation tool. At the same time, we also recognise that there remain considerable uncertainties in its development.

First, as we expect to have to import most of our low-carbon hydrogen, our cost of deployment, specifically for power and the industrials sector, will likely be higher than that for countries that have the ability to produce low-carbon hydrogen domestically. Today, global supply chains for low-carbon hydrogen have yet to develop, and key technologies that support the transportation of liquefied hydrogen and reconversion of hydrogen carriers are either nascent, or have yet to demonstrate scale.

Second, notwithstanding the good progress in recent years, whether hydrogen and ammonia can be used in key end-use applications in a safe manner at scale remains to be proven. In particular, these include the use of ammonia as a marine fuel in ships, the use of ammonia as a direct fuel for power generation, and the use of hydrogen directly in aircrafts. Faced with these uncertainties, Singapore will take a phased approach towards the adoption of low-carbon hydrogen across its economy. We will closely monitor technological developments of the different hydrogen carriers and end-use applications, and stage significant infrastructure investments accordingly to avoid stranded assets and land take. We will also identify potential synergies for low-carbon hydrogen adoption across various sectors and applications, to inform long-term land and infrastructural planning.

In the nearer-term, we will focus on building capabilities in industry, workers and the Government in selected areas that are critical to unlocking hydrogen adoption in Singapore. One particular focal area is to uncover and find solutions to technoeconomic challenges within the hydrogen value chain that are unique or more prominent for Singapore. With these important building blocks in place, Singapore will be in a strong position to scale up hydrogen deployment in the longer-term when the time is right.

TO BEGIN OUR JOURNEY, WE WILL ORGANISE OUR EFFORTS AROUND FIVE KEY THRUSTS:

1. EXPERIMENT WITH THE USE OF ADVANCED HYDROGEN TECHNOLOGIES AT THE CUSP OF COMMERCIAL READINESS THROUGH PATHFINDER PROJECTS

2. INVEST IN R&D TO UNLOCK KEY TECHNOLOGICAL BOTTLENECKS

3. PURSUE INTERNATIONAL COLLABORATIONS TO ENABLE SUPPLY CHAINS FOR LOW-CARBON HYDROGEN

4. UNDERTAKE LONG-TERM LAND AND INFRASTRUCTURE PLANNING

5. SUPPORT WORKFORCE TRAINING AND DEVELOPMENT OF BROADER HYDROGEN ECONOMY

EXPERIMENT WITH THE USE OF ADVANCED HYDROGEN TECHNOLOGIES AT THE CUSP OF COMMERCIAL READINESS THROUGH PATHFINDER PROJECTS

Through pathfinder projects, we aim to work with the industry to experiment with and build up capabilities in advanced hydrogen technologies, and identify and address any technical, safety, or regulatory issues that may arise. In identifying and implementing these projects, we will take into consideration the relative technological maturity of the technology and end-use application(s).

We envision each pathfinder project to start with a solicitation of proposals and ideas from the industry (such as through an Expression of Interest and/or a Request for Proposal), to uncover the level of interest and capabilities from our industry players. The projects should be implemented with close partnership between the selected industry partner(s) and the Government, to facilitate the co-creation of solutions to regulatory- and infrastructure-related challenges. This collaborative and iterative working relationship will be a key feature to facilitate the development of a hydrogen supply chain in Singapore.

As a start, we will build capabilities in importing, handling, and utilising low-carbon ammonia as a hydrogen carrier or directly as a fuel in power generation. The ammonia supply chain development efforts undertaken through this project will also support marine bunkering needs.

Ammonia production, transportation and storage are technologically mature processes that have well-established safety and operational protocols. There are also several low-carbon ammonia projects in the pipeline worldwide, signifying that that are concrete steps taken to develop low-carbon ammonia supply chains.

The key uncertainties and challenges lie in end-use applications of ammonia.

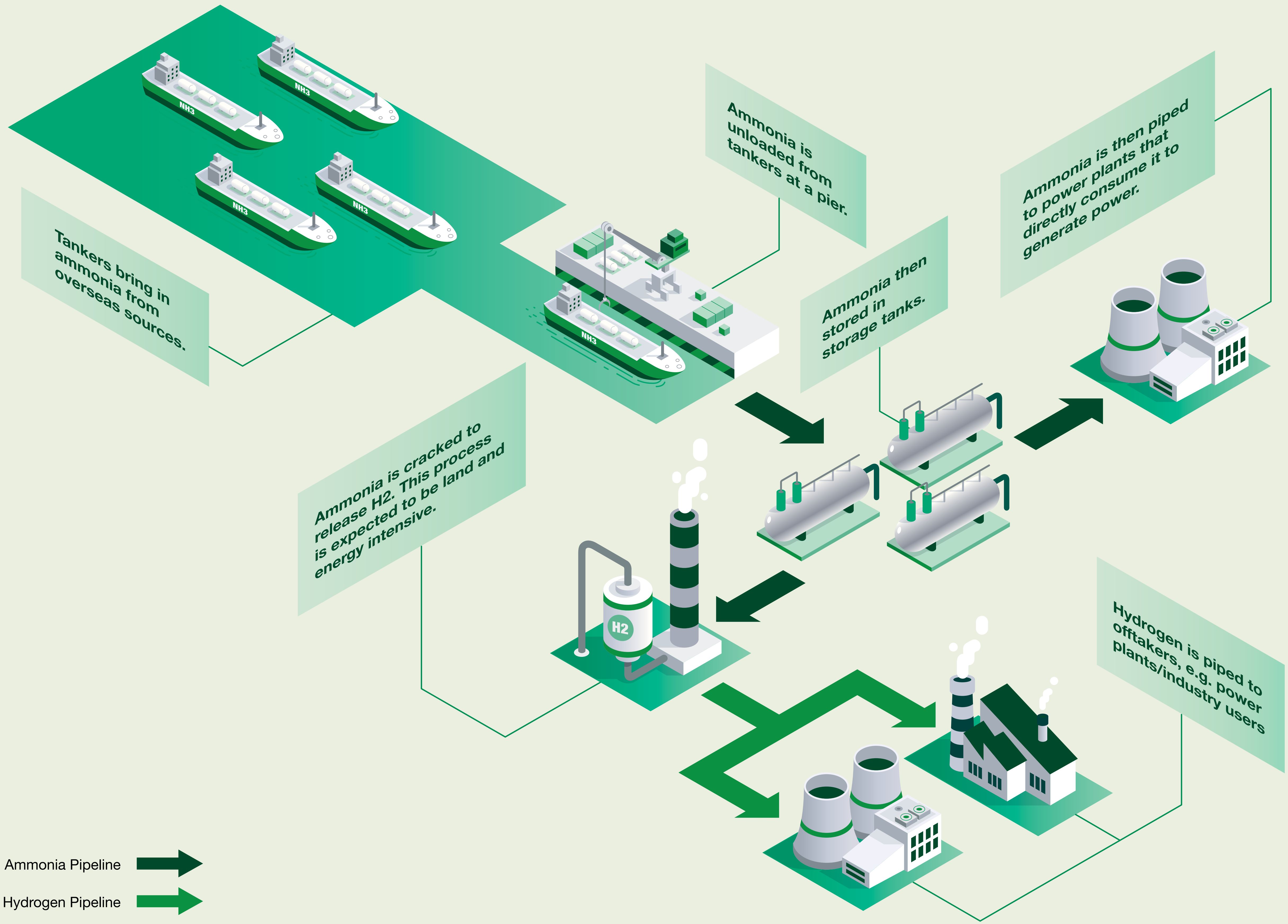
For power generation, small-scale direct ammonia-fuelled power generation gas turbines are expected to be commercially available by around the middle of this decade. As it is a new technology, its operating parameters and protocols will need to be established and its safety and efficiency ascertained for Singapore's context.

Ammonia can also be cracked back into hydrogen, and combusted in power generation gas turbines. Today, gas turbines that can take hydrogen at a 30 – 50% blend (by volume) with natural gas are already commercially available, and gas turbines that can combust 100% hydrogen are expected to be available by around 2030. The key technological uncertainty for this pathway is the cracking of ammonia; while the cracking technology already exists and has been in use for some time, it is typically deployed at smaller scale for niche applications such as the production of heavy water. Utilising ammonia as a hydrogen carrier for power generation at the national level requires cracking technology to improve in scale and efficiency.

The second key application for ammonia is as a maritime fuel. Multiple countries and industry consortia around the world are preparing themselves to support and bunker ammonia-fuelled ships, starting with the first ones that are expected to go into service in the second half of this decade. Singapore has already started efforts in this regard, as detailed in the chapter above.

Besides technologies that direct enable end-use applications, a key area of focus for us is to pursue process and regulatory innovation, so that the land footprint for the ammonia supply chain can be reduced without compromising safety for a densely populated urban city like Singapore. This will go a long way in improving the overall economic viability of hydrogen and ammonia deployment in Singapore.

While we will be starting with ammonia power generation and marine bunkering, we are prepared to undertake more pathfinder projects as new technologies and end-use applications demonstrate promise, and welcome ideas and suggestions from the industry. Through these pathfinder project(s), we will pave the way for the adoption of low-carbon hydrogen in Singapore.


Tankers bring in ammonia from overseas sources.
Ammonia is unloaded from tankers at a pier.
Ammonia then stored in storage tanks.
Ammonia is then piped to power plants that directly consume it to generate power.
Ammonia is cracked to release H2. This process is expected to be land and energy intensive.
Hydrogen is piped to offtakers, e.g. power plants/industry users
NH3
H2
Ammonia Pipeline
Hydrogen Pipeline

INVEST IN R&D TO UNLOCK KEY TECHNOLOGICAL BOTTLENECKS

Even as we embark on the first small-scale pathfinder projects, many technologies required to enable low-carbon hydrogen supply chains and end-use applications remain nascent or unavailable at scale. As we seek to leverage low-carbon hydrogen in our transition towards net zero emissions, the Government can accelerate the development of technologies that are critical for Singapore, by bringing together the research community and industry, and providing targeted research funding to deepen our capabilities and catalyse new breakthroughs in key areas.

Singapore has built up a strong base of R&D capabilities and a vibrant innovation ecosystem with strong academia industry linkages, through consistent investment in research and innovation over the decades. In addition to broad-based research grants that have supported low-carbon technology-related research and innovation efforts in our Institutes of Higher Learning and research institutes over the years, Singapore introduced the Low-Carbon Energy Research (LCER) Funding Initiative in 2020. The first phase of the programme awarded S$55 million to projects aiming to improve the technoeconomic viability of low-carbon technologies such as carbon capture, utilisation, and storage (CCUS) and hydrogen. For hydrogen, the LCER funded projects in areas such as the development of catalysts for ammonia cracking, and methane pyrolysis.

Given the rapid developments in the global hydrogen economy, we will redouble our efforts in supporting hydrogen R&D and innovation. As a start, we will set aside an additional S$129 million of research funding under LCER to support the development of low-carbon technologies including hydrogen. We will assess the need for further funding, depending on our national needs.

In addition to increasing research funding, we will also adjust our funding strategy, by taking a more directed approach in deciding which hydrogen-related technologies we want to direct R&D towards. This ensures that resources are devoted to areas that have the greatest impact to Singapore.

Given that Singapore will be a net hydrogen importer, being able to import, store, handle, and utilise hydrogen (and all carrier forms deemed suitable for Singapore) safely, economically and at scale is a priority.

For the mid-stream segment of the value chain, potential R&D areas include ammonia cracking to liberate hydrogen, where we aim to improve the efficiency of the process, reduce cost, and find ways to scale with minimal land footprint. We will also examine areas to improve the economics of transporting and storing liquefied hydrogen, which has yet to be carried out for large volumes and over long distances.

Downstream, we will build up our R&D capabilities in areas required for the use of hydrogen, and focus on areas that the industry or regulatory bodies do not have existing solutions given Singapore's unique operating context (e.g. dense urban population, high humidity). Managing hydrogen and ammonia deployment safely is a clear priority. While both molecules are widely handled in the chemicals industry today, their deployment in novel applications and at larger scale will likely require new operating standards and regulatory frameworks. Research efforts, such as the development of new processes and materials, can go a long way in improving the safety of handling and utilisation of hydrogen and its carriers.

In addition to supporting the adoption of hydrogen in Singapore, our continued investment into research and innovation will also support our researchers and enterprises in creating novel products and solutions. In doing so, they can contribute to the development of a global hydrogen economy, and create new opportunities for Singapore and Singaporeans.

To ensure that research projects are more relevant to industry and have a higher chance of commercialisation, we will bring together our research community and industry, to help shape the research problems statements. Collaborations with the international research community will also be essential to bring research from the bench to market.

PURSUE INTERNATIONAL COLLABORATIONS TO ENABLE SUPPLY CHAINS FOR LOW-CARBON HYDROGEN

Climate change is a global challenge that requires global solutions. Partnerships between countries and international organisations, in close collaboration with the business community from around the world, are vital to the effective scaling up and deployment of sustainable solutions.

Today, the global low-carbon hydrogen market is still nascent, as cross border trading of low-carbon hydrogen by sea has yet to be established. Discussions around standards and Guarantee of Origin certifications for low-carbon hydrogen are also in early stages. Without an international set of standards or certification methodologies that can credibly verify the emissions intensity of the hydrogen produced, low-carbon hydrogen trade could be impeded as buyers cannot be certain that they are buying (likely with a green premium) for a sustainable product.

As a small city-state with no physical resources of any kind, it is in Singapore's DNA to seek out international partners and work collectively towards mutually beneficial outcomes. The key areas we will focus on include – first, building a trading and financing ecosystem for low-carbon hydrogen to support the development of a global trading market; second, advancing the development of Guarantee of Origin certification methodologies, and ensuring that methodologies are interoperable across jurisdictions to facilitate cross-border trade; and third, supporting research collaborations and putting our best minds together to unlock common technological challenges.

We have already started building a network of partnerships with countries that are keen on making the hydrogen transition. We have entered into Government-to-Government (G2G) agreements that cover cooperation in low-carbon hydrogen with a number of like-minded countries who are keen to advance the development of hydrogen as a global decarbonisation pathway, on areas such as building up hydrogen supply chains, Guarantee of Origin certification schemes, and joint research and development efforts. These are important instruments that put low-carbon hydrogen squarely on the bilateral agenda, and provide a platform for both countries to engage each other's business communities and people sectors as well. We will endeavour to deepen these existing partnerships, while identifying new partners (including international organisations).

UNDERTAKE LONG-TERM LAND AND INFRASTRUCTURE PLANNING

For low-carbon hydrogen to be deployed or traded at a meaningful scale, new infrastructure needs to be built. These include import and storage facilities, distribution networks, and infrastructure for new end-use applications such as power generation units and bunkering jetties.

Given the nascency of the hydrogen supply chain, we do not expect to build up significant infrastructure in the near-term. However, we do expect careful land planning to be required, including for possible offshore solutions, given the significant footprint of the supply chain.

To prepare for longer-term deployment, we will build on the experience and findings of the pathfinder project(s), to study the safety and land use requirements for hydrogen, and work with the industry to develop plans to gradually build up the necessary infrastructure.

SUPPORT WORKFORCE TRAINING AND DEVELOPMENT OF BROADER HYDROGEN ECONOMY

The rise of a significant global hydrogen economy can open up many opportunities for Singapore enterprises and workers. Our position as an international financial, business and trading hub stands us in good stead to grow as a hydrogen services hub. We already see examples of global companies establishing hydrogen-related business units in Singapore, to tap into our deep international and regional networks and efficient business infrastructure. Our strong innovation ecosystem will also attract companies looking to provide hydrogen-based technological solutions to the region and beyond.

In addition, the adoption of low-carbon hydrogen in end-use sectors will also require upskilling and reskilling of our workforce. In particular, workers in the energy & chemicals, chemicals storage, marine bunkering, power generation, and aviation sectors may need to take on new skills as our hydrogen supply chain develops and hydrogen starts being used in their sectors.

The Government will work with the industry, unions, and the education sector to support workforce development, to equip Singaporeans with the skills and knowledge needed to thrive in a hydrogen economy should they wish to. In particular, we look forward to the pathfinder project(s) to uncover the new capabilities required in domestic end-use sectors. With early intervention and systematic training, these workers can successfully pick up the new skills required.

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CONCLUSION

Singapore is committed to doing its part to combat climate change, through decarbonising domestic emissions, as well as playing a catalytic role to decarbonising the international maritime and aviation sectors.

We view low-carbon hydrogen and its various carrier forms as a broad-based and scalable decarbonisation pathway for Singapore and the world. Given the uncertainties in global supply chains and key technologies as well as our limited size, we will take a calibrated and progressive approach in developing our domestic infrastructure and deployment. We will focus on seeding pathfinder projects and building up the capabilities of our regulatory agencies, industry and workforce, and undertaking long-term infrastructure and workforce planning, so that we are prepared to scale up deployment in tandem with global and technological developments. We will also invest in research and innovation to solve key technological bottlenecks that are most relevant to Singapore, and facilitate the commercialisation of these research outcomes.

Strong international partnership is a crucial enabler, without which we will not be able to successfully make this journey. Internationally operable Guarantee of Origin certification methodologies and emissions intensity standards is critical in facilitating international trade and hydrogen's global acceptability as a decarbonisation tool. Countries' commitment to allow the free trading of low-carbon hydrogen and its carrier forms is also important to build confidence in the market and end-users.

The journey ahead is an important and exciting one. Singapore welcomes ideas and suggestions from our industry and international partners on how we can better navigate towards a low-carbon hydrogen future. Together, we can build a more sustainable world for generations to come.

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