Agora Energiewende

Agora Industry

IMPULSE

9 Insights on Hydrogen – Southeast Asia Edition

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International PtX Hub

IKI International Climate Initiative

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Preface

Dear reader,

With most countries in Southeast Asia having adopted net-zero emissions targets, domestic and regional policy discussions have started to explore pathways that can realise these commitments. Hydrogen has generated an enormous amount of attention over the past few years: over 50 countries have published hydrogen strategies and many others, including those in Southeast Asia, intend to do so soon.

However, how hydrogen fits into national decarbonisation strategies remains uncertain. In the power sector, the use of ammonia coal co-firing to reduce emissions is being discussed. In the industrial sector, a wave of new investments in steel production could trigger additional dynamic demand for hydrogen.

On the supply side, the region is expected to soon become a net importer of fossil gas. At the same time, the development of renewable energy is still at an early stage and needs to be accelerated.

This report aims to inform discussions on priorities and 'no regret' uses of hydrogen specific to the Southeast Asian context. In addition to exploring different pathways of hydrogen demand and supply, it also examines the opportunities and challenges for energy infrastructure and Southeast Asia's position in the global hydrogen trade. We hope this will help to provide evidence to galvanise discussions around hydrogen throughout the region.

I wish you an enjoyable read!

Dimitri Pescia
Director, East and Southeast Asia, Agora Energiewende

Key findings at a glance

1 **Without increased support to develop renewable energy in Southeast Asia, the affordability of electricity and renewable hydrogen will be at risk.** Given the early stage of renewable energy deployment in the region, countries should prioritise renewable energy and supporting infrastructure such as grids and system flexibility. Cross-sectoral policy frameworks for renewables and hydrogen that include robust environmental and social standards can attract potential investors and create new jobs.

2 **Low-carbon hydrogen should be reserved for 'no regret' applications where no electrification alternatives exist.** Southeast Asian countries should focus on decarbonising demand by switching from fossil fuels to electricity wherever possible. Hydrogen is better suited to decarbonise heavy industries such as steel, while proposed applications such as ammonia coal co-firing are cost inefficient and ineffective in reducing emissions.

3 **Southeast Asia's rapidly growing heavy industries offer a timely opportunity to establish a low-carbon industrial sector.** Using renewable hydrogen for non-energy use in industrial processes such as steel, ammonia and fertiliser production can open the region to global low-carbon markets and avoid significant emissions. Future prospects for direct electrification may offer more efficient solutions than hydrogen, even for high-temperature heat in industry or heavy-duty vehicles.

4 **Southeast Asian countries should avoid overestimating their role as renewable hydrogen exporters in the dynamic global Power-to-X (PtX) market.** Despite having ample renewable resources to meet domestic energy needs, hydrogen costs are not as competitive compared to other potential exporting regions. Embracing a "global gas hub" strategy, as advocated by some Southeast Asian countries, could risk stranding infrastructures. Nevertheless, proximity to East Asian markets could increase Southeast Asia's potential for PtX trade through strategic partnerships.

Content

Hydrogen's role in Southeast Asia's energy security and decarbonisation

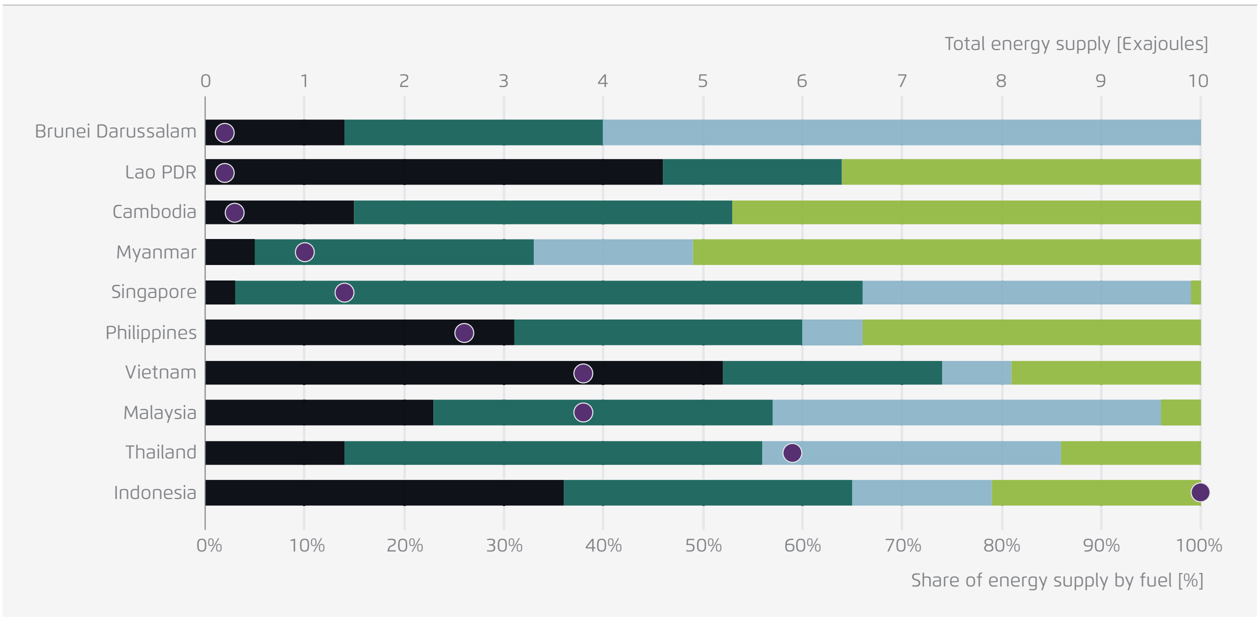
An overview of Southeast Asia's energy transition context: growing demand and a persistent reliance on fossil fuels

Despite being characterised by a high socio-economic and cultural diversity, the countries of Southeast Asia face a series of similar challenges and opportunities when it comes to the energy transition. As a consequence of growing population and economies, energy demand in the region has steadily risen over the past two decades. This trend is expected to continue to 2050, except for Singapore, Thailand and Vietnam, where demand is anticipated to stabilise after 2030 (Müller et al., 2024).

The region's energy consumption has been driven by industrialisation, urbanisation and a growing middle class. The industry sector has experienced the largest growth, surpassing all others, on the back of rapid expansion in the cement as well as iron and steel industries. As economic development and urbanisation have progressed, electricity has largely replaced traditional biomass usage in buildings. Power generation has nearly tripled since 2000, with coal accounting for the majority of new generation capacity.

Historically, Southeast Asia has relied heavily on fossil fuels for its energy needs (see Figure 1). Coal has made a rapid entry into the region's energy supply over the past decades. It is the dominant source for energy supply in countries like Lao PDR (46%), Vietnam (52%) and Indonesia (36%), given its widespread availability and competitiveness in the absence of ambitious climate policies. Meanwhile in Brunei (60%), Malaysia (39%)

Total energy supply by fuel for countries in Southeast Asia, 2020 → Fig. 1



IEA (2022b), IRENA (2023c). Note: * Renewables include traditional use of biomass.

and Singapore (33%) , fossil gas dominates national energy supply. This heavy reliance on fossil fuels is also reflected in the countries' power generation, where coal and fossil gas are also the dominant sources of electricity. Without any changes to current energy policies, the region is projected to become a net importer of fossil gas by 2025: this poses an additional risk to energy security, given its dependence on oil imports since the mid-1990s. Heavy reliance on international gas markets can expose the region to high price volatility as well as supply challenges, especially given unforeseen geopolitical dynamics. A clear example is the disruption of the global gas market caused by the war in Ukraine, when growing Liquefied Natural Gas (LNG) demand from the EU affected the LNG market in countries with less purchasing power, such as South Asian countries (Birol, 2022).

Southeast Asia is endowed with abundant renewable energy resources for electricity and hydrogen production. However, despite the resource potential, wind and solar PV energy comprised less than six percent of power generation in most countries in 2022, except for Vietnam (ACE, 2023b). While being the cheapest source of electricity generation in many locations, market entry and regulatory barriers as well as incumbent challenges, such as overcapacity in baseload capacity, continue to hinder the scale-up and integration of renewable power in Southeast Asia.

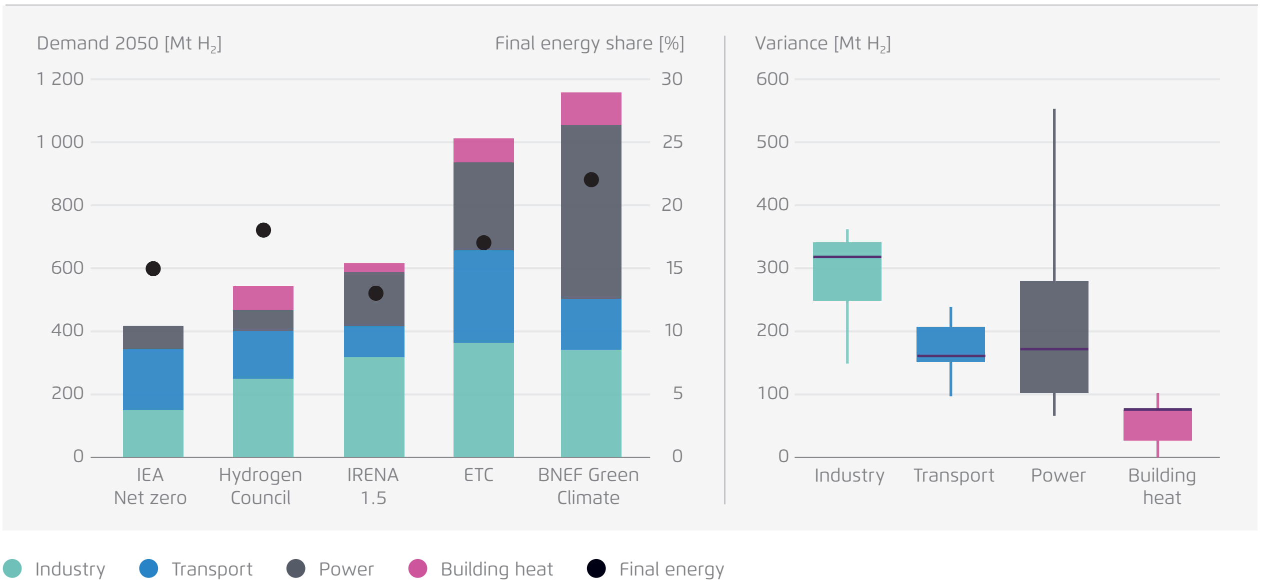
Most countries in the region have set ambitious climate targets and expressed interest in aligning their energy strategies with secure, affordable and sustainable energy goals. Nine countries have adopted net-zero emission targets to reach by mid-century (or soon thereafter): they are currently discussing long-term energy transition pathways appropriate to their circumstances to meet these commitments (ACE, 2022). Despite this significant momentum, short- and medium-term policy implementations are not yet aligned with long-term commitments. A wide range of low-carbon technology options are being considered in the region, with a specific focus on the power sector, including renewables but also potentially less economic options such as carbon capture and storage (CCS), coal co-firing with ammonia and nuclear power. Discussions on the use of hydrogen as an energy carrier are also becoming more prominent in the region, with the hope it will facilitate the achievement of climate mitigation commitments, while improving energy security by reducing dependency on fossil fuel imports.

Navigating the hydrogen hype: overview of global demand and strategies around the world

Hydrogen has taken centre stage in energy transition debates over recent years, with high hopes it can play its part in deep decarbonisation pathways. Hydrogen is currently used in various sectors, particularly as a feedstock in the industrial sector. However, the ability to produce low carbon hydrogen with different technologies such as water electrolysis using renewable energy or fossil-based hydrogen with carbon capture and storage (CCS) has positioned the molecule as a decarbonisation option for many applications.

Moreover, hydrogen's molecular versatility enables it to be transformed into various chemicals such as green ammonia or synthetic hydrocarbons such as e-methanol, e-sustainable aviation fuels (SAFs) and synthetic natural gas. These so-called Power-to-X (PtX) products can be used to de-fossilise various sectors that cannot become climate-neutral without PtX, such as the fertiliser, long-haul shipping and aviation as well as chemical industries (see Infobox 1). In this context, global demand for hydrogen is expected to continue to grow, given its role along the entire energy chain. As shown in Figure 2 the estimates in different global energy scenarios for hydrogen demand in 2050 range from 400 million tonnes (Mt) to more than 1 000 Mt. Most of the global energy scenarios agree that hydrogen demand will be driven by the decarbonisation of applications in industry and transport (mainly aviation and shipping). Hydrogen use in the power sector will mostly be concentrated in long-term energy storage applications that support the integration of variable renewable energy into the system. But hydrogen demand in the power sector is the most difficult to forecast, given complex techno-economic interactions and coupling effects with other sectors. Hydrogen can, in principle, also have several applications outside of

Estimates of global hydrogen demand in 2050: selected scenarios → Fig. 2



Agora Energiewende and Agora Industry (2023). Note: Final energy does not include feedstocks and other non-energy use; IEA = International Energy Agency; IRENA = International Renewable Energy Agency; ETC = Energy Transition Commission; BNEF = BloombergNEF. Final energy figures taken from respective sources.

the power sector, but its scalability will depend on its competitiveness against other low-carbon alternatives, in particular, direct electrification.

The hydrogen hype has spread across different areas, with over 50 countries worldwide having developed or announced a national strategy or roadmap

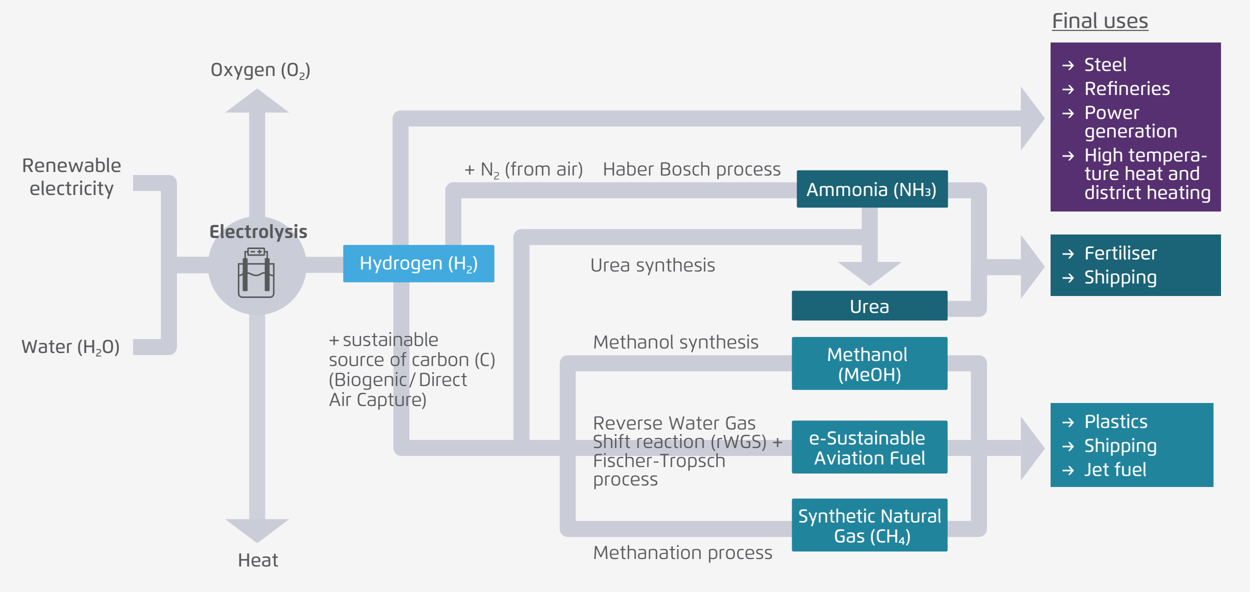
Infobox 1: The importance of carbon in the production of Power-to-X (PtX)

Figure 3 illustrates the paths for hydrogen to be transformed into various PtX products. In addition to the renewable hydrogen needed, CO_2 is a key component in the production of most hydrogen derivatives. For example, CO_2 is needed to produce fertilisers, such as urea, synthetic fuels like e-kerosene and chemical products such as e-methanol. Currently, sources of CO_2 can come from biogenic origins such as agricultural by-products or waste, renewable sources via Direct Air Capture (DAC) or from unavoidable CO_2 emissions as they occur in the cement industry. Yet these Carbon Capture and Usage (CCU) technologies demonstrate different levels of readiness and can be very energy-intensive, especially for DAC. In this regard, the capture of biogenic CO_2, called Bioenergy with Carbon Capture and Use (BECCU), shows some advantages as it represents an already mature market with the production of upgraded biogas and bioethanol (IEA, 2023a). Additionally, the CO_2 obtained is relatively pure, eliminating the costly purification process required in other carbon-sourcing methods. However, sustainability issues must be taken into consideration when using this type of carbon source.[1] The relevance of a carbon source for PtX production is not only important for the identification of a sustainable carbon source but also for the planning of such industrial processes, especially the carbon infrastructure required and identification of synergies with other potential economic activities in the country, such as the biofuels sector.

1 Additional biomass demand coming from the hydrogen industry must ensure that it does not lead to environmentally-harmful intensification of land use or to direct or indirect changes in land use, leading to detrimental effects on eco-systems and carbon cycles.

Paths for the production of PtX products

→ Fig. 3



Agora Energiewende, Agora Industry, Fundación Torcuato Di Tella (2023)

(BNEF, 2023a). These national documents display the climate ambitions of the specific countries and outline their strategies regarding a prospective commercial market for hydrogen and PtX products.

Table 1 provides an overview of selected national hydrogen strategies and roadmaps. Countries aspire to play different roles in the global hydrogen trade. For instance, Japan is positioning itself as a prospective importer of hydrogen and PtX in line with its historically high energy import dependency (only 14% of primary demand in Japan has been covered by national resources over the last decade – IEEFA, 2023). Similarly, Germany has also emphasised the need to import hydrogen and PtX because of its limited land availability and renewable resources. On the other hand, Chile and most Latin American and African countries are vying to position themselves as potential exporters. For example, Chile has prioritised renewable hydrogen production and is concentrating its efforts on promoting an export-driven pathway by highlighting the advantages of its vast and cheap renewable energy resources.

These growing ambitions around the world to produce, export and import hydrogen have led to major project development announcements in various regions. However, although a significant proportion of projects have reached advanced planning stages, only four percent of projects announced (with a total of 2 Mt of H_2) are actually under construction or have reached final investment decision (FID) (IEA, 2023b).

Understanding the drivers and interests for hydrogen in Southeast Asia

Current geopolitical challenges have affected global supply chains around the world, including those for fertilisers, LNG, grains and others. As a consequence, countries have recognised the need to diversify their partnerships with suppliers of industrial products, opening up new market opportunities. This is also the case for hydrogen, with potential importers beginning to engage in so-called "hydrogen diplomacy" to secure future hydrogen and PtX suppliers. Southeast Asia is no exception, with many countries seeking to position hydrogen development at the top of the regional agenda and countries such as Japan playing a prominent role in promoting the production of hydrogen and its derivatives in the region.

Summary of hydrogen strategies and roadmaps for selected countries → Table 1

Country	Document	Year	Importer/ Exporter	Hydrogen targets?	Policy instruments included
Chile	National Green Hydrogen Strategy	2020	Exporter	Start exporting ammonia by 2028, targeting international markets including Europe, China, Japan and Korea.	Plans to set up Public-Private-Partnerships as well as Standards and Safety regulations. Task force to support permitting and piloting processes under the German-Chilean partnership.
Germany	National H_2 Strategy	Last revision 2023	Importer	Reach production capacity of 10 GW. Development of a hydrogen transmission grid of more than 9 700 km by 2032. Develop R&D and build strong international partnerships.	Double-sided auction model H2Global for the import of PtX products. Carbon Contracts-for-Difference for Industries in Germany, among other subsidies allowed by the European Union.
Indonesia	National Hydrogen Strategy	December 2023	Exporter	Expected demand growth in transport from 2030 and in the industrial sector by 2040 to replace fossil fuels for high temperature heating processes. Replace current fossil-based hydrogen in the production of fertiliser, ammonia and oil refined products.	Three strategic pillars are outlined in the strategy: reduce the dependence on fossil fuels, develop a domestic hydrogen market and export hydrogen products globally. Among others, the government plans to support state-owned entities such as the national oil company Pertamina, the fertiliser company Pupuk Indonesia and the state utility PLN to implement pilot projects for low-carbon and green hydrogen.
Japan	National H_2 Strategy	Last revision 2023	Importer	Increase the supply of hydrogen and ammonia from 2 Mt to 3 Mt by 2030, to 12 Mt by 2040 and to 20 Mt by 2050.	Policy mechanisms to establish a hydrogen market and promote local technology development for hydrogen and PtX production in the country.
Singapore	National Hydrogen Strategy	October 2022	Importer	Intends to become a hydrogen hub in the region. H_2 expected to contribute up to 50% of the country's power needs and especially targets ammonia as an energy carrier and a fuel. Sectors: industry, aviation, shipping and power.	Subsidising of R&D through so-called Pathfinder Projects. Infrastructure for ammonia bunkering and shipping planned. Targets international markets through existing trading routes and port infrastructure.
Vietnam	Hydrogen Energy Strategy	February 2024	Exporter	Aims to produce 100 000–500 000 tonnes of clean H_2 annually by 2030, rising to 10 to 20 Mt by 2050. Facilitate the transition from fossil fuel to hydrogen use.	Tax incentives to attract investments in renewable energy and hydrogen projects while directing public investments in research and pilot projects for hydrogen.

Ministry of Energy of Chile (2020); Federal Ministry for Economic Affairs and Energy of Germany (2023); Ministry of Energy and Mineral Resources of Indonesia (2023); Ministerial Council on Renewable Energy, Hydrogen and Related Issues of Japan (2023); Ministry of Trade and Industry of Singapore (2022); Socialist Republic of Vietnam (2024)

Hydrogen discussions in SEA are driven by economic and business interests, as well as energy security concerns. The involvement and priorities of international partners (in particular of Japan and Korea) are also shaping national developments in the region, with over half of the existing pilot projects (see Figure 4) in the region funded by international sources.[2] International interests influencing the build-up of hydrogen pilot projects in the region are motivated in particular by (IEEFA, 2023):

- → **Securing hydrogen sources overseas.** Several developed Asian countries, such as Japan and Korea, will need to source hydrogen beyond their borders as domestic production is expected to be insufficient. Some hydrogen production projects have been initiated through bilateral agreements: for example, the project in Sarawak, Malaysia with an expected 0.6 Mt of ammonia to be exported to South Korea for use in the marine and aviation sector (MIDA, 2022). Another example is the pilot project by Japan's Advanced Hydrogen Energy Chain Association (AHEAD) to bring liquified hydrogen from Brunei to Japan for co-firing in a gas power plant (SP Global, 2020).
- → **Strengthening technology leadership.** Japan has been investing early in the hydrogen value chain with pilot projects from the upstream through to downstream applications. In addition, Japan has been a large exporter of coal-fired power plant technology in the region. Despite Japan's commitment to stop financing unabated coal projects overseas, several Japanese companies developed the idea of ammonia co-firing as a medium-term solution to mitigate emissions.

However, many countries in Southeast Asia have not yet defined a clear national strategy framework for hydrogen and PtX, nor have they identified a clear role for local use or export of molecules or clearly prioritised a hydrogen production pathway. Countries in the region need to assess (and reassess) their opportunities and risks before jumping into the hydrogen hype, using the interest of the international community to develop strategic hydrogen partnerships to benefit local economies and industrial low-carbon development. Renewable hydrogen can support the

2 Of the 7 renewable hydrogen projects identified (operational, under construction or having received FID) in Southeast Asia, 4 are financed or co-financed by foreign companies (IEA, 2023c)

Various renewable resources piloted for producing hydrogen → Fig. 4

IEA (2023c)

development of low-carbon industry segments in the region since several countries are or will become major producers of steel, chemicals, fertilisers and other products. In the context of stricter international climate-trade regulations (such as the EU's Carbon Border Adjustment Mechanism – CBAM)[3], manufacturing those goods with renewable hydrogen would support the development of low-carbon industry segments with high value-added and higher competitiveness on global markets.

The introduction of low-carbon hydrogen will require large investments in infrastructure for the production and potential trade of PtX products. Countries in the region will, therefore, need to look for new sources of funding. Furthermore, different sustainability aspects will need to be considered depending on the technology pathway chosen for hydrogen production. This will include its climate impact (e.g. fugitive emissions and CCS capture rate, if hydrogen is produced through fossil gas with CCS), and the protection of natural resources and local communities, in line with a comprehensive Economic, Environmental, Social and Governance (EESG) framework.[4] The development of a renewable-based hydrogen economy can stimulate investments both in the hydrogen value chain (electrolysers, infrastructure and end-use applications) and in renewables facilities. Some countries, such as Singapore, are expected to lead regional hydrogen developments but others could follow to create a more structured hydrogen market in the region that would also contribute to the adoption of a more supportive framework for renewable investments.

3 CBAM is a mechanism allocating emissions tariffs on imports of goods to the EU, including cement, ammonia, fertilisers, iron, steel, aluminium and hydrogen, among others. The CBAM transitional phase (with reporting obligations) starts on 1 October 2023 and runs until the end of 2025. The definitive methodology is expected to be fine-tuned by 2026. And financial obligations will only begin in 2026 when products imported into Europe will be taxed at around 100 euros per tonne of Greenhouse gas (GHG) equivalent (European Commission, 2023).

4 For example, the PtX Hub has developed a scoping paper distinguishing the different sustainability dimensions of the EESG framework for renewable hydrogen and PtX projects (International PtX Hub, 2022)

9 Insights on Hydrogen for Southeast Asia

1. Clear long-term support for renewables is crucial to reduce the cost of electricity and hydrogen production

Southeast Asia has vast renewables potential, sufficient to meet domestic energy demand, yet without ensuring that countries will transition into renewable hydrogen exporters

Most countries in Southeast Asia are endowed with good solar potential (above 1 000 full load hours). Wind potential is generally low, except for several onshore sites and along the coast of Vietnam and the Philippines. These renewable potentials could supply the anticipated growing electricity demand while ensuring the production of hydrogen for targeted domestic energy use (Agora Energiewende, 2023). IRENA estimates that the region could proɵ duce at least 50 million tonnes of hydrogen below a production cost of 2 US dollars (USD) per kilogram (kg), sufficient to meet dynamically-growing regional demand, estimated at between 7 and 34 Mt a year by 2050. However, other modelling approaches have shown that widespread use of renewable hydrogen, without targeting only the necessary ('no-regret') applications, could lead to production of around 37 million tonnes of renewable hydrogen per year by 2050. This would require significant deployment of renewables in the region and would face certain challenges related to infrastructure, land use constraints etc. (Müller et al., 2024) (see Insight 2).

However, this potential may not necessarily translate into countries in the region becoming hydrogen exporters. Firstly, there is a high level of uncertainty around future hydrogen demand in the region. Current demand lies at around 3.2 Mt per year, most of which is accounted by the petrochemical industry. Future hydrogen demand will be dependent on various factors such as economic growth, industrialisation trends and the pace at which decarbonisation towards net zero unfolds. Secondly, over-estimated renewable hydrogen production with a strong focus on exports but without the necessary safeguards, could threaten national energy transitions: by cannibalising renewable energy that could most effectively decarbonise other sectors through direct electrification. This could endanger the region's domestic climate mitigation targets. For countries like Thailand and Vietnam, untargeted renewable hydrogen production could also exhaust the solar and wind potential in the long-term (Müller et al., 2024). Thirdly, on a global scale, other regions in the world may produce renewable hydrogen at lower costs, potentially outcompeting Southeast Asian exports towards some markets, including countries in Latin America, Africa and Australia (see Insight 8).

Improving the conditions for renewable energy development will be crucial, not only to reduce the cost of renewable hydrogen, but also to create an attractive environment for renewable energy investment

Progress towards ramping-up renewables in Southeast Asia is still lagging. Despite significant resource potential, renewables currently only contribute to around 25% of power generation, with solar and wind only accounting for around 4% in 2022 (ACE, 2023a; Ember, 2024). The only exception is Vietnam where wind and solar reached almost 15% of power generation in 2022 due to an installation boom in 2019–2021. High development costs, driven by high costs of capital resulting from regulatory hurdles, are key factors hindering the growth of the region's renewables sector. For example, the average cost of capital for solar and wind projects in Southeast Asia lies between 5% and 10%, significantly higher than in neighbouring countries such as India (6%), China (2.5%) and Australia (3%) (IRENA, 2023b).

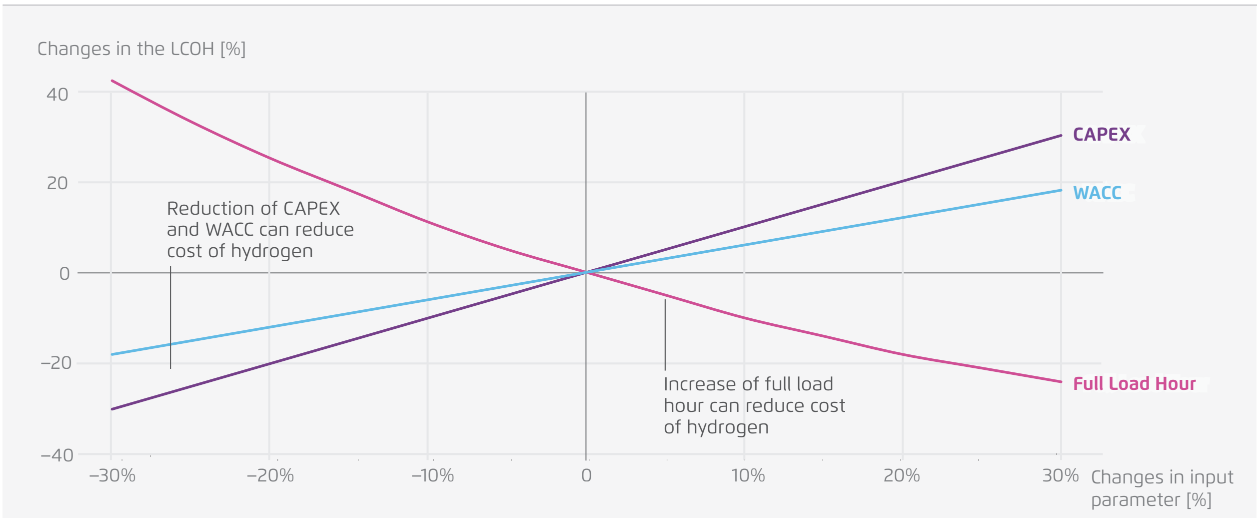
Electricity cost is one of the main cost drivers for renewable hydrogen (Agora Industry et al., 2023). Therefore, the capital costs of renewables together with resource availability (expressed as Full Load Hours – FLH) have a strong influence in the Levelised Cost of Hydrogen (LCOH) calculations. Capital expenditure (CAPEX) on electrolysers also plays a crucial role, especially for first movers seeking to enter the market during the ramp-up phase of the hydrogen economy, when electrolyser investment costs are expected to be higher. At the same time, other factors such as the discount rate (usually determined by the Weighted Average Cost of Capital WACC) will interact in the calculation of hydrogen costs, reflecting the risk of investing in a particular country. WACC estimates are influenced by contractual, country and technology risk. Figure 5 shows how the interaction of CAPEX, WACC and FLH is important in calculating hydrogen costs. For a site with good renewable energy resources (e.g. 20% more FLH than average), its attractiveness for renewable hydrogen production can be undermined if both the CAPEX and WACC are above 10% of the average.

Based on today's costs for solar and wind energy in Southeast Asia (USD 740 per MWh for solar and USD 1 700 per MWh for wind (IRENA, 2023a)), the LCOH is estimated to be USD 8–11 per kg, thus still expensive compared to other regions. Note also that country-specific regulations that impact on renewable electricity costs could also affect the cost of electrolysers. For example, local content requirement (LCR) on a utility-scale solar project in Indonesia with financial and administrative penalties for non-compliance could also affect the deployment of renewable hydrogen production in the region. Therefore, the investment conditions for renewable energy projects must be improved to make the market more attractive and competitive, thereby increasing the uptake of renewable energy and creating a friendlier environment for renewable energy project development.

Despite the uncertain outlook for renewable hydrogen demand and production, Southeast Asia should focus primarily on attracting investments in renewables-based electricity and facilitate their integration into the power system through grid investments, as well as regulatory and market refinements that incentivise flexibility. Supporting policies could include instruments to de-risk investments (such as contracts-for-difference, investment and production tax credits), market-based instruments (such as carbon pricing, green certificate markets) and broader regulatory measures (streamlined approval practices, preferential grid connections and others).

Sensitivity of hydrogen cost depending on CAPEX, WACC, and FLH

→ Fig. 5



Agora Energiewende (2023)

2. The role of clean hydrogen for reaching climate neutrality is crucial but secondary to direct electrification

Renewables-based direct electrification will play a more prominent role than hydrogen in future energy systems and should therefore be prioritised in decarbonisation strategies in Southeast Asia

Since the adoption of the Paris Agreement, many studies have analysed the pathways to achieving global net-zero emissions by mid-century. Most of these studies agree that the deployment of renewable energy will make up the largest part of the energy transition. For instance, IRENA's 1.5 °C scenario shows that 90% of total global decarbonisation in 2050 will involve renewable energy through direct electrification, efficiency gains, bioenergy with CCS and clean hydrogen. The share of hydrogen represents only 12 percentage points of this total (IRENA, 2023a). Likewise, the IEA's net-zero emissions scenario forecasts that electricity will dominate energy end-use, accounting for more than half of total final consumption by 2050 (IEA, 2023d). For Southeast Asia, the projections are in line with global scenarios, with direct electrification accounting for around 52% of total final energy consumption in 2050, compared to only 4% for hydrogen in the same timeline (IRENA & ACE, 2022).

However, hydrogen will have a crucial role in decarbonising applications where no alternative exists. This concerns some industry processes and some segments of the transport sector (mainly aviation and shipping). But renewable hydrogen production requires a significant deployment of renewable energy and is less efficient than direct electrification (because of conversion losses). Indeed, renewable hydrogen requires two to four times as much renewable energy capacity to achieve the same final energy use as direct electrification.[5] Therefore, its use needs to be targeted to applications which cannot be electrified.

A targeted set of 'no-regret' hydrogen applications should be prioritised as part of the hydrogen strategies and roadmaps in Southeast Asian countries

Targeted use of hydrogen will be key to optimising infrastructure investment and maximising the benefits of a potential hydrogen economy. In other applications, hydrogen will be outcompeted by more efficient decarbonisation technologies such as electric vehicles. Hence, it is necessary to prioritise hydrogen applications where hydrogen is the only decarbonisation option.

Figure 6 provides an overview of the different hydrogen applications that should be prioritised across different end-use sectors. These applications have been identified based on a review of prominent global energy system scenarios. This set of applications aims to provide a guideline for policymakers developing country strategies and roadmaps for specific hydrogen uses.

Additional renewable capacity for renewable hydrogen production should not hinder the path to meeting current renewable electricity targets in Southeast Asia

All Southeast Asian countries (except for the Philippines) have set targets to achieve net-zero carbon emissions by 2050 or soon thereafter. The region's growing energy demand and heavy reliance on fossil fuels make this a challenging endeavour. But renewables potentials, especially solar energy, are remarkable in the region. Solar PV will play a

5 For example, hydrogen can be as much as 84% less efficient than heat pumps in delivering like-for-like energy for direct electrification in the residential sector (due to 30% energy losses incurred in the production process of hydrogen and additional losses during its usage). In the transport sector, hydrogen can be as much as 60% less efficient than battery electric vehicles (Agora Verkehrswende et al., 2018).

Need for molecules in addition to green electrons → Fig. 6

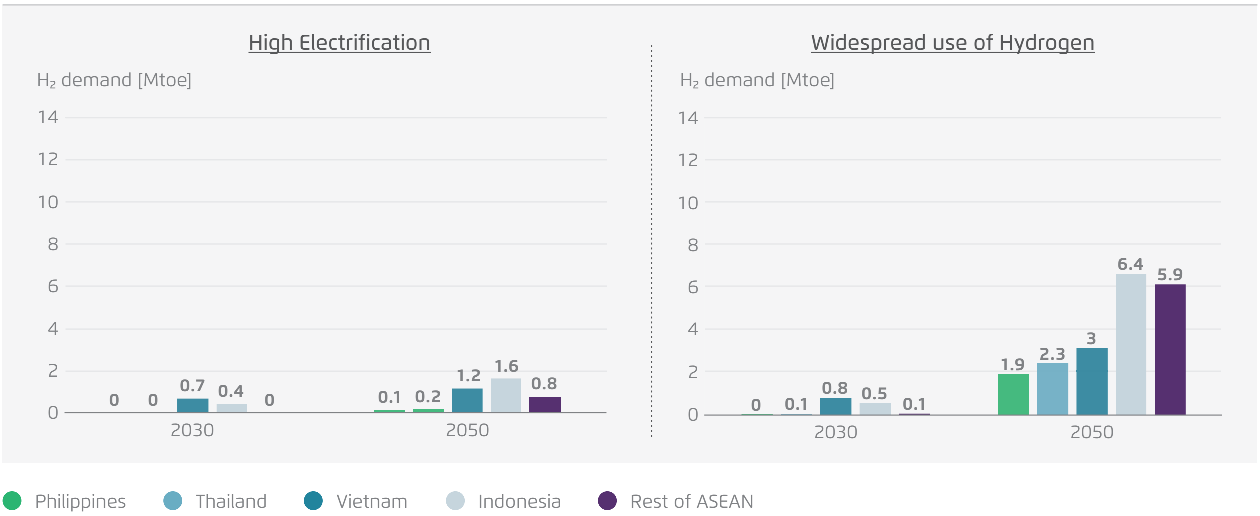
Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
'No-regret'	Non-energy use[1]: • Feedstock: ammonia, chemicals, fertilisers • Reaction agents: DRI steel	• Long-haul aviation • Maritime shipping	• Renewable energy back-up, depending on wind and photovoltaic share and seasonal demand structure	• Heating grids (residual heat load[2])
Controversial	• High-temperature heat	• Trucks and buses[3] • Short-haul aviation and shipping • Trains[4] • Non-road mobile machinery	• Absolute size of need given other flexibility and storage options	–
Bad idea	• Low-temperature heat	• Cars • Light-duty vehicles • Two- and three-wheelers	–	• Building-level heating

Agora Energiewende and Agora Industry (2021).
[1] Hydrogen may also be used as a reaction agent and/or feedstock in bio-refineries.
[2] After using renewable energy, ambient and waste heat as much as possible. Especially relevant for large, existing district heating systems with high flow temperatures. Note that according to the UNFCCC Common Reporting Format, district heating is classified as being part of the power sector.
[3] Series production currently more advanced on electric than on hydrogen for heavy-duty vehicles and buses. Hydrogen heavy-duty to be deployed currently in time only in locations with synergies (ports, mines, industry clusters).
[4] Depending on distance, frequency and energy supply options.

critical role throughout the region, which requires rapid expansion to 2030, and even more between 2030 and 2050. In this period, the annual capacity growth rate for solar PV required in Indonesia will be 24 GW per year, 9 GW in the Philippines, 13 GW in Thailand, and 13 GW in Vietnam to ensure that countries in the region are able to cover the majority of their electricity needs from local renewable resources (Müller et al., 2024).

In a scenario that prioritises electrification, hydrogen demand in the region is estimated to reach around 4 Mt per year by 2050. However, if hydrogen use becomes widespread across all sectors without prioritising it for 'no-regret' applications, hydrogen demand in Southeast Asia could be five times higher, reaching around 20 Mt per year by 2050. Figure 7 shows this comparison for the diff-ferent countries in the region. This high hydrogen demand will require countries to deploy additional renewable energy for hydrogen production, putting further pressure on electricity supply. Meeting only a third of renewable hydrogen demand domestically by 2050 will require an increase in renewable capacity of between 13% and 17% compared to the scenario with high electrification. This renewable expansion will come with different challenges for each country compared to the high electrification scenario. For Indonesia, for example, this will require an additional increase in solar PV capacity of about 20 % and battery storage capacity of 9%. In the case of the Philippines, the country may not be able to meet this demand domestically due to land-use constraints. And for Vietnam, solar PV would have reached its maximum capacity and a higher Levelised Cost Of Electricity (LCOE) for wind would have to be used, along with 15% more battery storage capacity. Countries in the region therefore need to carefully assess hydrogen demand and target it for applications where it is the only decarbonisation alternative.

Hydrogen demand for selected scenarios by 2030 and 2050 → Fig. 7



Müller et al. (2024)

Renewable hydrogen and PtX products can potentially enhance flexibility in the energy system but should be avoided for baseload generation

Integrating a large share of variable renewable energy into the energy system will require the mobilisation of various flexibility options that compensate for the variability of renewable power. Hydrogen and its derivatives can serve as a "fuel for flexibility" i.e. provide long-term energy storage solutions that can be utilised in hydrogen-fueled power plants during periods without sun or wind energy. Thanks to their flexible operation profile, electrolysers can adapt to variable power generation from renewables such as solar and wind, mitigating the curtailment of renewable power while facilitating the remuneration of such projects. In this way, electrolysers can also provide demand-side flexibility to the energy system (see Infobox 2). However, hydrogen is only one potential flexibility solution among others, with each technology having different technical and economic characteristics that need to be assessed according to the system needs. The future decarbonised energy system will require a technology-agnostic strategy tailored to all segments of the energy system.

However, cracking hydrogen derivatives for use in baseload power generation (directly or as a co-firing fuel) is highly inefficient (energy available after conversion and transport for different carriers: liquid H_2: 73–79%, ammonia: 63–64%, Liquid organic hydrogen carriers (LOHC): 57–59%) (IEA, 2022a). This would also increase the cost of electricity generation and the risk of carbon lock-in in the power system, strengthening the region's dependence on fossil fuel-based electricity generation (see Insight 5). Other renewables such as hydropower, biomass and geothermal can provide more competitive solutions for baseload power generation.

Infobox 2: Integrating renewable hydrogen into power systems

Despite the secondary role of hydrogen in global decarbonisation compared to electrification, renewable hydrogen production can be properly integrated into the power system, bringing flexibility benefits to it and, in some cases, even facilitating more cost-competitive production of green molecules and products. The production of hydrogen and its derivatives can be used to manage the surplus of renewable energy by converting it into PtX products. These products can be stored for long periods of time, addressing seasonal electricity storage issues. Hydrogen derivatives, such as synthetic fuels, are easier to store and can be used in other demand sectors such as transport, allowing greater cross-sectoral integration.

There are some examples around the world in the form of pilot projects or scenario modelling that assess the potential use of renewable hydrogen production in different contexts. For example, the study *Towards a collective vision of the Thai energy transition: National long-term scenarios and socio-economic implications,* developed by the Clean, Affordable and Secure Energy for Southeast Asia (CASE) project, highlights the importance of using renewable hydrogen and PtX products in the long term as a flexible demand mechanism through sector integration. Synthetic fuels and renewable hydrogen can be produced during solar generation hours, mitigating the curtailment of renewables and providing a potential flexible peak demand of around 16 GW. These products can then be used by the industrial sector. At the same time, this strategy of producing renewable hydrogen in the middle of the day with very high solar PV penetration can make renewable hydrogen more cost-competitive by taking advantage of low electricity prices, with the potential to achieve costs of around USD 1.15 per kg (USD 0.3 per KWh/1.2 Thai baht (THB) per KWh) by 2045. This will make the cost of renewable hydrogen comparable to that of fossil gas at USD 1 to 1.7 per kg (USD 0.3–0.5 per KWh/THB 1–1.8 per KWh), facilitating its use in the industrial sector (CASE, 2022a).

Another example can be found in Germany, where wind generation in the north of the country causes grid bottlenecks during periods of high wind, as there is insufficient infrastructure to transport electricity to the larger demand centres in the south of the country, leading to high levels of clean electricity curtailment. In 2013, a demonstration project funded by a public programme was developed to integrate hydrogen production and storage. The project uses 210 MW of wind turbines to power a 1 MW electrolyser connected to a 300 kg H_2-storage system. This project reduces the curtailment of renewable energy in the area and alleviates the urgency of grid expansion (RH_2-PTG, 2018). Additionally, the recent grid development plan published by the transmission system operator in Germany considers electrolysers as an important source of flexibility for the power system. In the scenarios for the year 2045, a significant portion of Germany's hydrogen demand will be covered by domestic electrolysis, with installed electric capacity ranging between 50 and 80 GW. By strategically locating electrolysers to support the grid, bottlenecks in the transmission network can be minimised. Moreover, due to their proximity to renewable energy facilities, curtailment of renewable energies during periods of high generation can be significantly reduced (50Hertz Transmission GmbH et al., 2023).

3. Renewable hydrogen can enhance energy security by mitigating dependency on fossil fuel imports

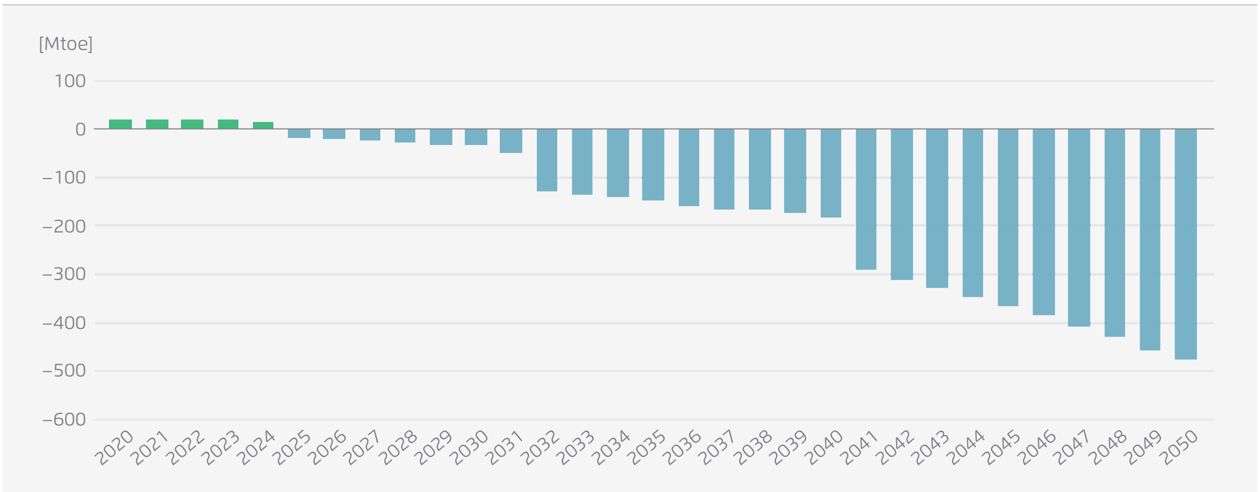
As Southeast Asia is expected to become a net importer of fossil gas, renewable hydrogen can mitigate the dependence on energy imports

Almost all of the world's current hydrogen production is based on fossil fuels, mainly fossil gas. The price of hydrogen derivatives is directly linked to fossil gas prices. Any price shocks to the fossil gas price have a negative impact on several sectors' value chains. With the rapid increase of fossil gas demand and the global LNG market expected to tighten, price-sensitive buyers in Southeast Asia may need to look for alternative solutions. It is also important to emphasise that LNG is a fossil fuel and is not compatible with a net-zero future envisioned by almost all Southeast Asian countries.

As shown in Figure 8, Southeast Asia is expected to become a net importer of gas by 2025. For example, Thailand's gas production is expected to decline from 27 million Tonnes of Oil Equivalent (Mtoe) in 2021 to 4 Mtoe in 2050. Despite the expected production growth from Indonesia and Malaysia, total fossil gas production in the region is expected to be 30% to 50% below expected demand. Therefore, fossil gas imports will increase dramatically in the medium- and long-term if countries in the region continue to rely on this energy source for their energy supply.

The growing demand could potentially be met by importing LNG. However, this presents an ambivalent picture as some LNG import terminals have been shelved or delayed due to regulatory issues as well as complex commercial and financial structures (IEA, 2022b). This situation could leave the region vulnerable to the volatility of international markets. Renewable hydrogen presents an additional tool for enhancing energy security. Production of renewable hydrogen with domestic renewables could diversify value chains and mitigate the region's dependence on energy imports. It is important to note that energy security does not mean securing fossil fuel supplies. Diversification away from fossil fuel to climate-compatible energy systems will enhance energy security and mitigate dependence on fossil fuel imports. In order to reach this goal, the region's energy transitions need to be accelerated, focusing on (1) bringing forward investments in renewable energy technologies, (2) increasing the role of energy efficiency in the policy frameworks and (3) accelerating fossil fuel phasedowns. This would help countries in the region

ASEAN's fossil gas trade balance (current/projected) → Fig. 8



ACE (2022)

move forward and be better prepared for future energy shocks (CASE, 2022b). Policies should address long-term energy security risks and structural changes required for a clean energy transition.

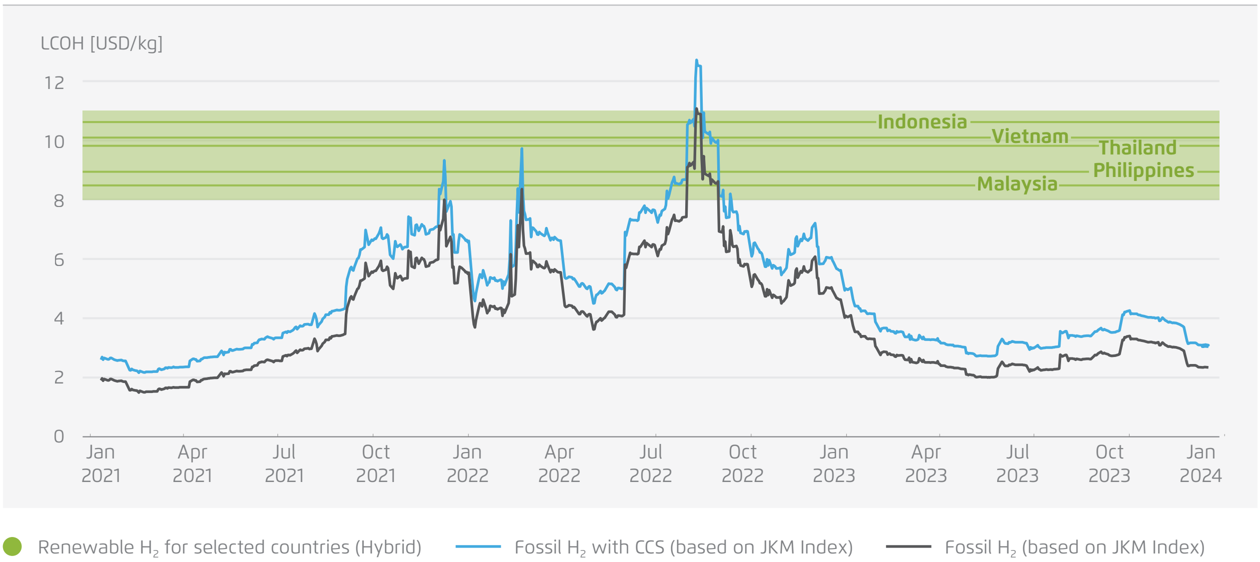
Fossil-based hydrogen with CCS may be considered as a bridging technology in some Southeast Asian countries but certain risks need to be assessed such as sustainability, stranded assets and carbon lock-in

The outlook for fossil-based hydrogen in the region is undermined by declining fossil gas production, limited LNG supply and rising gas prices. With the volatility of fossil gas prices, the cost of fossil-based hydrogen in the region has reached values of up to USD 13 per kg at the gas price peak in 2022 (Figure 9). This directly affects the competitiveness of fossil-based hydrogen with CCS which also loses competitiveness compared to renewable hydrogen, especially in countries such as the Philippines (Figure 9). The region's future reliance on fossil gas imports would make countries vulnerable to the volatile fossil gas market, putting pressure on industrial users facing price spikes, as happened in Europe with the fossil fuel crisis in 2021 and 2022. The development of the future gas market will be strongly influenced by geopolitical uncertainties as well as tight supply which is forecast in the short term (IEA, 2024). Most of these factors are external to the countries of Southeast Asia, making the region vulnerable to potential future price spikes and large market fluctuations.

However, fossil gas producing countries such as Malaysia may have a different perspective, with the possibility of considering fossil-based hydrogen with CCS as a bridge to a low-carbon alternative for the country's decarbonisation. However, several considerations need to be taken into account before prioritising this technology pathway:

1. **Sustainability of CCS technology:** The use of fossil gas with CCS for hydrogen production requires very high standards of sustainability to ensure

Costs of renewable H_2 and fossil based H_2 with CCS for selected countries in Southeast Asia → Fig. 9



Agora Industry (2024) based on Agora H2 PyPSA model. Note: Agora H_2 PyPSA model, Full load hours of renewables are collected for optimal locations in respective countries. Natural gas prices: JKM LNG Index, fossil H_2 with CCS is based on steam methane reforming with a 95% of capture rate. Renewable H_2 is based on the optimised hybrid capacities of wind & solar PV, including electricity and hydrogen storage costs but excluding transport costs.

emission reduction benefits. CCS requires high carbon capture rates (above 95%) which makes technology development challenging. Such a high capture rate requires not only the capture of emissions from the steam methane reforming (SMR) process but also their capture from the combustion of natural gas to produce the thermal energy needed for the reaction (about one third of the total process emissions). At the same time, some CCS practice is focused on enhanced oil recovery (EOR), where CO_2 is used to increase recovery of oil from active fields. It is unclear whether EOR is an appropriate method of carbon storage as it increases fossil fuel production in some regions, offsetting the benefits of CO_2 storage (OIES, 2023).
2. **Infrastructure development:** While fossil-based hydrogen with CCS appears to be an opportunity to accelerate the development of hydrogen infrastructure in the medium term, it will also require the development of infrastructure for CCS technology. The carbon infrastructure for the capture, transport and storage of CO_2 may require significant investment, especially if this pathway is regarded as a bridge technology. Appropriate planning will therefore be required to ensure that the developed infrastructure (e.g. for capture and transport) can be used in the long term, for example, to produce PtX products such as synthetic fuels, e-methanol etc.
3. **Fugitive emissions:** The extraction and use of fossil gas carries the risk of fugitive methane emissions which have a significant impact on climate change. Concurrently, carbon leakage from CO_2 capture, transport and storage needs to be carefully monitored. Hydrogen leakage, together with methane leakage, has a significant greenhouse effect. Thus, fossil-based hydrogen with CCS may have a greater climate impact than continued use of fossil fuels for hydrogen production (Ocko & Hamburg, 2022).
4. **Carbon lock-in and stranded assets:** New investment in fossil-based hydrogen with CCS may contribute to increased dependence on fossil gas, delaying the potential transition to cleaner technologies such as renewable hydrogen. At the same time, the global market is moving towards green products from renewable hydrogen whereas derivatives from fossil-based hydrogen with CCS may experience lower demand in the future, creating stranded assets for infrastructure still depending on fossil fuels.

Fossil gas producing countries in Southeast Asia will need to carefully assess all of the above risks before considering fossil-based hydrogen with CCS as a bridging technology. As shown in Figure 9, fossil-based hydrogen with CCS is still not competitive with fossil-based hydrogen and requires mechanisms such as carbon pricing to achieve cost parity. With the low to non-existent carbon pricing mechanisms in the region, ensuring the competitiveness of low carbon hydrogen will be more challenging.

In addition, the region's experience and readiness for CCS projects is still limited compared to other regions. For example, there are no commercial projects in operation in Southeast Asia and only limited projects at an early stage of planning, with the majority of applications in fossil gas processing with offshore storage. Estimates of storage capacity in the region, mostly in deep saline formations, are also highly uncertain. The potential is expected to reach 170Gt but only a fraction will be economically and technically viable (IEA, 2021b). The necessary regulatory frameworks are not yet in place and progress would depend heavily on international funding.

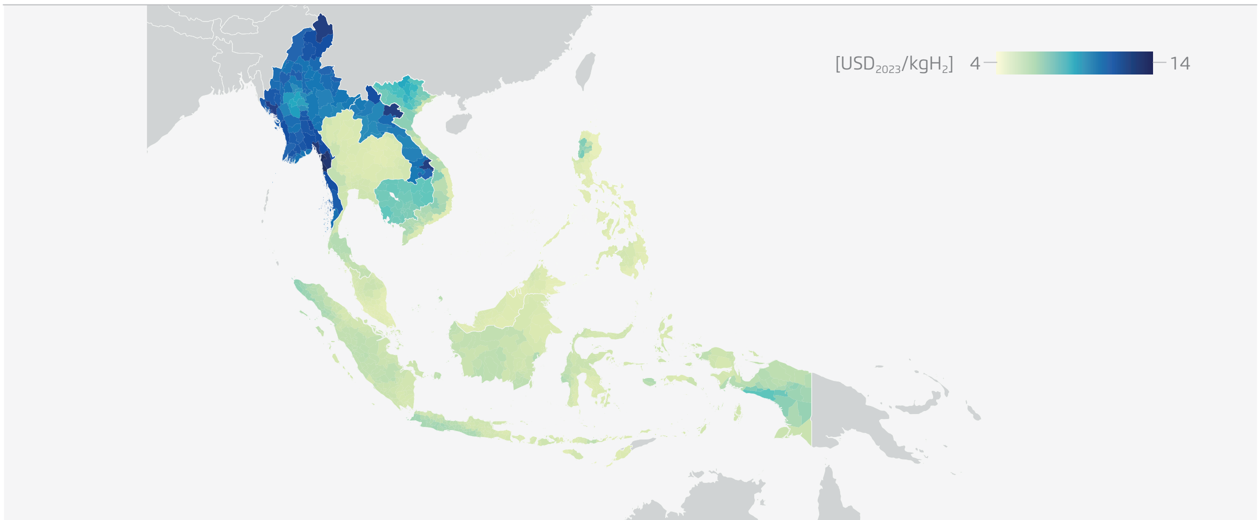
Fossil-based hydrogen with CCS is unlikely to be a competitive option for the region; the potential for cost declines in renewable hydrogen is much greater – on the back of targeted support policies

Renewable hydrogen costs in Southeast Asia have the potential to be competitive with fossil-based hydrogen with CCS before 2030. The region has the potential to achieve LCOH values between USD 4 and 14 per kg by 2030, based on solar and onshore wind resources alone. LCOH values in countries such as Myanmar and Laos are very affected by the WACC, despite their strong renewable resource potential. In most of the countries, areas with onshore wind potential can achieve the most competitive costs in the region, with values of around USD 4–4.5 per kg. These costs would be comparable to other potential renewable hydrogen producing countries in Africa and Latin America. At the same time, this analysis does not take into account the offshore potential in the region, which may be significant in the Philippines and Vietnam, thus creating better conditions for renewable hydrogen production. However, a number of important policy and regulatory factors affect the competitiveness of green hydrogen production in several Southeast Asian countries. Despite good resource potential, the cost of renewable energy is falling more slowly in some countries and this also affects the cost reduction of renewable hydrogen.

Policy support should focus on promoting renewable electricity in the region to make it more cost-competitive, while closing the cost gap between renewable and fossil technologies and promoting the use of renewable hydrogen in the long term. This is particularly important given the uncertainty of the global gas market and the risk of future fossil gas price volatility, which will have a direct impact on the cost of fossil-based hydrogen with CCS in the region. This applies to the whole region as it will become a net importer of this fossil fuel and, in particular, to countries in the area that are already fossil gas importers, such as Vietnam and the Philippines. They should focus their efforts on implementing policy support to reduce the cost of renewable hydrogen and achieve the potentially competitive costs shown in Figure 10.

Prioritising renewable hydrogen in the long term will create opportunities for Southeast Asia to access existing international mechanisms to close the price gap for green products by creating a green market. For example, the *H2Global Foundation* organises competitive procurement and sales of renewable hydrogen-based products. Purchase contracts span a ten-year time period to guarantee investors recovery of their costs. The green products are then sold in Europe in annual auctions. If the cost of reselling the product is lower than the purchase cost, a grant authority (such as a public or philanthropic funding body) covers the difference. The first auction to purchase ammonia was launched in November 2022 in Germany. In the meantime, more European governments have joined the initiative, for example, the Netherlands (H2Global 2023).

Levelised Cost of Hydrogen (LCOH) for hybrid (photovoltaic and wind) production in selected regions of Southeast Asia, 2030 → Fig. 10



Agora Industry (2024) based on Agora H_2 PyPSA model. Note: Island system (renewables not connected to the grid) with underground pipeline storage to maintain near constant hydrogen delivery for industrial off-take.

4. The targeted use of renewable hydrogen can provide a boost to the decarbonisation of industry in Southeast Asia

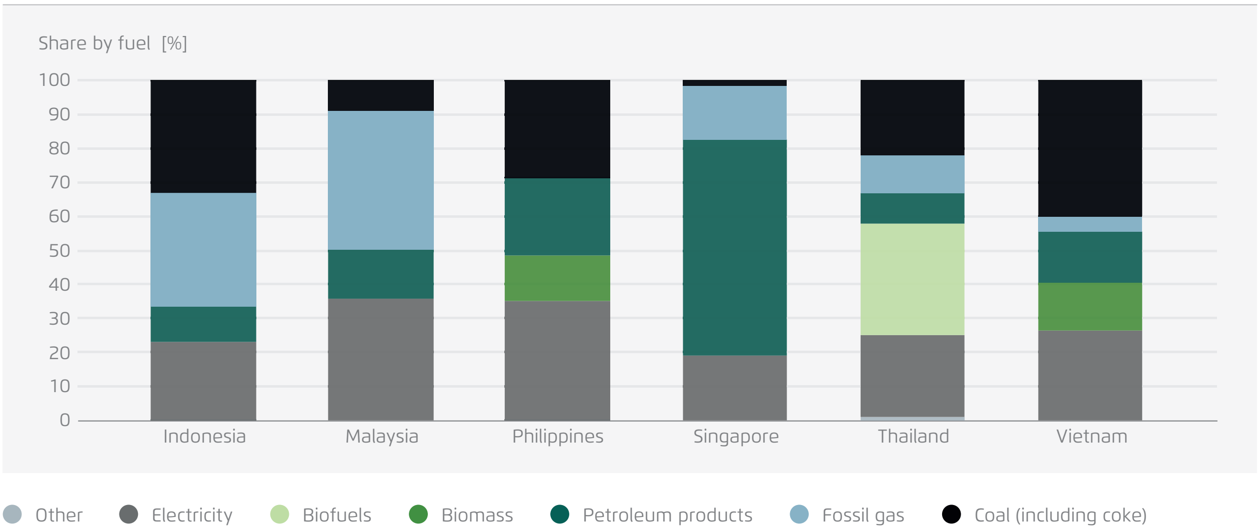
The industrial sector in Southeast Asia is growing faster than the global average, creating an opportunity for low-carbon investments

Over the past decades, Southeast Asian economies have shifted from agriculture-based economies to those based on manufacturing, industry and services. By 2022, the share of agricultural production in GDP had fallen below 13% in the region and the share of the manufacturing sector now ranges between 17% (the Philippines) and 27% (Thailand) – above the world average of 16% (World Bank 2023a). The growth of the manufacturing sectors was particularly rapid between 2005 and 2022, with value added more than doubling in Southeast Asia, including a threefold increase in Indonesia and even a ninefold increase in Vietnam. As the pace of industrialisation continues, Southeast Asia faces the dual challenge of decarbonising the existing manufacturing base and ensuring that new investments in manufacturing capacity across industrial sub-sectors are compatible with net-zero emission reduction pathways. Countries in the region therefore need to establish clear industrial decarbonisation strategies that cover the role of energy and material efficiency, electrification, biomass and renewable hydrogen for 'no-regret' applications (see Insight 2).

As shown in Figure 11, Southeast Asia's industry is heavily dependent on fossil fuels, with coal being the largest single energy source for industry in Indonesia, Vietnam and the Philippines. Future industrial development should seek ways to reduce this dependency and convert existing industrial parks to low-carbon options. As for the distribution of energy consumption across industrial sub-sectors in the region, cement, chemicals plus iron and steel account for more than 40% of industrial energy consumption. These sectors account for more than half of total industrial energy use in Vietnam, Malaysia and Indonesia. Growth prospects for all three sectors in the region are strong due to growing demand in buildings, construction, infrastructure and downstream manufacturing.

Therefore, renewable hydrogen can be a key component in the decarbonisation of the steel and chemical sectors, mainly as a feedstock. Clear decarbonisation strategies for these industrial sectors are required

Industrial energy consumption in ASEAN's largest economies, 2022 → Fig. 11



CASE (2022a), MEMRI (2022), TNSO (2023), SDS (2022), DEM (2020) providing a clear role for renewable hydrogen and PtX products, exploring cross-sectoral synergies and creating an attractive environment for investments aligned with a net-zero pathway. Renewable hydrogen and PtX products will, however, have limited applications for high temperature heat or as a fuel due to their high cost and low efficiency. In those sectors, direct electrification and direct use of renewable energy such as geothermal and solar thermal will likely be the most competitive option for the most heat production.

With the support of strategic partnerships to align foreign investments with net-zero strategies and the use of renewable hydrogen as a reducing agent, the steel industry can be a fast-to-abate sector

Steel demand and production in Southeast Asia is growing rapidly: it is expected that the region will contribute to a 23% increase in global steel demand, driven mainly by infrastructure expansion and population growth. Steel demand in the region is forecast to reach around 127 Mt in 2030 (global steel demand is estimated to reach 1 925 Mt in 2030) (McKinsey & Co, 2022). Therefore, decarbonisation strategies for the Southeast Asian steel sector should be prioritised to avoid an increase in emissions as the sector continues to grow.

Southeast Asia is currently a net importer of steel. Steel demand in the region reached 91 Mt in 2021, with Southeast Asian countries having a supply capacity of 51.2 Mt, equivalent to around 56% of the region's steel demand. However, ongoing investments in the sector will gradually reduce import dependency in the coming years and it is expected that, by 2030, ASEAN countries will rely on imports for only 25% of their supply (McKinsey & Co, 2022).

As shown in Figure 12
regions, Electric Arc Furnace (EAF) technology has historically dominated the region's relatively young steel industry, resulting in lower sectoral emissions. But since 2014, foreign investments, mainly from China, have supported the development of integrated Blast Furnace-Basic Oxygen Furnace (BF-BOF) steel mills – a technology which is largely reliant on coal. Southeast Asia's total crude steel capacity reached around 72 Mt by 2020, two-thirds of

Historical and forecasted crude steel capacity in ASEAN-6 → Fig. 12

SEAISI (2022). Note: ASEAN-6 correspond to Indonesia, Malaysia, Philippines, Singapore, Thailand and Vietnam.

which came from EAF technology. The growth rate of BF-BOF technology has been very rapid (32% between 2011 and 2020) and more than 80 Mt of integrated BF-BOF steel capacity is expected to come on stream in the coming years, compared to only 2.2 Mt of additional EAF capacity. As a result, BF-BOF technology is expected to grow each year by 25% on average between 2020 and 2026, compared to only 1% for EAF over the same period. Consequently, emissions from the steel sector in the region are projected to triple between 2020 and 2026 and continue to increase thereafter (SEAISI, 2022).

Industrial decarbonisation strategies in the region should take advantage of the sizeable EAF fleet, encouraging its transition to renewables (electrification) and renewable hydrogen as a reducing agent for green steel production. Countries should also consider technology options to mitigate emissions in recently built BF-BOF plants, such as CCS, with a medium- and long-term perspective of moving to Direct Reduced Iron-Electric Arc Furnace (DRI-EAF) for green steel production (see Infobox 3). However, CCS does not allow full decarbonisation of the BF-BOF plants and presents several challenges,

Infobox 3: Available technology for steel production and potential decarbonisation routes

Steel is produced through three production processes:

1. **BF-BOF (blast furnace-basic oxygen furnace):** About 70% of the global steel is produced through this route. It involves the production of pig iron with coking coal in the BF and, subsequently, the production of steel through BOF. BF-BOF is an integrated technology, meaning that iron and steelmaking are linked and occur on the same production site. The blast furnace uses coking coal to reduce iron ore which can be purchased but is generally produced on-site.
   → The coke plant and blast furnace account for most of the emissions released from BF-BOF steel production. In 2022, the global average emissions intensity of BF-BOF steel was 2.3 tCO_2 per tonne crude steel (World Steel Association, 2023).
   → BF-BOF-CCS: CCS technology can contribute to the mitigation of emissions from this technology, however, its potential is limited to mitigating up to 73% of carbon emissions. Other risks to consider are fugitive methane emissions from coal mining, CO_2 infrastructure development, the potential for stranded assets or finding off-takers in the future etc.

2. **EAF (electric arc furnace):** This technology uses an electrically-charged furnace to make steel out of recycled steel scrap, as well as other metallic inputs such as sponge iron or pig iron, depending on the final quality requirements.
   → Scrap-EAF, also termed secondary steel, has a significantly lower emissions intensity – at a global average of 0.7 tCO_2 per tonne crude steel in 2022 (World Steel Association, 2023). In addition, it is important to highlight that EAF offers the potential to achieve near-zero emissions when the technology is powered by renewable electricity.

3. **DRI (direct reduced iron):** DRI is an iron production process where iron ore is reduced by a syngas that currently comes either from fossil gas or from coal. Contrary to the BF-BOF route, iron ore reduction takes place in the solid state. DRI is usually paired with EAF to produce steel products.
   → In 2022, the global average emissions intensity of DRI-EAF steel was 1.4 tCO_2 per tonne crude steel (World Steel Association, 2023)
   → Hydrogen can replace fossil fuels as a reducing agent in the DRI route to produce sponge iron to be fed into an EAF. H_2-DRI-EAF is being pioneered and provides a promising production route for green steel. The first commercial H_2-DRI plants have been built in China and several H_2-DRI plants are planned to come online in Europe by 2026.

such as developing CO_2 infrastructure, upstream emissions and so on (Agora Industry. et al., 2024).[6]

Foreign investment in the region's steel sector accounts for around 90% of total investment (China: 66%, Taiwan and Japan: 20% each, Korea: 5%) and is an important driver in making the region a potential steel exporter. However, the competitiveness of BF-BOF will be impacted as trade measures favouring green products are being deployed amongst major economies, such as the CBAM and Climate Club,[7] thus penalising the carbon content of the region's products. Meanwhile, the net-zero commitments of Southeast Asian countries by the mid-century are incompatible with new BF-BOF technologies, hence these investments create a risk of not achieving such climate targets in the region.

6 Agora Industry has developed the study "Low carbon technologies for the global steel transformation", analysing in more detail decarbonisation options for the steel sector globally.

7 Launched at COP28, the Climate Club is an open, inclusive and ambitious high-level forum for cooperation on accelerating climate action and raising ambition, particularly in the field of industrial decarbonisation – with the aim of achieving the objectives of the Paris Agreement. Currently, the initiative counts with 38 who are committed to supporting the effective implementation of the Paris Agreement and the decisions made under it (Climate Club, 2024).

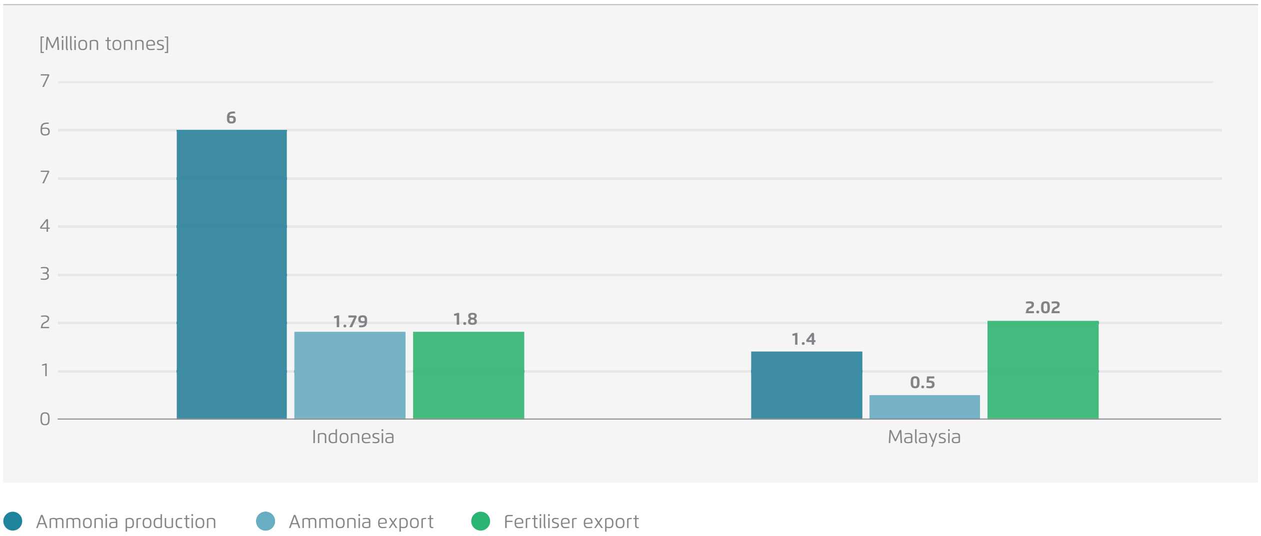
Countries should therefore review the pipeline of new investments and re-direct investments planned for BF-BOFs in favour of hydrogen-ready DRI-EAFs. At the same time, they should seek strategic partnerships that will provide the region with the necessary investments, aligned with net-zero strategies and coupled with the growth of renewable energy and renewable hydrogen production. A net-zero steel sector and a phase-out of coal in steelmaking by the early 2040s are technically feasible, in view of key strategies such as material efficiency, an increase in scrap- and hydrogen-based steelmaking plus bioenergy, accompanied by a regulatory framework to deploy renewable electricity capacity and low-CO_2 steelmaking technologies (Agora Industry and Wuppertal Institute, 2023).

Renewable hydrogen can be a decarbonisation enabler for the chemical sector, mainly ammonia, fertilisers and methanol production

The chemical sector in Southeast Asia is diverse, with oil- and gas-producing countries like Indonesia, Malaysia and Singapore being the main petrochemical producers. With the exception of

Annual ammonia and fertiliser production, consumption and exports: Indonesia and Malaysia

→ Fig. 13



USGS (2023), WITS (2023), Fertimetrics (2023), Argus Media (2023a), Argus Media (2023b)

Singapore, most countries in the region are net importers of chemicals. Global and regional demand for certain chemical products, such as fertilisers and methanol, is on an upward trend which will strengthen the export role of certain countries in the region. Indonesia and Malaysia export 2.3 Mt of ammonia, about 4% of total world consumption (see Figure 13). Both countries are also exporters of urea. In 2023, they exported 1.8 and 2.02 Mt of urea respectively. Furthermore, both countries are major producers and exporters of methanol, with Malaysia being the fourth largest methanol producer in the world (IEA, 2021a).

In net terms, the region is still heavily dependent on chemical imports. This dependence on the global market can be critical for some chemicals, such as fertilisers. The volatility of international fossil gas prices has a direct impact on the price of fertilisers which in turn affects food supply and energy security (see Insight 5). Promoting low-carbon development of the chemical sector based on local renewable hydrogen as a feedstock can not only benefit the competitiveness of the region's chemical sector, but also open up opportunities to diversify the supply chain of certain products such as green ammonia, fertilisers, e-methanol and synthetic fuels. These green products can also unlock new opportunities for value-added trade, given the growing demand for sustainable aviation fuels and e-methanol for the marine sector (see Insight 6). Malaysia is already promoting the development of low-carbon hydrogen projects: they will be operational in 2027 with an annual production capacity of 460 000 tonnes of e-methanol, in addition to 630 000 tonnes of green ammonia and 600 000 tonnes of fossil-based ammonia with CCS. Clear decarbonisation strategies for the chemical sector should include renewable hydrogen as an important feedstock contributing to the low-carbon development of the chemical sector in the region. A gradually increasing share of renewable hydrogen in current chemical production can serve as a transitional measure, especially in fossil fuel producing countries. But in the medium- to long-term, renewable hydrogen should be prioritised as a feedstock in the sector, complementing more efficient use of materials, recycling (mechanical and chemical) and electrification measures.

The biomass sector[8] may also play a role in the low-carbon development of the chemical sector as it can replace fossil feedstocks (Agora Industry, 2023). Thailand has already seen some investment in bio-based chemical production, given its important sugar cane sector. In addition, the biomass sector can provide carbon sources for the synthetic production of chemicals, facilitating the de-fossilisation of the chemical sector.

8 Additional biomass demand coming from the industrial sector must ensure that it does not lead to environmentally-harmful intensification of land use or to direct or indirect changes in land use, leading to detrimental effects on eco-systems and carbon cycles.

5. Green ammonia should be reserved for the decarbonisation of the fertiliser and shipping industries. Its use in coal-power plant co-firing is inefficient and costly

Countries in Southeast Asia should prioritise the use of green ammonia for applications where its use is an indispensable low-carbon option, such as in the chemical and fertiliser industry and shipping

The current ammonia production process is highly carbon-intensive with approximately 1.8 tonnes of CO_2 emitted per tonne of ammonia (Agora Energiewende and Wuppertal Institute, 2021). Over two-thirds of today's ammonia output is used as a feedstock to produce nitrogen-based fertilisers such as urea and ammonium nitrate while the remaining part is used for various industrial applications, such as plastics, explosives and synthetic fibres (IEA, 2021a). By mass, ammonia is the second most-produced chemical and supports food production for around half of the world's population. Demand for ammonia is expected to more than triple by 2050 (IRENA & AEA, 2022).

The use of hydrogen produced via water electrolysis to replace fossil-based hydrogen is expected to contribute strongly to the de-fossilisation of global fertiliser production. This would decouple fertiliser production from the price volatility of fossil gas and it would enable more Southeast Asian economies to produce their own fertilisers and not depend on imports – with positive spillovers in terms of job creation, food security and industrial decarbonisation. Beyond fertilisers, green ammonia is positioning itself as an alternative future clean fuel for the shipping industry. Ammonia could potentially supply 43% of the shipping sector by 2050, corresponding to 183 Mt of green ammonia, or roughly today's global ammonia production (IRENA, 2021). However, ammonia engines for vessels are not yet market-ready as present projects are mainly on the pilot and demonstration levels: market uptake could be by 2027 at the earliest and the need for international infrastructure has also to be considered, such as bunkering in ports (IEA, 2023e). In addition, low-carbon development of the shipping sector also involves exploring other alternative fuels, such as e-methanol which has the potential to reduce the sector's use of ammonia so that it can be better targeted for fertiliser production (see Insight 6).

Co-firing green ammonia with fossil fuels for power generation is inefficient, expensive and can have significant implications for food production and supply

Japan and the Southeast Asian coal industry have recently started promoting co-firing of ammonia in coal power plants as a medium-term "clean coal" option to mitigate emissions in the power sector (E3G, 2023). This technology option is gaining momentum given the region's young coal fleets, especially in coal-dependent countries such as Indonesia, the Philippines, Malaysia and Thailand. Indeed, Southeast Asia harbours an almost 80 GW fleet of coal-fired power plants which are younger than 20 years old. This has led several countries to pilot some level of co-firing with Japanese companies: for example, Vietnam which plans to co-fire its young coal fleet from 2035, gradually increasing co-firing before phasing out coal altogether in 2050 (Agora Energiewende, 2023). However, coal plants with co-firing retrofits are expected to continue using coal as an energy input, leading to ammonia co-firing rates of around 20 to 50%, thus rendering them more carbon-intensive than other technologies, including even gas power plants. Development of the technology is still needed to reach a high level of ammonia blending and the latter would require technical retrofit measures that may also prolong payback periods, and hence, the required operating hours over the plant's lifetime.

The use of ammonia for decarbonising the existing coal power plant fleet is driven by the political and economic interests of the coal sector and a lack of confidence about the reliability of renewables. This lack of trust has already significantly delayed the investments in clean technologies to meet the announced climate targets in the region (ASEAN

Centre for Energy, 2022). While countries in Southeast Asia understandably try to minimise the cost of stranded assets, calculations have shown that co-firing is one of the most cost-inefficient ways to decarbonise the power sector (see Figure 14). In Indonesia, for example, installing solar PV is cheaper by 270% than co-firing coal powerplants with as little as 20% green ammonia. Furthermore, the economics of substituting coal with ammonia are highly dependent on the availability of low-cost ammonia. Thus, the high abatement costs of ammonia co-firing render it economically unviable and divert investments from clean and cheap renewable options, risking valuable public funding on a carbon-intensive technology.

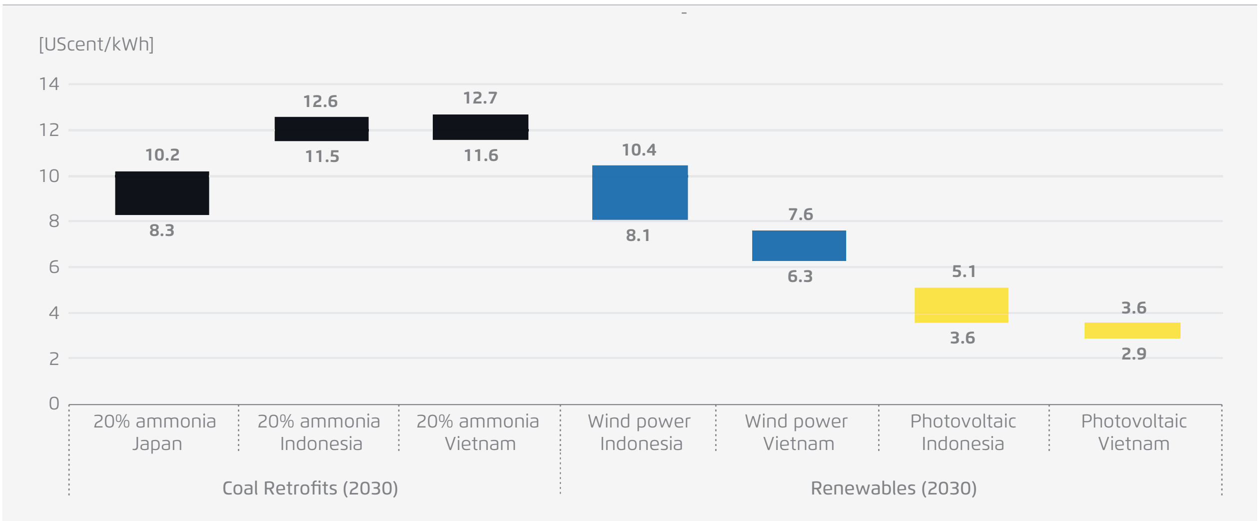
Ammonia co-firing in power plants is not aligned with 1.5 degree C pathways and presents higher emissions compared to other options

Ammonia co-firing technology is planned to be implemented gradually as the technology is not fully developed yet. In the short-term, ammonia co-firing rates are expected to be around 20%, before increasing to 50% in the mid-term and potentially 100% in the long-term. Calculations have shown that 20% to 50% ammonia co-firing in coal plants in Southeast Asian countries would lead to emissions that are significantly higher than those of existing thermal generation, such as gas-fired power plants. Compared to an average gas power plant, a coal plant co-firing 20% ammonia would result in emissions that are 94% higher in Malaysia, 77% higher in Thailand, 60% higher in the Philippines and 44% higher in Indonesia (TransitionZero, 2023). Additionally, low ammonia co-firing rates generate nitrous oxide, a gas with high global warming potential. In order to tackle this problem, companies would have to invest in nitrous oxide capturing technologies to secure the decarbonisation potential of co-firing, further adding to the prohibitive costs of this technology (BNEF, 2022). Moreover, none of these solutions are in line with the power sector emission trajectories required to achieve net zero targets (IEA, 2021a).

Additional demand for ammonia co-firing in coal power plants would increase the pressure on the fertiliser industry, due to farmers' lower purchasing power, and eventually lead to inflated food prices

Due to a dependency on fossil gas price fluctuations, switching to green ammonia will help the fertiliser industry to become more resilient, in addition to

LCOE for different technologies including ammonia co-firing in selected countries → Fig. 14



Agora Energiewende (2024) based on BNEF (2022) releasing less greenhouse gases.[9] The recent energy crisis and the consequent high natural gas prices have led global fertiliser prices to triple, affecting millions of farmers dependent on the use of fertilisers and putting at risk food security in fertiliser-importing regions (World Bank, 2023b). Similarly, the use of ammonia co-firing in coal power plants could increase the pressure on the availability of fertilisers (Rosa & Gabrielli, 2023). Indeed, back-of-the-envelope calculations have shown that introducing 20% ammonia co-firing in all the existing coal power plants in Japan and Southeast Asia by 2030 would increase global ammonia demand by up to 100 Mt, which represents half of global ammonia demand in 2020 (IEA, 2021a). Thus, co-firing ammonia in coal power plants would increase demand competition and disadvantage farmers, who usually have less purchasing capacity than energy and shipping companies.

9 Two-thirds of the life cycle emissions of nitrogen-based fertilisers occur after application, so green ammonia can only reduce production emissions which account for one-third of the total life cycle emissions of fertilisers.

6. The potential future market for hydrogen vehicles is shrinking daily

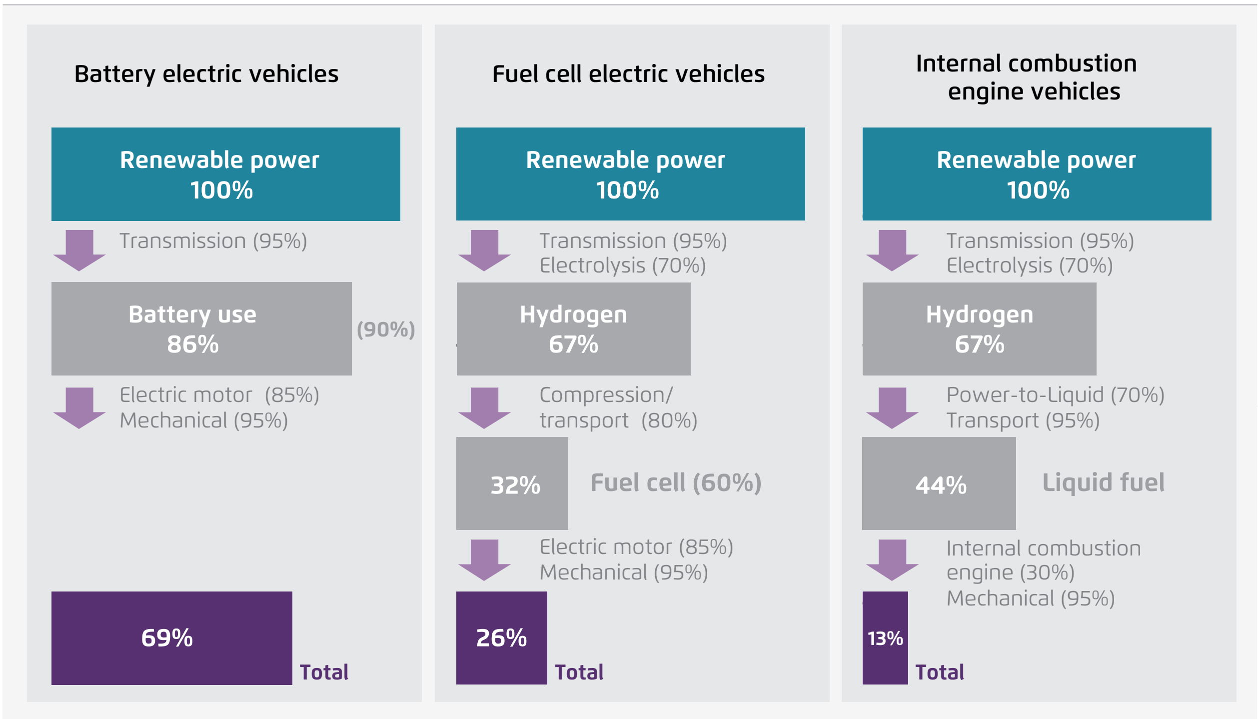
Battery electric vehicles are technically the most efficient technology to decarbonise the road transport sector

When considering the options for decarbonising the road transport sector, different technologies are commercially available. However, some are technically more efficient than others, especially when analysing the role of hydrogen and synthetic fuels compared to battery technologies. Assuming that the main energy source used is renewable electricity, Figure 15 shows the conversion losses for three different passenger car drive technologies: Battery Electric Vehicles (BEVs), Fuel Cell Electric Vehicles (FCEVs) and internal combustion engine vehicles (using synthetic fuels, such as e-gasoline). While BEVs have an efficiency rate of 69% due to a short conversion cycle, FCEVs have an efficiency of only 26%, mainly due to the intermediate step of generating hydrogen by electrolysis. Yet it is worth noting that the least efficient way to power vehicles is to use synthetic fuels in internal combustion engines as the two-step chemical conversion, combined with the inefficiency of the internal combustion engine, results in an overall efficiency of a mere 13%. BEVs are therefore significantly more efficient than FCEVs and internal combustion engines running on renewable synthetic fuels and are thus also the most cost-effective option (Agora Energiewende et al., 2021).

Battery electric vehicles dominate the global car market, limiting the role of hydrogen-fuelled cars to specific applications, such as heavy-duty vehicles

Fuel Cell Electric Vehicles (FCEV) were once seen as key for the decarbonisation of the transport sector. But this technology has gradually been losing the race

Individual and overall efficiencies for cars with different vehicle drive technologies, based on renewable electricity → Fig. 15



Agora Verkehrswende et al. (2018) Note: Individual efficiencies are indicated in parentheses. Multiplied together, the individual efficiencies yield the overall cumulative efficiencies in the boxes.

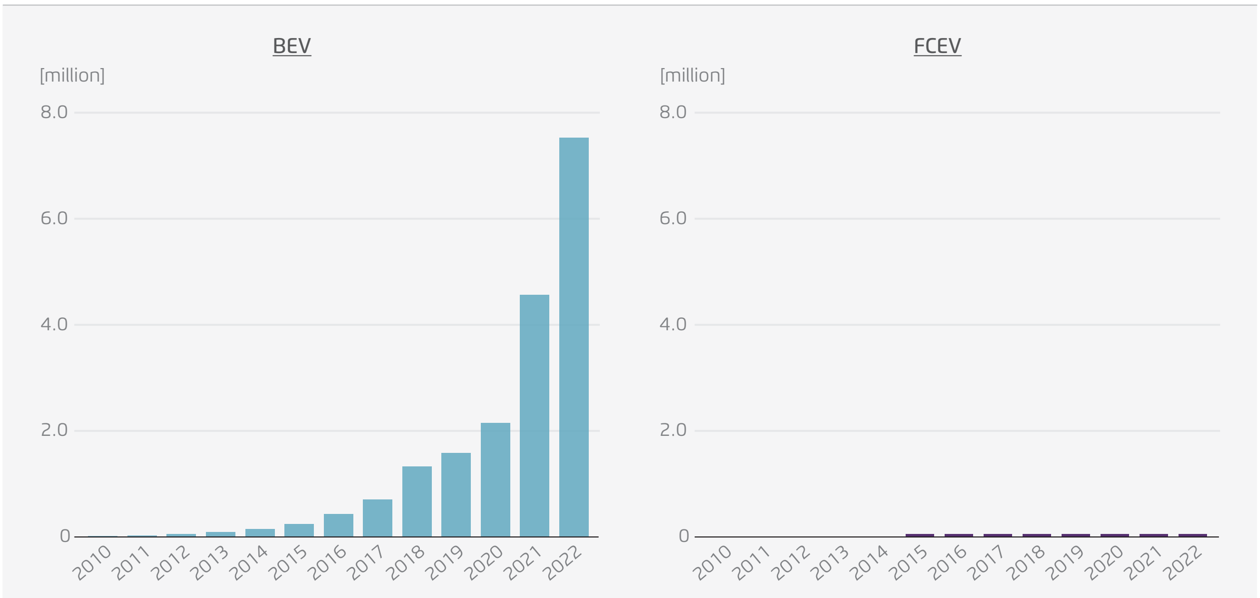
against Battery Electric Vehicles (BEVs) which today completely dominate the global market of passenger cars, as shown in Figure 16. In 2022, BEVs reached sales of about 7.5 million vehicles globally with an annual growth rate of 67.5% since 2019. Global sales of BEVs in 2022 were concentrated in just three major markets (China, Europe and the US, accounting for 60%, 25% and 8% of total global sales in 2022 respectively). BEVs still face economic barriers in less developed countries (IEA, 2023f). However in 2022, ASEAN countries recorded BEVs sales of around 39 000 vehicles, representing a 165% increase from the previous year (ICCT, 2023a). On the other hand, global FCEVs had sales of around 154 000 in 2022, with an average annual growth rate of 26% since 2019. In 2022, FCEVs sales experienced a slight decline in comparison to 2021 (155 000) (BNEF, 2023b). This trend continued during 2023, global sales of hydrogen-powered vehicles (cars, buses and trucks) fell by 30% in comparison to 2022, especially affecting the Asian market in Japan and Korea where hydrogen has been prioritised to transform the transport sector (Collins, L., 2024). Even on the Chinese market, where sales did not drop in the same period, market growth is still not comparable to that of battery-electric vehicles (Collins, 2023).

With FCEVs representing less than 0.02% of global passenger vehicles sales in 2022 (BloombergNEF, 2023b), they are not expected to play a major role in the decarbonisation of the road transport sector, especially for passenger cars, but it is expected that the market will see some hydrogen vehicles for heavy-duty purposes. Fuel-cell trucks will have an application where the hydrogen resource is widely available such as in industrial hubs or ports focusing on trade in PtX products. For countries with specific geographical characteristics limiting the expansion of power infrastructure or requiring much longer travel distances, hydrogen could provide an option to decarbonise heavy-duty transport. The mining sector sees fuel-cell technology as the only available option to decarbonise its transport activities and some countries with significant extraction activities are prioritising the use of hydrogen in the sector, although there are also early developments in battery electric mining trucks.[10]

10 Companies in the US and Germany are making progress in the development of battery-electric mining trucks that are currently being tested at mining sites, with plans to expand and offer them to mining sites around the world (Caterpillar, 2022) (E-Mobility Engineering, 2023).

BEV versus FCEV annual sales globally (passenger vehicles)

→ Fig. 16



BNEF (2023)

Electrification is the main strategy for decarbonising the transport sector in Southeast Asia

The region's transport sector is heavily dependent on fossil fuels. In the early 2000s, the sector's total energy supply relied entirely on oil and its derivatives but has become more diversified with the uptake of natural gas and biofuels (which represent 5% of the total transport energy supply in 2019) (Müller et al., 2024). Several countries, such as Indonesia, Malaysia, Myanmar, Thailand and Vietnam, have already implemented biofuels blending mandates (IRENA, 2022). In addition to the introduction of biofuels, electromobility is rapidly growing in relevance for the countries' decarbonisation strategies in the transport sector. All ASEAN countries have adopted strategies to accelerate electrification of the transport sector so as to reduce their dependence on fossil fuels in this sector. For example, Singapore has banned the sale of new diesel cars from 2025 and will require all cars and buses registered by 2040 to run on clean energy. Indonesia has accelerated its EV target, aiming for 12 million electric cars and 13 million electric motorcycles by 2030. Malaysia's *Low Carbon Mobility Blueprint* 2021–2030 targets a 15% share of electric motorcycles and 20 000 electric cars by 2030 (IRENA & ACE, 2022). This is complemented by strategies to develop BEV manufacturing in the region, such as Indonesia's interest in developing EV batteries leveraging on their nickel reserves (ACE, 2024) and Thailand's plan to boost local EV production (Bloomberg, 2023). As mentioned above, hydrogen-based transport is likely to follow global trends and take place for very specific cases in the region, most probably concentrated in the heavy-duty segment.

Hydrogen-based power-to-liquids (PtL) products will contribute to the decarbonisation of the shipping and aviation sectors and can serve as a new economic driver for the region

For other transport modes, such as long-haul shipping and aviation, pure hydrogen might not be seen as a viable option, most notably because of its lower energy density, making liquid fuels the most likely option for the next decades. For shipping, hydrogen derivatives such as green ammonia and e-methanol are emerging as potential alternative fuels to decarbonise the sector in the medium term. These efforts are driven by the international maritime organisation's (IMO) commitment to reach net-zero GHG emissions from international shipping by or around 2050 (IMO, 2023). The aviation sector has similarly ambitious targets, committing to a net-zero pathway by 2050 (ICCT, 2023b). Low carbon technologies such as hydrogen or battery electric aircraft could play an important role in mitigating the negative impacts of short-haul and regional aviation in the medium to long term. As for long-haul flights, however, sustainable aviation fuels (SAFs) are the only option for the foreseeable future. In Southeast Asia, Singapore is leading regional efforts on the production of SAF since it is the country with the largest aviation fuel demand in the area. The country is aiming to become the regional SAF hub. Singapore will initially focus on the production of biofuels for SAF (the country has announced 1.4 Mt per year of SAF by 2030), with hydrogen and its derivatives being considered in the medium term. Other countries in the region have also announced SAF production targets by 2030, mostly focusing on biofuels production (Indonesia: 0.9 Mt per year; Malaysia: 0.3 Mt per year; Philippines: 0.1 Mt per year; Thailand: 0.3 Mt per year) (WEF, 2023).

Southeast Asian countries need to assess the opportunities offered by the maritime and aviation industries' decarbonisation for the development of their hydrogen economies and examine the potential production of synthetic fuels for these industries as part of their efforts to scale up hydrogen and PtX production. The deployment of PtL and SAF technologies, particularly in developing and emerging economies, could generate positive trends for social innovation, job creation and advanced education.

7. Power infrastructure should be prioritised in the short- to medium-term and hydrogen infrastructure development should integrate energy, industrial, climate and trade considerations

The region's power infrastructure should be strengthened, while taking into account overall energy system needs, so as not to disproportionately focus efforts on renewable hydrogen production alone

Electricity transmission and distribution grids in Southeast Asia have been reinforced over the last decade, reducing transmission and distribution losses, facilitating the integration of variable renewable energy and improving access to reliable electricity services in most countries (UNESCAP & ACE, 2020); (World Bank, 2023c). However, given the region's growing electricity demand and climate mitigation commitments, the existing electricity infrastructure, including ancillary services, must be further developed to facilitate the integration of larger shares of renewable energy.

Many countries have been reluctant to promote variable renewables based on the myth that their grids are not ready for variable generation. As a result, the share of solar and wind power in the region covers only about 2.4% of electricity generation (ACE, 2023b), corresponding to about 10% of the total installed capacity of 310 GW in 2022. Further investment and changes in operational practices are therefore needed to facilitate the integration of larger shares of renewables without compromising service reliability. The investment requirements are diverse, as countries in the region have different starting-points, physical constraints and needs. With its large hydropower resources, Laos plans to become the storage hub of Southeast Asia. Vietnam needs to further develop its transmission grid to transport more renewable generation (solar PV, offshore wind) from the best resource location to the consumption centres in the north and south. Indonesia and Malaysia would benefit from better integration with other regional markets to increase their system flexibility (Huang et al., 2019).

With the plan to also develop renewable hydrogen in the future, additional pressure will be put on electricity grid infrastructure. Integrated planning will need to consider both electricity and hydrogen demand. Flexible resources will be a key component of the region's development and expansion plans, with battery storage playing a growing role to facilitate mobilisation of the region's high solar potential. The region will need to invest around USD 200–245 billion per year by 2050 in renewables, energy efficiency and enabling technologies to significantly improve grid infrastructure and achieve net-zero (IRENA & ACE, 2022). However, most countries' current Power Development Plans (PDPs) have not addressed infrastructure needs in a holistic way, focusing on expanding generation capacity rather than sector integration, supply reliability and flexibility (Lee, 2023).

If planned properly, the production of renewable-based hydrogen can provide additional flexibility to the electricity system. In addition, PtX products contribute to the indirect electrification of other sectors such as industry and transport that will also compete with direct electrification options. Countries must, therefore, carefully assess this interaction from a system perspective so as not to disproportionately focus efforts on renewable hydrogen production alone. In the short term, renewable hydrogen projects are likely to be developed off-grid. While those projects are likely to be more expensive than those connected to the grid, they minimise additional infrastructure needs and benefit areas with high renewable potential and low infrastructure backbones. In the medium- and long-term, countries should consider a coordinated way to potentially integrate renewable hydrogen projects into the existing system, to simultaneously develop the grid, spur investments into power infrastructure and improve the economics of hydrogen projects in the region, making them more competitive.

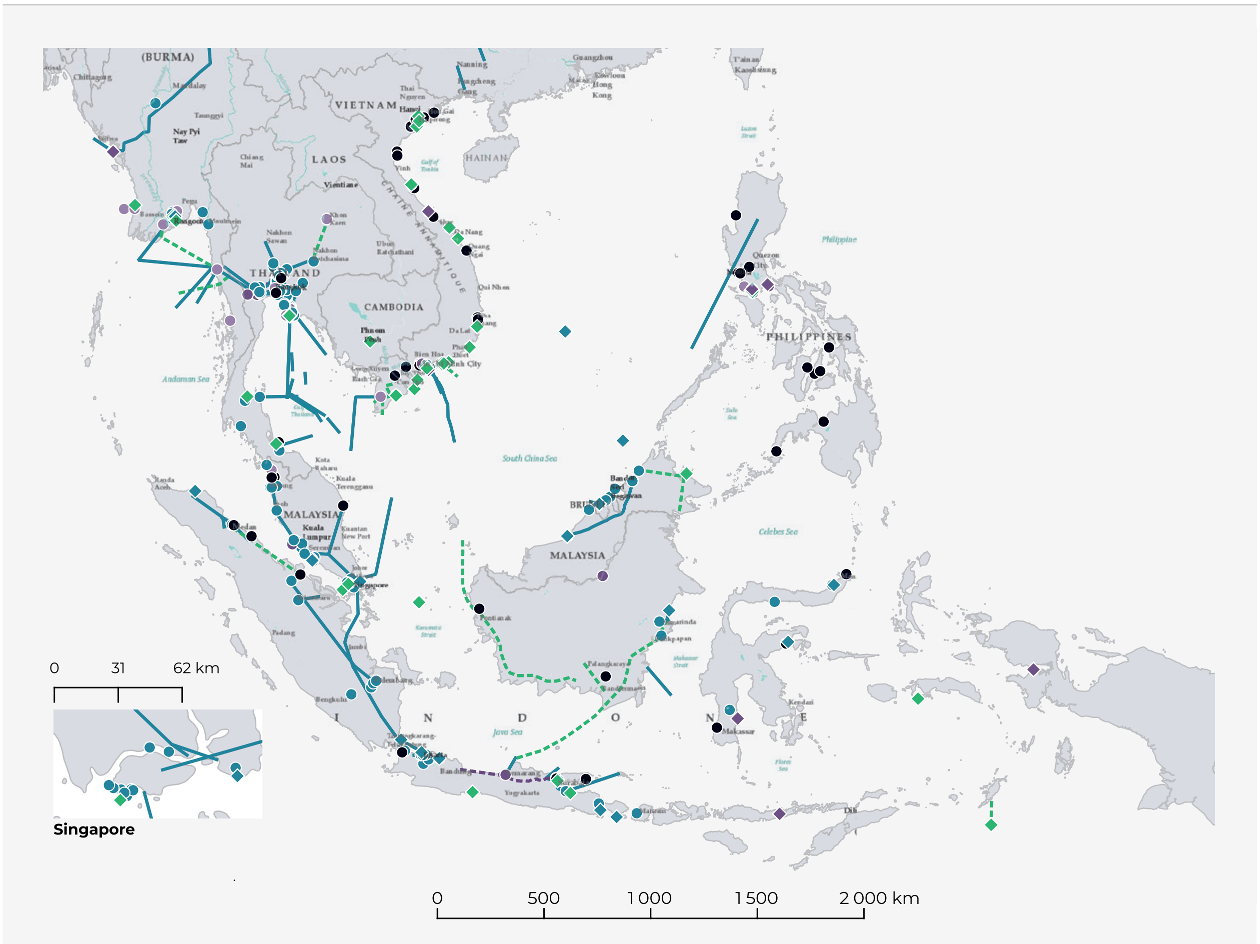
Large investments in fossil gas and LNG infrastructures risk being stranded and their future conversion into low-carbon infrastructure is associated with economic and technical uncertainties

Southeast Asia has significant gas reserves (3 600 billion cubic meters or 3 240 Mtoe). However, at current production rates, the region's largest producers – Malaysia, Indonesia and Thailand – would be able to extract at current levels only until 2040, 2037 and 2024 respectively (Energy Institute, 2023). Hence the significance of new projects to these countries, with at least 19 new gas fields (540 billion cubic meters or 486 Mtoe) having reached or being expected to reach final investment decisions between 2022 and 2025 (GEM, 2023). Despite those reserves, the region is forecast to become a net importer of gas by 2025 (IEA, 2022b).

LNG is expected to become the dominant supply source in the region due to its inherent flexibility in supplier choice (compared to the rigidity and

Overview of existing, planned and proposed fossil gas and LNG infrastructure in Southeast Asia

→ Fig. 17



LNG terminals: Construction, Operating, Proposed

Gas plants: Announced, Construction, Operating, Pre-Construction, Retired

Gas pipelines: Construction, Operating, Proposed

Green Network Asia (2023)

geographical constraints of gas pipelines) (see Figure 17). The Asia-Pacific region has already some of the largest regasification capacities under development (for an additional total capacity of 46.6 Mt per year), which would correspond to an 80% increase compared to capacities currently in operation (58.2 Mt per year) (IEA, 2023h). Over 70% of this capacity is expected to be built in Vietnam and the Philippines, two countries that have only recently started to import LNG (GEM, 2023).

While the development of additional LNG capacities is driven by energy security concerns, it represents a double-edged sword. Indeed, LNG supplies can be quickly diverted to higher bidders, as seen in the early months of Russia's war on Ukraine, leaving countries with less purchasing power short of supply. And overall, it risks increasing the region's exposure to volatile international gas prices. In addition, cost-competitive renewables threaten the economic and financial viability of all gas infrastructures (e.g. power plants, pipelines and LNG terminals) in the medium-term, as countries move towards net-zero emissions. Any gas infrastructure built after 2030 is therefore likely to result in carbon lock-in, stranded assets or become burdened with expensive energy supply that would put long-term economic development at risk (Kemfert et al., 2022). Although the asset lifetime of LNG terminals (25 to 40 years) is shorter than for pipelines (50 to 80 years), such infrastructure still risks diverting investment portfolios that could be used to expand renewable energy.

In order to resolve the tension between "fossil gas as a transition fuel" and "net-zero commitments", some countries, including Germany, hope to retrofit their fossil gas infrastructure to be able to gradually fuel economies with low-carbon hydrogen and its derivatives (such as ammonia). This transition pathway remains uncertain, however. It presents significant technical challenges, requires additional investments and carries a high risk of stranded assets and carbon lock-in (see Infobox 4).

Infrastructure development in Southeast Asia should be developed in a sustainable manner and support long-term growth for the region. Assessing investments in fossil fuel infrastructure should involve a comparison with alternative options: direct electrification fuelled by renewables, or PtX products may provide a more cost-effective and resilient development pathway, especially if the cost of renewable hydrogen becomes cost-competitive for the region in the early 2030s. Trade infrastructure needs to take into account this changing context, in particular when it comes to the future commercialisation of higher value-added PtX products (see Insight 8). Given such a development (for example, for the production of e-SAF, e-methanol or green fertilisers), the storage and transport infrastructure will probably be completely different from that for LNG.

A coordinated planning of energy, industry and trade infrastructures is key to deliver a resilient low-carbon hydrogen and PtX production backbone for Southeast Asia

Renewable hydrogen and PtX production span multiple sectors, necessitating improved coordination. In order to maximise investments, long-term industrial and commercial expansion plans must incorporate hydrogen and PtX considerations. Coordinated action is crucial, especially when considering trade in PtX products. Ports, central hubs for storage, transport and production should strategically align their expansion plans with hydrogen and PtX ambitions. This alignment will enhance infrastructure investment and unlock co-benefits, such as integrating low-carbon technologies into trade.

Simultaneously, ensuring that green electrons are available for direct electrification strategies and renewable hydrogen production is essential for the development of future low-carbon industrial centres. Coordinated planning and investment in energy and industrial infrastructure will create opportunities for new industrial and commercial zones, fostering socio-economic benefits like long-term job creation and economic diversification within local communities.

In addition, as shown in Figure 3, the production of various PtX products will rely on sustainable carbon sources. The biomass sector holds promise as a potential source of biogenic carbon for industry. During the transition period, carbon emissions from cement processes can also be considered, especially while technologies such as Direct Air Capture (DAC) gain competitiveness. Currently, the cost of DAC ranges from USD 125 to 335 per tCO_2 and is projected to decrease to around USD 100 per tCO_2 by 2030 in locations with high renewable energy potential (IEA, 2022c). The availability and location of carbon sources will significantly affect the prioritisation of PtX production pathways and infrastructure requirements, including CO_2 transport to regions with high renewable hydrogen potential.

Infobox 4: Transitioning infrastructure from LNG to liquid hydrogen and low-carbon ammonia

Transitioning from an LNG-based infrastructure to one adapted to liquid hydrogen and low-carbon ammonia is currently subject to several technical and economic uncertainties, given the limited experience gained so far. The technical feasibility of this conversion will depend on the type of molecule.

For liquid hydrogen, most parts of the LNG terminal will need to be replaced and only those that have been built from the outset with hydrogen-compatible materials will be able to be reused. Using hydrogen-compatible materials for the LNG terminal would allow about 50% of the CAPEX investment to be reused but it will also increase the initial cost of the terminal. Overall, the conversion of LNG infrastructure is feasible but technically challenging, given the low boiling point of the molecule. In addition, there is currently a lack of experience in implementing such projects on a large scale, which adds further uncertainty to their feasibility.

In the case of low-carbon ammonia, conversion is technically feasible and less challenging, in view of the physical properties of ammonia. However, the toxicity of this molecule must be taken into account as it will increase the investment cost of LNG for its conversion. If compatible materials for LNG and ammonia are considered in the construction of terminals, the initial CAPEX could increase by 11% to 20%, including its future conversion. The use of ammonia will have an important impact on infrastructure investments as cracking units will increase their cost while the direct use of ammonia will make it more cost competitive (Riemer et al., 2022).

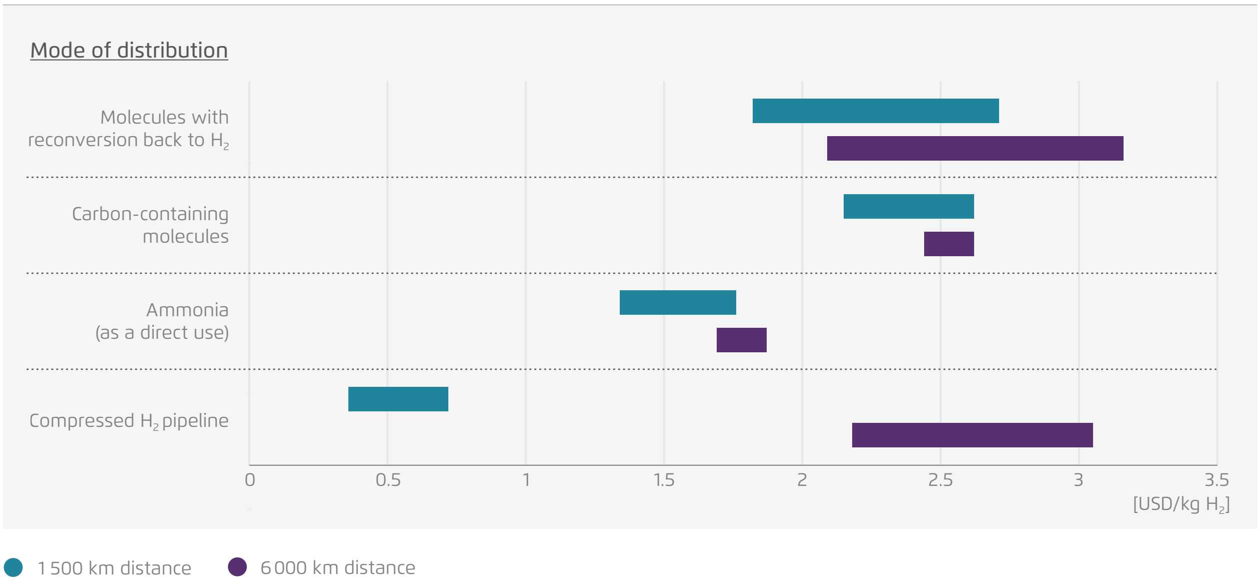
8. Hydrogen trade will be regional but Southeast Asian countries could capitalise on their proximity to key demand centres in East Asia for the export of PtX products

The pace of renewable energy deployment and the growing demand for energy in the region put countries in Southeast Asia at a disadvantage compared to other potential hydrogen-exporting regions. However, trading PtX products with neighbours such as Japan or South Korea may still be attractive for some countries in Southeast Asia since they will have a competitive advantage in terms of transport costs compared to distant exporting regions such as Latin America and the Middle East. Australia is positioning itself as a potentially important hydrogen supplier to East Asian countries and this may affect the competitiveness of Southeast Asian countries to enter the trade market but there may still be some trade opportunities for PtX products. Another potential market in the region may be China but the country does not have a clear position as an importer or exporter, given its high hydrogen potential but also high potential domestic demand. There may be some trade opportunities with China in the future, depending on how hydrogen and PtX develop in the region. In view of this, strategic partnerships will be a key component to position the region on the future global PtX market and to benefit from the socio-economic advantages that come with trading renewable hydrogen derivatives.

Exporting the hydrogen molecule is technically and economically less feasible than exporting higher-value PtX products

The technical and economic feasibility of trading hydrogen and its derivatives depends on the transport distance. For the hydrogen molecule, compressed hydrogen pipelines are the most cost-effective option for distances less than 1 500 km but this changes dramatically for distances over 6 000 km, which is roughly the distance from Southeast Asia to the East Asian market (Figure 18). In that case, using pipelines results in transport costs four to six times higher. The opposite is true for PtX products such

Cost of hydrogen transport for various distances and carriers, 1 500 km and 6 000 km → Fig. 18



Oeko-Institut, Agora Energiewende and Agora Industry (2023)

as green ammonia or carbon-containing molecules such as e-methanol which become more competitive at longer distances (6 000 km), with transport costs starting at around USD 1.7 per kg of H_2 for green ammonia and USD 2.4 per kg of H_2 for carbon-containing molecules.

PtX products, such as green ammonia, are more competitive when they are used directly, for example as a feedstock in the chemical sector. Reconverting PtX products back into hydrogen for power generation, for example, would be significantly more expensive, whatever the transport distance, with costs up to 50% higher than the direct use of the PtX products (for the case of green ammonia). Therefore, Southeast Asian countries should focus on developing PtX products for direct use in order to facilitate their attractiveness on other global markets, particularly in East Asia. (Agora Energiewende et al., 2023).

Southeast Asia is close to two of the largest potential hydrogen importers, Japan and South Korea, making the potential hydrogen trade very attractive. However, given geographic constraints (the archipelagic nature of both importing and exporting countries) and limited existing infrastructure (pipeline interconnections), hydrogen and its derivatives will probably need to be shipped. PtX products (such as green ammonia, e-methanol, synthetic fuels and others) are technically easier to transport via ship. Higher value-added products, such as synthetic fuels and green fertilisers, could bring even greater socio-economic benefits to the region by stimulating the development of a low-carbon industry and the creation of new jobs and dedicated industrial hubs (see Insight 4). Therefore, Southeast Asian countries should focus their trade strategies on hydrogen derivatives and value-added products rather than exporting molecular hydrogen.

The cost of renewables in Southeast Asia puts the region at a disadvantage compared to other potential PtX exporting regions

When taking into account transport costs (pipeline or shipping), the cost of renewable hydrogen exported from Southeast Asia to global markets is expected to be higher than in other potential export regions. For instance, Indonesia, Thailand and Vietnam will reach LCOH of between USD 4 and 7 per kg H_2 by 2030, compared to other countries such as Brazil, where hydrogen costs could reach around USD 2.7 per kg H_2 by the same time. As a consequence of these high LCOH levels in the region, traded prices for PtX products will not be competitive with other regions. As shown in Table 2, other countries such as Australia, Brazil and South Africa can achieve lower costs for

Comparison of costs of producing and delivering various PtX products from selected countries to Japan in 2030 → Table 2

Country	Cost PtX product delivered to Japan (USD per tonne)			
	Green ammonia	Synthetic methane	E-methanol	FT* (e-fuels)
Australia	600	1 200	720	1 700
Brazil	665	1 930	760	1 660
Thailand	730	2 160	900	2 090
South Africa	790	2 290	920	2 100
Vietnam	880	2 500	1 000	2 250
Indonesia	1 200	3 300	1 360	3 200

* FT: Fischer Tropsch. Note: Calculations are done using alkaline electrolyser, Wind-PV hybrid as renewable electricity source, year 2030 using low-cost reduction pathway, Direct Air capture as carbon source, water desalination as water source and shipping as transport mode.

Oeko-Institut, Agora Energiewende and Agora Industry (2023)

exporting hydrogen derivatives to Japan than Indonesia, Thailand and Vietnam.

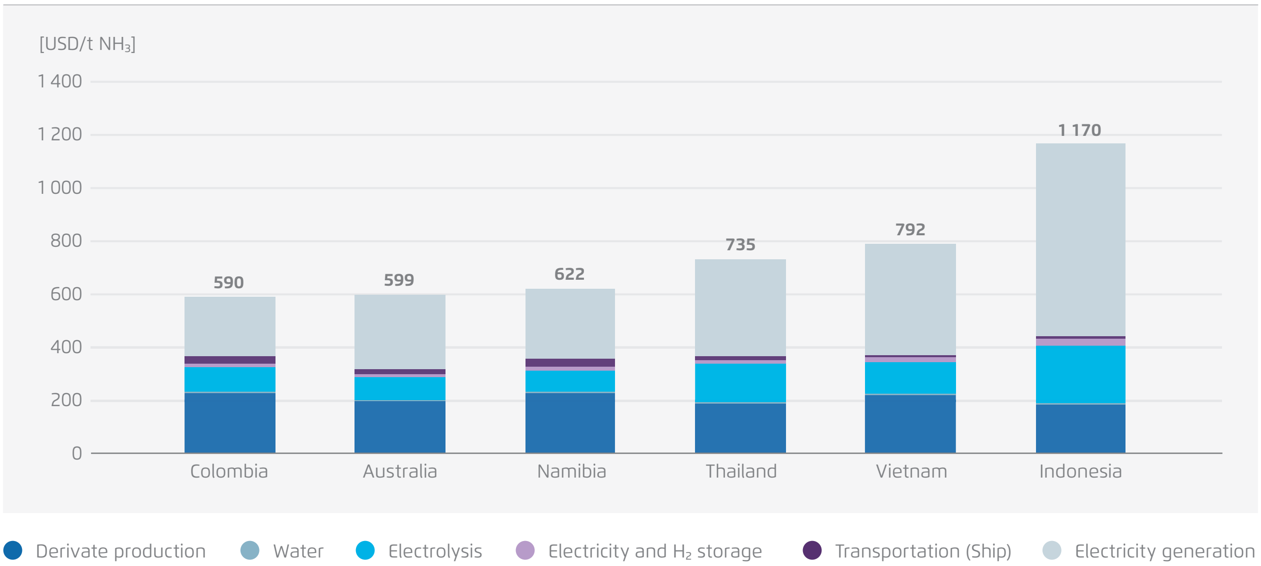
Consequently, local industries in Southeast Asia will initially drive demand for PtX production in the region. In addition, climate-trade instruments such as the EU's CBAM can serve to create a more attractive green market globally (initially starting with the EU). Therefore, the use of low-carbon products in the manufacture of industrial goods will ensure the competitiveness of the sector in the face of global green trends.

However, Southeast Asian countries will have a competitive advantage in terms of transport to the East Asian market due to their proximity to Japan and Korea. Figure 19 shows the cost breakdown for exporting green ammonia from different countries to Japan. While transport costs from Southeast Asia to Japan are indeed significantly lower than those from other regions (60% cheaper than from Colombia and Namibia), this competitive advantage is offset by higher costs associated with electricity generation (60% higher for Indonesia, 50% higher for Vietnam and 40% higher for Thailand compared to Colombia and Australia). Supporting the development of renewable energy will, therefore, be key to improving the competitiveness of Southeast Asian countries in the global trade of PtX products, while leveraging existing advantages such as distance to potential markets and industrial expertise to enable countries in the region to enter the global PtX trade.

International cooperation can attract investment to the region and help negotiate global standards for hydrogen and PtX

Before embarking on the journey to trade PtX products, Southeast Asian countries will need to evaluate some aspects, such as certification schemes and the development of trading infrastructure. Southeast Asian countries could use international cooperation as a tool to attract investment. Building on existing ports and industrial hubs (see Insight 7), Southeast Asian countries will need to negotiate mutually-beneficial strategic partnerships and trade agreements with potential buyers of PtX products. Integrating PtX products into existing trade agreements could be a first step in the right direction but the trade of hydrogen derivatives

Cost comparison of exporting ammonia from selected countries to Japan in 2030 → Fig. 19



Oeko-Institut, Agora Energiewende and Agora Industry (2023)

will need a comprehensive economic, environmental, social and governance (EESG) framework to mitigate negative local impacts (International PtX Hub, 2022).

Certification of hydrogen and its derivatives has become a priority for the many countries around the world which have taken the initiative to develop their own standards (Breakthrough Agenda, 2023). Nevertheless, standards from different regions are not always compatible and regulations imposed in some jurisdictions are not always fully applicable in others. Therefore, regional cooperation in Southeast Asia could be a good driver for developing and negotiating standards and certification mechanisms for hydrogen and PtX products that take into account the socio-economic specificities of the region. Using existing platforms such as ASEAN, countries can negotiate as a bloc with potential importing countries on the terms of trade for PtX products and agree on common certification schemes to facilitate the trade of such products. Regional cooperation can also help to mitigate the political influence of other international interests, in particular when it comes to promoting technologies that may trap the region on a development path that is not aligned with its long-term socio-economic development and climate goals (such as ammonia co-firing in coal-fired power plants or new investments in Blast Furnace-Basic Oxygen Furnaces).

9. Clear and resilient long-term policy frameworks will attract investors and increase local value creation

Clear and resilient long-term hydrogen strategies are required at national and regional levels in Southeast Asia

In order to attract private and international investments, countries must set clear policy goals and specific hydrogen and PtX targets in order to send positive signals about the region's medium and long-term pathway while considering key sustainability goals. As the Southeast Asian hydrogen market will be predominantly regional, integrated trading infrastructures and cross-sector applications are essential. In order for these goals to be achieved and for the necessary investments to be leveraged, Southeast Asian countries should work together to develop aligned hydrogen strategies and policies. ASEAN could play a leading role in coordinating and promoting regional hydrogen partnerships, in line with its vision of regional economic integration and adherence to multilateral trade rules (ASEAN, 2008). The ASEAN Centre for Energy (ACE) has signalled an initial interest in establishing a regional hydrogen economy and is advocating more ambitious targets to enhance energy security and achieve carbon neutrality goals (ACE, 2023). However, there are certain recommendations about subsidising fossil-fuel based hydrogen and blending it with fossil gas[11] or co-firing it in coal-fired power plants: they carry the risk of stranded assets, lock-in effects and misallocation of public funds. Instead, the region should focus on 'no-regret' applications for renewable hydrogen and promote the expansion of renewable energy to decarbonise various sectors where electrification is the most efficient solution.

At the national level, Southeast Asian countries can promote hydrogen through clear policy and regulatory frameworks, tailored to the needs of their economies. Needs assessment should revolve around future projected domestic demand, targeted renewable energy supply and import/export opportunities. By focusing on these objectives, hydrogen policies and strategies will stimulate investment in 'no-regret' infrastructure. They will also bring socio-economic benefits such as a potential trade market and job creation. Clear policies will also pave the way for future public and private partnerships with international partners, encouraging the exchange of technology, expertise and best practice. Within the region, Singapore was the first to publish its official *National Hydrogen Strategy* in October 2022, targeting hydrogen demand in industry, shipping, aviation and primarily focusing on hydrogen imports, given its limited land availability (Ministry of Trade and Industry of Singapore, 2022). In the long-term, Singapore is aiming to develop import and storage facilities and use its role as a regional LNG hub and its interconnectivity with international shipping routes to become a future hydrogen trade hub. In December 2023, Indonesia's Ministry of Energy followed Singapore with its *National Hydrogen Strategy* which is oriented at developing domestic production of low-carbon and green hydrogen with the long-term aim of exporting hydrogen and its derivates on the global market (SP Global, 2024). Indonesia's strategy aims at "increasing capacity and investment" in the hydrogen sector with sectoral hydrogen targets in the fertiliser industry (Green Hydrogen Association, 2023). Similarly, Malaysia has developed a *National Hydrogen Economy and Technology Roadmap* with the objective of becoming a major renewable hydrogen exporter, building on the country's existing fossil-based hydrogen production infrastructure, as well as developing research on fuel-cell technologies (MOSTI, 2023). In the same vein, Vietnam recently published its national hydrogen strategy with a goal to focus on domestic use and exports (Collins, 2024).

Figure 20 summarises the state of hydrogen readainess in Southeast Asia, illustrating the disparities between certain countries in terms of regulatory and economic advances but also in terms of expected hydrogen import/export orientation available for the trade of hydrogen. Although they have not published a national hydrogen strategy, Thailand and the Philippines have shown interest in developing a domestic

11 A 20% renewable hydrogen blend by volume would raise the price of wholesale gas by around 33% but reduce emissions only by 7% (Agora Energiewende et al., 2021)

Status on the publication of a national hydrogen strategy or roadmap in Southeast Asia → Fig. 20

Ministry of Trade and Industry of Singapore (2022), MEMRI (2023), MOSTI (2023), Parkes (2023), PIA (2023), Socialist Republic of Vietnam (2024)

hydrogen economy with the first announced green hydrogen pilot projects (PIA, 2023); (Parkes, 2023). The countries that have planned to export hydrogen, whether via government initiative or not, are Vietnam, Malaysia, and Indonesia. Only Malaysia and Vietnam have disclosed their potential point of export departure. Indonesia's hydrogen exploration is at scattered locations with not yet a fixed point of export departure. Singapore is ramping up to become the region's hydrogen net importer through expansion of the Port of Singapore.

Attracting investment for renewable energy and hydrogen development in Southeast Asia will require innovative blended finance, leveraged through the development of pilot projects

To speed up the development of renewable energy, the power grid as well as production capacity and infrastructure for hydrogen in the region, the introduction of sound financing instruments is a crucial priority. As many countries in the region do not have the necessary public funding to subsidise hydrogen production or demand on a large scale, enabling demonstration and pilot projects could be the missing link to attract market players interested in developing hydrogen and PtX products in the region.

In the case of hydrogen projects in Southeast Asia, uncertainties and risks are currently high as the technologies and commercialisation of hydrogen still need to be developed. Thus, the blending of various financing instruments and support from international financial institutions (IFIs) can help to reduce risks (see Infobox 5). In fact, financing instruments offered by development banks and finance institutions at concessional rates aim to reduce the associated risks of early-movers projects (OECD, 2023). In Southeast Asia, various development finance institutions such as the Asian Development Bank (ADB), the World Bank or the Asian Infrastructure Investment Bank (AIIB) have committed to align their operations with the climate goals of the Paris Agreement and are actively supporting renewable hydrogen projects (ADB, 2023a). Collaboration with such institutions to access the initial funding and expertise needed to finance demonstration and pilot projects could reduce potential project risks in the early stages of market uptake. This in turn can mobilise further private capital and cost efficiencies through the provision of missing risk assessments on the bankability

Infobox 5: Different financing mechanisms for hydrogen projects in different market stages

The development of renewable hydrogen and PtX projects will require the unlocking of appropriate financing instruments for new technological developments, such as large-scale electrolysers or transport and storage facilities for hydrogen and its derivatives. Both public and private actors should be involved in the early stages of project development because the uncertainties are the highest during this period. Therefore, the financing of first hydrogen projects is usually based on a flexible mix of equity and debt, (see Table 3). Venture capital, a form of equity financing which is usually opted for in the case of immature and unproven technologies, can help kickstart renewable hydrogen projects, overcome technological barriers and increase certainty for future projects by producing the necessary data to create risk profiles of projects in the region. Once uncertainties have decreased with the maturation of technologies, ordinary equity becomes the more common form of equity financing. Debt financing, or the buying of loans together with interest, exposes investors to lower risks but is usually applied to technologically mature projects. One form of debt financing is corporate finance where repayments of the loans are backed by the borrower's balance sheet, requiring a sound underlying business activity. In the case of hydrogen, this type of financing concerns proven technologies but commercially unproven business models, for example: off-taker uncertainties or high starting costs of hydrogen fuel which are expected to decrease rapidly. Another form of debt financing is project finance where loan repayments are based on the project's future cash flow, demanding a high level of certainty about the project's viability. Use of this type of financing usually means that the technology is mature and commercially viable. For renewable hydrogen, project finance can help to finance projects with limited supporting infrastructure, long asset replacement periods, high capital costs or a slow scaleup of renewable electricity (AIIB, 2023).

of projects in the region. Furthermore, countries in Southeast Asia can seek the support of international bodies to install frameworks on standards, trade and sales/purchase terms for renewable hydrogen (Green Hydrogen Association, 2022). For example, Vietnam has seen a few large-scale projects planned for the decarbonisation of national hydrogen usage as well as for export to neighbouring countries such as Singapore, South Korea and Japan.

Comprehensive R&D and education programmes are required to accompany the value-chain transformations in the region

Hydrogen and PtX technologies are still, in some cases, at an early stage of their development and will require further investments and research, especially into large-scale projects and facilities to store, transport and transform the molecules. The technology readiness for recent technologies, such as bunkering of some PtX products or certain electrolyser types, is still in development and must be tested on a large scale (IEA, 2023g). Additionally, the chemical attributes of hydrogen can make it difficult to handle, needing additional expertise to develop adapted production facilities. Multi-disciplinary and coordinated research and development (R&D) efforts among the different countries in Southeast Asia could contribute to the development of local technology, while building professional and technical capacity in the region. In addition, R&D can serve as a pathway to identify innovative solutions and applications of hydrogen and PtX products for the regional context. This R&D is crucial to avoid the inefficient allocation of limited hydrogen resources, stranded assets and disjointed energy systems. Therefore, R&D on the local applications of renewable hydrogen as well as capacity building are key to ensuring the socio-economic viability of hydrogen projects in Southeast Asian countries.

Additionally, the broader transformation of global value chains due to decarbonisation efforts in many parts of the world will profoundly change the region's

Summary of financing instruments for emerging technologies → Table 3

Category	Product	Source of returns	Required Conditions		
			Certain project cashflow	Strong corporate balance sheet	Sound underlying business activity
Equity	Venture capital	Dividends and equity appreciation, through uncertain business activities with high upside return	No	No	No
	Ordinary equity	Dividends and equity appreciation, through well understood business activities	No	No	Yes
Debt	Corporate finance	Repayment backed by the borrower's balance	No	Yes	Yes
	Project finance	Repayment, through the project's future cash flow	Yes	No	Yes

AIIB (2023)

competitivity in certain sectors, such as the export of CO_2-intensive, low added-value goods. According to an analysis by the Asian Development Bank, ASEAN's added-value contribution to its exported products is lower than the added-value of its imported products (ADB, 2023b). In other words, the region's economy does not benefit as much from the revenues from its exported products compared to the costs of inputs coming from imports, such as petroleum, coal and oil products. As a result, the region's exported goods, on average, only account for 30% of added value within the region. Given that, aside from services, the region's main exported goods are electronic manufacturing, oil products, textiles and processed foods, this high level of foreign added-value to these products is a lost opportunity to increase value-creation in the region. Therefore, it is in the interests of Southeast Asian countries to transform their economic export sectors towards the production of higher added-value goods. In order to compete on future international markets, countries could support the transition to producing green products based on available local resources (such as green fertilisers). The green products with higher value added will thus create numerous jobs as well as attract foreign direct investments.

Depending on the trade balance and energy endowment of each country in Southeast Asia, the energy transition will have different effects on a country's output. For example, long transportation for goods by ship or planes adds extra emissions to the traded goods, and they might get penalised in the future by importing regions such as the EU. Countries which are highly dependent on trade in fossil fuels such as Brunei Darussalam, Indonesia, Thailand or Malaysia will necessarily need to balance the losses in income due to the decrease in trade and consumption of their national reserves. However, the transition to cleaner technologies and inputs represents a tremendous opportunity for the region's countries to reduce their dependence on fossil-fuel imports, on the one hand, and turn towards a more sustainable, added-value and skilled-labour economy. This does not mean that the transformation will happen automatically, nor that it will be without any costs. Indeed, the transformation requires adaptation of an education system based on a market for low-skilled workers towards training a generation of medium- to highly-skilled people who can compete in a growing digitalised and decarbonised world where the requirements from workers will drastically change. Adherence to the sustainable development goals as well as stricter EESG frameworks and standards for the production of hydrogen could improve not only social and local benefits but also competitiveness.

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