Hong Kong Hydrogen Economy Study and Report

Market Study on the Use of Hydrogen in Green Transportation in Hong Kong

September 2023

A. Executive Summary

In the latest Policy Address, the Government is committed to reducing carbon emissions, including exploring different types of zero-carbon energy and decarbonisation technologies, to strive toward carbon neutrality. Hydrogen is one of the potential sources of energy carrier which has versatility to substitute fossil fuel in various utilization scenarios. The *Clean Air Plan for Hong Kong 2035* (released in June 2021) clearly identifies six major areas for further action, which include green transport, liveable environment, comprehensive reduction, clean energy, scientific management, and regional collaboration.

Hydrogen can typically play a role in contributing to a resilient, sustainable energy future in two major directions: (1) current/ traditional practice of hydrogen usage, dominantly present in industrial activities (e.g. refinery, steel production, fertilizer manufacturing etc.), can use hydrogen produced from greener alternative methods; (2) hydrogen receives interest in new and emerging applications mainly in **electricity generation**, **heating source** and **transportation** (i.e. fuel cell vehicle FCV). In Hong Kong's context, hydrogen usage in the (2) finds its ultimate relevance. Hydrogen can be directly used in its pure form stored in different physical states (including uncompressed gas, compressed gas, liquefied hydrogen and solid-state hydrogen as metal hydride). Alternatively, hydrogen can be converted to hydrogen-based fuels such as ammonia, methane or liquid alcohol fuels. With these multiple facets of hydrogen, there is potential to connect different parts of the energy system with hydrogen-derived fuels.

Disregarding the raw sources of hydrogen, Hong Kong has an obvious advantage over other cities in the world in that the hydrogen mixture distribution network is readily available throughout Hong Kong. The significant portion of hydrogen in the utility gas mixture with its extensive network accessibility is rendering Hong Kong convenient in extracting pure hydrogen for its dedicated usage at the desirable sites. The existing infrastructures capable of handling hydrogen-blended mixture also offer the potential of cost effectiveness in further developing the application of pure hydrogen for transportation purpose. Promoting hydrogen-fuelled vehicles, in addition to battery-powered electric counterparts, in Hong Kong will help to decarbonise the transportation sector. Both modes of green transport (hydrogen and battery-powered) have complementary roles in satisfying vehicles with different energy demands. Enactment of policies and regulations on hydrogen utilization would be the next major effort in facilitating the real adoption of hydrogen in Hong Kong.

B. Market Analysis on the Use of Hydrogen in Hong Kong

Hong Kong's Potentials

The release of the "Clean Air Plan for Hong Kong 2035" in June 2021 is likely to mark a turning point for many sectors. As Hong Kong looks to create a more sustainable society with healthy living through low-carbon transformation, it will become increasingly focused on low-carbon energy, including hydrogen. Within the six major areas covered in the Clean Air Plan for Hong Kong 2035, there are at least three major areas that can see the potential rapid growth of hydrogen, including the areas for green transport, comprehensive emissions reduction and clean energy.

Hydrogen has been used in a wide range of applications for many decades. It is an important reagent in oil refining, steel making, fertilizer production, and manufacturing of plastics, fabrics and dyes. These traditional usages of hydrogen are relatively distant to the context of Hong Kong because of their trivial presence in those industries. However, as a tool in realizing decarbonisation, hydrogen may have a role to play in transportation and power generation, and also as a means of energy storage. It remains relatively infancy in Hong Kong but there are promising signs of building momentum for the deployment of hydrogen in the below areas.

Green transportation. As elaborated in the Clean Air Plan for Hong Kong 2035, green transportation has been identified as a major area and hydrogen deployment has therefore seen the potential room albeit still in its initial phases. In Asia-Pacific, a broad range of commitments across the government and private sectors to support the introduction of hydrogen in the transportation sector is observed as this sector is a major emissions contributor. While battery electric vehicles are the current preferred option for small vehicles travelling through shorter distances, hydrogen has been considered a more suitable candidate for heavy vehicle transportation owing to its much larger energy density as compared with battery. This may represent a sub-sector within green transportation to facilitate preferential growth of hydrogen fuel-cell vehicles (FCV) for heavy duty transportation such as buses, domestic trailers and cross-border trucks for logistic services. Japan, China and South Korea have expressed objectives and targets to increase the usage of hydrogen FCVs. According to Japan's Basic Hydrogen Strategy, they have set a total number of 200, 000 FCVs by 2025 and 800, 000 FCVs by 2030.The numbers are inclusive of vehicles of all categories. Japan is constructing 320 hydrogen stations by 2025. Hence, there would be more references of deployed hydrogen stations from Japan that could be of valuable to Hong Kong's pathway towards hydrogen. To enable green transportation by hydrogen in Hong Kong, hydrogen gas station must be the foundation for the promotion of hydrogen FCVs. Strategical location for the initial installation of hydrogen station is most likely to be outskirt of Hong Kong to avoid populated area. The construction of a hydrogen gas station on the outskirts may also be a preferred option for heavy duty vehicle operators owing to the nature of their routine route operation. Besides road transportation, there is also potential for its use as a marine fuel in Hong Kong's context. Domestic ferries and intermediate-distance ferries could be the potential users of hydrogen because the electrification of ferries by battery technologies appears to be inadequate. The International Maritime Organization's new bunker fuel regulations have set the limits of Sulphur content of marine fuels to 0.5% from 1 January 2020. Although this has no direct translation into the use of hydrogen, there are a few commitments announced by the marine private sector to explore the use of hydrogen as fuel for the international/inter-continental shipping industries. As one of the busiest ports in the world, Hong Kong may be impacted by the latest rapid adoption of green technologies.

Power and heating sector. Hong Kong is currently underway to replace coal with natural gas in power generation. It has seen a great and continuing reduction of greenhouse gas emissions from the power utilities companies (i.e. CLP, HK Electric and Towngas). The construction of the offshore natural gas terminal is another important milestone for Hong Kong in achieving the further replacement of coal by natural gas in the power generation sector. In order to achieve net zero emission after obsoleting coal-firing, natural gas could also be gradually and eventually replaced (to a certain extent) by hydrogen. Hydrogen injection into the existing pipeline is already part of the national hydrogen strategy for a few countries including the UK, Australia, Japan and South Korea. Hong Kong-based company has been involved in these initiatives and could be an important contributor in adopting the strategy in Hong Kong. Initial plans are the blending of hydrogen in a low mixture percentage with natural gas for injection to avoid major modifications to pipeline networks. Higher concentrations may require network modifications such as the replacement of steel with composite pipes or the replacement of compressors. Other than pipelines for transporting hydrogen, there is also the development of more advanced gas turbines capable of accepting fuel blends which may contain 50% or more hydrogen. Major turbine manufacturers are developing gas turbines that could run on 100% hydrogen. Although there is a long way before hydrogen might fully replace natural gas for electricity generation, and the predicted timeline for such transition has uncertain factors, it is a very significant step away from fossil fuels towards a low (or zero) carbon economy.

In contrast, utility gas mixture in Hong Kong has seen the adoption of high content hydrogen (up to 51% of the mixture) for decades. The extensive accessibility of utility gas pipeline throughout entire Hong Kong is an obvious advantage in further extending its usage, including extracting pure hydrogen for hydrogen fuel stations. Note that the hydrogen in the existing utility gas is not produced from the clean source at the current stage.

Short-term energy storage. Hydrogen can couple with renewable energy (solar and wind) to address the drawbacks of reliance on renewable energy. Energy generated by wind or solar power plants can be stored and transported from regions with higher production (e.g. offshore for wind farm, rural area for solar PV farm) to areas with higher demand. Otherwise, it can be simply stored during low-consumption periods until there is a peak in energy demand. Certainly, the production of hydrogen and subsequently re-conversion to electricity will carry an additional cost and involves energy losses. However, the continuing falling cost of renewable energy can still enhance the viability of hydrogen as the storage medium in a long term, seasonal and transportable manner. This may not be the most ideal situation in long term but it is important in the early days for developing the utilization of hydrogen. Hong Kong has a number of large-scale deployments of wind farms and floating photovoltaic (PV) systems. The use of electricity from these renewable facilities may find an opportunity in the medium of hydrogen because the direct usage of electricity from wind farms/ floating PV generation sites may not be conveniently feasible in the near term.

Recent development in Hong Kong

Hong Kong is making efforts to keep up with other OECD countries in hydrogen-related development and initiative is beginning to be put in place (for example, the much anticipated Green Technology Fund GTF). Hong Kong Government has set up the GTF in 2021 to provide better and more focused funding support for research and development (R&D) projects which can help Hong Kong decarbonise and enhance environmental protection as Hong Kong strives towards its goal of carbon neutrality before 2050. The GTF is considering all categories of green technologies. However, the funding outcome has suggested the vision of the Hong Kong Government in pro-actively exploring the suitable way of the City's own hydrogen developmental plan. Out of the 14 approved projects out of over 190 applications in the first round of funding, four projects centred on hydrogen technologies have been approved at multimillion Hong Kong dollar scale.

The four hydrogen-focused projects led by Hong Kong local universities cover the scope of green hydrogen production, hydrogen storage, and hydrogen applications. In the space of green hydrogen production, two projects using new photocatalytic technology and membrane-less electrolysers have been selected for further development. Both projects aim to utilise water as the hydrogen source. Another project was approved to develop solid-state hydrogen storage as a potential way in tackling the storage issue of hydrogen, while a long-life hydrogen fuel cell project secured another slot in the first round of the GTF call.

Hong Kong's Climate Action Plan 2050 released in October 2021 has included green hydrogen energy in its medium-term decarbonisation targets. It is also mentioned that the uncertainty of the technology will depend on its maturity, reliability and cost-effectiveness for large-scale applications. Beside the adoption of electric vehicles (generally referred to batteries-powered electric vehicle), many automobile players are developing hydrogen-power vehicles (such as heavy-duty type) and Hong Kong is collaborating with franchised bus companies in the next three years (2022-2024) to test out hydrogen fuel cell electric buses and heavy vehicles. Guangdong Province has established hydrogen production facilities that might provide hydrogen supply to Hong Kong. Hence, feasibility studies on hydrogen-fuelled transport and construction of hydrogen-filling facilities are or soon will be underway. Following the release of the Clean Air Plan, the Government has set up an Interdepartmental Working Group on the application of hydrogen energy in Hong Kong. City University of Hong Kong (School of Energy and Environment) has been working with the Working Group in this initiative and delivered a training module to the interdepartmental personnel on hydrogen production technologies.

Beside the Government's initiatives, Hong Kong utilities companies have launched hydrogen-focused development plans. CLP has kick-started collaboration with GE to jointly develop a decarbonisation roadmap for CLP's gas-fired power generation facilities in Hong Kong. CLP and GE explore the feasibility of burning a variable blend of natural gas and hydrogen up to a possible 100% hydrogen, to reduce carbon emissions at the Black Point power plant. Hong Kong and China Gas (Towngas) is developing the capacity to produce zero-carbon hydrogen as part of its long-term decarbonisation plan. Towngas has been conducting pilot programmes on hydrogen utilisation and equipment installations for the past years.

Hong Kong's limitation

Despite the promising aspects of hydrogen, there are major challenges for widespread use in worldwide, including in Hong Kong. In general, hydrogen is used at large scale in many industries (e.g. steel making, oil refining, fertilizer producing etc.). Decarbonizing industrial sectors through green hydrogen is an indispensable strategy in many industrialized nations as the carbon emission from the industrial sector is significant. The utilization of hydrogen in industries in Hong Kong is basically rare. Instead, as elaborated earlier, hydrogen finds potential in new applications such as green transportation and clean energy. Below are some of the challenges encountered in Hong Kong and how they might be overcome.

Green hydrogen is expensive. As of now, the production cost of blue or green hydrogen remains much higher than that of fossil fuels. Currently, the cost of production of green hydrogen is estimated to be USD $2.50-6.80 per kgH2 while blue hydrogen is estimated to be USD $1.40-2.40 per kgH2. For green hydrogen to become commercially competitive, it has been said that the production cost needs to be lowered to or lower than USD $2 per kgH2. There are projections to see the price of green hydrogen fall below USD $2 per kg before the end of this decade. The main drivers for lowering the green hydrogen production cost are the falling cost of renewable electricity (especially large-scale solar PV) and the price of electrolysis facilities (benefits of scale-up manufacturing). The trend is expected to continue. The cost of CCS will need to be reduced and its efficiency needs to be improved. One critical factor often overlooked or ignored is the access to a water source for electrolysis. The current electrolyser technologies, as elaborated in the above sections, are relying on either alkaline water or clean (deionized-grade) water for operation. While the water resource may not be an immediate problem, the provision of treated clean water for the operation of electrolysis might pose a long-term challenge, especially when it is produced at a megawatt scale.

Though green hydrogen is expensive, there are examples of increasing government support for the uptake and usage of hydrogen. Government support is in the form of (1) financial subsidies and investment to make hydrogen more economical, and (2) carbon taxes or emissions trading schemes to increase the cost of fossil fuels. China, Japan, and South Korea have already implemented emissions trading schemes in different forms. This is critical, especially during the initial deployment phases of new green technologies, including hydrogen. Hydrogen subsidy schemes may be coordinated with other environmental incentive schemes.

Transportation of hydrogen. If hydrogen is not produced locally, the transportation of hydrogen can comprise a significant component of the final cost of hydrogen. For shorter distances (for example, from Greater Bay Area to Hong Kong), hydrogen might be transferred by ground transport or upgraded pipelines. For long distance transportation (e.g. from Australia or Chile to Hong Kong), the most realistic option at the moment would be liquefied hydrogen. Ammonia as the hydrogen-carrier has also been seriously considered an option by Japan and Australia. There are energy losses incurred during the conversion of hydrogen-nitrogen into ammonia at the exporter site; there are also energy losses during the re-conversion of ammonia back to hydrogen. However, it may still offer cost benefits when compared with the price associated with liquefying hydrogen at extremely low temperature for ultra-long distance transportation (such as from Australia to Japan). In Hong Kong, it might be ideal to produce hydrogen on-site at outskirt facilities through water electrolysis. Transportation needs could be removed if the generation sites are the utilization point. Transportation through pipelines from GBA might be another option prior to considering of inter-continental transportation of hydrogen through shipment. The variation in standards adopted in the GBA and Hong Kong should be sorted.

Lacking of distribution infrastructure. Widespread deployment of pure hydrogen within Hong Kong will require extensive investment in the distribution infrastructure. In general, existing pipeline infrastructure will need to be retrofitted to accept the injection of more concentrated or pure hydrogen. More critically, for the promotion of green transportation through hydrogen FCV, there is no refuelling infrastructure in Hong Kong. To start with, FCVs cost considerably more than cars with combustion engines. Without the provision of easily accessible hydrogen refuelling stations, it is unlikely that there will be an uptake or demand for hydrogen FCVs. The dilemma encountered is that parties may not invest in infrastructure unless there is a demand, but demand will not materialize without the infrastructure. The drive towards hydrogen infrastructure investment may see a role for the government to provide financial and policy support.

The needs for clear and comprehensive regulatory framework. Operational, environmental, safety, and technical standards need to be implemented in order to ensure consistent standards for utilization, transportation, and storage of hydrogen. In Hong Kong's context, if hydrogen is sourced from Mainland China, the cross-border transportation of hydrogen is still in its infancy. Clear regulations pertaining to transportation can, in turn, promote the growth and development of hydrogen projects. There are examples of countries that have rolled out initial laws on hydrogen usage and domestic safety standards. For example, South Korea has passed the Hydrogen Economy Promotion and Hydrogen Safety Management Law. However, substantial further work is still in progress to develop detailed rules and regulations. International and cross-border regulations of hydrogen trade and transportation are also in the early stages.

C. <u>Analysis of the Supply Chain of Hydrogen</u>

C1. Hydrogen Production

Green Hydrogen Trend

Although green hydrogen has been vigorously discussed and consensually agreed as one of the effective solutions in addressing decarbonisation strategy worldwide, 99% of the ~70 million metric tonnes (Mt) is still produced from the steam reforming of natural gas (71%) and the gasification of coal and oil (27%), as shown in **Figure 1**. The production of this 70 Mt of hydrogen was accompanied by the release of 830 Mt of CO_2. It is clear that the use of hydrogen produced from carbon intensive sources has little relevance to decarbonisation. This hydrogen is categorized as grey hydrogen in which the CO_2 emission is unsustainably high relative to its usage. Grey hydrogen is the dominant and traditional source used in refineries, ammonia and methanol production. Ammonia is the important raw material for fertilizer production which supports the agricultural activities (e.g. food crops) while methanol is used in plastic production and fuel additive.

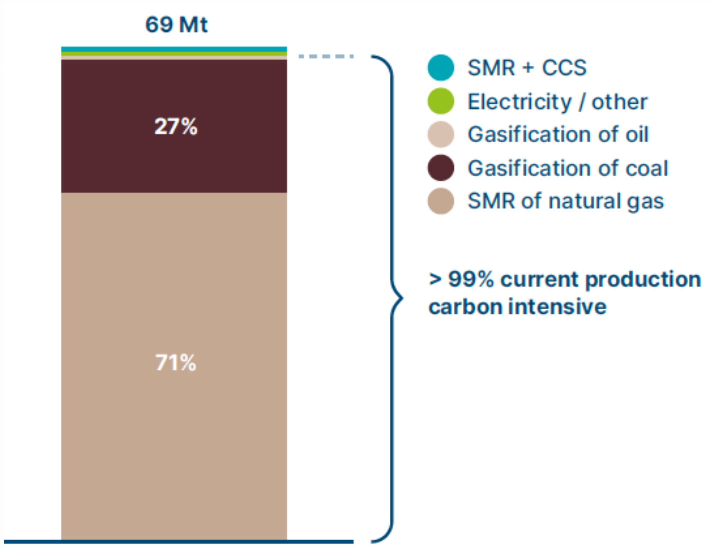

Figure 1 Hydrogen production methods used in 2018. Source: IEA *The Future of Hydrogen*.

The scenario is expected to change in which low-carbon hydrogen will be the dominant source of hydrogen while grey hydrogen will be completely phased out by 2050, mainly driven by the falling price of green hydrogen enabled by technology. Figure 2 shows that the projected 500-800 Mt of hydrogen produced in 2050 will comprise green (85%) and blue (15%) hydrogen. Blue hydrogen is essentially an upgraded version of grey hydrogen equipped with carbon capture and storage (CCS) technology. Blue hydrogen is considered an intermediate stage before the full transition from grey to green in hydrogen production. Ideally, existing grey hydrogen production facilities can be retrofitted with CCS and become an option for the existing hydrogen stakeholders to achieve lower greenhouse gas (GHG) emissions. This allows for the promotion of hydrogen market growth. In principle, a theoretical 85-95% of carbon emissions from traditional grey hydrogen can be captured by the installation of CCS. Existing industries like ammonia plants and steel production could use blue hydrogen as an initial solution before the maturation of green hydrogen technologies.

Figure 2 Multiple-fold increase in clean hydrogen production by 2050. Source: ETC (2021) *Making the Hydrogen Economy Possible*.

However, fierce debates continue to take place on the feasibility of the CCS approach (blue hydrogen). As CCS is generally regarded as an intermediate stage or short-term solution, blue hydrogen encounters a few major challenges including the doubts cast on its best capture efficiencies to reach 85-95%. The remaining 5-15% of the CO_2 will still be emitted and the scale is still massive. Furthermore, these high capture efficiencies have yet to be achieved. Moreover, additional costs associated with retrofitting existing facilities to include CO_2 transport, storage and monitoring also face acceptance issues. The stored carbon would need long term monitoring mechanism while the risk of leakages continues to be a liability.

As reported by many international surveys, green hydrogen is produced from water electrolysis powered by renewable energy/ electricity. Commonly adopted scenario in those major reports (such as IEA, ETC, ARENA, IRENA) includes the use of solar photovoltaic and wind turbine to drive various types of electrolysers that split water into hydrogen and oxygen. The hydrogen production cost projection is mainly based on the above-mentioned technologies. Other non-electrolysis renewable-based solutions do exist and have been discussed widely but not a mainstream practise when it comes to cost projection. These options include biomass pyrolysis, thermochemical water splitting, photocatalysis and anaerobic digestion of biomass. Green hydrogen is therefore, in many cases, solely referring to renewable-powered water electrolysis. Renewable energy, with particular interest in solar photovoltaic technology, shows decreasing costs accompanied with improvement in efficiency, which brings possibilities to low cost green hydrogen. The presence of mature electrolyser (alkaline electrolysers) and emerging new type of electrolyser (polymer electrolyte membrane (PEM) electrolysers) are another factor in strengthening the impression of green hydrogen being derived from renewable-powered electrolysis of water. Hence, in this study the evaluation of green hydrogen is closely associated with this technology.

Hydrogen Generation

Hydrogen production can be grouped into three primary pathways, namely

(a) Thermochemical pathway

(b) Electrochemical pathway

(c) Emerging pathway

Existing or traditional dedicated hydrogen production methods are mostly from the category of thermochemical approach. It is, however, unfair to perceive thermochemical pathway as the unclean hydrogen production method. The existing thermochemical approach is a carbon intensive process only because of the use of fossil fuel as the hydrogen source.

Thermochemical approach

The thermochemical method is a process involving the use of heat to interact with precursors. The use of fossil fuel as the hydrogen source dominates the thermochemical approach. Hydrocarbons, coal, natural gas and the biomass are common carbon-based fuels referred in the above. In the first stage of thermochemical approach, syngas made of hydrogen and CO/ CO_2 mixtures are produced. The syngas is subsequently subjected to the mature “water-gas shift reaction” to concentrate the amount of CO_2 and hydrogen. Conventionally, CO_2 is produced as the by-product without being paired with CCS. Figure 3 shows the mature and traditional thermochemical hydrogen production technologies. Steam methane reforming (SMR) is the most widely used method for hydrogen production followed by the coal gasification. The percentage of SMR and coal gasification varied from country to country but persistently both of them are the most used mature technologies. Hydrogen produced from these approaches requires further purification such as pressure swing adsorption (PSA) and gas separation membrane. Towngas in Hong Kong is adopting PSA in their production. With current purification methods, hydrogen purity levels of 99.9999% can be obtained.

Process	Description	Dis/Advantages
Steam Methane Reforming (SMR)	Light hydrocarbons, such as natural gas or biomethane (upgraded biogas), are mixed with steam in the presence of a catalyst at high temperature (~750°C) and moderate pressure to produce syngas. SMR on its own uses approximately 4.5L of water per kgH_2.	+ Established technology – Requires purification – High temperature required
Coal Gasification	Gasification involves reacting dried and pulverized coal with oxygen and steam or controlled amounts of oxygen in a gasifier at high temperatures and pressure to produce syngas. To date, black rather than brown coal has been the dominant fuel source globally. This currently comprises 18% of global hydrogen production. Coal gasification uses approximately 9L of water per kgH_2.	+ Abundant fuel – Requires purification

Figure 3 Mature thermochemical hydrogen production technologies. Source: ARENA *National Hydrogen Roadmap*.

Table 1 Mature, fast growing and emerging hydrogen generation methods

Item	Hydrogen generation method

1	Thermochemical - Fossil fuel without CCS (Grey hydrogen) - Fossil fuel with CCS (Blue hydrogen) - Thermochemical Water splitting (Green hydrogen)
2	Electrochemical - Polymer Electrolyte Membrane (PEM) - Alkaline Electrolysis (AE) - Upon connecting with renewable energy, it will be Green hydrogen
3	Emerging Approach

Table **1** summarizes the technologies which are mature, fast growing and emerging for producing hydrogen with low-carbon emission. As mentioned above, the current practice of thermochemical approach is solely producing grey hydrogen as CCS has not been associated. CCS is possible by retrofitting the existing plants, but the scale of production is an important factor. SMR and coal gasification plants must be built at large scale to offset the capital-intensive for the CCS asset. It is predicted that the capacity of CO_2 shall determine the size of the SMR/gasification plant eventually. The feasibility study performed by Hakamada (Hakamada 2012, Feasibility study of CO_2 free hydrogen chain utilizing Australian brown coal linked with CCS) also suggested that the size of the coal gasification plant will also be influenced by the economics of the liquefaction shipping vessel. Liquefaction of hydrogen is believed to be the dominant mode of overseas hydrogen shipping (e.g. route of Australia-Japan hydrogen supply chain).

The motivation to couple CCS into existing grey hydrogen production facilities is also depends on the market growth of hydrogen application by end users (beyond traditional feedstock usage). According to the prediction by ARENA (2019), a small-scale plant with 100,000 kgH_2/day would require 235,000 passenger fuel cell vehicles (FCV) on the road. Therefore, solely depending on domestic demand from one country is unlikely to establish the motivation. For that reason, emerging hydrogen production countries such as Australia and Chile, with relatively limited domestic demand, are eyeing on the hydrogen market growth in other countries with growing needs such as China and Japan. Only when the export offtakes are established, domestic market can also benefit.

The above analysis forms the foundation of challenges faced by the development of blue hydrogen because of the complex yet uncertain external stimuli. This partly explains the emergence of new technologists and global players diving directly into developing green hydrogen technologies without the blue intermediate.

Thermochemical water splitting is another potential thermochemical approach for producing green hydrogen as the need for carbon-based starting material is eliminated. Unlike the fossil-fuel starting materials, thermochemical water splitting drives the hydrogen production from water using metallic component (e.g. aluminium). When the reactive metallic materials interact with water, water reduction takes place to release hydrogen. The metallic materials are correspondingly oxidized into metal oxides and become inert. Subsequently, the metal oxides are subjected to high temperature to thermochemically reduce the metal oxides back into their metallic counterparts. The source of heat could be from renewable energy such as solar thermal or geothermal. These processes are repeated to sustain the continuous hydrogen production.

Albeit uncommon, thermochemical approach can be potentially green in producing hydrogen when non-fossil resources are used as the hydrogen source.

<u>Electrochemical approach</u>

The electrochemical approach for hydrogen production is referred to a process called water electrolysis occurs in an electrolyser. An electrolyser is a device with a simple working principle consists of a positively charge electrode (anode) and a negatively charge electrode (cathode) immersed in water medium. When sufficient voltage is supplied to the anode and cathode, water is oxidized at the surface of anode releasing a hydrogen ion (from a water molecule). The hydrogen ions then diffuse to the cathode and be reduced to form hydrogen. Overall products of water electrolysis are hydrogen and oxygen gases. With proper electrolyser design, hydrogen and oxygen can be separated upon generation and can be use with or without further purification.

Hydrogen produced from water electrolysis is green with low carbon emission ONLY when the supplied voltage/electricity come from the renewable energy. If the electricity is supplied by conventional non-renewable grid, it can only be considered as a typical electrochemical process (e.g. electrochemical process in chloralkali-water chlorination) with carbon emissions determined by the source of the power plant. A complete plant involving water electrolyser requires balance of plant

(BoP) which usually includes compressors, heat exchangers, pumps, control systems and various valves.

Water is the hydrogen source in water electrolysis. It has been regarded as the cleanest source of hydrogen. However, the applicability of water electrolysis strongly depends on the geolocation of the plants. Nine litres of water are required to be electrolyzed into one kg of hydrogen. It is, therefore, convenient to understand its limitation in regions with water resource issues. It could be a heavy burden on municipal planning when water usage should be divided into multiple facets (e.g. drinking water, agricultural activities, industrial usage and now hydrogen production at large scale (GW scale).

Although the electrolysis of water is based on simple concept, the technologies used in developing electrolysers are considerably varied. There are three types of electrolysers, namely: alkaline electrolyser (AE), proton exchange membrane electrolyser (PEM) and solid oxide electrolyser (SOEC). Among these three types of electrolysers, AE is the most mature technology and is readily available at a large scale. Chloralkali water treatment with a long application history has contributed to the development of improved AE. PEM electrolyser is relatively new but is already commercially available. It is the fastest-growing electrolyser type used for hydrogen production. SOEC is currently limited to the laboratory scale at this stage. Although SOEC demonstrates higher efficiency, its high operating temperatures ranging from 650-1000 °C may find usage in niche applications. Both AE and PEM analysers have operating temperatures of 50-80 °C. In this study, AE and PEM electrolysers are compared and analysed accordingly.

Figure **4** compares the operational of AE and PEM electrolysers. Advantages and disadvantages of the two electrolysers are included in the table but will be discussed in more detail below.

ELECTROLYSER	DESCRIPTION	DIS/ADVANTAGES
AE	Electrochemical cell that uses a potassium hydroxide electrolyte to form H_2 at the negative electrode and O_2 at the positive electrode	+ Currently lower capital costs + Benefits from Chlori-alkali process improvements + Well established supply chain and manufacturing capacity – Poor current density/larger footprint – Oxygen impurity in the hydrogen stream – Low pressure hydrogen product
PEM	Also known as a proton exchange membrane. Water is catalytically split into protons which permeate through a membrane from the anode to	+ Smaller, flexible and modular + Faster dynamic response and wider load ranges + Lower temperature operation

	the cathode to bond with neutral hydrogen atoms and create hydrogen gas	+ Higher power cycling capability + Higher current density + Higher purity hydrogen – Currently higher capital costs

Figure 4 Description of AE and PEM electrolysers.

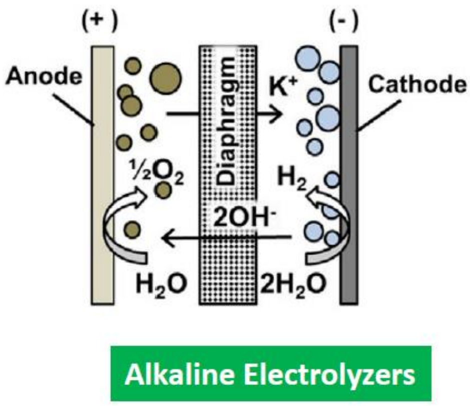

Figure 5 Cross-sectional view of alkaline electrolysers

Due to its maturity, AE electrolyser has a lower capital cost and has found a few practical applications not limited to hydrogen production. Figure 5 shows the design or geometry of AE. As explained, oxygen and hydrogen are produced at anode and cathode, respectively, upon supply of sufficient voltage across the electrodes (presumably voltage supplied by renewable sources). AE uses a low-cost diaphragm (usually porous materials) as the separator allowing the transmission of ions. By examining the structure in Figure 5, it is also convenient to understand the possible transmission of oxygen bubble into the hydrogen chamber or vice versa, resulting in the presence of a gas mixture requires gas product purification to obtain pure hydrogen before it can be fed into fuel cell for electricity generation. Post-reaction gas purification is an element of cost for AE system. The diaphragm made of porous materials could be blocked by impurities when the water is not clean and thus needs replacement periodically. The most critical disadvantage of AE electrolyser is its geometry, in which the cathode and anodes are physically distant from each other. This introduces internal resistance, resulting in lower current densities ranging between 0.1-0.4 A cm^{-2} of electrode. The low current density has direct implications of the size (footprint) of the electrolyser. As current density reflects the amount of hydrogen produced, a larger AE is needed to sustain a meaningful production hydrogen. Furthermore, it has stringent requirements on water input in which strong alkaline water is needed. Potassium hydroxide (KOH) with 25-35 wt% relative to water is typically added to water for its operation. The handling of the electrolyser together with the discharge of strongly alkaline water is a serious consideration when adopting AE.

The disadvantages of AE in using strong alkaline electrolyte and low operating current can be addressed and hence the emergence of PEM electrolyser. In general, PEM has a smaller equipment footprint with higher current density. High pH water is not needed in PEM electrolyser. However, it introduces different kinds of challenges as below.

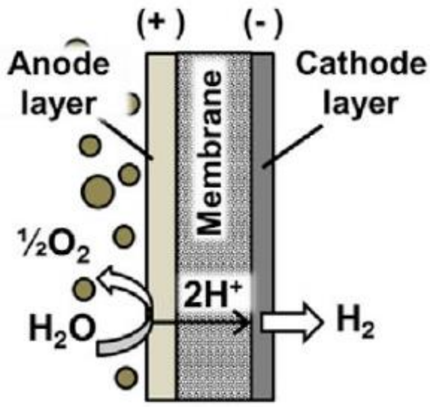

Figure 6 Cross-sectional view of PEM electrolysers

Figure **6** depicts the geometry of a PEM electrolyser. As a counter solution to address the low operating current density of AE, the anode and cathode materials are placed on an opposite sides of proton exchange membrane (a paper-like thin membrane) as indicated in the figure above. This is called a “zero-gap” membrane electrode assembly (MEA) using Nafion as the membrane. This membrane allows ONLY protons to be transferred from anode to cathode. Due to the close proximity of both electrodes, internal charge resistance is significantly lower, thus affording higher operating current densities ranging from 0.6 - 2.0 A cm^{-2}, which is 5-6 times higher than that of AE. With this improvement of current density, a much smaller equipment footprint is afforded. Furthermore, as the membrane is not a porous material and does not allow the transportation of bubbles, high purity gas of hydrogen is produced. Purity of hydrogen produced from PEM electrolyser can be directly used without further gas separation. Alkaline water is also not needed for operation of PEM electrolyser. This is another merit of PEM electrolyser.

However, PEM electrolyser requires the use of highly pure water in which the use of deionized water is commonly practiced by manufacturer and academia. The usage of highly clean water is to prevent the fouling of membrane as well as the deactivation of catalyst by impurities. Such a requirement for water quality poses stringent challenges because the providing highly clean water as the input may not be widely practical at many places. The price of PEM electrolyser is also much higher than that of AE. The high price is mainly due to the expensive platinum being used as the electrode catalytic materials for PEM electrolyser. Furthermore, the assembly of zero-gap membrane is complicated and the proton-exchange nafion is also subjected to fouling issue. Hence, the durability of the PEM electrolyser needs further improvement. These issues are currently under tackling by academia and industries. Mainstream efforts include the search for active non-noble metal catalyst as the replacement of platinum. The membrane and catalytic materials with better robustness against fouling and deactivation are also under formulation. Robust materials (catalysts and membrane) will remove the needs of the highly pure water as input.

Emerging approach

Water electrolysis enabled by renewable energy is dominantly perceived worldwide as the closest practical way in producing green hydrogen. The technology readiness levels (TRL) of both renewable energy (predominantly photovoltaic) and electrolyser suggest the feasibility of this combined approach. Nonetheless, other emerging approaches continue to be explored and developed as the possible longer-term solutions. **Figure 7** shows the projected timeline of the U.S. Department of Energy for hydrogen production technologies. As can be seen, electrolysis driven by solar (the so-called Green Hydrogen – Electrochemical approach in this study and many other reports) is within the roadmap after coal gasification (or SMR) with CCS. The longest-term in the figure suggests other approaches such as photocatalysis and photo-biological methods to be ultimate hydrogen production methods.

According to **Figure 7**, the approaches located at the longest term are photoelectrochemical method (PEC), solar thermochemical hydrogen production (STCH) and photo-biological method. All of these approaches are considered "solar pathways" as they are all triggered by sunlight. They are in general guided by the development of new and improved inorganic or biological catalytic materials. A specific term of "solar-to-hydrogen" (STH) is used as an expression of efficiency elucidating the conversion of solar energy directly into hydrogen. An ultimate goal of STH of 25% is set and currently the best STH of around 16% has been achieved on tandem PEC devices. The progress of these non-electrochemical approaches has seen steady but slowly incremental increase in efficiency. The ultimate goal of 25% STH is predicted to be achieved within this decade. The cost of PEC hydrogen is at this stage still unaffordable high. The improved STH efficiency and scale up production are expected to further lower the hydrogen cost.

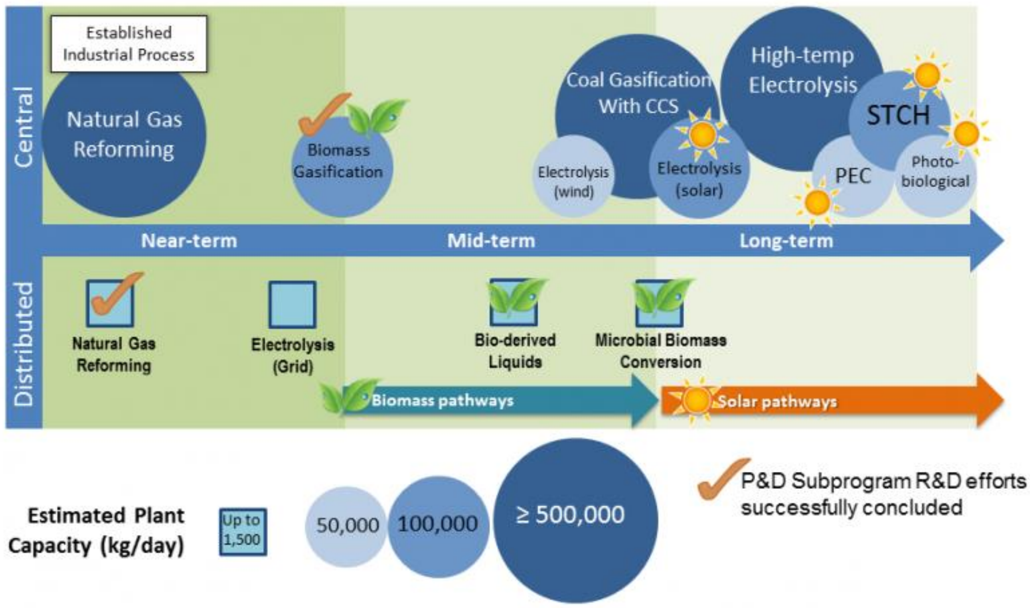

Figure 7 Near-term, mid-term and long-term technologies for hydrogen production.

C2. Hydrogen Distribution

Hydrogen Storage and Transportation

While the general discussion on hydrogen economy has been focussed on hydrogen production and its cost, the storage and transportation of hydrogen are yet other critical components requiring different technologies and associated with different costs.

As of today, hydrogen (which is not green) is produced and used on the same sites. Industries consuming hydrogen in processes such as ammonia plant and petroleum/ petrochemical refining facilities are producing hydrogen at the same facilities or places geographically adjacent that allows transportation by truck or pipelines in the form of compressed gas or liquefied hydrogen. The scale of total transportation of hydrogen is small. For example, there is less than 5000 km of hydrogen pipelines in use (BloombergNEW 2019 – *Hydrogen-the economics of storage, transport & delivery*).

When the hydrogen is used in small scale and at distributed locations, the additional cost for hydrogen storage and transport would be the greatest. Lowest green hydrogen costs for end users could be achieved in the large scale hydrogen production with co-located user points. In this regard, green hydrogen has the possibility to exercise flexibility in co-location or has close proximity to the hydrogen end use.

With the new green hydrogen applications (beyond conventional hydrogen-consumed industries) in energy and transportation sectors, the development of extensive storage and transport system appears to be needed. For instance, the availability of low-cost renewable electricity or natural gas with CCS may require separating production site and the location of end use. The transportation of hydrogen from its favourable production sites to end use locations will be an indispensable cost factor for hydrogen usage.

Hydrogen can be transported in pure form as compressed gas at pressures up to 1000 bar or in liquid form at -253 °C. It can also be transported in the form of hydrogen vectors such as ammonia or solid state hydrogen carriers (e.g. metal hydrides). Energy loss incurred during the transport of hydrogen depends on the mode of conversion. Compression and decompression of hydrogen may have total energy loss ranging from 0.5 to 11%. However, conversion into ammonia followed by re-conversion back to hydrogen may experience total energy loss of up to 73%. However, the selection of most economical transport mode is not solely influenced by energy loss factor. It depends on the volumes and distances. Three critical points largely define the scope of use of different technologies: volume, distance and physical states.

By evaluating the above three critical points, hydrogen can then be transported via (a) compression, (b) liquefaction, and (c) materials based or chemicals. Compression is performed by pressurization of hydrogen in cylinders made of either steel (relatively lower pressure) or carbon composite (high pressure). However, compression technology is facing the issue of lower hydrogen density (limits the total of total transported amount of hydrogen). Liquefaction solves the problem of the total amount of transported hydrogen. It is high cost because of the cryogenic condition and the requirement of advanced materials for storage. Alternatively, hydrogen can be stored in material carriers such as ammonia, liquid organic hydrogen carriers (e.g. toluene) and solid-state metal hydrides. It has higher hydrogen density than compression and less costly than liquefaction. However, it suffers from energy loss during the recovery of hydrogen from the materials based or chemicals.

Compression

Once produced from electrolysis, hydrogen can be readily pressurized at 35 bar. Hence, it can be stored directly at this pressure without further compression. This is an economical and viable method but only suitable for lower volumes of hydrogen. It is chosen when there is plant space limitations as well as higher capital cost of larger tanks.

If hydrogen is produced at elevated pressures, its compression related costs can be reduced significantly. However, electrolysers are typically operated at lower pressures of up to 35 bar. There are two main compressors commercially available: ionic compressors and the widely used mechanical compressors. Mechanical compressors are the most common mechanism provided at the much lower cost. However, the bearings and seals within mechanical compressors are the most common sources of system failure and may cost an additional burden on maintenance. Bearings and seals are not required for ionic compression but ionic compressors have a higher price. Electrochemical compressor is another potential compressor in the future. It is not commercially available with a TRL of 3. It has the potential to compete with mechanical compression as it can operate at higher efficiencies of 80% with a smaller footprint. As bearings and moving parts are not present in the electrochemical compressor, it may lower its maintenance and have quieter operation. With the continuing improvement in compressor, it is likely to continue to play a role in dealing with transportation of a lower amount of hydrogen.

Table 2 Mature hydrogen compression technologies. Source: ARENA 2019 – *National Hydrogen Roadmap*.

Technologies	Description
1. Low pressurized tanks	No additional compression is needed for hydrogen production. It is only used for stationary storage where lower quantities of hydrogen are needed relative to available space. It is an established technology but with poor volumetric energy density.
2. High Pressurized Tanks	A mechanical device increases the pressure of the hydrogen in its cylinder. Hydrogen can be compressed and stored in steel cylinders at pressures of up to 200 bar, while composite tanks can store hydrogen at up to 800 bar. Typical pressure ranges are 350 to 700 bar. Compression is used for both stationary storage and the transport of hydrogen. Compression is an energy intensive process with a low volumetric energy density
3. "Line packing" gas pipelines	This technique is already used in the natural gas industry, whereby, by altering the pipeline pressure, gas can be stored in pipelines for days and then used during peak demand periods.

Liquefaction

Liquefaction involves cooling hydrogen to -253 °C and therefore incurring much higher cost than that of compression technologies. However, it might become more economic where there is stringent plant space, high hydrogen demand, and ultra-long distance transportation (considering the higher volumetric density compared with compression). The first shipping demonstration using cryogenic liquefaction will only be available in 2022 with Japanese company Kawasaki Heavy Industries as the technology provider to transport liquefied hydrogen from Australia to Japan. Continued research and developments are focused on improving the efficiency of liquefaction. The aspects include the reduction of vaporization rates of liquefied hydrogen, improvement of the heat exchanger for insulation, and the provision of larger insulated storage tanks. Liquefaction is expected to add another \$2/ kgH_2 to the cost of hydrogen by 2025.

Table 3 Mature hydrogen liquefaction technologies.

Technologies	Description
1. Cryogenic tanks	Through a multi-stage process of compression and cooling, hydrogen is liquefied and stored at -253 °C in cryogenic tanks. Liquefaction is used for both stationary storage and the transport of hydrogen. It has higher volumetric storage capacity than that of compression. It, however, requires advanced and more expensive storage materials.
2. Cryo-compressed	Hydrogen is stored at cryogenic temperatures and combined with high pressure at 300 bar.

Material Based / Chemicals

The Storage and transportation of hydrogen using hydrogen vectors also represent an important opportunity. Ammonia, liquid organic carriers and metal hydride are the serious candidates that offer different scenario of end use applications. While existing ammonia plants via traditional Haber Bosch facilities will require modifications to incorporate clean hydrogen, the capital costs for ammonia could be reduced by leveraging current infrastructure. There are also a number of emerging direct ammonia synthesis technologies using electrolysis. This non-Haber Bosch processes claim to be less energy intensive. One shortcoming of using ammonia as a hydrogen vector is the energy penalty during its conversion back to hydrogen. Though ammonia cracking can separate hydrogen, metal catalytic membranes with a TRL of 6 are needed to produce highly pure hydrogen of fuel cells grade.

Metal hydrides have long been known as a hydrogen carrier. They can store hydrogen by binding the hydrogen to form a solid-state compound with metal with a better safety prospect. However, it faces challenges in the temperature requirements for releasing hydrogen from metal hydride and its slow release kinetics hampers its wider acceptance thus far. In its solid form, it is also a heavy storage unit. Though its heavy weight is often seen as a disadvantage, it can find uses in niche applications. For example, its weight can provide stability in a natural-disaster prone area as compared to a lithium battery or pressurized hydrogen tank system.

Organic liquids can be used to carry hydrogen upon sufficient hydrogenation reaction. Toluene and dibenzyltoluene (DBT) have been widely studied as potential candidates. Toluene, in particular, has been studied since the 1980s. Adding hydrogen into toluene can form methylcyclohexane (MCH) or dibenzyltoluene (DBT), as a hydrogen carrier with a TRL of 7. DBT is safer, easier to handle and cheaper than MCH. However, temperatures of >200 ° are still required to release hydrogen through the dehydrogenation process.

Table 4 Alternative hydrogen storage technologies in the media of vectors

Technologies	Description
1. Ammonia	Hydrogen is converted to ammonia via the Haber Bosch process. This ammonia can be added to water and transported at room temperature and pressure. The resulting ammonia may need to be converted back to hydrogen at the point of use. Some infrastructures is established and high hydrogen density can be achieved. However, the energy loss is huge (up to 73%) for conversion back to hydrogen. The handling of ammonia could be hard because it is a toxic material.
2. Metal hydrides	Metals bond to hydrogen to form a new compound. This approach has mobility problems due to the temperature requirements, the weight of storage units and slow hydrogen release kinetics. This method is now being examined for other niche hydrogen applications such as in military use.
3. Liquid organic hydrogen carriers (e.g. tolune)	Organic liquids can carry hydrogen through hydrogenation. Subsequent dehydrogenation using catalysis can release hydrogen for other applications. This enables the storage and transport of hydrogen as a liquid at ambient temperature and pressure. Converting toluene with hydrogen to form methylcyclohexane (MCH) with a TRL of 7 has been achieved. Challenges include the high operating temperature and purification requirements. Some organic carriers are also considered toxic substances.

C3. Hydrogen Usage

Applications of hydrogen

Hydrogen has a number of potential or readily available applications across the energy and industrial sector (mainly as feedstock). It is also clear that the efficiency and cost of using hydrogen systems are less favourable than those of direct conversions of energy generation to electricity such as solar photovoltaic and wind turbine. As a feedstock usage, green hydrogen can directly displace non-green hydrogen with comparable efficiency. However, in the electricity sector, hydrogen could be an alternative means of energy storage and it can be converted to electricity using:

(i) Fuel cell, or

(ii) Turbine

A fuel cell is an electrochemical cell that reacts hydrogen with oxygen to generate electricity with water by-products. A turbine is an old technology where hydrogen gas is combusted to produce steam followed by electricity. As a fuel cell stack size can now be packed from kilowatts to megawatts, conversion of hydrogen into electricity via fuel cell technologies can be made suitable for many application scenarios. For centralized large-scale systems (e.g. >100 MW), combustion of hydrogen (co-firing) with turbine technology may be more likely.

Stationary application - Building Sector

Hydrogen could be used to generate electricity for stationary applications via either fuel cells or turbine. Fuel cells with different capacity are more likely to be relevant in the building(s) sector because turbines are suitable for large-scale system with > 100 MW capacity (e.g. power plants).

Remote area power systems (RAPS) or stand-alone power systems with difficulty in accessing grid electricity usually rely on transported diesel to power local generators for electricity. Transportation of fuels to those remote communities can be inconvenient and the associated cost could be high. Reliance on fossil fuels also has adverse environmental impact. A RAPS should include a hydrogen generator, low pressure storage (for short term but frequent use control) and a fuel cell. Although batteries systems have also been considered for similar scenario, hydrogen has additional benefit of being more cost effective, flexibility in scaling-up, and hydrogen storage period is generally longer than that of the rechargeable batteries. Furthermore, depending on the size of RAPS (ranging from single building to complex and to small villages with multiple buildings), there is potential to design hydrogen systems with centralized or decentralized systems. In a more centralized situation for larger electricity demand, hydrogen could be generated by large scale renewables and electrolysis, the produced hydrogen being fed into a centralized fuel cell to generate electricity. A precedent of this type of system has been built in the ENE-Farm in Japan. ENE-Farm is a large-scale fuel cell demonstration and commercialization programme aiming to deliver efficient and affordable fuel cell technologies for building applications. Presently, ENE-Farm units reform natural gas or liquefied petroleum gas in situ to feed a fuel cell with hydrogen. Although the use of fossil fuels has no CO_2 reduction effects, it helps to deliver cost reductions that pave way for low-carbon hydrogen distribution later. The initial cost per unit has reduced by 75% in almost 10 years (from more than USD 35000 in 2009 to around USD 9000 in 2018).

Alternatively, a more localized model could involve hydrogen generation via rooftop PV and electrolysis, where the hydrogen is consumed onsite. While it is more economical to have a more centralized model in the early stages of development, site specific feasibility studies should be considered for comparing the benefits of both. Smaller remote operations such as facilities in farm or mining sites without direct access to the electricity network present a favourable demonstration for hydrogen RAPS. This is due to the need for a continuous energy supply to support operation.

Remote power systems offered an attractive opportunity for hydrogen production and storage to lower the costs and GHG emissions of diesel or natural gas based remote power systems. 100% renewable energy on remote sites is possible with hydrogen, potentially at lower levelized cost than diesel only systems. Hydrogen storage could offer a lower cost option to batteries because of its longer duration storage although capital cost for a hydrogen system is higher. Hydrogen for RAPS is likely to be viable under the following conditions:

(i) Alternatives are expensive, such as diesel that has to be trucked long distance;

(ii) Battery costs for long duration storage remain high;

(iii) Hydrogen electrolyser costs decline steadily.

For zero emission off-grid systems, hydrogen energy could become a key technology. Beyond generating electricity with hydrogen via fuel cell, there are also opportunities in using hydrogen for heat production in buildings. Hydrogen could be blend with existing natural gas network or be used directly to heat local district energy that supply to buildings.

Mobility application - Transportation Sector

Hydrogen gas has long been envisioned as a potential transport fuel. Hydrogen fuel cell electric vehicles (FCEVs) have zero tailpipe emissions. Light-duty FCEVS receive most public attention when it comes to the direct use of hydrogen in mobility applications. FCEVs have also been considered for heavy-duty types such as buses, trucks, trains and ships.

In principle, FCEV consist of a PEM fuel cell stack and hydrogen storage tank pressurized at certain level. It has been seen as a complementary technology to battery electric vehicles (BEVs). In fact, they may be more suitable for traveling long distances (400-600 km without refuelling), have shorter refuelling times and lack easy access to BEV recharging infrastructures. Currently, a 6 kg tank can allow FCEVs to travel between 500-800 km. Toyota Mirai model has just achieved 1000 km travel distance with one time hydrogen refuelling and this sets a new milestone for passenger FCEVs.

Heavy-duty FCEVs such as trucks, buses and trains, have a much more favourable energy density by mass than BEVs and operate using different size fuel cell modules depending on the vehicle payload and distance requirement. Heavy vehicles also typically accept hydrogen at 350 bar due to the greater on-board storage space. 700 bar models are currently being developed. The higher hydrogen demand of heavy vehicles and typical “back to base” transport routes can make them a more favourable target market than passenger vehicles during the scale up of refuelling stations.

Although heavy-duty vehicles are more suitable to opt for adopt hydrogen fuel, globally, intercity heavy-duty trucks have seen less FCEV uptake due to the lack of refuelling infrastructure across highways. In 2018, about 4000 passenger FCEVs were sold to reach a total stock of 11200 units, which is an increase of 56% over previous year. This is still a small number compared with the BEV stock of ~5 million or the global car stock of more than 1 billion. Almost all passenger car FCEVs are made by Toyota, Honda and Hyundai, although Mercedes-Benz has recently begun selling limited volumes of a plug-in hybrid electric vehicle with a fuel cell.

Hydrogen fuel cell electric forklifts are already commercially viable as replacements for existing battery electric forklifts and it is globally estimated that 25000 forklifts have fuel cells. In the case of buses, China has reported the largest deployment, with more than 400 registered. Fuel cell electric buses were also operated in Europe and US at a smaller fleet size. Other demonstrated projects have rolled out fuel cell electric buses in Korea and Japan. Thousands are expected to be in operation now (mostly in China).

Regarding to fuel cell electric trucks, China is leading the global deployment and accounts for the majority of demonstration projects. Country-level statistics in 2018 indicate 412 units registered in China, supplemented by 100 vans. Separately 500 hydrogen fuel cell delivery vehicles are reported as operating in the city of Rugao alone and well over 100 are in full daily operation in Shanghai. Outside China, FedEx and UPS are trialling fuel cell range-extender Class 6 delivery vehicles in the US. The French postal service and other logistics companies in France have also installed small fuel cells onto 300 battery electric vehicles in their fleet.

For maritime sector, as of today, ships do not use hydrogen-based fuel (pure hydrogen or ammonia). However, several research and demonstration projects are looking at using ammonia as fuel for ship. Targets are also in place in some countries for low-carbon alternatives in domestic shipping. Sweden and Norway are two examples while the EU is developing a strategy to set CO_2 reduction targets for maritime transport. Among businesses, the world's largest maritime company – Maersk has announced in 2018 that it aims to become carbon neutral by 2050. To achieve this, it acknowledges that low carbon vessels will need to be commercially viable by 2030.

Hydrogen Refuelling Infrastructures

Hydrogen refuelling infrastructure is one of the key considerations for end users when considering the choice of clean energy vehicles. The promotion of the use of FCEVs faces obvious competition from BEVs, particularly within the passenger vehicles (light-duty type) category. On a global scale, the installation of hydrogen refuelling infrastructure is slow but has started to pick up momentum currently. The cost for building hydrogen refuelling stations is high. According to the International Council on Clean Transportation, a hydrogen refuelling station costs USD 0.6 to USD 2.0 million. The lower end of this cost is for stations with lower capacity of 50 kgH2 per day at 350 bar; while the upper end is for stations with 1300 kgH2 per day operate at 700 bar. A typical station consists of a standard overall system includes compressor, cascade storage up to 1000 bar, a cooling system and a dispenser at either 350 bar or 700 bar. Hydrogen in gaseous form is first compressed for intermediate storage with pressures of up to 1000 bar. If hydrogen is to be delivered in liquid form, an alternative station setup where the liquid hydrogen is delivered via truck, stored cryogenically onsite, vaporized and then dispensed. To facilitate a fast fill, the hydrogen needs to be pre-cooled to -40 C prior to dispensing and this increases electricity costs. Due to the temperature range requirements, control systems are needed to monitor volume, temperature, flow rate and pressure. Current dispenser nozzles also cost up to 100 times more than the petrol nozzles.

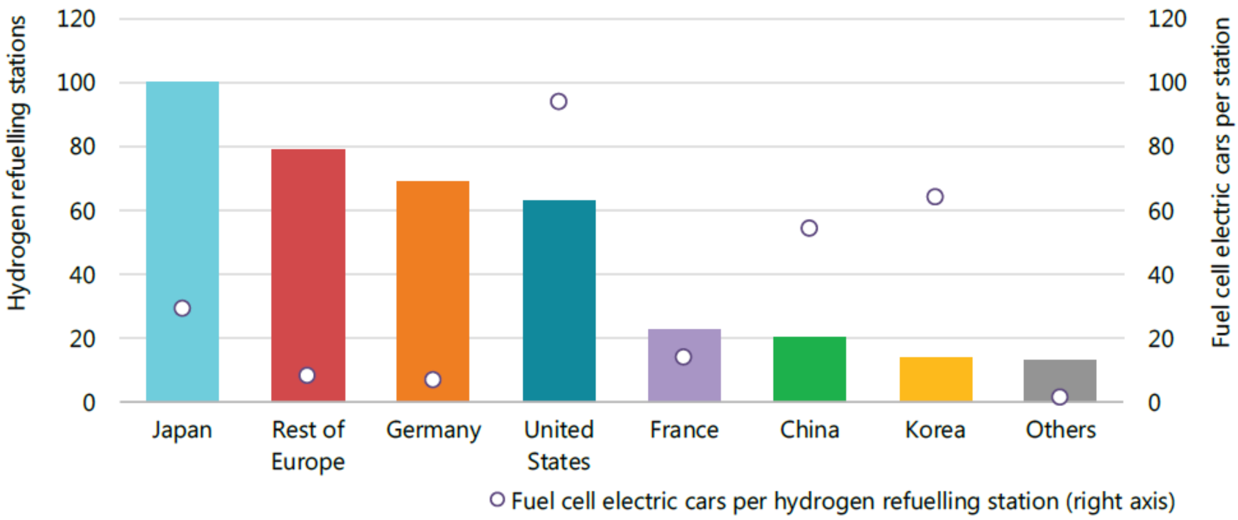

Figure 8 Hydrogen refuelling stations and utilization in different countries.

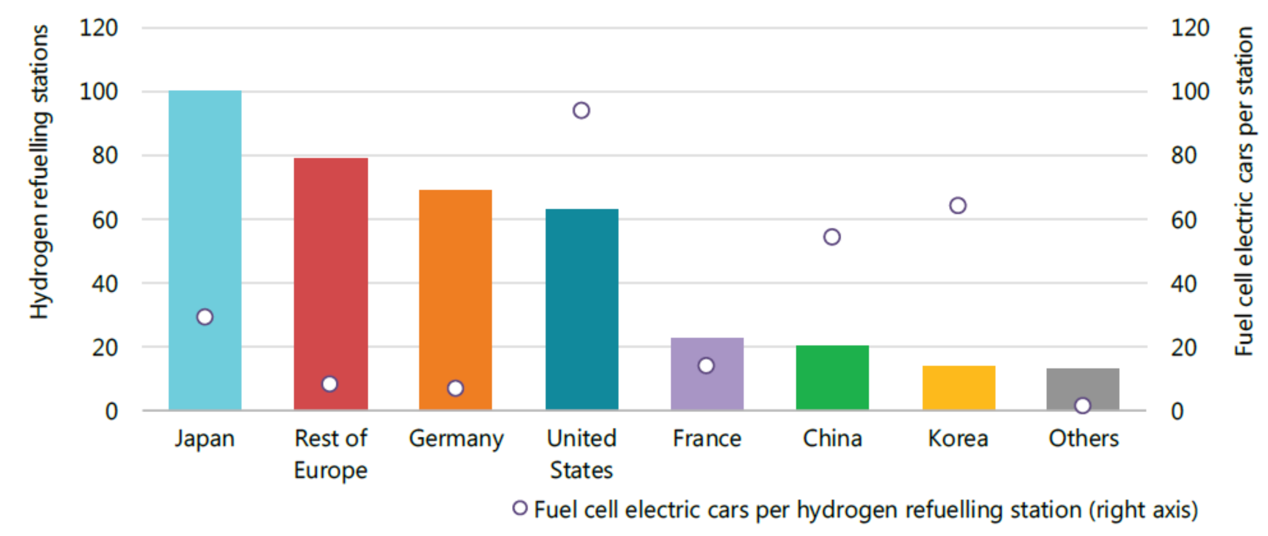

Figure 8 shows the hydrogen station numbers and its ratio with the number of FCEVs. The average number of FCEVs for every hydrogen refuelling station in most countries is much higher compared with the ratio of BEVs to their public charger (~10 BEVs per public charger). Delivered hydrogen prices are determined by the hydrogen refuelling station utilization. A ratio of 10 FCEVs per station (as in the case of Europe) implies that pumps operate less than 10% of the time if the refuelling stations were as small as 50 kgH_2 per day. This results in a high price of hydrogen per kg.

A higher ratio of FCEVs to refuelling stations as in China and Korea means better coordination between vehicle and infrastructure, which leads to lower hydrogen prices. France has paid close attention to this ratio and keeping it at a low ratio. They achieve this by focusing more on fleet with known demand and driving patterns, rather than private cars.

The variability of this ratio among countries is also an indicator of different approaches towards risk assessment. Approaches include tying the installation of refuelling station at or near hydrogen production site to serve dedicated fleets (such as buses or taxis). Onsite generation also reduces the delivery risk, decreases transport costs and provides station operators with better control in managing asset.

The high cost of hydrogen refuelling station is mainly attributed to two cost components: i.e compressor (can be up to 60% of the total cost at 700 bar station) and the storage tank (large size due to lower hydrogen density). These two factors are also subjected to the economies of scale. Increasing of capacity from 50 to 500 kgH2/day could reduce the specific cost by 75%. However, the actual cost of building a station will also be depending on countries with different safety and permitting requirements.

D. Impact on Related Industries

Industrial Sector

Green hydrogen may find new role as a clean energy source for new applications in electricity generation and electric vehicles, it has been (regardless of shades of origin) used in industries for decades. Today, hydrogen is an important feedstock for major industrial processes. Around 70 Mt of hydrogen is produced yearly and the vast majority of them are being used in industry. The four major industries are in the field of oil refining (33%), ammonia production (27%), methanol production (11%) and steel production via the direct reduction of iron ore (DRI) (3%). As of today, all of this hydrogen is NOT green hydrogen and is produced using fossil fuels (~70% from natural gas). The existing uses of hydrogen are important to the global economy and our daily lives because these industrial processes produce refined fuels for transport, fertilizers for food production, and construction materials for buildings.

Since it is an established practice in these important sectors, the use of green hydrogen involves direct displacement of hydrogen derived from fossil fuel as the incumbent source for production. The break-even point will be primarily driven by the price of natural gas against green hydrogen from renewable-electrolysis cycle. The falling price of green hydrogen is expected to be lower than grey hydrogen before 2030. As there is an established market for industrial use of hydrogen, there is less that must be done for market activation.

Although there is no oil refineries that are currently using electrolytic hydrogen, Shell's Rheinland refinery in Germany has announced a 10 MW electrolyser project that will supply around 1 ktH_2, or 1% of the refinery's hydrogen needs. Also in Germany, Heide, a small refinery near Hamburg, has announced a 30 MW electrolyser paired with offshore wind power to replace purchases of up to 3 ktH_2 per year. BP, Nouryon and the Port of Rotterdam are also jointly assessing the feasibility of a 250 MW electrolysis plant for the production of 45 ktH_2/year for the BP refinery in Rotterdam.

In chemical industries, more than 31 MtH_2/year of hydrogen are used as feedstock to produce ammonia, and more than 12 MtH_2/year to produce methanol. A further 2 MtH_2/year are consumed in comparatively small-volume processes (such as production of hydrogen peroxide and cyclohexane). However, most of this hydrogen is supplied from by-product generated within the sector. Chloralkali processes are another source of by-product hydrogen in the chemical sector, supplying around 2 MtH_2/year. In locations with the lowest cost renewable electricity (e.g. Chile, Morocco and China), electrolytic hydrogen would be close to being competitive in cost terms with natural gas for ammonia and methanol production. Much of the technology and equipment required for the cleaner pathways in the chemical sector is already in use across the industry, including the pumps, compressors and separation units.

For steel making industry, Sweden SSAB, LKAB and Vattenfall formed the HYBRIT joint venture to explore the feasibility of hydrogen-based steelmaking using a modified DRI-EAF process design. Currently at pilot phase, the first commercial plant is expected in 2036. Of the USD 147 million estimated cost of the pilot plant, the Swedish Energy Agency will provide USD 56 million with the joint venture partners contributing the rest. GrInHy and H2FUTURE, funded by the European Union's Fuel Cell and Hydrogen Joint Undertaking, aim to scale up emerging electrolyser designs to ensure that variable sources of renewable electricity can be utilized in steel production. The H2FUTURE project is employing a 6 MW proton exchange membrane design while GrInHy comprises a reversible solid oxide cell unit.

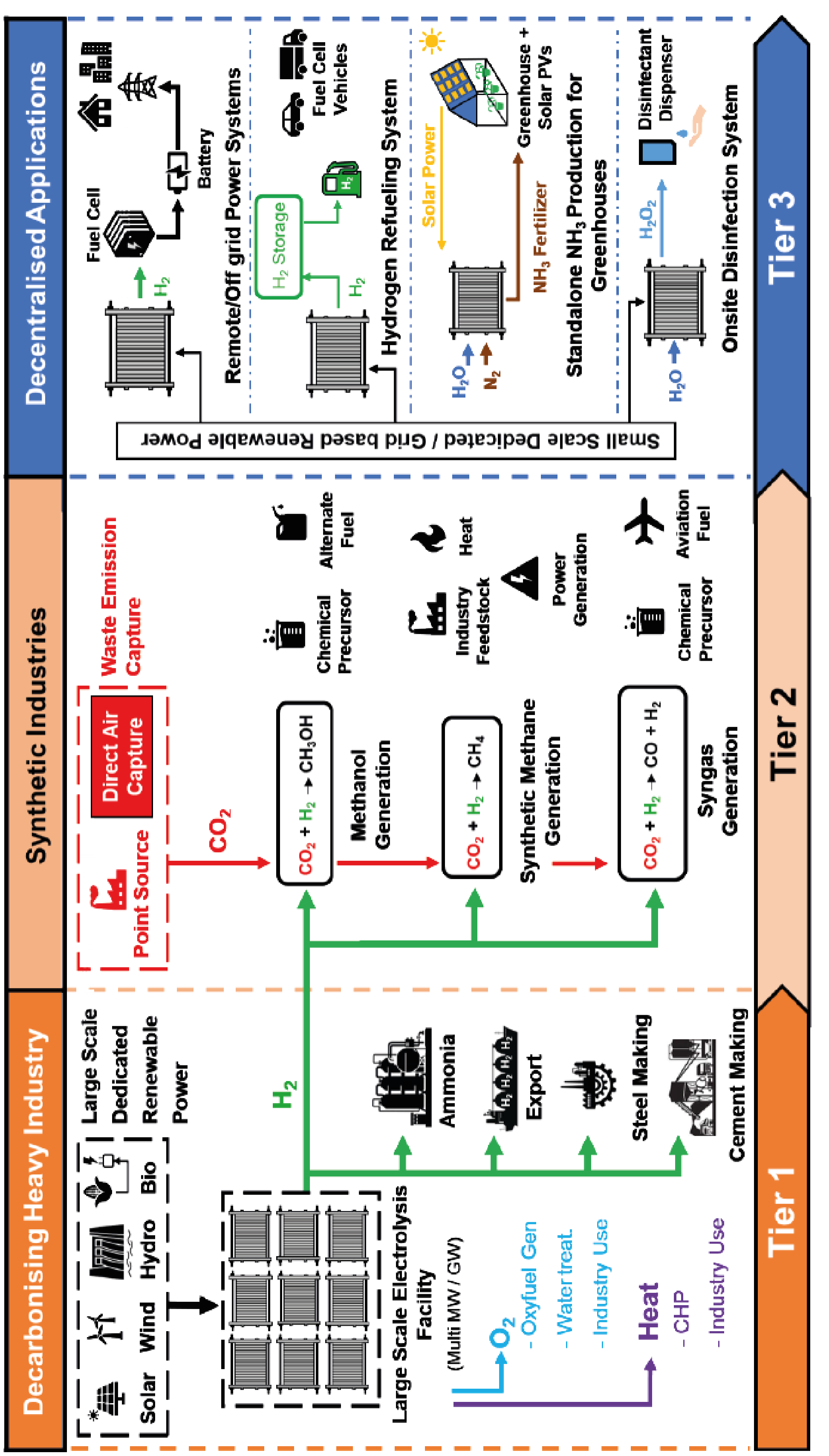

Figure 9. Hydrogen technologies for the applications under three tiers of end user groups.

If the availability of low-cost electricity and low electrolyser capital costs can be ensured, both will be the key drivers to the deployment at scale for hydrogen technologies in the current focus on renewable electricity-electrolyser system. Judging from the directions of most governments across the world, the growth in the renewable energy sector is certainly making this possible by not only lowering the cost of electricity generation, but also the availability of this electricity for longer durations within a day, which is termed as higher capacity factor. Specifically, the costs of solar P and wind-based electricity generation has seen a decline in costs since 2010. Electricity from solar PV and wind-based technology has decreased by 82% and 32%, respectively, while the capacity factors (duration of usability in a day) have increased by >30% for both solar and wind. In addition, the costs of electrolyser are reducing steadily (though not as steep as the solar PV market). By projection, the electrolyser manufacturers are projecting a decline in capital costs up to 40% by 2030 (near term) and 80% by 2050 (long term), respectively. The manufacturer Nel has recently announced their expectation of 75% reduction of electrolyser cost when Nel eventually shifts to their mega automated manufacturing facility.

Combined, the development in renewable electricity (dominant by PV) and all types of electrolysers are opening avenues for cost competitive hydrogen generation, which is expected to reach a meaningful price decrease to a range of $2 – 4 per kg, in countries like Australia and Chile in the near term. This range of price could be at par with fossil-fuel based hydrogen cost, as early as 2030. When this is achieved, green renewable fuels and chemicals would first receive significant opportunities to replace their fossil counterparts across the economy. This represents the strategy to decarbonise hard-to-abate industries such as gas networks, aviation, steel manufacturing and fertilizer production, without the need for major modification to existing supply chains. However, these activities are not the traditional stronghold of Hong Kong economy.

In **Figure 9**, the hydrogen technologies can be grouped into different Tiers according to the end user groups. **Tier 1** potentially involves deployment of large-scale hydrogen electrolyser with the hydrogen for export (relevant to the case of Australia and Chile) or in existing heavy industries (including steel making and cement manufacturing). Injecting hydrogen into the natural gas grid could be of relevance to Hong Kong's context. **Tier 2** involves development of additional process and infrastructure to convert H_2 into green vectors like methanol, methane and syngas for local (Hong Kong) use. **Tier 3** would have wider and possibly smaller decentralized applications. This is the opportune period for Hong Kong to build the required infrastructure building blocks to facilitate the mass adoption of H_2 as it pivots to low-carbon.

Green hydrogen standard and certification. Internationally, there is currently a lack of consistency of definition in classifying hydrogen based on carbon footprint. Though electrolysis of water powered by renewable energy is categorized as green hydrogen, the selection of specific electrolysers and renewable energy technologies would have huge impact on the total carbon emission during the life cycle analysis. Furthermore, hydrogen generated from fossil fuel but equipped with carbon capture and storage (CCS) mechanism is grouped as blue hydrogen. Based on similar argument, CCS capacity is significantly varied from low to high efficiencies. It is apparent that, under current terminology used to describe the grades of hydrogen, blue hydrogen could have huge range of carbon emission footprint. Hong Kong (especially EMSD) has rich experience in providing certification to rectify the standard of practice. In this regard, there is an opportunity for Hong Kong to take a leading role in establishing the standard of green hydrogen production technologies as well as providing the platform to certify the status of "greenness" hydrogen technology. The market demand for a trustworthy and reputable standard provider could be immense.

E. Recommendations

Without a doubt, numerous challenges await for hydrogen to be widely adopted in Hong Kong as a mainstream energy source (or fuel) for various applications, including in the transportation sector. While the provision of green or clean hydrogen may not be readily available shortly, preparations of readiness should be carried out immediately. There are existing fossil-derived hydrogen facilities used in Hong Kong. Non-green but hydrogen-related infrastructures could be built before the arrival of clean hydrogen. To enable long term sustainable hydrogen promotion, incentives for industries (e.g. hydrogen producer, hydrogen refuelling stations, and hydrogen certification) could be considered. Establishing policies and regulatory frameworks on hydrogen might be an immediate need to facilitate such hydrogen development.

Hong Kong Hydrogen Economy Study and Report

Survey Analysis

Background

A market survey, in which the respondents are mainly from the Hong Kong-based industrial sector, was conducted in August to September. The purpose of the market survey is to understand the status of awareness, readiness, acceptance, and potential concerns on hydrogen-related development among industrial stakeholders. A total of 88 respondents were recorded and documented. The scope of the survey questionnaires covers the topics on motivation, technology, safety, adoption, environmental, policy/government support, and economy of hydrogen in Hong Kong. Based on the responses from these industrial respondents, certain information can be derived and could form the basis for future considerations by the relevant authorities.

Findings and discussions

While hydrogen continues to be discussed rigorously in Hong Kong, **40.9%** of the respondents considered that Hong Kong is unlikely (in which 9.1% most unlikely; 31.8% unlikely) to produce sufficient hydrogen locally. It might be correlated to the opinion on the insufficient provision of land for green hydrogen production in Hong Kong. On this, **51.1%** of respondents expressed that they agree (in which 18.1 % strongly agree; 33.0% agree) Hong Kong has insufficient land for green hydrogen production via the means of renewable energy, such as using solar and wind technologies). This perception on land scarcity for industrial development of hydrogen production in Hong Kong might be addressed should there be a clear plan on hydrogen production locally by the government.

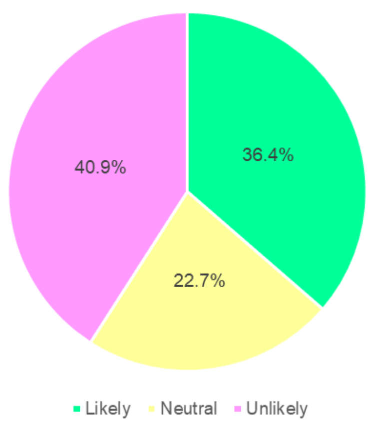

Figure 10. Survey question: To what extent do you agree that Hong Kong is capable of producing sufficient amount of hydrogen?

Among the 88 respondents, **62.5%** considered import of hydrogen from China to be a likely scenario. As the questionnaire on this topic allowed multiple selection, there was also **42.0%** responses documented the likelihood of having hydrogen import from other foreign countries. Examples of the foreign countries include Australia, Chile and South Africa. Australia and Chile have national roadmaps on hydrogen development to make hydrogen an export commodity. Together with Japan (Kawasaki Heavy Industries), Australia has demonstrated in 2022 the feasibility of transporting liquefied hydrogen via hydrogen ship from Australia to Japan. Large cargo containment system (CCS) with capacity of 160,000 m^3 is now being built in Japan. Hence, importing hydrogen via marine route (e.g. Australia and Chile) could be an alternative to pipeline (import from China) to sustain hydrogen demand in Hong Kong. On a special note, the awareness on the hydrogen-content in Towngas gas mixture (utility gas contains up to 51% of hydrogen in the existing pipelines) might be not high among the respondents. **64.8%** of respondents felt from neutral-to-unlikely on the use of Towngas to provide hydrogen in Hong Kong. This opinion might be changed if the understanding of current scenario is improved.

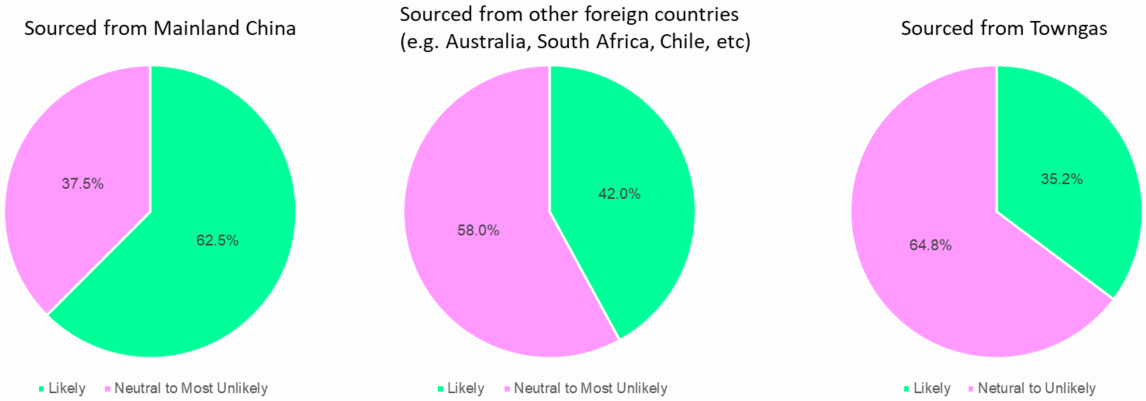

Figure 11. Survey question on the likelihood of hydrogen sources for Hong Kong usage.

The safe use of hydrogen is, in general, a public concern everywhere, not limited to Hong Kong. However, from this market survey with respondents from industrial sector, we found that **68.2%** of responses documented disagreement on those hydrogen-powered vehicles would be more dangerous in operation than that of petrol-powered, diesel-powered or electric vehicles. Only **10.2%** of respondents agreed that hydrogen-powered vehicles are more dangerous. These unexpected findings could be related to their extensive experience in handling fuels in their industrial practice. If appropriate international standards/ requirements are enforced, **71 out of 88** respondents considered hydrogen is safe to use. This is on par with the opinion on the safe use of electricity (73 out of 88). This finding is rather encouraging that the industrial practitioners consider hydrogen could be safely use when established standards are enforced accordingly. Based on this response, it strongly suggests that the establishment of standards and the plan for enforcement are of critical to facilitate the further development of hydrogen (as a fuel) in Hong Kong. To assist the general public perception on the safe use of hydrogen, **88.6% respondents agreed** (in which 44.3% strongly agree; 44.3% agree) that the trial run of hydrogen as fuel on, for example, electricity generation, public transport, commercial vehicles and etc. in Hong Kong should be increased.

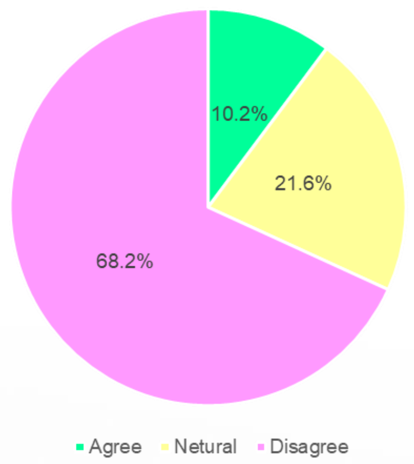

Figure 12. Survey question: In your general perception, do you agree hydrogen-powered vehicles in operation are more dangerous than petrol-powered, diesel-powered, or electric vehicles?

On the transportation side, in order to compete with battery electric and petrol fuel-powered vehicles, **56.8%** of respondents considered the selling price of hydrogen another key factor in determining the acceptance or adoption of hydrogen vehicle. It is reasonable to expect the higher operating cost of hydrogen-powered vehicle at least in its initial stage. On this aspect, **54.5%** of respondents considered the cost difference up to 20% (in which 28.4% on 5-10% of cost difference; 26.1% on 10-20% of cost difference) to be the ceiling in switching to hydrogen-powered vehicle compared with petrol-powered vehicles. Similarly, **55.7%** of respondents (in which 37.5% on 5-10% of cost difference; 18.2% on 10-20% of cost difference) documented the same opinion if switching against battery electric vehicles. There is also **64.8%** respondent agreed that hydrogen-powered is preferred to electric commercial vehicles when the range of mileage and charging/refuelling time are considered. Despite the above-mentioned input, there is also a significant portion of respondents

(**~22%**) expressed their non-interest at all in switching to hydrogen-powered vehicles regardless of the operating cost.

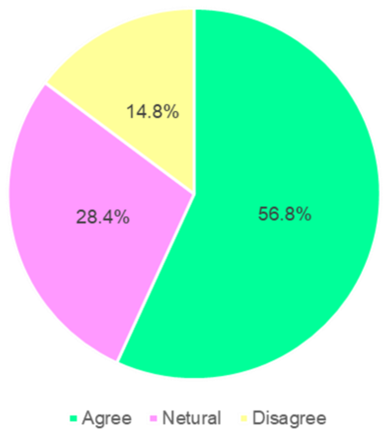

Figure 13. Survey question: Do you agree that the selling price of hydrogen would hinder the widespread use of it?

As the promotion of hydrogen usage in Hong Kong is part of the overall plan of decarbonisation towards carbon neutrality, **87.5%** respondents agreed (in which 39.8% strongly agree; 47.7% agree) that hydrogen would become one of the important energy sources in the future to reduce air pollution and will contribute to decarbonisation. Based on multiple choices, 73 out of 88 responses considered Hong Kong government to have the role in developing a clear and consistent regulatory framework on the use of hydrogen. This is followed by offering hydrogen infrastructure (66 responses), providing policy direction such as roadmap and delivery targets (64 responses), and adopting fiscal incentives to drive behavioural change (56 responses). Above items are considered the role(s) of government in promoting hydrogen development by the respondents in this market survey. In addition to the roles of government, there are also actions to be considered by Hong Kong government to support the development of hydrogen-related industries. Among the popular choices, **48 out of 88 respondents** considered offering of tax incentives to the consumer/buyers of hydrogen-powered vehicles would be welcomed. The other top three popular actions are offering land to hydrogen-related industries at low rental rate (43 responses), offering tax incentives to hydrogen-related industries (34 responses) and subsidizing hydrogen refuelling station operator, including construction and operation cost (33 responses). Some of these suggested items may have been implemented previously in other strategic development, such as in popularising electric vehicle. The advantages or lessons learned previously could be of reflective when considering hydrogen development.

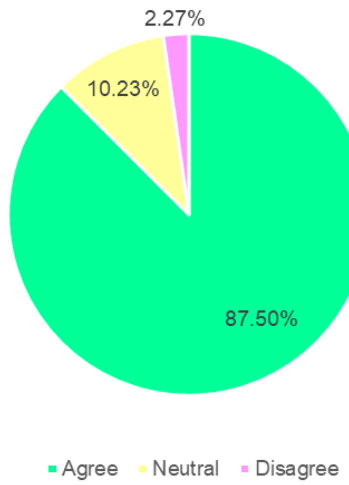

Figure 14. Survey question: Do you agree hydrogen would become one of the important energy sources in the future to reduce air pollution, and contribute to decarbonization?

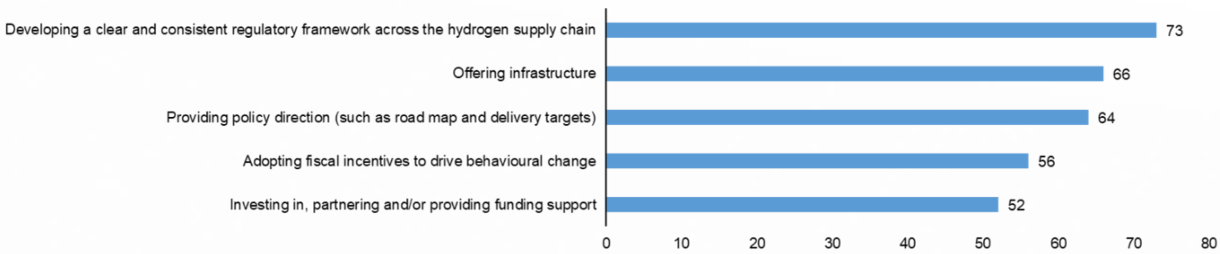

Figure 15. Responses on the roles of Hong Kong government in developing hydrogen-related industries.

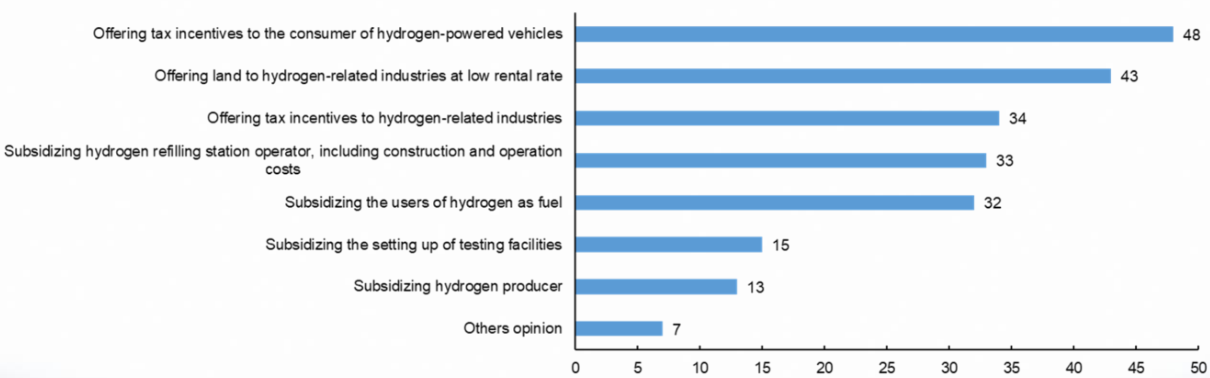

Figure 16. Responses on the actions should be initiated by Hong Kong government to support hydrogen-related industries development.

Although hydrogen-related development is one of the Hong Kong-wide focused matters and multiple forums on different facets of its relevance have been conducted over the past few years, the awareness on the availability of professional bodies and associations is rather low. **59.1%** respondents answered that they had no idea (or 0 professional body) on the professional body formed in Hong Kong relating to hydrogen. Similarly, **95.5%** respondents have no idea if there are programmes or courses offered by local universities/ institutions to train people who intend to work or have already worked in hydrogen-related industry. Respondents are not aware of the path to becoming a technical specialist or an expert in hydrogen field (i.e. technologies, economies, policies, etc.). Therefore, the public educational efforts could be another important aspect in promoting the development of hydrogen-related industries.

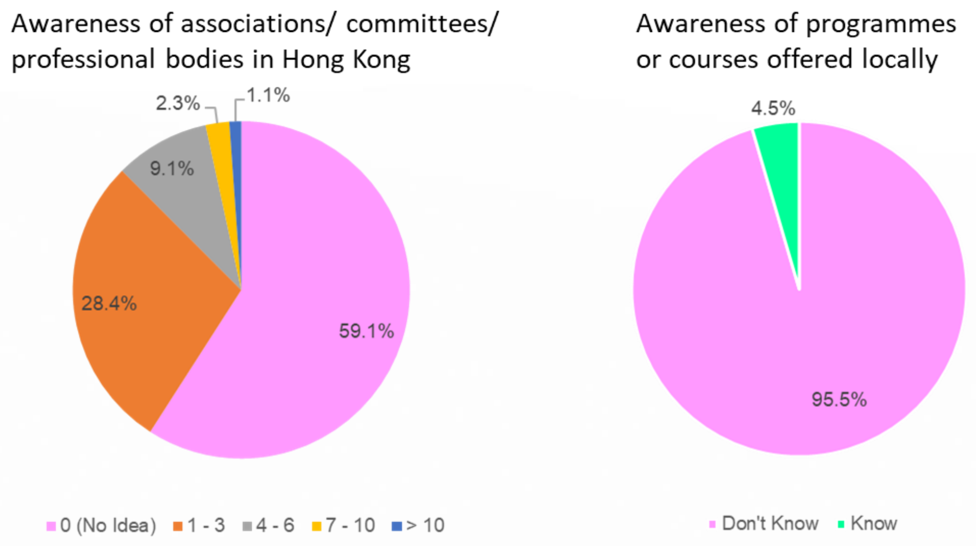

Figure 17. Awareness of the provisions of hydrogen-related professional bodies and training programmes available in Hong Kong.

Aligned well with the general discussion above, this survey found that **54.5%** respondents considered Hong Kong to have potential but not ready in developing industries while **26.1%** respondent considered Hong Kong to be partially ready for developing hydrogen industries. According to the survey, the situation can be improved by collaborating with Mainland China (47.8%

of respondents), Asia Pacific countries such as Japan, South Korea and Australia (31.6%) and European countries (15.4%). 5.1% respondents considered collaborating with the USA and Canada in developing hydrogen-related technologies to be helpful.

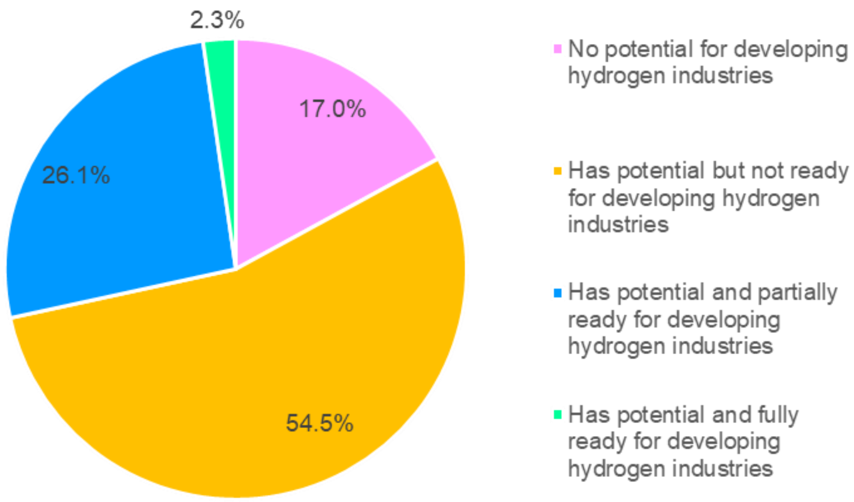

Figure 18. Survey question: Do you think Hong Kong is ready for developing hydrogen industries?

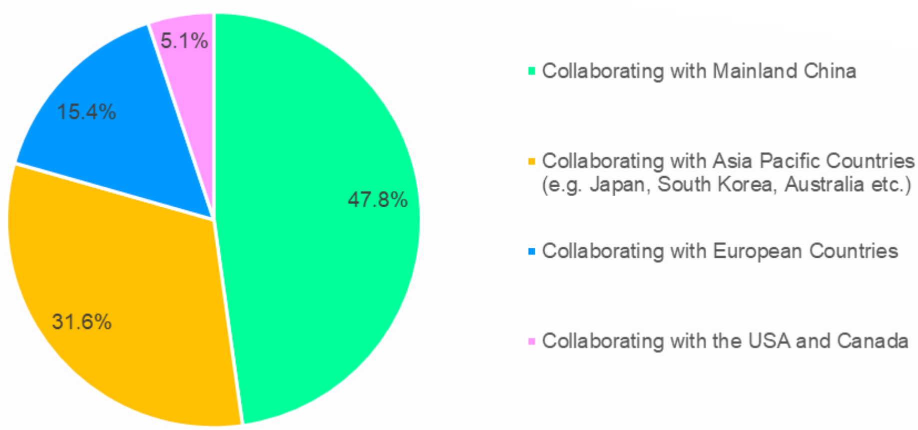

Figure 19. Survey question: Which of the following region(s) is / are Hong Kong should enhance the collaboration in researching and developing hydrogen-related technologies? (Only up to two options can be chosen below)

Despite the interest indicated above, there is **51.1%** respondents indicated that they have no intention to run hydrogen-related business. Among the 48.9% respondents who have intention, **27.9%** are interested in running consultancy service on hydrogen business. The second and third popular options are becoming hydrogen equipment supplier (16.3%) and conducting research & development

(16.3%), respectively. Interests in involving in hydrogen production, storage & distribution, setting up hydrogen refuelling station, and running testing and certification of hydrogen equipment are below 10%. Availability of affordable land use, amount of capital, provision of talent, and certainty of mature technologies are the top four obstacles considered to be the major hurdles in entering hydrogen industries. For the respondents who expressed no intention to run hydrogen-related business, **44.4%** of them are motivated by the potential growth of renewable energies and hydrogen technologies in Hong Kong. The other major motivations are the concern on climate change and sustainability (37.8%) and new perspectives and opportunities of market (35.6%), respectively.

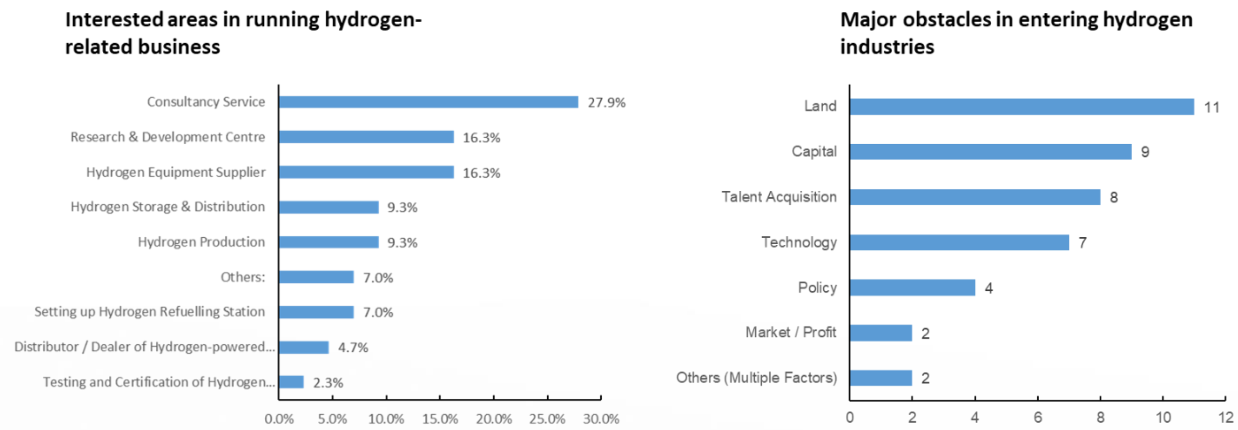

Figure 20. Responses on the interested business areas and the perceived obstacles encountered in hydrogen-related industries.

Based on the survey analysis, it can be suggested that Hong Kong's industrial stakeholders are in general interested in hydrogen-related business and do believe that it has constructive role in decarbonizing Hong Kong to achieve carbon neutrality. However, concerns due to the traditional challenges (e.g. land scarcity, hence this factor is not limited to hydrogen-related activities) and uncertainties (availability of mature technologies, potential of profitability, unclear policy and regulatory framework) are hindering the sector to make rapid decision in marching towards hydrogen-related areas. Clarity to reduce or remove the uncertainties would be of next important milestone should hydrogen is going to emerge as one of the main energy sources for Hong Kong's future.