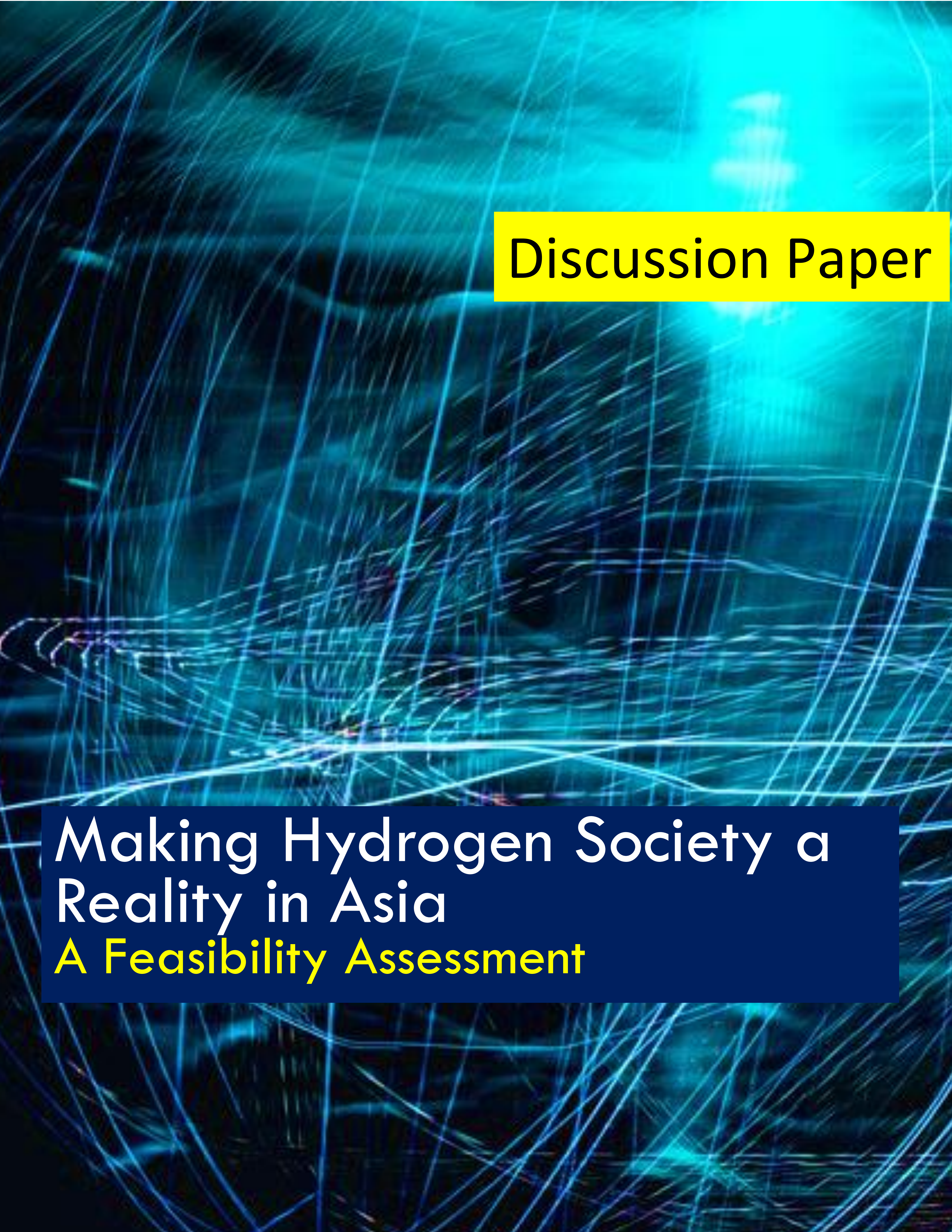

Discussion Paper

Making Hydrogen Society a Reality in Asia

A Feasibility Assessment

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Making Hydrogen Society a Reality in Asia: A Feasibility Assessment

Abstract

Hydrogen is a potentially transformative multi-functional fuel that could help many countries achieve ambitious decarbonisation targets. High concentrations of heavy industries and rising transport emissions make hydrogen's potential particularly enticing in Asia. However, hydrogen's widespread deployment requires assessing multiple dimensions of its feasibility. This paper analyses the environmental, economic and geopolitical feasibility of making hydrogen mainstream in Asia. That analysis suggests that relevant policies in Asia need to prioritise green hydrogen over blue and grey hydrogen; create financial incentives that facilitate transitions from grey and blue to green hydrogen; and commit to infrastructure that eases the import and export of fuels, raw materials and related technologies. A regional cooperative framework that is led by Japan and places a mutually beneficial co-innovation process at its core could also help make the hydrogen economy a reality in Asia.

Introduction

Hydrogen is a potential game-changer for energy production and consumption. A growing body of work has underscored this potential in power, transportation and other sectors (IEA, 2021). Hydrogen's promise is particularly sizable in Asia. The region's concentration of heavy industries and fast-rising transport emissions could make interventions promoting hydrogen critical components of climate and energy policies in Asia. However, hydrogen's transformative impacts are far from assured. The availability, accessibility and affordability of cost-effective technologies to develop, store, transport and use hydrogen will influence whether the scale and depth of its impacts in Asia.

This paper assesses the feasibility of hydrogen contributing to a clean energy transition in Asia. While the paper discusses on grey, blue and green hydrogen, focus has been given to the green hydrogen. Analysis suggests that relevant policies in Asia need to prioritise green hydrogen over blue and grey hydrogen; create financial incentives that facilitate transitions from grey and blue to green hydrogen; and commit to infrastructure that eases the import and exports of the fuel, raw materials and related technologies. Further a regional cooperative framework that is led by Japan and places a mutually beneficial co-innovation process at its core could also help make the hydrogen economy a reality in Asia.

The remainder of the paper is divided into six sections. The next section provides a brief overview of Hydrogen potential and barriers to realising it. The third section summarises several hydrogen promotional strategies in Asia. The fourth section examines multiple dimensions of exploiting hydrogen's potential in Asia. The fifth section outline why and how regional cooperation could capitalize on that potential. The final section concludes with a suggestion for strengthening this research in the future.

Hydrogen's Potential and Related Barriers

Many analysts believe hydrogen—in combination with decarbonised electricity—will contribute greatly to net-zero emissions pathways (IPCC 2018). Its role is envisaged to be particularly pivotal in achieving net-zero emissions in "hard-to-electrify" sectors, such as steel-making, high-temperature heating and long-distance transport (IEA, 2019). It can also provide load balancing for intermittent renewable energy, such as wind power and solar PV. Electrolysis could absorb excess supplies and, when there is little wind or sun, hydrogen could be burned in gas turbines to ensure electricity demand is met. Thus, hydrogen is essential to achieving net-zero emissions [IEA, 2019; Hydrogen Council , 2021].

Studies reflect the above scenario. The IEA, for instance, estimates the global carbon-free hydrogen demand of 520 million tonnes (Mt) in 2070 when global carbon neutrality is achieved under the Sustainable Development Scenario (2050 for advanced economies, 2060 for China and 2070 for remaining all the countries) (IEA, 2020). Numbers like these are pushing many governments and private companies to invest in hydrogen supply chains. For example, the Japanese government and many Japanese companies are advancing the development of ammonia/hydrogen co-firing technologies. Since these technologies can be added to existing power plants, they can maintain the existing hydrocarbon-based energy system infrastructure. Further, because of their compatibility with existing thermal power assets, ammonia/hydrogen co-firing technologies could be a "realistic" option for decarbonising the coal- and gas-dominant power sector in Asia. This expectation is related to a huge export market. Japan's Ministry of Economy, Trade and Industry (METI) estimates that a JPY 500 billion (USD 4.6 bn) market would emerge, if 1% of coal-fired power plants introduce co-firing technology in Southeast Asia [METI, 2021].

Although there is considerable potential for hydrogen, it is far from being realised at present. The current global annual demand for hydrogen is around 70 Mt per year (around 2,750 TWh energy equivalent), out of which 39 Mt is for the refining sector and 31 Mt is for ammonia production (mainly used in the production of nitrogen fertilizers) (IEA, 2019). This hydrogen is almost entirely supplied from fossil fuels. Thus, it is critically important for policymakers to simultaneously create and expand demand for and supply of carbon-free hydrogen.

The widespread deployment of hydrogen confronts several barriers. Chief among these are costs. The cost of hydrogen needs to be drastically reduced across the hydrogen supply chain, i.e. production, transport, storage and usage (IEA, 2019). In addition, to contribute to decarbonisation, hydrogen needs to be produced with carbon capture and storage (CCS) or electrolysers, which add both costs and uncertainty to the hydrogen equation.

Another challenge involves hydrogen's environmental sustainability. One critical question is to what extent are 'blue' hydrogen and 'blue' ammonia actually 'green'. In addition, since green hydrogen is more expensive than blue hydrogen, the initial production of low-carbon hydrogen is likely to be mainly blue. However, life-cycle assessments indicate that blue hydrogen from methane reformulation with CCS and blue ammonia from lignite reformulation with CCS are 'not green' (Howarth & Jacobson, 2021). Therefore, 'blue' hydrogen could lead to the development of supply chains but would need to be replaced by green hydrogen. Government policy ensuring the avoidance of lock-in of blue hydrogen is required to smooth the transition from blue to green hydrogen.

This leads to another set of barriers for hydrogen, namely, its relationship with renewables. The generation cost of green hydrogen- and ammonia-fired power plants are inevitably higher than that of renewable electricity since green hydrogen and ammonia are produced from electrolysis powered by renewable electricity. This poses a significant challenge for hydrogen- and ammonia-fired power plants in a carbon-neutral world.

Hydrogen Strategies in Asia

Well-designed hydrogen strategies could foreseeably overcome these challenges. As of this writing, two countries in the Global East[1] have developed national strategies or roadmaps for hydrogen, which include Japan in 2017, the Republic of Korea (RoK) in 2019 and some countries including India are proposing long term development plans to expand hydrogen sector. Due to the limited domestic capacity of hydrogen production, Japan and South Korea's strategies are seeking to facilitate hydrogen imports and develop an international supply chain. In 2021, India announced the launch of the National Hydrogen Mission to make India a global hub for green hydrogen production and content—though the details of that strategy are not yet public. While China has made substantial progresson the renewable and clean technology front, on the the hydrogen front the country's progress is yet to match that of Japan or RoK. Since these strategies could have significant implications for Asia[2], the next section turns to their core provisions.

Hydrogen Development Plans in Japan

Japan intends to expand the use of its advanced technologies domestically and overseas as part of an effort to create new infrastructure for a hydrogen value chain (METI, 2017). These plans are consistent with aspirations to lead the world in creating a 'hydrogen-based society'. However, achieving this goal is neither easy nor guaranteed. Rather it will require adapting existing technologies to diverse contexts as well as generating a higher level of interdependence among countries that would become part of the hydrogen value chain.

Japan formulated its Hydrogen Basic Strategy in 2017 with the stated aim of realising a 'hydrogen society'. Cost is seen as the biggest obstacle to achieving this goal. The Hydrogen Basic Strategy considered the import of carbon-free hydrogen energy as a promising to reduce these costs. Such carbon-free hydrogen can be produced from either inexpensive fossil fuel combined with CCS or inexpensive renewable energy sources overseas. Toward this end, the Strategy aims at establishing international supply chains that cover hydrogen production, storage, transportation and use. In line with this 2017 Hydrogen Basic Strategy, several demonstration projects for the production and importation of carbon-free hydrogen have been launched--although the ongoing revisions to the Hydrogen Strategy also promote domestic production.

Table 1: Hydrogen Imports to Japan

Country	Company	Type	Category
Brunei	Chiyoda Corp., Mitsubishi Corp., etc	Hydrogen (MCH)	Blue
Australia	Kawasaki Heavy Industries, JPower, etc	Hydrogen	Blue
Malaysia	ENEOS	Hydrogen (MCH)	Blue/Green
Saudi Arabia	ENEOS	Hydrogen/ Ammonia	Blue
Indonesia	JOGMEC, Mitsubishi Corp., etc.	Ammonia	Blue

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[1] Global East: Often used to denote the countries in the Pacific side of Asia

[2] The discussion in this paper related to Asia largely surround countries including Japan, Republic of Korea, India and China.

UAE	INPEX, JERA	Ammonia	Blue
Australia	Marubeni Corp., IHI, etc.	Ammonia	Green
Australia	JERA	Ammonia	Blue
Russia	Itochu Corp., Toyo Engineering Corp. etc.	Ammonia	Blue
Source: Compiled by authors			

One of the main features of Japan's hydrogen strategy is prioritising the use of hydrogen and ammonia as fuels for power generation. The potential of ammonia was initially examined as a hydrogen carrier since ammonia is easier and cheaper to transport. But ammonia can be directly used as a fuel. In particular, ammonia co-firing and hydrogen co-firing technologies can decarbonise thermal power plants. The existing coal-fired and natural gas-fired power plants can significantly reduce CO2 emissions by being retrofitted with ammonia co-firing and hydrogen co-firing technologies, respectively, if carbon-free ammonia and hydrogen are used. Ammonia and hydrogen content will increase to 100% over time, thereby decarbonising thermal power generation. These technologies are also attractive to other Asian countries with large thermal power capacities. Therefore, these technologies could not only decarbonise domestic power but fuel Japan's export strategy.

The Green Growth Strategy (Government of Japan, 2021) provides roadmaps for ammonia and hydrogen use for the power sector. According to the plans by 2030, ammonia co-firing (20%) technology for coal power plants will be established. According to these roadmaps, international supply chains for hydrogen/ammonia will also be created. Around 2030 and afterward, ammonia co-firing technologies will be exported to Southeast Asia and other regions. Japan also intends to establish large scale ammonia- and hydrogen-firing technologies by 2050.

Infrastructure that includes production facilities, transportation networks and physical security is essential to creating a hydrogen society in Asia. Japan's interest in a hydrogen society in Asia, therefore, requires involving other countries that contribute to and benefit from the industry. The Japanese government's Green Growth Strategy (Government of Japan, 2021) provides that the country alone can produce 3 million tons of hydrogen in 2030, rising to about 20 million tons in 2050 (MoEJ, 2021); these projections require an active domestic hydrogen industry without imports (Mukano, 2021). However, there is a need for greater interdependence among countries in the Asian region to ensure adequate supply for the energy market.

South Korea's approaches towards the development of Hydrogen

In October 2021, the Korean government released the '*Hydrogen Economy Performance and Vision of a Hydrogen Leading Nation*' (Government of the Republic of Korea, 2021) as a plan to boost domestic hydrogen consumption. The plan projects consumption to grow tenfold to 3.9 million tons by 2030 and 27 million tons by 2050 from an estimated 220,000 tons in 2021. To reach these levels, the government aims to move from the current 70 hydrogen charging stations to over 2,000 by 2050. The Korean government will provide considerable support to hydrogen-related companies and their overseas hydrogen projects, including debt payment guarantees and tax deductions. The country also envisions that hydrogen will drive economic growth worth KRW43 trillion (USD43 billion) and contribute 420,000 jobs by 2040--equivalent to 75% of the automobile industry workforce (Ministry of Trade, Industry and Energy, 2020).

Korea's Hydrogen Strategy reports point to several achievements. Since 2013, the country has developed a reputation for mass-producing hydrogen fuel cell electric vehicles. The country also has experienced success with fuel cells. The release of commercial cars in 2018 with the longest driving range is held up as a symbol of Korea's success.

India's Hydrogen Development Plans

The Indian government has a long history of supporting work on hydrogen, initiating research on the fuel in 1976 (Sastri, 1989). Today, India is among a few nations in Asia with a national hydrogen plan. The development of hydrogen is also a key part of the Ministry of New and Renewable Energy, a dedicated ministry for the development of non-conventional energy sources. Government agencies have been planning for hydrogen and, in early 2021 the government of India allocated a budget for hydrogen.

The National Hydrogen Mission, which is currently under development will plan for both short term (about 4 to 10 years) and long term (beyond 10 years), is the latest sign of India's commitment to hydrogen. The National Hydrogen Mission has five objectives: (1) prioritising and developing green hydrogen, (2) synergising with the development of renewables as it provides one of the remarkable storage options, (3) meeting the future energy demand of the industry with hydrogen supplies, (4) reducing dependency on fossil fuels, and (5) meeting fuel demand in the transportation sector. The mission also aims to transform India into a global hub for the manufacturing of hydrogen and fuel cell technologies (MNRE, 2021).

Above and beyond the National Hydrogen Mission, the government is also aiming to encourage demand for hydrogen in specific industry sectors such as fertilizers, steel and refineries. The government of India has been encouraging research and development activities of different aspects of hydrogen that include production, consumption and storage as well as fuel cell development. Several leading technical and scientific institutions (MNRE, 2020) as well as companies have been undertaking intensive research and development (R&D) on hydrogen.

Development of Hydrogen in China

Similar to the other countries discussed in this paper, China is also working on hydrogen. In June 2021, the China Hydrogen Alliance published a white paper on 'Hydrogen Energy and Fuel Cell Industry in China 2020'. The White Paper estimated that demand for Hydrogen will increase from 33.42 to 130 Mt by 2060. Reaching this goal could help China achieve its carbon neutrality targets. The White Paper also states that the consumption of hydrogen in 2060 would account for more than 20% of domestic primary energy consumption and that green hydrogen from renewables would reach 80% of the total. To reach this target, the country needs to secure electrolysers of 500 GW capacity by 2060, which can help bring down 1.6 billion tonnes of emissions per year. Combined with CCUS, this could also contribute to reducing another 0.4 billion tonnes of emission per year. In addition, the China Hydrogen Energy Alliance suggests that there are other benefits to hydrogen: the output value of the hydrogen energy industry in China could reach CNY 1 trillion by 2025, and CNY 12 trillion by 2050.

Hydrogen would further complement China's increasingly ambitious climate policies. In October 2021, the Chinese government released the 'Action plan for carbon dioxide peaking before 2030' (The State Council, 2021), reiterating China's targets that President Xi Jinping announced last year. This action plan sets out to increase wind and solar capacity to 1,200 GW by 2030, build more hydropower, nuclear plants and further develop natural gas resources. The action plan set the targets of green and low-carbon transportation to reach a peak in petroleum consumption for land transportation before 2030 by increasing the share of incremental vehicles fuelled by new and clean energy by around 40%. It further aims to promote the replacement of public service vehicles with electric cars and the use of heavy cargo trucks driven by electricity, hydrogen fuel and liquefied natural gas. To reach those targets, China will need to enhance innovation capacity and personnel training on hydrogen energy; boost related application-oriented basic research, and accelerate the R&D and broader application of advanced technologies on low-cost hydrogen production from renewable energy sources.

China's national government has not been alone in its interest in hydrogen. Local governments in China are actively fostering the development of the hydrogen industry. On 16 August 2021, the 'Beijing Hydrogen Energy Industry Development Implementation Plan (2021-2025)' issued by the Beijing Municipal Bureau of Economy and Information Technology proposed that by 2025, 10-15 industry chain leaders with international influence should become cultivated enterprises. The Beijing-Tianjin-Hebei region has invested more than CNY 100 billion in the hydrogen energy industry supply chain and reduced carbon emissions by 2 million tonnes. In the field of transportation, Beijing Municipal government are working to complete the construction of 37 additional hydrogen refuelling stations and get more than 10,000 fuel cell vehicles on the road. In late July, the Hebei Provincial Development and Reform Commission issued the 'Fourteenth Five-Year Plan for the Development of the Hydrogen Energy Industry in Hebei Province' that seeks to reach CNY 550 billion in annual output value for the hydrogen energy industrial chain by 2025; build a total of 100 hydrogen refuelling stations, and make 10,000 fuel cell vehicles operable

Assessing the Feasibility of Hydrogen in Asia

Asia's interest in a hydrogen economy stems from a desire to enhance the region's energy security in a cost-efficient and environmentally sustainable manner. Tapping hydrogen's disruptive potential through its large-scale deployment, however, depends on increasing its feasibility in Asia. This section assesses the feasibility of developing a hydrogen-based economy in Asia. In so doing, it looks beyond frequently studied technical feasibility issues such as the availability of energy resources in the region, readiness/maturity of the technologies (Mueller-Langer, et al., 2007).

Environmental Feasibility

One aspect of feasibility that could loom large in Asia involves its effect on the environment. At present, hydrogen is predominantly used in the chemical, refinery and steel industries (Mueller-Langer, et al., 2007). Further, almost all hydrogen is generated from fossil fuels (natural gas and coal) (IEA, 2019) with steam reforming of hydrocarbons as the most significant technology (Kalamaras & Efstathiou, 2013). Despite hydrogen combustion being pollution-free, its production can be carbon-intensive if produced from conventional fossil fuels without CCUS. Hydrogen can be produced from a variety of energy resources and through a range of technological processes that would boost its environmental feasibility.

Of course, not all types of hydrogen technologies have the same environmental impacts. Renewable-based technologies such as water electrolysis are least polluting, but a major challenge is the high energy demand of these technologies. While electrolysis is a mature, well-known method that has been used for commercial production of pure hydrogen for more than a century, its application is limited to only 4% of global hydrogen production due to the high costs associated with the electricity needed. Reforming hydrocarbons such as natural gas is one of the most advanced technologies for hydrogen production currently in use. The gasification of coal is also a cost-competitive option (Otsuki, et al., 2019). Most fossil fuel-based technologies, however, generate significant GHGs. These technologies, bundled with CCUS, could serve as interim options until cleaner options mature.

Economic Feasibility

Another dimension of feasibility is economic. Indeed, a recent study on hydrogen in the electricity and transport sector found that along with emissions regulations, increasing the cost-efficiency of hydrogen-producing technologies is a prerequisite for its expansive rollout (Otsuki, et al., 2019). To date, the production of hydrogen has involved cost-intensive technology. According to the Hydrogen Council (Hydrogen Council , 2021), the production cost of hydrogen varies in different locations and based on different processes and technologies—though much of hydrogen production globally is captive in a single county and only a limited amount is traded. Given the low-carbon benefits of green hydrogen over grey or blue, bringing green hydrogen costs to affordable levels in the coming years is critical. IRENA (IRENA, 2020) argues that the falling renewable power costs and improving electrolyser technologies could make ‘green’ hydrogen cost-competitive by 2030. IRENA analyses indicate that, with an electricity price of USD65 per MWh, hydrogen could be produced at a cost of USD 3 per kg by 2050, and with an electricity price of USD20 per MWh, the cost of hydrogen could fall as low as USD 2 per kg (IRENA, 2020).

This appears to be happening in some cases as the cost of low-carbon (blue) and green hydrogen (renewable based) has fallen substantially since 2020. While the production cost of grey hydrogen in those countries that depend on imported fossil fuels is likely to remain high, natural gas-producing countries like Saudi Arabia and major coal-producing countries like Australia may be able to produce hydrogen cheaply. It is estimated that the cost of grey hydrogen within gas-producing countries could fall between USD 1 to 1.5 per kg of hydrogen, while Australia (as a major coal producer) could produce hydrogen at around USD 2 per kg.

Geopolitical Feasibility

An additional dimension of feasibility involves geopolitics. For more than a century, the political interest to dominate other countries on matters of national security in specific geography has defined geopolitics (Kjellen, 1899). Today geopolitics has wider-ranging connotations that reflect struggles among states as well as non-state actors over a growing list of policy concerns. Geopolitical clashes in the petroleum sector have typically involved countries aiming to secure their access as well as control over resources. Unlike the petroleum reserves which are mostly geography-specific, the feed source for producing hydrogen is water. Moreover, the key determining factor will be efficiently deploying cost-effective technologies that ease the availability, accessibility and affordability of hydrogen. Yet, even countries such as Japan have been pioneering in advanced technologies will need to depend on other countries for imports and exports or technologies and fuels. This could potentially create a new set of tensions.

Some have pointed to new sets of interdependencies (Graaf, et al., 2020). Conventionally the petroleum energy sector has witnessed the dominance of OPEC and other major non-OPEC producers as the source of energy production and supply. These countries have traditionally controlled the energy trade and have been at the epicentre of energy geopolitics. As hydrogen production, trade and technology development takes centre stage, the world may witness new players with the potential for investment and technology, with the emergence of a movement away from conventional forms of energy dependency and to new configurations of power.

A related issue that exemplifies the overlap among geopolitics, economics and technologies, involves the need for more investment in hydrogen production to enhance the production of green hydrogen in many countries. This could also potentially catapult countries into becoming major producers and suppliers of hydrogen to meet the demands in diverse geographical regions. Against this backdrop, market interest and economic ambitions will undeniably create new relationships among countries that seek to leverage physical supplies and access advanced technologies. Another set of concerns pertains to logistics and trade. As the hydrogen sector develops, conventional geopolitical challenges could be brought into sharp relief. Dependency on long sea lanes of communications (SLOCs) for the supply of hydrogen, availability of ammonia and its trade, investment and physical facilities for the development of hydrogen and its production, etc. can all be vulnerable to political volatilities and the threat of non-state actors.

The Multiple Dimensions of Feasibility

A final perspective concerns the multiple dimensions of feasibility. For instance, some studies conducted a review of various hydrogen production technologies, including their current state and possible future developments. The Table below on 'technological and economic viability' has been developed based on (Kalamaras & Efstathiou, 2013) as well as information from other sources (Mueller-Langer, et al., 2007; Otsuki, et al., 2019; Kannah, et al., 2021), and summarises points related to the multiple dimensions of feasibility for different technologies. Both fossil fuel-based technologies (steam reforming, partial oxidation, autothermal reforming and plasma reforming) and renewable resources-based technologies (biomass gasification, pyrolysis and copyrolysis, aqueous phase reforming, electrolysis, photoelectrolysis, and thermochemical water splitting) are considered. For each technology, the table shows what types of energy resources are needed (fossil fuel or renewables); economic viability (high or low operational and production costs, etc.); environmental impacts; and additional considerations (such as the stage of technology development, efficiency, use, and technical limitations). The table suggests that, while several renewable resources-based technologies have either been developed or are at various stages of development, most are either not cost-efficient or mature enough for widespread deployment.

TABLE 2: TECHNOLOGICAL AND ECONOMIC VIABILITY

Name of the technology (resources used)	KEY ASPECTS (EFFICIENCY, USE ETC.)	ENVIRONMENTAL IMPACTS	ECONOMIC VIABILITY
Steam reforming (fossil fuel (natural gas, other hydrocarbons such as methanol))	*Endothemric process, energy-intensive *Predominant technology *Highly efficient operation *Modest temperature required	*Generates a high amount of CO, which is then converted into CO2 via other processes. *Using other fossil fuels such as coal can lead to higher CO2 production/emission. *Possible use of CCS to reduce environmental impacts	Low operational and production costs (least cost process)
Partial oxidation (fossil fuel - hydrocarbons such as methane and biogas)	*Endothermic process, energy-intensive *Proposed for hydrogen production for automobile fuel	*Generates a high amount of CO, which is then converted into CO2 via other processes.	*The whole process including operation and conversion is more expensive

	cells and some other industrial applications *Safety concerns (high temperature)	*Possible use of CCS to reduce environmental impacts	than steam reforming
Autothermal reforming (fossil fuel -methane)	*Autothermal process *Compact *Simple operation *Gasoline and other hydrocarbons can be converted into hydrogen and used in autothermal process	*Generates a high amount of CO, which is then converted into CO_2 via other processes. *Possible use of CCS to reduce environmental impacts	*Less expensive than methane steam reforming *Lower capital cost requirement *Potential for economies of scale
Plasma reforming (fossil fuels -variety of hydrocarbon fuels)	*Similar to other reforming methods but energy and free radicals used in the reaction are provided by plasma generated with electricity/heat *High dependence on electricity *High-pressure operation required *Compact and low-weight *Can be used for mobile applications (fuel cell power vehicles etc.)	*Relatively less polluting	*Cost may be dependent on the price of electricity
Biomass gasification (renewable sources)	*Allows the use of renewable substitutes to petroleum *Requires huge amount of resources to gather biomass to the processing plant *Commercialisation is difficult due to high logistics costs and removal of tars to acceptable levels *Further development of smaller efficient plants required for cost-effectiveness	*NO_x may be produced if air is used in the gasifiers instead of O_2	*Not yet that cost-efficient; plant needs to be at least medium scale to benefit from scale economies - Low-cost, efficient oxygen separators needed to avoid NO_x generation
Pyrolysis and copyrolysis (renewable sources - raw organic material	*Offers fuel flexibility, simplicity and compactness	*Clean carbon by-product; easy sequestration of solid carbon; significant emissions reduction *CO_2 emissions can occur if the materials used are not dry	*Well-developed processes that can be used commercially
Aqueous phase reforming (fossil fuels -oxygenated hydrocarbons, or	*Technology under development *Requires low temperature *Energy-saving as vaporising water is not needed	*A low amount of CO is needed in a single stage to generate H_2 and CO_2 (conventional steam	*Can be low-cost if nickel-based catalysts are used

renewables - carbohydrates of biomass resources)	*Reactors are usually large *Catalyst activity and durability needs to be improved	reforming requires multi-stages)	
Electrolysis (water)	*Well-known method, but only 4% hydrogen is currently produced with this method *High energy-demand	*Ecologically clean; no GHG emitted	*Expensive as the technology is energy-intensive; electricity cost ranges between 40%-57% of the cost of hydrogen *Generates oxygen which has other industrial use
Photoelectrolysis (renewable resources -solar)	*Technology in development *Depends on the type of semiconductor material used and on solar intensity *Low efficiency	*No GHG emitted	*High capital cost requirements
Thermochemical water splitting (water)	*High temperature (2500°C) needed *Sustainable heat sources are difficult to avail *Scaling up the processes may improve thermal efficiency	*No GHG emitted	

Source: Based on (Kalamaras & Efstathiou, 2013), with additional information from (Kannah, et al., 2021; Mueller-Langer, et al., 2007; Otsuki, et al., 2019).

A Regional Cooperative Framework for Hydrogen in Asia

The previous section implied that increasing the feasibility of hydrogen economy requires action from not just one country but cooperation across many. Developing a hydrogen economy in Asia will also require an efficient hydrogen market that enables cooperation and trade within the region and beyond. In sum, although it is still at the nascent stage, realising a hydrogen society in Asia is feasible. However, countries will need to work on enhanced collaboration and cooperation to make it a reality.

Why Cooperation is needed

Cooperation is needed for environmental, economic and security reasons. The IEA predicts that by 2050 the Middle East, Australia and Chile will become the important hydrogen supplier for Asia. While Saudi Arabia, UAE, Australia and Chile have announced net-zero pledges in place, however, most of them have not set stringent, mid-term domestic mitigation action. Since the supply chains of blue hydrogen in exporting countries (exploration, production and processing of fossil fuels, reforming fossil fuels to produce hydrogen with CCS, compression and pipeline of hydrogen, conversation of hydrogen into liquefied hydrogen, MCH, or ammonia for shipping) require electricity and emit GHG to some extent. Therefore, importing countries will need to encourage and guarantee relevant supply investments if they want their hydrogen imports to be low-carbon (IEA Global Hydrogen Review

2021). Otherwise, the CO2 reduction in the importing countries will be offset by the increase by producing blue hydrogen in the exporting countries.

Such cooperation is partially warranted for economic reasons as well. Because hydrogen production cost varies across countries and regions. East Asia and Southeast Asia are among the regions where hydrogen production is most expensive (considering the upper bound). The cost (upper bound) is significantly lower in Central Asia and South Asia. This variation also suggests the potential for collaboration within the region, especially as the region aims at greening the hydrogen market.

As pointed out in the previous sections, many of the environmental and economic issues interact with each other. In Asia, without a decrease in the levelised cost of electricity (LCOE) from renewables or a reduction in capital expenditure for hydrogen production, storage and transportation, green hydrogen exports will not be competitive. Nevertheless, when looking at Brunei and Indonesia, the export of grey hydrogen produced from natural gas or coal could be marginally competitive (Hydrogen in ASEAN 2021). Moreover, Indonesia and Brunei could produce the lowest cost hydrogen, around USD 5 per kg, in a form of grey hydrogen. The cost in these countries is considered competitive for advanced markets such as Japan, Korea and China. From the perspective of green hydrogen, the cost in all ASEAN countries is still high considering the high capital investments for electrolysers and the high cost of renewable electricity (Hydrogen in ASEAN 2021). Before Asia sees any decrease in LCOE of renewables and a reduction in the cost of electrolyser, using grey and blue hydrogen is reasonable. In that case, natural gas-rich countries such as Brunei, Indonesia and Malaysia will play a major role of grey and blue hydrogen manufacturers in Asia.

Due to the initial reliance on grey and blue hydrogen, a critical tipping point in Asia will be when green hydrogen catches up with grey and blue hydrogen. The ASEAN Centre for Energy estimates the cost of hydrogen exported from ASEAN in a 2030 scenario on the assumption that the cost for both hydrogen production and renewable electricity are predicted to fall, and fossil fuel costs could increase by 16% by 2030 according to IEA's Energy Outlook 2020. Among the 10 ASEAN countries, five countries (Cambodia, Myanmar, Philippines, Thailand and Viet Nam) could produce green hydrogen lower than blue hydrogen (SMR+CCS) and two countries (Cambodia and Thailand) could produce lower than grey hydrogen. By 2030 green hydrogen exported by some ASEAN countries to Japan could be more competitive than blue and grey hydrogen.

Cooperation is further merited for geopolitical and safety reasons. Due to the chemical and physical properties of hydrogen, its storage, transportation and distribution can pose safety issues that need to be addressed at a regional level (Gerboni, 2016). Further, as countries experience shifts in power with the changing energy economy, tensions could come to the fore. A framework that enables candid discussions over these shifts will be much needed.

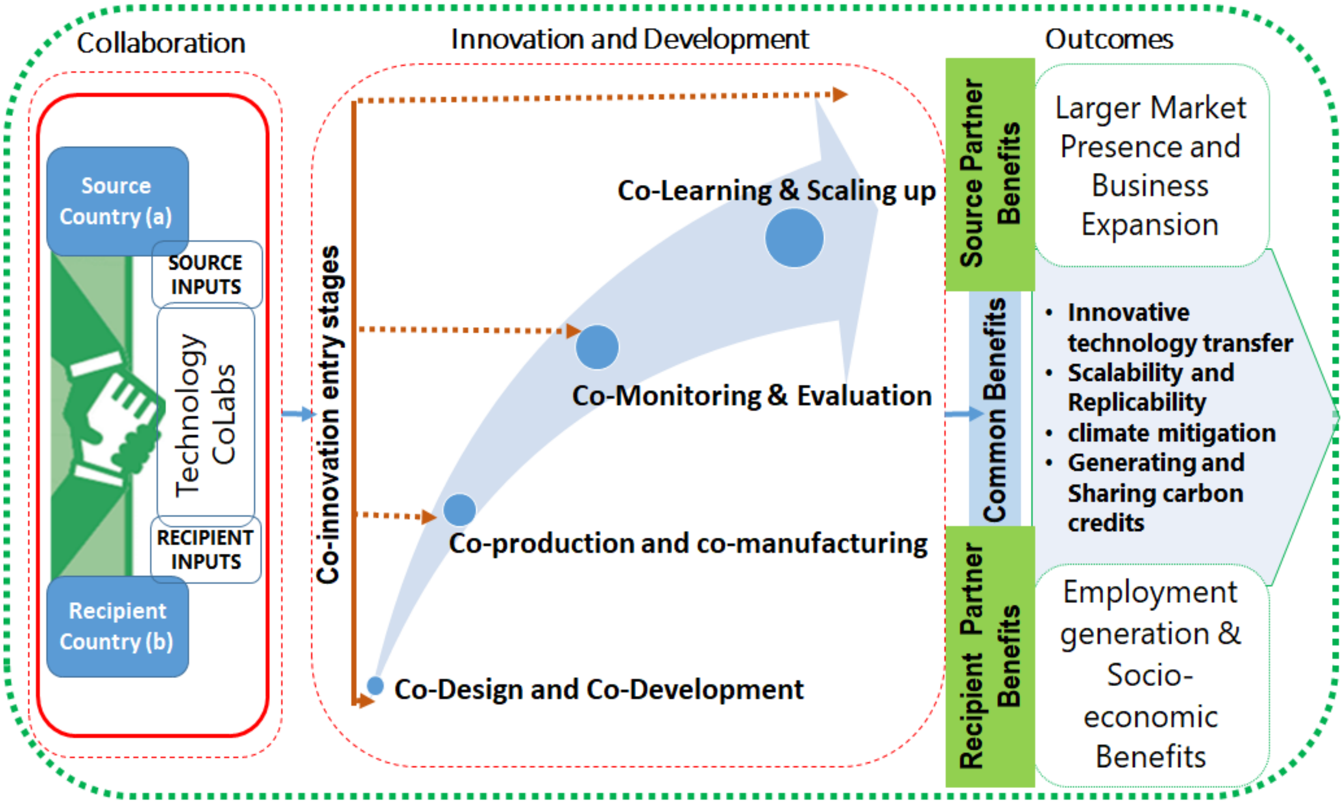
How Cooperation could be structured

Cooperation is likely to require leadership from one or more countries in Asia. One possible way forward is for Japan to take the lead in Asia.

Japan has significant potential to lead the largescale commercial development and collaboration among countries towards the same. Japan, being an industrially-advanced economy, has been investing in hydrogen-related R&D, and developed key hydrogen-related technologies (Otsuki, et al., 2019; Janardhanan, et al., 2021). Supporting regional cooperation is also consistent with Japan's interest in leading the development of a hydrogen-based economy and developing a robust hydrogen supply chain (Nakano, 2021) with investments close to JPY 300 billion (Reuters, 2021). In addition, Japan has already launched a liquefied hydrogen vessel in 2019 and finished the development of a hydrogen receiving terminal in 2020, the world's first in both instances (Nakano, 2021).

There is also already some of the necessary research in place for institutional cooperation. A collaborative framework for the development of hydrogen in these countries is being built by Japan. In August 2021, Japanese refiner ENEOS announced the launch of a demonstration using grey hydrogen from unused gas and extracted hydrogen from methylcyclohexane (MCH) at refining facilities in Brunei[3]. ENEOS considers the production of blue and green hydrogen in the near future. In Malaysia, ENEOS concluded a memorandum of understanding with state-owned oil and gas company PETRONAS in September 2021 to conduct collaborative studies toward the development of a hydrogen supply chain. The study uses grey hydrogen from co-product at the petrochemical plants. According to ENEOS 'green hydrogen derived from renewable energy and blue hydrogen by capturing and storing CO2 (CCS) will also be considered'[4].

Co-innovation Framework



Source: (Janardhanan, et al., 2020; Janardhanan, et al., 2021)

Another reason Japan could lead is due to its technological capacities. Many countries in Asia possess the necessary resources but lack the required technology for hydrogen. India, for instance, has abundant renewable resources but lacks the required technologies for production and use of hydrogen and associated infrastructure. Cooperation between Japan and India could help ease relevant bottlenecks and tap potentials by co-investing in

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[3] First demonstration in Japan to feed MCH into existing facilities 20210810_01.pdf (eneos.co.jp)

[4] ENEOS Begins Collaborative Studies and Researches with PETRONAS Group 20210910_01.pdf (eneos.co.jp)

and co-developing hydrogen production, as well as co-developing and co-deploying hydrogen storage and carrier technologies—a concept is known as co-innovation [for details see (Janardhanan, et al., 2021)].

Yet the case between Japan and India underscores another salient point. No single country in Asia will be able to have a monopoly on the development and efficient supply of hydrogen in Asia. Instead, collaborative mechanisms need to be envisioned wherein Asian countries could pool their knowledge and resources to efficiently develop, produce and supply hydrogen. Co-innovation (Janardhanan, et al., 2020; Janardhanan, et al., 2021) as an approach to strengthening collaboration among countries to jointly innovate and produce hydrogen could open avenues of cooperation that could expand as mutual trust is built across relevant actors.

Co-innovation could deliver multiple benefits for countries in the region. The clearest of these is climate benefits—assuming a smooth transition to green hydrogen. As suggested in the figure above (co-innovation), these benefits extend to other kinds of desirable outcomes, including new jobs, skill sets and other socioeconomic gains. Last but not least, co-innovation could allay concerns that efforts to promote hydrogen are part of a one-sided power grab. Hence, if a regional cooperative framework is going to be cooperative co-innovation should sit at its core.

The Way Forward

Efforts to establish an international hydrogen supply chain are underway in Asia and around the world. However, many factors could frustrate these efforts from realising their potential to achieve ambitious climate targets. This paper has outlined a set of considerations that should inform national policies and regional cooperation on hydrogen in Asia. Those considerations are based on a review of relevant strategies and an assessment of multiple dimensions of feasibility. In future iterations of this work, it will be useful to hold up national policies and regional cooperation efforts to these feasibility considerations. This could help Asia realise a hydrogen economy that is good for the region and the world.

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