International Cooperation Potentials for Korea's PtX Technologies

Investigation of potential PtX providers for Korea, and EU's and Germany's R&D and PtX support programmes

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The authors would like to thank the advisory members, Ms. Sunwha Lee (Korea Development Bank), Dr. Boreum Lee (Chonnam National University) Dr. Hyunsuk Jang (Institute for International Trade), Ms. Hyejin Lee (H2Korea), Dr. Sungwoo Cho (Samsung Engineering), Mr. Minwoo Han (Korea South-East Power Company) as well as the student researcher, Ms. Chaerin Lim (NIGT) for assisting data collection. The authors would also like to thank Dr. Stefan Pfenninger (TU Delft) for allowing the use of weather data from renewables.ninja.

Suggested citation: Miha Jensterle, Wona Lee, Hyunha Shin, Lea Mohnen, Dominik Ehlert, 2023: Title. Subtitle. Berlin: adelphi consult GmbH

Publisher:	adelphi consult GmbH Alt-Moabit 91 10559 Berlin +49 (030) 8900068-0 office@adelphi.de www.adelphi.de
Status:	December 2023

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Introduction

In 2022, the Republic of Korea unveiled a national policy direction aimed at nurturing strategic technologies pivotal for shaping the future society and upholding national security in the midst of intense global tech competition. In an era where the trajectory of a nation's economy, security, and diplomacy hinges on emerging and essential technologies, this initiative identified 12 national strategic technologies. These encompassed semiconductor and display, secondary cells, leading-edge mobility, next generation nuclear energy, leading edge bio, aerospace and marine, hydrogen, cybersecurity, AI, next generation communications, leading edge robotics and manufacture, and quantum. Subsequently, in 2023, aligned with the 1st National Basic Plan for Carbon Neutrality and Green Growth, the government declared the Carbon Neutral Technology Innovation Roadmap and delineated the 100 Core Technologies for Carbon Neutrality. Notably, this compilation encompasses the hydrogen supply sector, covering the spectrum of hydrogen production, storage, and transport.

In the same year, the Ministry of Science and ICT (MSIT) of Korea and the Federal Ministry of Education and Research (BMBF) of Germany convened their Joint Committee on Science, Industry, and Technology. The purpose was to affirm the similarities of the two countries' policy directions and reached a consensus on the need to cooperate in future research on "strategic technology development policies" between Korea and Germany. Consequently, an agreement was reached to enhance the partnership on strategic technologies, commencing with collaborative research involving the science and technology policy think tanks of both countries. The National Institute of Green Technology assumed a pivotal role in facilitating the implementation of these discussions and actively engaged in developing this collaborative research in conjunction with adelphi.

This research, conducted with the explicit goal of overcoming the limitations identified in prior studies undertaken by the National Institute of Green Technology (NIGT), seeks to address several key questions. Firstly, it aims to expand upon existing cost assessments, recognizing the previous research's focus on literature-based data, which was confined to a limited number of countries. Secondly, the study endeavours to enhance the assessment at the country level, moving beyond generic indicators by incorporating hydrogen-specific indicators. Furthermore, the research explores potential collaboration opportunities with Germany, acknowledging both Korea and Germany as hydrogen-importing countries. Despite differing specific conditions, the intention is to identify and capitalize on opportunities for cooperation as strategic allies. Lastly, the research aspires to achieve global impact by transcending the predominantly domestic orientation of existing studies on Korea's hydrogen-related environment. Through this comprehensive investigation, the aim is to assess and share Korea's PtX (Power-to-X) related status and goals, providing valuable insights to a global audience. The research is structured into three distinct work packages: the first assesses PtX import potentials, while the second and third work packages examine German, EU, and Korean PtX policies and R&D programs, conducting a comparative analysis.

In the context of evaluating the PtX import potentials in Korea, the assessment process comprises three sequential steps: a comprehensive cost assessment, a political assessment, and the subsequent identification of potential partner countries. The primary objective of this analysis is to facilitate a comparative evaluation of countries, pinpoint potential locations, and identify the principal cost drivers associated with PtX imports. It is crucial to note that the analysis does not aim to conclusively determine specific cost levels or definitively answer the question of whether to import hydrogen or ammonia from a particular country. Instead, its focus is on providing valuable insights into comparative aspects and key considerations influencing PtX import potentials in Korea.

The subsequent section of the report provides an overview of the German energy policy and energy security landscape, emphasizing the National Hydrogen Strategy developed in 2020 and updated in July 2023. This segment delineates the governance structure and expounds upon the pertinent policy instruments for ensuring the security of hydrogen imports. For a comparative analysis, the paper elaborates on Korea's hydrogen strategy, highlighting the Hydrogen Economy Promotion and Hydrogen Safety Management Act of 2020, the 1st Master Plan for Hydrogen Economy Implementation, and the governance structure of Korea's hydrogen economy

Lastly, this report outlines German and EU’s R&D and innovation programmes with a focus on German R&D and innovation programmes classified according to the responsible ministries and its purpose. Korea’s hydrogen focused R&D programmes defined and classified according to responsible ministry, R&D area and stage, duration, budget and its purpose to draw implications.

Finally, this document outlines the Research and Development (R&D) and innovation initiatives in both Germany and the European Union (EU). The emphasis is placed on categorizing German R&D and innovation programmes based on the responsible ministries and their intended objectives. Similarly, Korea's R&D programmes centered on hydrogen are detailed, classified by the responsible ministry, R&D area, stage, duration, budget, and intended purpose, aiming to derive meaningful implications from the analysis

1 PtX import potentials analysis

1.1 Cost Assessment – Hydrogen and Ammonia Cost Model

Modelled was an island (off-grid) system which generates its electricity exclusively from solar PV and wind power plants. Energy storage is only used for the product – liquefied hydrogen or ammonia – before it is evacuated from the production site, but no energy storage was used in order to increase the full load hours of the system, e.g. by battery electric storage. Minimum operating capacity was set to 20% of the nameplate capacity for all components (electrolyzer, liquefaction plant, Haber-Bosch process). Potential ramping limitations were not taken into account. Power generated in the PV and wind but not used to produce the PtX product was considered to be discarded and generate no revenue. The hydrogen and ammonia production system models are displayed in Figure 1 and Figure 2 below, respectively.

Figure 1: Hydrogen production system model

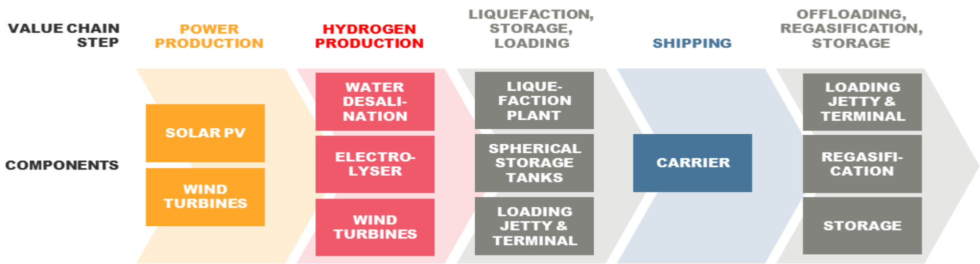


Figure 2: Ammonia production system model

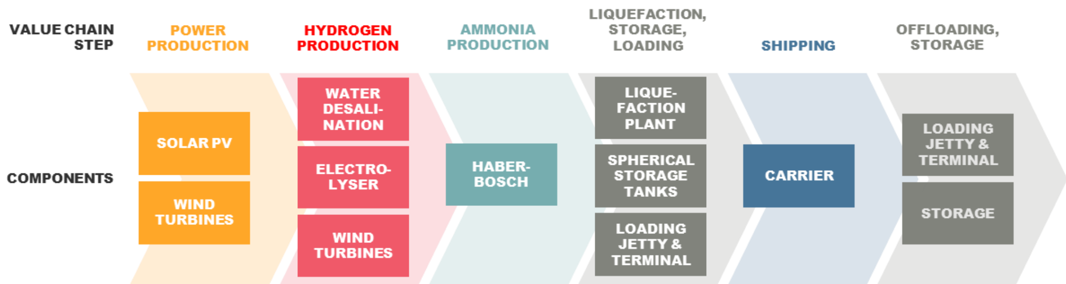


Table 1 below shows the most important techno-economic parameters of the PtX production system model. For all components and value chain steps, $Opex_{var}$ is considered to be limited to energy consumption and therefore zero since the entire system is powered by the energy initially generated by the PV and wind power plants (higher energy consumption of any downstream component would translate into higher capacities of PV and wind power plants and be reflected in their higher capex).

System component	Capacity	Capex	$Opex_{Fix}$	Lifetime	Conversion efficiency
Renewable energy					
Solar PV plant	Determined in-model	876,000 US$/MW [1,2]	0.9% of capex/y [2]	20	
Wind power plant	Determined in-model	1,274,000 US$/MW [1]	2.0% of capex/y	25 [3]	
Hydrogen					
Water desalination	16,988	1,500 US$/(t/d) [4]	1.0% of capex/y	20	
Water electrolysis	4000 Mwel	900,000 US$/$MW_{el}$ [5]	2.0% of capex/y	20 [5]	66% [5]
Hydrogen liquefaction	2640 MW_{el}	1,500,000 US$/$MW_{el}$ [6]	2.0% of capex/y	20	
Onshore hydrogen storage	160000 m^3	20 US$/$m^3$ [6]	1.0% of capex/y	30	
Hydrogen (off)loading - jetty & terminal	700000 t_{H2}/a	240 US$/($t_{H2}$/a) [6]	1.0% of capex/y	30	
Hydrogen carrier	160000 m^3 [7,8]	30,000 US$/$m^3$ [6,9]	4.0% of capex/y + 15 Mio US$/y [9]	25	
Hydrogen regasification	2640 MW_{el}	100 US$/$MW_{el}$ [6]	1.0% of capex/y	20	
Ammonia					
Haber-Bosch process w/ Nitrogen PSA	2,459 MW_{NH3}	340,000 US$/$MW_{NH3}$ [6]	3.0% of capex/y	20	87%
Ammonia liquefaction plant	2,459 MW_{NH3}	300,000 US$/$MW_{NH3}$ [10]	3.0% of capex/y	20	
Onshore ammonia storage	160,000 m^3	710 US$/$t_{NH3}$ [6]	1.0% of capex/y	30	
Ammonia carrier	160000 m^3	1,500 US$/$t_{NH3}$ [7]	4.0% of capex/y + 15 Mio US$/y [9]	25	

Table 1: Techno-economic parameters of the model

[1] (IRENA 2023), [2] Fn ISE, [3] (IRENA 2017), [4] Voutchkov 2018, [5] (IRENA 2021), [6] (IRENA 2022), [7] (Shoji Kamiya et al. 2015), [8] (Hank et al. 2020), [9] (Mohammed Al-Breiki und Yusuf Bicer 2015), [10] No capex estimate for ammonia liquefaction found in literature; 20% of the hydrogen liquefaction capex assumed in the model

The system was optimised so as to achieve the lowest cost of hydrogen/ammonia delivered to the port of Ulsan, South Korea. While the capacities for other components were fixed, the optimisation algorithm was used to determine the optimal capacity of wind and solar power plants as well as the number of hydrogen/ammonia carriers. The electrolyzer capacity was fixed at 4.000 MW for both value chains and all locations. While this is substantially higher than any of the plants in operation or under construction at present, such a capacity, in combination with the typical full-load hours that the electrolyzer can be expected to run at and the shipping distance of about 10,000 km, has enough output to fully utilise one to two hydrogen/ammonia carriers with a capacity of 160,000 m^3. The carriers use their cargo – hydrogen or ammonia – for their propulsion, with entire boil-off being used (Hank et al. 2020). At a shipping distance of about 10,000 km, this imposes a penalty of about 11% and 6% in terms of delivered hydrogen and ammonia, respectively. The onshore storage for both the on- and offloading port was considered to be equal to that of one carrier ship so as to ensure no time is lost in the port. For the on- and offloading ports, the model includes the construction of a terminal with a jetty, but excludes any deepening of the port berth. For both hydrogen and ammonia, regasification is included in the model. For ammonia, cracking is not included, since ammonia is considered the final product.

All locations chosen for hydrogen/ammonia production were on the coast so as to avoid any additional cost for transporting the PtX product over land. The locations were chosen so to be green field, avoid natural parks, and allow for to construction of a blue water port in the vicinity. For determining the shipping distances from each location to the port of Ulsan in South Korea, only shipping routes appropriate for LNG tankers were considered. Consequently, a cost assessment was conducted for a total of 81 sites.

1.2 Political Assessement

To determine suitable countries and sites for import, the process involved three steps. Initially, locations for hydrogen and ammonia production were chosen based on a generic assessment considering factors like country size, the share of manufacturing, and trade volume with South Korea. Subsequently, countries aligning with findings from existing studies (Galimova 2023, Hydrogen Council 2022, Jensterle et al. 2019, Frontier Economics 2018), which identified optimal locations for PtX, were selected. The IEA's Hydrogen Project Database was then utilized to narrow down countries and sites most relevant to the cost assessment, focusing on electrolysis technologies like ALK, PEM, SOEC, and dedicated to Solar PV and on/offshore wind renewable sources meant to produce hydrogen and ammonia. This process led to the selection of 54 countries for the initial political assessment.

The political assessment of potential partner countries involved choosing seven specific indicators grouped into three criteria: general, hydrogen, and bilateral relations with South Korea. The general criteria aim to evaluate a country's ability for export business by examining its industrial capacity and business environment. Therefore, indicators like the share of manufacturing per GDP and the ease of doing business index were used, providing insights into the industrial landscape. It's important to note that the latest available data for ease of doing business is from the year 2020, as the World Bank discontinued publishing the data due to internal ethics issues. The hydrogen criteria focused on assessing a country's readiness for the hydrogen economy. This involved evaluating the presence of a hydrogen strategy or equivalent outlining the country's potential future role in the global hydrogen market as either PtX importer, neutral or exporter. Additionally, the assessment considered the existence of green hydrogen projects and agreements related to hydrogen cooperation with South Korea. Lastly, to assess bilateral relations with South Korea, factors like political and strategic relationships, as well as trade volume, were taken into account. Political and strategic relationships encompass diplomatic relations and economic ties, such as free trade agreements. This assessment was carried out by expert evaluation with support of adelphi’s climate diplomacy and security personnel.

Criteria	Indicator	Indicator description		Weight
General				
Industrial capacity	Share of manufacutring/GDP [1]	Share of GDP, 0-1		5%
Business environment	Ease of doing business[2]	Score, cont. From 0-1		5%
Hydrogen				
Hydrogen strategy or equivalent	Hydrogen strategy or eq. published[3]	Strategy, Roadmap, Programme, Mission, Plan published or under development		0%
Potential role in global hydrogen market	Hydrogen strategy trade balance[4]	Score, discrete: 0 or 1	1: Export; 0: Neutral/Unknown; -1: Imports	20%
Green hydrogen projects	No. of green hydrogen projects in different stages (weighed) [5]	Score, cont. from 0 to 1	Relative grades: Concept: 15; Feasibility study: 20; DEMO: 40; FID/Construction: 56; Operational: 100	20%
Hydrogen coop. agreement w/ ROK in place	Energy agreement or hydrogen R&D cooperation MoU in place[6]	Score, discrete: 0 or 1	1: Energy agreement or hydrogen R&D MoU in place; 0: no agreement/MoU in place	10%
Bilateral relations w/Korea				
Political/strategic		Score, discrete: -1, 0 or 1	Expert assessment[8]: 1: Partner/Ally; 0: Good/Neutral; -1: Competitor/Adversary	30%
Trade relations	Trade volume/GDP[7]	Score, cont. from 0 to 1		10%

Table 2: Political assessment indicators

[1] (World Bank 2023), [2] (World Bank, 2020), [3] Each countries’ hydrogen related strategies or equivalent to that of were reviewed, [4] Reviewed the hydrogen related strategies or eq. to check whether they plan to export or import hydrogen, [5] (IEA, 2023), [6] (National Law Information Centre, 2023), [7] (Korea International Trade Association Statistics, 2023), [8] Assessment was carried out by expert evaluation with support of adelphi’s climate diplomacy and security personnel

As a result of the political assessment, the highest-ranked countries were Australia, Canada, Norway, Greece, Ireland, the United States, Vietnam, Oman, Chile, and the United Kingdom

1.3 Results

A total of 81 locations from 54 countries were mapped to compare the PtX import potential for Korea as depicted in the figure 3 and 4. Apart from the costs of PtX imports from a specific location and the exporting country’s political assessment, a final assessment step was taken: Potential exporting countries and locations were separated in two groups based on their potential future ability to export any PtX products to off-takers over short distances and/or via pipeline. The logic is that since PtX products are cheaper to move over shorter distances, in particular if this can be done via a pipeline (as is the case for hydrogen, more than for ammonia), it is reasonable to assume that regional trade of PtX products will take precedence over intercontinental trade. Therefore, countries with obvious PtX export potential through pipelines to its neighbours – such as like Norway, Ireland, and Denmark supplying PtX products to Germany – were deemed less interesting from Korea's standpoint. In the figures 3 and 4 below, this distinction is made by lighter shading for the with higher likelihood for regional exports, and darker shading for the countries which are most interesting as potential PtX suppliers for Korea.

The results seem to confirm – at least in the case of Korea – the common perception of countries such as Australia, Canada (here, its west coast) and Chile as some of the countries best positioned as potential future PtX exporterts – should large-scale intercontinental PtX trade materialise, which is by no means certain. Brasil, Columbia, New Zealand, Malaysia, Oman and United States (west coast) also appear well-positioned as potential PtX suppliers for Korea. Overall, locations in the Americas tend to appear better positioned than locations in the Middle East for exporting PtX to Korea. Noticeable is that especially locations with good to great wind potentials tend to be the ones with the lowest cost of PtX exports to Korea – and that this can offen compensate for longer shipping distances necessitating more carriers for the same amount of PtX delivered. Locations which are sun-rich but lack wind resources are currently not as competitive , due to the combination of large capex expenditure and low full-load hours. This could change in the future to some degree, should we see specific cost of components such as electrolysers and liquefaction terminals drop significantly. Another important – and often to some degree overlooked – factor is the cost of capital used to finance the PtX infrastructure. The results clearly demonstrate the significance of political stability and other factors determining a country's risk profile in its position as a potential PtX exporter.

Figure 3: Hydrogen import potential results

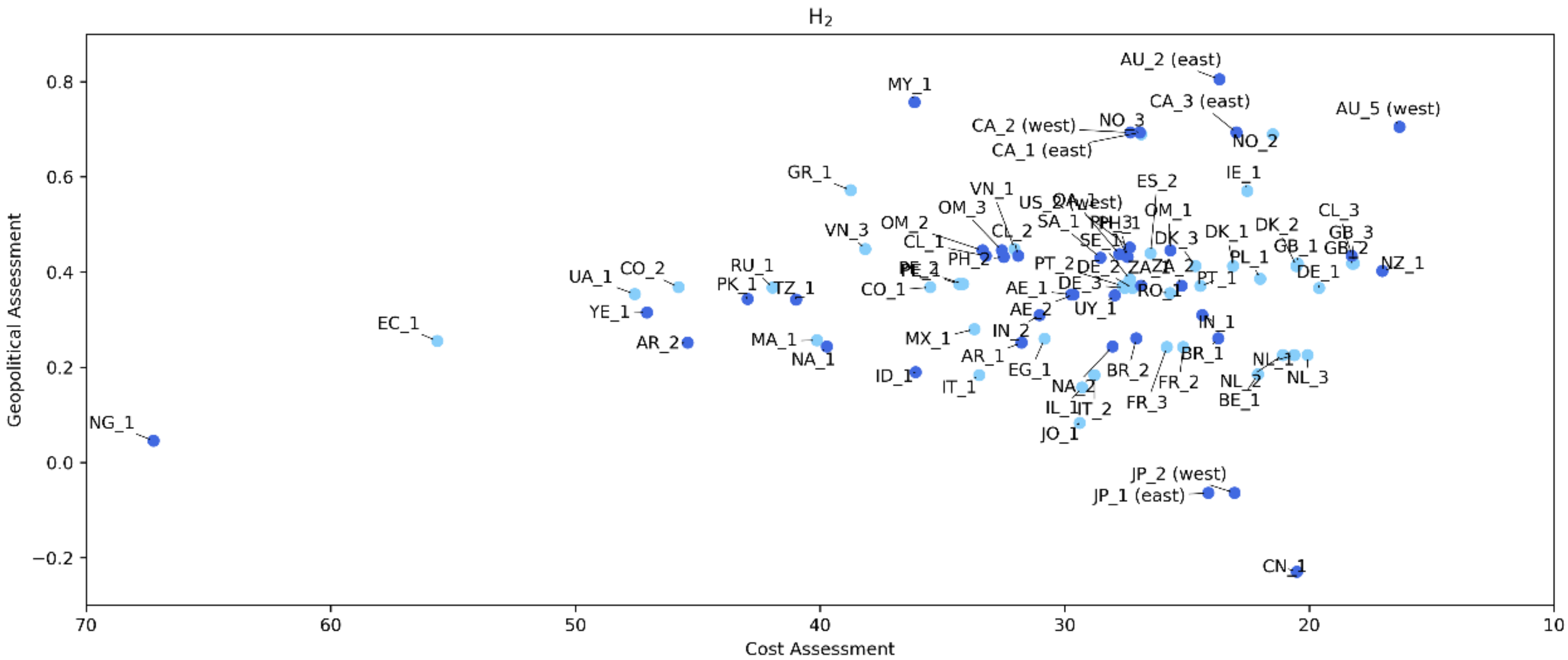


Figure 4: Ammonia import potential results

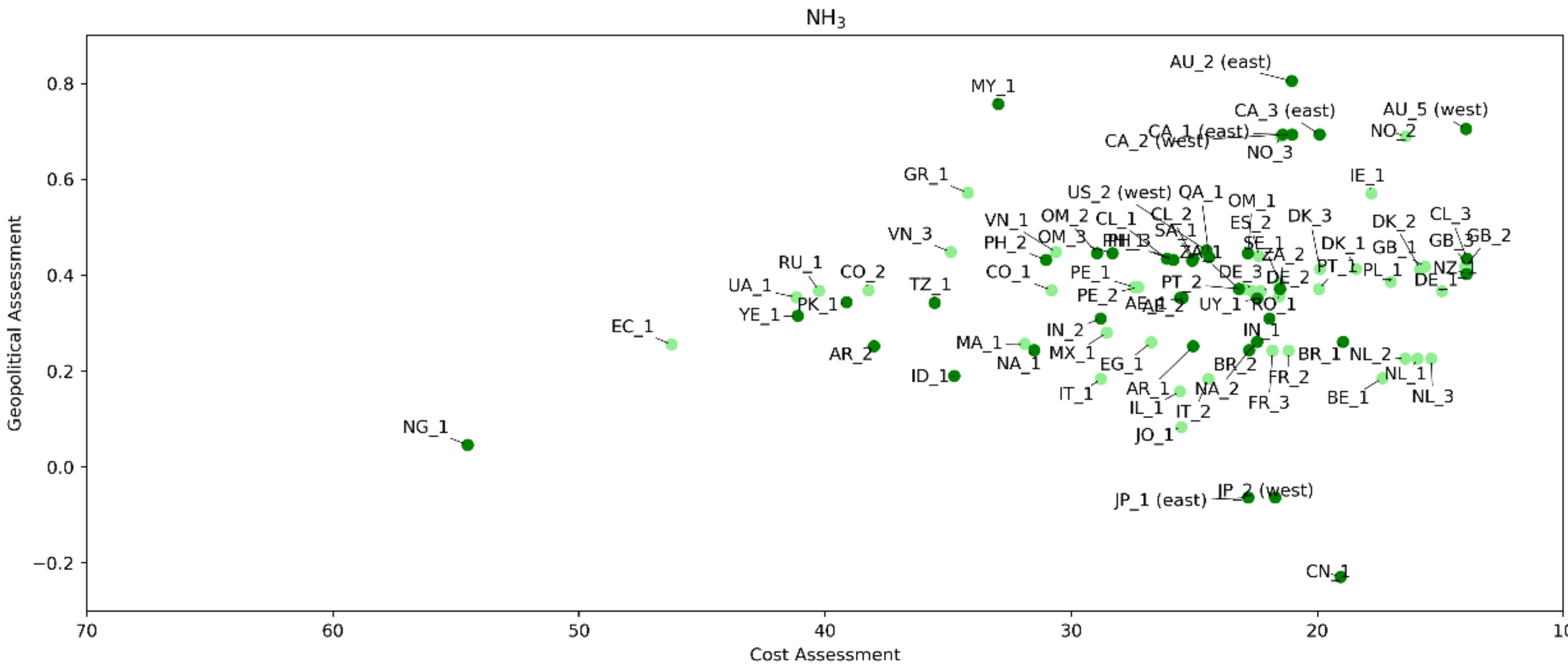
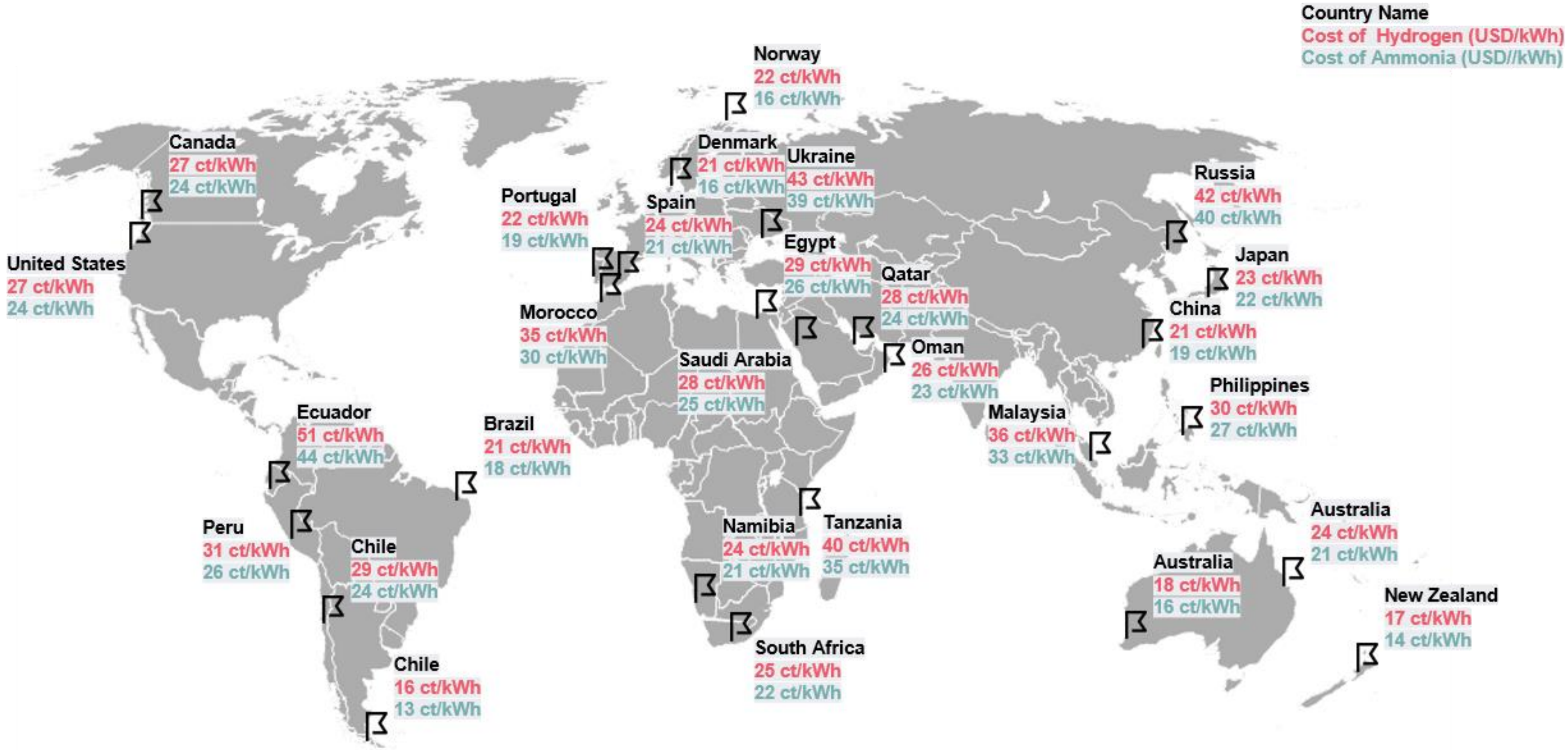


Figure 5: Import potential results mapped



2 Germany and Korea’s approaches and instruments for securing PtX imports

2.1 Germany's energy policy/security situation, similarities/differences to Korea's

2.1.1 Germany’s geostrategic and economic situation

Germany is the biggest economy in the EU, as well as the economy with largest share in industrial production at 20% of gross value added (Statistisches Bundesamt 2021). Within the industrial sector, the most important branches are the automotive industry, the manufacturing sector, the chemical industry and the electronical industry (Orth 2023). At the same time, Germany is the world’s third largest exporter after China and the US (Statista 2022) and the industry sector is characterized by a large number of medium-sized, highly-specialized companies. Geographically, Germany is the most populous country in Europe and the fifth largest in terms of area space. Hence, it is also one of the most densely populated countries in Europe (Statista 2023a). Being surrounded by 9 other EU member states it disposes of only a limited amount of coastline to the Northern and Baltic sea.

Germany’s large share of industrial production is one of the main drivers for high shares of fossil energy demand with natural gas and coal being of high relevance to meet high temperature demands in Germanys basic materials industry. Overall, Germany’s share of natural gas in overall energy demand is significantly higher than the European average (Statista 2023b). Since Germany disposes of only small volumes of own natural gas resources (in 2022 47 TWh natural gas were produced (BMWK 2023c) it is highly dependent on natural gas imports which account for about 95% of the overall natural demand (Statistisches Bundesamt 2022). For many years, Russia was the most important importer of natural gas to Germany, but that changed with its invasion of Ukraine and import shifted towards Norway, the Netherlands and Belgium (BMWK 2023c). With concerns of gas shortages in 2022, reducing energy import dependencies became a key political priority. Overall, Germany’s import dependency was 63.7% in 2020 compared to the European average of 57.5% (Wettengel 2023).

There is a wide consensus that Germany will remain a net importer of energy in the long term, as its own energy resources – including renewable – are limited, with space area availability and price competitiveness of domestically produced energy the most important limitations (Sensfuß 2022).

2.1.2 Germany’s energy and climate policy

Policy driven structural changes to the energy system has shaped Germany’s energy energy production and use for more than two decades. Driven by public opposition to nuclear energy as well as commitments with respect to the Kyoto-Protocol, Germany passed its first renewable energy law in 2000. For the first time, the law established the priority of renewable energies before conventional energy production and granted fixed feed-in tariffs for 20 years to renewable energy producers. At the time the law was passed, renewable energies accounted for around 6.5% (Umweltbundesamt 2023) of gross energy production and the law committed to the target to double this share by 2010 (BMWK 2022a). Since 2000, the national targets for renewable energy production were gradually increased, from 50% by 2030 to 80% by 2030 as postulated in the most recent amendment of the law.

In 2002, the ruling coalition of Social Democrats (SPD) and The Greens decided to abandon nuclear power by prohibiting the construction of new nuclear power plants and by determining a successive exit from existing production. In the following years, the nuclear phase-out and the energy transition to renewable energies were accompanied by continued societal and political discussions as well as some political U-turns when a conservative-liberal coalition in 2010 initially decided to extend the lifetimes of existing power plants, only to reverse this decision again in 2011 after the Fukushima nuclear disaster. Since, Germany has pursued an accelerated nuclear phase out and took its last three nuclear power plants off grid in April 2023.

Since the mid-2010s, discussions on the phase-out of coal power production intensified as well, leading to the adoption of the coal phase-out law in 2020. In the law, Germany has set binding exit dates for all coal power production plants, with the last one to be taken of grid in 2038. In their coalition agreement from 2021, the current German government has agreed to assess the possibility of accelerating the phase-out to ideally conclude it before 2030. In support of this promise, in 2022, the government reached an agreement with one of the largest fossil energy producers to voluntarily cease power production from lignite by 2030. Similar agreements with other producers are assumed to be under discussion.

Alongside its ambitions to transform the energy system, Germany initiated its first climate protection program in 2000, setting the goal of 25% GHG emissions reduction by 2005 (compared to 1990). The first legally binding climate law was passed in 2019. In its first version, the law established an overall emission reduction target of 55% by 2030 (compared to 1990), as well as the long-term goal of achieving climate neutrality by 2050. One important element of the law was the inclusion of sectoral targets and a legally binding control mechanism that would force the responsible ministry to implement an immediate climate protection program in case one sector misses its emission reduction targets. After a groundbreaking ruling of the federal constitutional court in 2021, the government was forced to increase its GHG emissions targets in order to warrant intergenerational justice. Today, Germany's climate protection targets aim for a reduction of at least 65% until 2030, 88% by 2040 and climate neutrality by 2045. With these targets, Germany exceeds the ambition levels of the European Union which is targeting a reduction of 55% by 2030 and climate neutrality by 2050. However, a new amendment of the climate law is currently under discussion which would do away with sectoral targets and is generally seen as scaling back Germany's climate protection ambitions.

2.1.3 Role of hydrogen and its derivatives in the energy transition

Hydrogen demand

A multitude of scientific studies have assessed the need for hydrogen and its derivatives for reaching Germany's climate protection targets. Most importantly, "The Big 5" from 2021 examined potential pathways for Germany to reach its climate targets in an integrated economic modelling (see also section 3.2.3). They estimate a 2030 PtX demand in range from 0 to 60 TWh (0 – 1.80 Mt[1]). For 2045, the PtX final demand ranges from 124 to 376 TWh (3.72 – 11.28 Mt).

Together with a current hydrogen demand of 55 TWh (1.65 Mt) used in conventional applications such as basic chemicals and the petrochemicals sector, the total amount of hydrogen demand in 2030 may increase to 95 – 135 TWh (2.85 – 4.05 Mt), according to the National Hydrogen Strategy (BMWK 2020). A meta study by Fraunhofer institutes IEG, ISE and ISI for the National Hydrogen Council displays even larger variety is modelling results, with additional hydrogen demand in 2030 varying between close to zero and 80 TWh (2.4 Mt), with the majority of scenarios ranging between 10 (0.3 Mt) and 50 TWh (1.5 Mt). By 2050, the projected overall demand for hydrogen and its downstream products amounts to 300 TWh (9.0 Mt) and 800 TWh (24 Mt) (Wietschel et al. 2021). With respect to the which of hydrogen-based

[1] Conversion between TWh and Mt of hydrogen always on lower heating value basis, 1 Mt = 33.3 TWh

energy carriers will be required, most academic findings agree that demand will be focused on molecular hydrogen until 2030, and that hydrogen derivates will start playing an increasingly important role only after 2030. For PtX demand estimates range between 0 to 158 TWh (4.74 Mt) in 2040 and 0 to 653 TWh (19.69 Mt) in 2050 (Wietschel et al. 2021). With respect to the demand sectors, most scenario assessments agree that largest hydrogen demands will materialize in the industry sector, chemical and steel industry being the main drivers. With respect to the building sector, a large majority of independent studies find none to limited demand for hydrogen and its, with a smaller number of studies find hydrogen to account for up to 20% of the overall heating energy demand. In the mobility sector, demand estimates for hydrogen range from 0 to 210 TWh (6.30 MWh). In both sectors, significant demand increases are only observed after 2030 (ibid.).

Hydrogen supply

Currently, Germany only disposes of limited own production capacities for green hydrogen production with a total electrolysis capacity of approx. 135 MW (acatech 2023), which translates into the production of 0.36 TWh (0.011 Mt), or under 1% of current Germany's demand. According to the announced number of projects, Germany is on track in reaching its goal of 10 GW production capacities by 2030 as already announced projects accumulate to 9.7 GW by 2030, but the question remains of how many of the announced projects will actually be built.

Given Germanys limited own renewable energy capacities, large shares of the demand increase for green hydrogen and its derivates will probably have to be met by imports (BMWK 2023e). The meta study of "The big 5" net-zero scenario studies identified a wide range of results both in terms of the type of hydrogen-based energy carriers and in terms of import share. The 2030 import share for molecular hydrogen lies between 43 and 70% of the overall demand, and the 2050 share between 50 and 83% (…). In some of "The big 5" studies, import shares of hydrogen downstream products tend to be significantly higher than those of pure hydrogen, which can be explained by its more favorable transport and storage characteristics.

A recent study by Fraunhofer ISI on the most cost-efficient import hydrogen and PtX options for Germany has found that while transport distance has a significant impact, even distant locations can become relevant trading partners if production conditions are extremely good, as is the case for e.g. Australia. Analyzing 39 regions in 12 countries, their results find lowest costs for gaseous hydrogen imports from Spain and Algeria, and for liquified hydrogen from Brazil, parts of Columbia and Australia. For green ammonia, most favorable locations for supplying Germany are also found in Brazil, Australia and Algeria (Hank et al. 2023).

2.2 Germany's hydrogen strategy and governance framework

Germany published its first hydrogen strategy in 2020. In this strategy, the government sets seven strategic areas of action:

1. Regulatory framework conditions for the market ramp-up of hydrogen
2. Production capacities in Germany for green hydrogen and its derivatives
3. Infrastructure for hydrogen value chains, including refueling stations
4. Competitiveness of green hydrogen and its derivatives
5. Progress in decarbonization in the areas of transport and industry through the use of hydrogen
6. Germany as a leading provider in the in the field of green hydrogen production and application technologies
7. International cooperation (EU and outside the EU) with regard to hydrogen import and technology export

With respect to goal number two, the strategy commits to the goal of increasing domestic electrolysis capacity for green hydrogen production to 5 GW by 2030 and 10 GW by 2040. The strategy does not focus on certain demand sectors, and does not exclude the use of hydrogen for low-weight transport and in the heating sector. With respect to different production routes, the strategy clearly states priority to green hydrogen which is considered the only one to be fully sustainable in the long run (BMWI 2020).

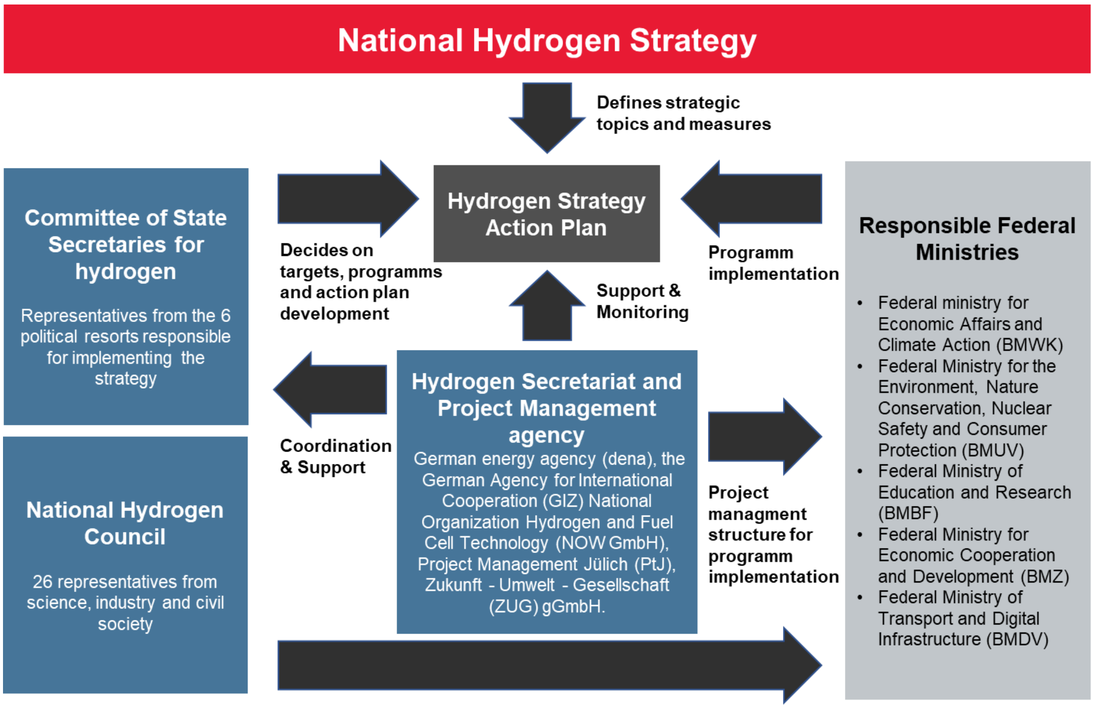
A recent update of the hydrogen strategy published in July 2023 keeps these basic premises but increases the targets levels and further develops underlying measures. Most importantly, it doubles the domestic electrolyze capacity target to 10 GW in 2030 and increases the infrastructure build-out ambitions. 3 GW of the electrolysis capacity should be achieved via tenders for constructing power system-supporting electrolysis, 2 GW via subsidies for IPCEI projects, 1 GW via to new subsides for offshore electrolysis capacities, and 3.5 GW through other measures (other subsidy schemes, regulatory changes etc.).

Acknowledging that high levels of hydrogen demand cannot by far be met by national production, the recent update on the national hydrogen strategy places strong emphasis on the support of hydrogen imports also supported by the announcement to develop a hydrogen import strategy.

The national hydrogen strategy was developed under the lead of the Federal Ministry of Economic Affairs and Climate Action. The State Secretary's Committee for Hydrogen is responsible for the strategic management of the strategy, i.e. it monitors and further develops the action plan as defined in the national hydrogen strategy. The state Secretary's Committee is assisted and advised by the National Hydrogen Council, an advisory body composed of 26 experts from science, industry and civil society. Hydrogen Coordination office coordinates and supports the hydrogen council and provides project management services for the implementation of the hydrogen strategy. The implementation of concrete measures is undertaken in the responsible ministries in cooperation with relevant partners.

In addition to the national hydrogen strategy, most federal states have developed their own strategies representing regional priorities. Some of these strategies state more ambitious production targets than the federal one.

Figure 6: Goverance structure of the German National Hydrogen Study (source: own elaboration based on various sources)



2.3 Most relevant policy instruments for securing hydrogen imports

Germany's National Hydrogen Strategy includes a number of strategic targets and measures for hydrogen imports (see box below for deep dive). In addition to that, the German Government is working on a **hydrogen import strategy**, expected in early 2024. In the following, an overview of Germany's most important policy measures and instruments is provided.

Energy and Climate Partnerships have been an important part of Germany's diplomacy with 30 energy or energy and climate partnerships established so far. Intended to provide a platform for political, scientific and economic exchange on diverse topics with respect to climate protection and energy transition, many of these partnerships have dedicated working streams on hydrogen. Within the framework of energy and climate partnerships, Germany has also set up seven **hydrogen partnerships** between 2020 and now, with Australia, Namibia, Morocco, Chile, Canada, Saudi Arabia, and Egypt (BMWK 2023b). In addition, Germany has implemented other forms of bilateral alliances, built on formal agreements or declarations of intent. The first declaration of intent on hydrogen cooperation was signed between Morocco and Germany in 2020 shorty after the publication of the hydrogen strategy. The agreement

Deep Dive – Political strategies and measures with PtX import measures in the Updated National Hydrogen Strategy

Strategic focus

- Foresees ship-based import of ammonia in the short-term, of molecular hydrogen and other derivatives in the mid-term, and pipeline-based transport for after 2030
- Diversification of supply sources from both European and other countries
- Prioritisation of green hydrogen in support mechanisms, but no general ban of grey hydrogen

Short-term measures

- Development of an import strategy that also considers sustainability criteria for imports (e.g. water resources and economic impacts in exporting countries)
- Extension of the existing IPCEI projects on the import of hydrogen from EU neighbouring countries
- Evaluation and potential scale-up of available subsidy mechanisms to bridge the cost gap
- Develop regional cooperation platforms within H2lobal
- Support global market ramp-up by elaboration of international standards and regional cooperation formats in international platforms such as IEA, CEM/MI, IPHE und G7/G20

Mid-term measures

- Enhance European cooperation to harness European hydrogen production potential and to develop joint hydrogen import strategies. Joint measures include a joint purchasing platform and joint contracts for difference
- Use exiting bilateral hydrogen, energy and climate partnerships to build up cross-border value chains, e.g. by scaling up joint research efforts
- Enhance hydrogen dialogue in existing energy and climate partnerships, and create new hydrogen partnerships and use them to harness export potentials, to increase mutual infrastructure investments and to support joint R&D activities
- Support international light-house projects
- Support private investments in hydrogen market, in particular in the context of international development cooperation

includes a financial support for a solar-based hydrogen production facility as well as the establishment of a research and knowledge transfer platform (Arab-German Chamber of Commerce and Industry e.V. 2023). In 2021, Germany signed a hydrogen cooperation agreement with Australia. As part of it, the HySupply research project analyzed the viability of setting up a hydrogen supply chain and developed an action plan for enhanced cooperation (BMBF 2023a).

Based on the results, Germany and Australia jointly funded the **Hydrogen Innovation and Technology Incubator HyGATE**. It has the mission to finance applied research and innovation projects along the hydrogen value chain implemented by a consortium of German and Australian partners. As part of the cooperation agreement with Namibia, Germany is financing German-Namibian research and innovation projects on hydrogen production and applications, as well as the development of Namibia's national hydrogen strategy and capacity building activities (BMBF 2022a). Joint research and development projects are also core components of the German's energy partnerships with Canada and New Zealand. Together with Canada, Germany in currently financing four projects dedicated to enhancing the transatlantic supply chain and decreasing costs of hydrogen production. First imports of hydrogen derivates from Canada to Germany are planned for 2025 (BMBF 2023c). Together with New Zealand, Germany is supporting research projects in the area of hydrogen production, storage and system integration (BMBF 2022b).

In addition to these bilateral cooperation agreements and projects, Germany has developed a number of multilateral cooperation platforms.

The dialogue platform H2Diplo is implemented by the German Agency for International Cooperation (GIZ) on behalf of the Federal Foreign Office targeting fossil fuel exporting economies. The initiative focuses on strengthening diplomatic relations and advising countries on how to profit from growing demand for green hydrogen. Key element of the measure is the implementation of hydrogen diplomacy offices in partner countries to cooperate with foreign and energy ministries. Partner countries include Nigeria, Angola, Saudi Arabia, as well as Kazakhstan and Ukraine (under development) (H2Diplo 2022). The **International PtX Hub** is a network to support PtX projects globally by means of project assessment and consulting services.

Apart from these cooperation initiatives targeting increased political cooperation and coordination, Germany has also set up various subsidy schemes for financing international hydrogen production projects. The most important is **H2global,** a double auction-based subsidy instrument intended to bridge the gap between the high production costs of hydrogen and its derivatives (the supply side) and end-use prices that would be low enough to incur no operational costs disadvantage for the end user (demand side). An intermediary agency called Hintco will award 10-year hydrogen purchase contracts to the winners of a bidding process, and sell the hydrogen and its derivatives to off-takers via short-term contracts. H2Global is set up as an independent foundation that may receive funding from different stakeholders, and can tailor individual rounds of funding to different funding priorities. In the first round, the Federal Ministry for Economic Affairs and Climate Protection provided 900 Mio. EUR for the establishment of trade partnerships outside of EU for supply of green ammonia, methanol and sustainable aviation fuel (SAF) to industrial users in Germany (H2GlobalStiftung 2023). The first tendering round started in end of 2022 and first deliverables are expected by 2024 (BMWK 2022d).

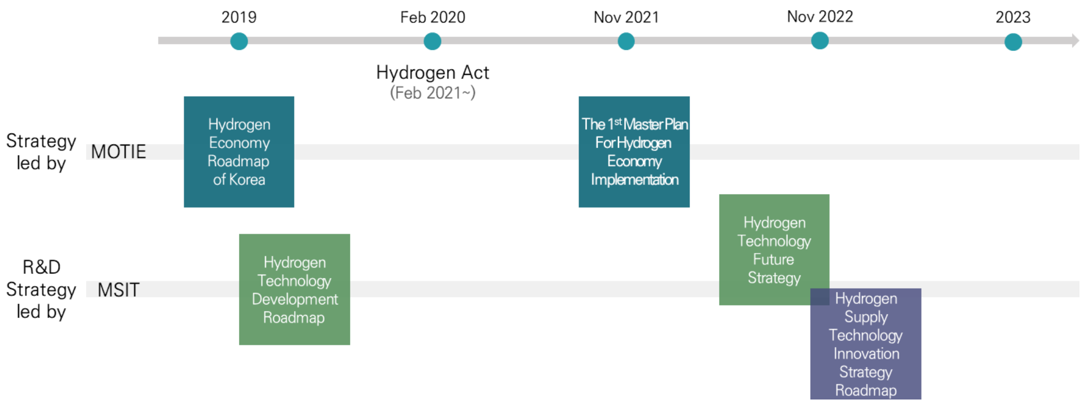
Further, the **subsidy directive for international hydrogen projects** (*FRL internationale Wasserstoffprojekte*) granted non-repayable support grants of up to 15 Mio. EUR to innovative but not yet economically viable hydrogen production projects with reference character implemented outside of EU and EFTA countries. Eligible are the funding of production plants of green hydrogen and its derivatives, as well as projects with respect to storage, transport and integrated application of hydrogen (module 1), as well as accompanying scientific research (module 2). The program started in 2021 and is to end in 2024, its two modules had three call each in 2021 and 2022 (Deutsche Industrie- und Handelskammer 2022).

H2-Uppp is focused on SMEs and supports a public-private partnership aiming to carry out pilot projects in developing and emerging countries with a relatively small funding amount (max 200.000 EUR). In addition, the project supports the identification of pilot projects in partner countries, potential consumers, technical advice, as well as political support and assistance in setting up supportive frameworks in partner countries. The program is implemented by the German Agency for International Cooperation (GIZ) in Cooperation with German Chambers of Commerce Abroad (AHKs) and funded by the Federal Ministry of Economics and Climate Action.

2.4 Korea's National Hydrogen Strategy and Implications

Korea's national hydrogen strategy has been shaped since 2019. Hydrogen had been included as a part of previous plans, e.g., renewable energy plans, however it was in 2019 that a strategy specifically targeting hydrogen was established and discussed in earnest. In 2019, the *Hydrogen Economy Roadmap of Korea* was announced for the first time under the leadership of the Ministry of Trade, Industry, and Energy (MOTIE), and in relation to that, the Ministry of Science and ICT (MSIT) announced the *Hydrogen Technology Development Roadmap*. These have been continuously updated through several adjustments up to date which are currently effective.

Figure 7 Overview of Korea's National Hydrogen Strategy

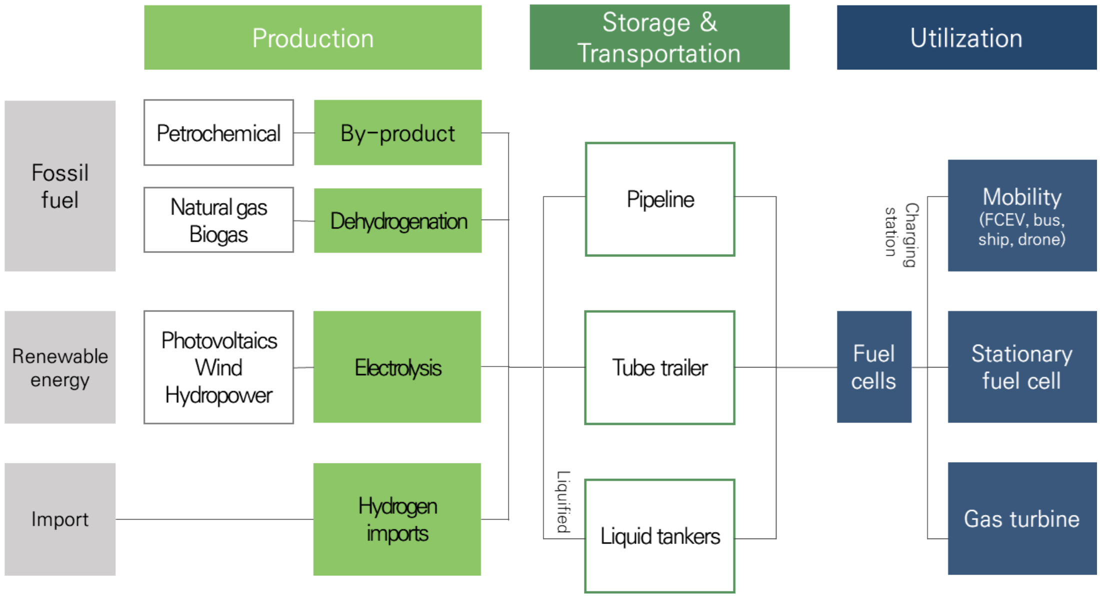


2.4.1 Korea's Hydrogen Act and Hydrogen Economy

One major distinguishable point in Korea's hydrogen strategy when compared to other countries is that Korea has enacted a hydrogen act: *Hydrogen Economy Promotion and Hydrogen Safety Management Act* (hereinafter referred to as "Hydrogen Act")[2]. It was enacted in February 2020 and went into effect in the following year. Korea is the first country to enact a hydrogen law thereof to establish a legal basis for implementing hydrogen economy. Goal of the law stated in Article 1 of the Act says, "*Establishing the foundation for facilitating the implementation of the hydrogen economy, promoting the systematic development of the hydrogen industry, and prescribing matters related to the safety management of hydrogen*." Here, the term hydrogen economy is also defined in the law: Hydrogen economy is "*the economic and industrial structure using hydrogen as a major energy source where the production and utilization of hydrogen leads to fundamental changes in a nation, society and people's lives, driving new economic growth*" (Article 2). The hydrogen economy was also specified in the very first roadmap in which illustrates the value chain of hydrogen economy constituting of production, storage & transportation, and utilization (see Fig 4).

[2] English version of the Act provided by Korea Law Translation Center (KLT), https://elaw.klri.re.kr/eng_service/main.do.

Figure 8 Hydrogen Economy Value Chain in Korea

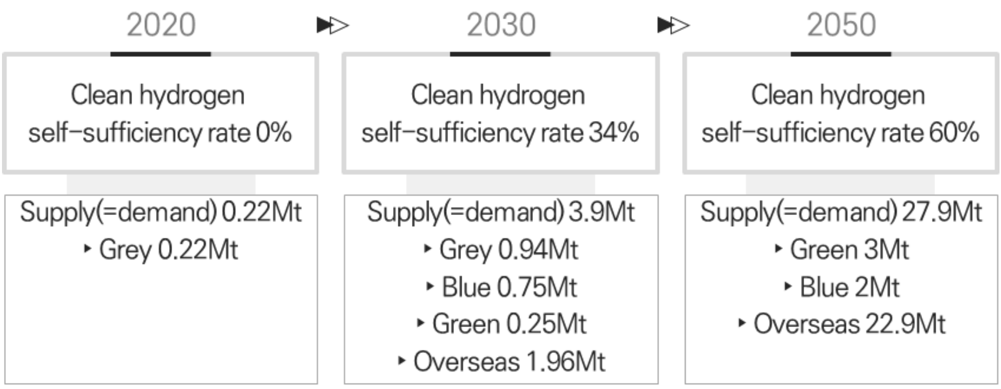


(Source: Lee & Kim (2021))

In addition, formulation of action plans for achieving hydrogen economy is legislated by the law. So-called *Master Plans for Hydrogen Economy Implementation* must be established that includes basic direction for policies, improving an institutional system, plans for financing, plans for hydrogen supply and demand, etc. In particular, hydrogen supply and demand plans should be set to promote development, production, and distribution of clean hydrogen to achieve carbon neutrality. *Hydrogen Economy Committee* is then specified in the law to be established to cope with the matters including: formulating and executing mater plans, reviewing and evaluating the results, relevant policy coordination, cooperation, and support, cooperation between countries, and so on.

Consequently, the *1st Master Plan for Hydrogen Economy Implementation* was announced in November 2021. The plan provides 4 strategies and 15 tasks to achieve the vision of leading the clean hydrogen economy by building a full-cycle ecosystem for the hydrogen economy. As part of those, the plan sets out a short- and mid-to-long plans in production, storage & transportation, and utilization with detailed hydrogen supply and demand targets and missions. The 2030 and 2050 targets are clarified as below in Fig 8. Currently, Korea is supplying hydrogen with 100% of grey hydrogen, but aims to reach 60% of self-sufficiency in clean hydrogen production and 100% of clean hydrogen utilization in 2050.

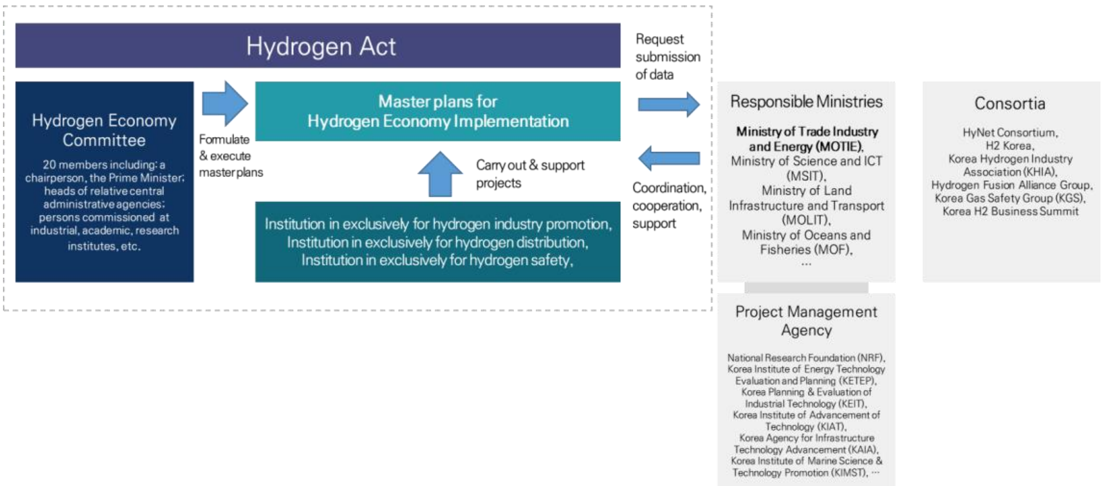
Figure 9 Korea's Hydrogen Production Targets in the Master Plan



2.5 Korea's hydrogen governace framework

Fig 9 depicts the governance structure of hydrogen economy specified in the Act. Under the Hydrogen Act, master plans are formulated and executed by Hydrogen Economy Committee with the support of institutions designated exclusively for hydrogen industry promotion, distribution, and safety. Also, the law requires responsible ministries and local governments to coordinate and cooperate in developing the strategies.

Figure 10 Governance Structure of Hydrogen Economy in Korea



In terms of R&D strategy, relevant strategies at the moment include *Hydrogen Technology Future Strategy* (Nov 2022) and *Hydrogen Supply Technology Innovation Strategy Roadmap* (Nov 2022) led by the MSIT to establish plans and provide directions for national R&D outline. The former one is the updated version of Hydrogen Technology Development Roadmap to reflect updated NDC targets of Korea, and the latter one was issued as a part of *Carbon Neutrality & Green Growth Technology Innovation Strategy* (Oct 2022). Difference between these two is that the former one consists of technologies in production, storage & transportation, utilization, and safety which are the full-cycle components involved in the master plan, while the latter one is the one that focuses on production and storage & transportation part only, as Korea has recently selected 'hydrogen supply' as one of core carbon neutrality technologies. The hydrogen supply Technology Innovation Strategy Roadmap emphasizes that it is necessary to secure hydrogen supply technologies such as production technologies linked to carbon-free power sources and overseas clean hydrogen import and storage & transportation technologies to meet the expected hydrogen demand in Korea (see Table 3). As mentioned earlier, the supply is planned through hydrogen production expansion and overseas imports to meet the demand, with detailed tasks of particular relative technologies outlined in the roadmap.

Demand (million ton)	2020	2030	2050
Power generation	0.22	3.53	13.5
Transportation	0.002	0.37	2.2
Industry			10.6
Others (ESS, etc.)		0.0005	1.6
Total	0.22	3.9	27.9

Table 3 Hydrogen Demand Outlook in Korea

In summary, in Korea, the Hydrogen Act serves as a legal basis for national plans for hydrogen economy, and it clarifies the ideal image that Korea aims for through hydrogen. Furthermore, since it legislates inter-ministerial cooperation, swift implementation of strategies is possible once a decision is made, and this made it possible to, e.g., already accumulate track records in hydrogen utilization projects such as the spread of hydrogen vehicles which have been the focus in Korea's hydrogen economy implementation. Along with the plan for implementation of hydrogen economy, R&D strategies present technology development roadmap to meet the goals and targets set in the plan. Especially, Korean government is aware of the importance of securing hydrogen supply: therefore, established technology roadmap for hydrogen production and storage & transportation part with the emphasis on overseas imports of clean hydrogen.

3 Germany, EU and Korea's PtX R&D programmes

3.1 EU's R&D and innovation programmes

The European key funding activities for research and development are implemented by the **Horizon Europe** program. Its total budget amounts to EUR 95.5 Billion between 2021-2027 and it is targeted towards a range of different research and innovation activities in a multitude of topics. Hydrogen and other low carbon innovations are supported in Pillar II (global challenges and European industrial competitiveness) and Pillar III (Innovative Europe) of the program. In Pillar II, in particular research and innovation partnerships with industry are supported, including a few hydrogen-relevant applications, most importantly the Clean Hydrogen Partnership (European Commission 2023a). 374 hydrogen-related projects have been funded until now (including the 100 below), with topics ranging from basic research on PEM membranes and training and professional qualifications for hydrogen experts to manufacturing scale-up and establishing the so-called hydrogen valleys (Cordis 2023).

The **Clean Hydrogen Partnership** (also called **Clean Hydrogen Joint Undertaking**) is a public private partnership between the European Commission, the industry representation Hydrogen Europe and the research body Hydrogen Europe Research. The initiative seeks to support technological development and deployment of clean hydrogen technologies through the funding of research projects in line with the EU hydrogen strategy and by implementing knowledge management activities. One important knowledge management activity is the European Hydrogen Observatory, a platform for data and information on hydrogen (Clean Energy Transition Partnership 2023). The strategic research and innovation agenda guide the research focus of the partnership. Exactly 100 hydrogen-related projects have been funded under the Clean Hydrogen Partnership since the start of 2022 alone (Clean Hydrogen Partnership 2023a).

The **LIFE program** is another EU funding program targeted towards the promotion of innovative technology solutions. In the area of hydrogen, suitable projects would focus on demonstration and governance projects or projects preparing large-scale deployments of technological or policy solutions. According to the database, 81 projects finances so far have had some relation to hydrogen (however, hydrogen was often not the primary focus) (European Commission 2023d).

The Clean Energy Transition Partnership (CET) is a network initiative seeking to bring together public and private stakeholders from the research and innovation system in order to foster transnational innovation ecosystems. Under the CET Partnership, members can pool their resources and propose joint research calls. Additionally, the initiative implements learning activities, provides a shared knowledge Database and organizes working groups on 7 key transformation topics. So far, more than 60 institutions are members of the initiative including institutions from 11 non-EU countries (Clean Energy Transition Partnership 2023). Five of the 46 projects funded so far include hydrogen in their scope, with research topics as diverse as microbial risks associated with hydrogen underground storage and hydrogen use for powering mining equipment (Clean Hydrogen Partnership 2023b).

Innovation fund is another large-scale European funding instruments targeted towards the support of commercial demonstration of innovative low carbon technologies in order to bring them to market. Under the subsidy scheme, different parts of the value change can be supported, from hydrogen production, electrolyzer manufacturing to end-use of clean hydrogen. The subsidy scheme is financed from the revenues of the EU ETS allowances from 2020 to 2030 and can – in case of large-scale projects – support both capex and OPEX additional costs (European Commission 2023c), Hydrogen Europe Research is a network of almost 150 research institutions within Europe supported by the industry initiative Hydrogen

Europe. 11 of the 62 projects that received funding until now have focused on hydrogen (European Commission 2023b).

Important Projects of Common European Interest (IPCEI) is one of the most important frameworks to facilitate large-scale subsidies for private investments into scale-up and deployment of strategic, innovative technologies. The projects are proposed and financed by the member state governments; if they are awarded the IPCEI status, they can benefit from an exception to state aid rules while IPCEI rules ensure that distortions to competition remain limited. The first three IPCEI calls were for microelectronics and two for batteries. In 2020, the first call for hydrogen technologies was carried out, with 76 hydrogen related projects having been granted the IPCEI status, receiving a total volume of EUR 10.6 billion (European Commission 2023e).

Projects of Common/Mutual Interest (PCI/PMI) are similar to IPCEI, but are clearly focused on energy infrastructure. Here, member states can propose cross-border energy infrastructure projects to be granted the PCI/PMI status and benefit from both state funding and accelerated permitting procedures. 2022 was the first year where hydrogen projects were eligible, with 147 projects submitted; the results are not known at the time of writing this study. The EU has also designated three priority hydrogen corridors: the East, the West and the Baltic (Gas Infrastructure Europe 2023).

3.2 Germany's R&D and innovation programmes

3.2.1 Research Offensive Hydrogen Technologies 2030

Forschungsoffensive Wasserstofftechnologien 2030 is the measure no. 25 from the 2020 National Hydrogen Strategy. It lays out strategic goals and areas of focus, and already identifies some concrete programmes and instruments for the upscaling of hydrogen technologies. Those programmes and instruments that have been implemented by now are presented below in more detail. Apart from these, the 2020 National Hydrogen Strategy also identified the need to carry out research projects on large-scale hydrogen use in the steel and chemical sector, on hydrogen use in the mobility sector do achieve cost reductions, conduct feasibility and potential studies to identify the future hydrogen production locations, and form international research networks and collaborations to secure export markets for German hydrogen technologies.

Research Network Hydrogen Technologies (*Forschungsnetzwerk Wasserstofftechnologien*) aims to facilitate interdisciplinary networking and feedback from private companies and research institutions on the strategic hydrogen research and innovation support policies. The members are tasked with elaborating reports with concrete proposals for the political decisionmakers. The network is comprised of four clusters (production of hydrogen and its downstream products; infrastructure and system integration; hydrogen use; safety, acceptance and sustainable market integration (Forschungsnetzwerke Energie 2023).

Regulatory Sandboxes for the Energy Transition (Reallabore der Energiewende) provide innovative technologies the opportunity to be tested in real-world environment and identify opportunities and risks associated with them at an early stage. To do that, a regulatory exception must sometimes be granted, e.g. when a novel technology would otherwise have not received a permission to operate. So far, six regulatory sandboxes have focused on hydrogen (EnergieSystemForschung 2023a):

- **H_2Stahl** has demonstrated the first-ever partial switch of coking coal with hydrogen in a blast furnace under operation in 2019 in Duisburg, North Rhine-Westphalia, in a project carried out by Thyssenkrupp Steel and other partners (EnergieSystemForschung 2023c).

- **H2Wyhlen** is testing a Power-to-X application in Grenzach-Wyhlen in Baden-Württemberg since 2021, converting renewable power (the project is located right next to a hydropower plant) to hydrogen in an existing 1 MW alkaline electrolyzer and a new, yet-to-be-built 5 MW one. Also to be tried out is a 3.8 tonne, 500 bar hydrogen storage tank. Energiedienst, an energy supplier, has the lead role in the project (EnBW 2023).
- **Westküste100** is demonstrating the use of excess wind power that cannot be transported from the northern state of Schleswig-Holstein due to grid bottlenecks for the production of hydrogen in a yet-to-be-built 30 MW alkaline electrolyzer (which could be expanded to 700 MW in a second phase). The project started in 2021 and is lead by Raffinerie Heide (EnergieSystemForschung 2023d).
- **Norddeutsches Reallabor** is also located in the north of Germany, in the city state of Hamburg. Started in 2021, it aims to try out the entire hydrogen value chain, from production of hydrogen from dedicated renewable energy installation in eight PEM electrolyzer s with total capacity of 40 MW, to its use in the industrial and transport sector, as well as the use of residual heat for heating. The project of over 50 partners is led by the Competence Center for Renewable Energies and Energy Efficiency (Norddeutsches RealLabor 2023).
- **Energiepark Bad Lauchstädt**, located in Saxony-Anhalt. is also focusing on the entire hydrogen value chain. Hydrogen is to be produced from 40 MW of wind power directly connected to a 30 MW alkaline electrolyzer , stored at scale in salt caverns, transported through natural gas pipelines and used as feedstock in the chemical park Leuna. The project started in 2021 and is led by VNG, a group of companies from the gas sector (EnergieSystemForschung 2023b).
- **RefLau** in the industrial park Schwarze Pumpe in Brandenburg, formerly the location of a lignite power plant, will produce hydrogen from renewable electricity and convert it back to electricity in a power plant, providing ancillary services to the power system and coupling the electricity, heating, industry and mobility sectors. The project started in 2023 (RefLau 2023)

3.2.2 8th Energy Research Programme

The *8. Energieforschungsprogramm* will come into force on January 1st 2024. Its priorities and goals for applied energy research for the coming years are already known (BMWK 2023a). It contains five "missions", or areas of focus. Apart from hydrogen, these are the energy system as a whole, the heating transition, the electricity transition, and a cross-cutting mission of rapid transfer of the research results into application in practice. The 8th edition of the Energy Research Programme is also designed as self-learning, incorporating a continuous monitoring intended to provide early feedback so that its goals and the relevant subsidy programmes can be rekindled in a fast and agile manner.

Mission Hydrogen 2030 (*Mission Wasserstoff 2030*) of the 8th Energy Research Programme is meant to put Germany in the position of a global frontrunner in green hydrogen across its value chain, orchestrating a scale-up in production, storage, transport and use *(BMWK 2023g)*. Its four main goals are

- Efficient production of green hydrogen and its derivatives
- Development of resilient hydrogen infrastructure
- Efficient use of re-electrification of green hydrogen
- Conversion of industrial processes to efficient use of hydrogen

In addition, the programme contains five "sprinter" or short- to mid-term goals:

- Driving down electrolyzer specific investment costs to 400 EUR/kW until 2030
- Increasing the hydrogen power plant capacity by 10x, as well as significantly increasing the overall efficiency of fuel cell power plants, by 2035

- Demonstration of at least one large-scale, integrated value chain encompassing hydrogen production, transport, storage and complete conversion of an industrial process to hydrogen by 2030
- Publication of a cross-ministry technology and innovation roadmap on the basis of the National Hydrogen Strategy by 2024
- Completing the modelling of future gas and hydrogen network, consistent across the entire area of the Federal Republic of Germany, by 2027

Applications for research projects focusing on hydrogen under the 8th Energy Research Programme, together with a project outline, can be handed in for evaluation from January 1st 2024 when it officially supersedes the 7th Energy Research Programme (BMWK 2023d).

3.2.3 Other projects and initiatives

H2-Compass (H2-Kompass), launched in June 2021 and concluded in August 2023, aimed at providing high-level orientation to the political decisionmakers by processing and bundling knowledge dispersed across different domains and stakeholders. Its scope was the vision of Germany's hydrogen economy in 2030 and 2050. The insights are to be used as input for the Hydrogen Roadmap. The project was led by the National Academy of Science and Engineering (acatech) and DECHEMA, a research institute from the chemical sector (acatech 2023).

National Hydrogen and Fuel Cell Technology Innovation Program (*Nationales Innovationsprogramm Wasserstoff- und Brennstoffzellentechnologie, NIP*) targets demonstration, innovation and market preparation for hydrogen and fuel cell technologies. The first phase from 2006 to 2016 focused on the market readiness of these technologies. The current second phase, running until 2026, adds a second pillar of the programme and aims to make hydrogen technologies competitive in the power and especially transport sector by mid-2030s. Entitled as potential recipients of state grants are hydrogen- or fuel-cell-based technologies with a high technology readiness level and environmental advantages vis-à-vis incumbent technologies, but which are not yet price-competitive, e.g. fuel cell-powered land, air or rail haulers, forklifts, backup power generators, combined heat and power plants, hydrogen refilling stations etc. (PTJ 2022).

Hydrogen Lead Projects *(Wasserstoff-Leitprojekte, Förderaufruf Ideenwettbewerb Wasserstoffrepublik Deutschland)* provides funding to technologies and solutions along different steps of the hydrogen value chain. It aims to provide an initial spark for conception, development and implementation of industrial-scale hydrogen projects and establish Germany as technology and market leader (BMBF 2023b) in areas such as electrolyzer manufacturing and hydrogen transport and storage infrastructure. In addition, it supports basic research and innovation in the fields of material science, catalysts and alternative hydrogen production methods. So far, three sets of lead projects have received funding (BMBF 2023e):

- Three **H_2Giga** projects aim to advance serial production and upscaling of established and future electrolyzer types (alkaline, PEM, high-temperature and anion exchange membrane electrolysis). The research focuses on increasing the efficiency of production processes as well as flexibility and recyclability of the electrolyzer s. the project also addresses work force qualifications
- Four **H_2Mare** projects focus on offshore production of hydrogen and its derivatives such as methanol or ammonia, e.g. by developing wind turbine-integrated electrolyzers and profiting from lower investments costs due to no requirement for a power connection. Also investigated are steam and saltwater electrolysis, direct air capture of CO2 and nitrogen adsorption, as well as environment effects of such projects.
- 10 **TransHyDE** projects are conducting research on transport and storage of hydrogen in pressure vessels, as ammonia or chemically bound in LOHC. They are also investigating the possibility to repurpose LNG terminals and pipeline for hydrogen, ship-to-ship ammonia transfer, as well as materials and sensors suitable

for newly-built hydrogen pipelines. Further, the use of cold from regasification of liquefied hydrogen in industrial application is being examined.

Hydrogen Basic Research (*Wasserstoff-Grundlagenforschung*) has been launched in parallel to the Hydrogen Lead Projects under the *Förderaufruf Ideenwettbewerb Wasserstoffrepublik Deutschland* (see above). As the name suggests, it focuses on basic research and development and covers all steps of the hydrogen value chain. 36 research projects have received a state grant so far, with most focusing on hydrogen production and use (12 for each), as well as three projects addressing both (BMBF 2023f).

Decarbonisation of the industry (*Dekarbonisierung in der Industrie*) is one of BMWK's flagship programmes, which is also reflected in its budget of 3.5 billion EUR for 2023 and 3.8 billion EUR 2024 (…). The programme is targeting the sectors especially hard to decarbonise, such as steel, cement, lime and glass. The programme provides subsidies for investments and covers trial, piloting and industrial-scale projects, including for hydrogen-related. Its sister programme, the so-called climate protection contracts (Klimaschutverträge) is addressing the operational cost side of such projects, ensuring that early adopters of climate-friendly solutions, including hydrogen, suffer no financial disadvantages (BMWK 2023f).

Carbon2chem is investigating using CO_2 emissions from steel, lime and cement industry as well as waste treatment as carbon source for the production of synthetic fuels and basic chemicals, which in turn are used in the chemical industry as replacement for fossil fuel inputs. Financed by the BMBF and led by the research institute Fraunhofer UMSICT, the first phase of the project ran from 2016 to 2020; the second is to run until 2025. Besides technological aspects, the project is also investigating the effects of decarbonisation on competitiveness and jobs (Fraunhofer UMSICHT 2023).

Hydrogen Innovation and Technology Center (ITZ) *(Innovations- und Technologiezentrums Wasserstoff)* targets small and medium-sized companies and supports them with innovations in the fields of testing, inspection and development. The center also aims to contribute to establishing international standards in the field of hydrogen and fuel cell technologies, and thus contributing to the business and market environment which Germany's companies can grown into. The center will be set up in four different locations: Chemnitz, Duisburg, Pfeffenhausen and another location in the north of the country that is yet to be determined and will focus on air and maritime applications (BMDV 2022).

HyLand was started in 2019 by BMDV and is already in the second phase. The programme aims to establish hydrogen regions and has a very wide scope and supports municipalities and regions with conception, development and implementation of integrated and innovative hydrogen projects in the transport sector (NOW GmbH 2023).

Within the **WIR! program line** (*WIR!-Programmlinie)*, meant to provide support for sustainable structural change in Germany's structurally weak regions, one of the projects is focusing on the conversion of diesel units to hydrogen and natural gas (BMWK 2022b).

The four **Kopernikus** projects represent the flagship energy transformation research initiative of the German government. Its three phases run from 2016 to 2025. **Ariadne** intends to answer the big questions of the *Energiewende* across the technical, economic, societal and governance domains and provide high-level orientation to the political decisionmakers. Among many other topics, research on hydrogen and its derivatives focused on potentials for scaling up hydrogen production, securing supply through imports, priorities for hydrogen use and uncertainties that need to be addressed through policy (Kopernikus-Projekt Ariadne 2023). **Kopernikus P2X** project focuses entirely on hydrogen and its derivatives, conducting basic research and investigating manufacturing processes, transport, use of hydrogen in industry as fuel and feedstock. One of its successes was the first-ever integrated power-to-fuel plant (BMBF 2023d).

Apart from the Kopernikus Ariadne project, four other studies from 2021 provided comprehensive modeling of Germany's transition to climate neutrality by mid-century across all sectors. Together, they were dubbed "**The Big 5**" (Kopernikus-Projekt Ariadne 2022). Coming from five different institutions or consortia, not all of them were funded by public funds. Whereas all of them essentially agree on the central approaches such as increased commitment to energy efficiency, deep electrification of heating and transport, substantial increase in deployment rate of renewables, and the need for some hydrogen and synthetic fuels, they diverge in details thanks to variations in assumptions, scrutiny and level of detail. Together, their insights considerably advanced the coherence and robustness of the debate on net zero policies in Germany, and wider.

3.3 Korea's Hydrogen R&D Programmes and Implications

This part presents an analysis of Korea's hydrogen R&D programme status compared to that of Germany. The objective is to draw implications and identify future cooperation opportunities in Korea's hydrogen sector. Among all the governmental R&D programmes funded by FY2023 budget, 34 programmes were specified as hydrogen-focused ones of which the term "hydrogen" appears in the programme title, e.g., *Future Hydrogen Core Technology Development*. Besides, one renewable energy programme was added as hydrogen-related, since it is highly relevant to green hydrogen production and PtX technologies. Subsequently, total of 35 programmes were selected as analysis subjects (see Table XX). Information on these programmes, i.e., responsible ministry, relative technology areas, research implementers, purpose, stage, duration, budget, etc., were retrieved from *National Research Development Project Comprehensive Guide* that are published annually by Korea Council of R&D Funding Agencies (CORFA) which provides comprehensive information on the entire national R&D projects that are promoted by government funds (general accounting and special accounting combined). According to CORFA(2023), the budget for entire national R&D projects to be announced in 2023 are appropriated KRW 31.7 trillion, and those 34 hydrogen-focused programmes (excluding the renewable energy programme) accounted for KRW 135 billion.

Here, it should be noted that in Korea, R&D budget is distributed to responsible ministries so that R&D programmes are managed and operated by each individual ministry with their own allocated budget. In the field of hydrogen, the MOTIE and the Ministry of Land, Infrastructure, and Transportation (MOLIT), stand out as major players: 15 of the programmes are managed by MOTIE and 10 by MOLIT. Others in charge of hydrogen R&D programmes include the Ministry of Ocean and Fisheries (MOF), the MSIT, National Fire Agency, and Rural Development Administration.

Hydrogen programs were categorized into components of the hydrogen economy cycle: production, storage & transportation, and utilization, as shown in Table XX and Fig XX. Utilization takes up a big portion of the budget (22 programmes, 891.37 KRW 100 million), followed by storage & transportation (9 programmes, 348 KRW 100 million) and production (8 programmes, 332.16 KRW 100 million)[3]. This bias to utilization is likely that since the hydrogen economy strategy is led by MOTIE, Korea has been focusing particularly on utilization sectors and technologies so far, such as hydrogen vehicles and mobility, which explains this high proportion of spending in utilization. Composition of the ministries in charge becomes also understandable considering that MOTIE and MOLIT are the ones who are largely involved in utilization sectors in the field of hydrogen compared to other ministries. However, investment in production and storage & transportation programmes is expected to increase due to the new R&D strategy that limits its focus to those two areas, the *Hydrogen Supply Technology Innovation Strategy Roadmap*, which was announced recently in late 2022 and will be reflected in future budget allocations.

Additionally, an analysis was conducted to evaluate the alignment of programs with the plans for overseas import and international cooperation outlined in the R&D strategy. Based on the information of the purpose assigned to R&D programmes, such as, research and development,

[3] The number of programmes and their budget summation of each component are double counted, however, the renewable energy programme is not included.

industrial technology development, manpower training, international cooperation, etc., we sought to find programmes supported for international cooperation. Surprisingly, however, no programs explicitly designed for international cooperation in the field of hydrogen were discovered were found.

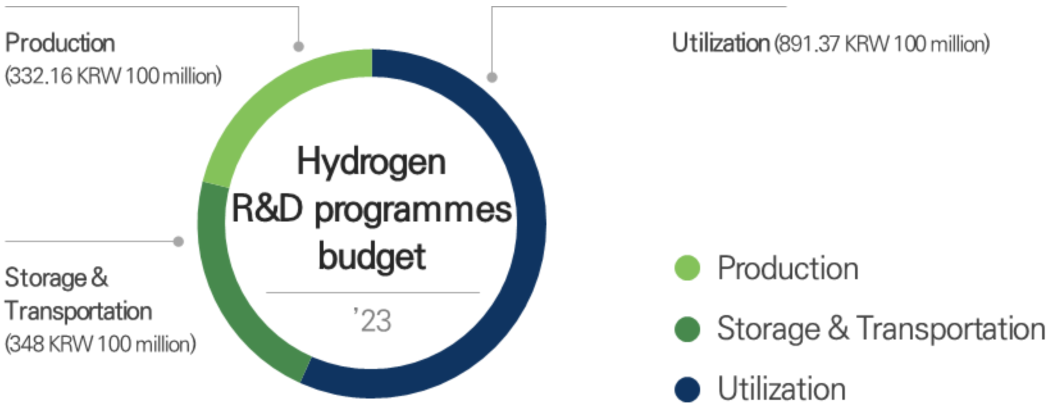
Ministry	Programme	Stage[1]	Duration (months)	Budget (KRW 100million)	Production	Storage & Transportation	Utilization
MIST	Hydrogen energy innovation technology development	BR, AR	43-55	21	O	O	
MSIT	Future hydrogen core technology development	BR, AR	54-66	62	O	O	
MOLIT	Overseas hydrogen-based public transportation infrasturcture technology development	DR	57	64			O
MOLIT	Hydrogen Pipeline Technology Localization and Demonstration for Citie	DR	45	26		O	
MOLIT	Development of urban hydrogen mobility diffusion infrastructure using urban railway regenerative power idle energy	AR, DR	45	26			O
MOLIT	Development of a hydrogen fuel cell-based propulsion certification system for small aircrafts	DR	57	10			O
MOLIT	Hydrogen Production Technology Development and Commercialization Using Petroleum Coke	DR	57	56	O		
MOLIT	Hydrogen pilot city infrastructure technology development	AR, DR	45	18			O
MOLIT	Development of hydrogen bus safety evaluation technology and equipment	DR	45	48			O
MOLIT	RE100-based hydrogen city infrastructure technology development	DR	45	71			O
MOLIT	Commercial-grade liquid hydrogen plant core technology development	DR	57	10	O	O	O
MOLIT	Commercial-grade liquid hydrogen plant compressors core technology development and demonstration	DR	69	38	O	O	O
RDA	Green hydrogen-based agricultural facility energy supply system development and demonstration	AR, DR	57	50			O
MOTIE	Development of open fuel cell system design verification platform technology to expand hydrogen mobility	DR	57	47			O
MOTIE	Hydrogen fuel cell-based 200kg cargo drone technology development	DR	57	48			O
MOTIE	Development of next-generation fuel cell system technology for hydrogen vehicles	DR	56	48			O
MOTIE	Hydrogen truck modification technology development and demonstration	DR	45	36			O
MOTIE	Development of local production technology for hydrogen truck electric power components	DR	45	47			O

MOTIE	Safety-based small hydrogen ship technology development and demonstration	DR	57	27			O
MOTIE	Development of an atypical hydrogen storage device for hydrogen vehicles of electric vehicle sharing platform	DR	57	42			O
MOTIE	Eco-friendly (LNG-hydrogen) vessel for marine floating waste collection technology development and demonstration	DR	57	27			O
MOTIE	Green hydrogen production and storage system technology development	DR	35	43	O	O	
MOTIE	Hydrogen charging infrastructure safety management core technology development	DR	48	71			O
MOTIE	Technology development and operation demonstration of storage containers and hydrogen supply systems for liquid hydrogen charging stations	DR	33	69.5			O
MOTIE	New and renewable energy core technology development	AR, DR	36-60	2,737	O		
MOTIE	Liquefied hydrogen charging core components and facilities safety technology development	DR	45	64		O	
MOTIE	Hydrogen Co-firing Gas Turbines Technology Development and Demonstration	DR	57	38		O	
MOTIE	LNG Pipeline Hydrogen Blending Safety Technology Development	DR	36	28		O	
NFA	ESS･Hydrogen facility fire safety technology research and development	BR, AR, DR	21-57	34.25			O
NFA	Development of hydrogen electricity-based fire engine power transmission module	BR, AR, DR	33	5			O
MOF	Development of hydrogen ship safety standards	AR	57	51.10			O
MOF	Safety-based small hydrogen ship technology development and demonstration of	DR	33-57	23.52			O
MOF	Green Hydrogen Production Technology from Marine Renewable Energy	DR	24-48	65.16	O		
MOF	Commercialization of Marine Biohydrogen Production Technology	AR, DR	33	19	O		

Table 4: Korea’s Hydrogen-focused R&D Programmes

[1] Basic research (BR), Applied research (AR), Development research (DR)

Figure 11 Overview of hydrogen-focused R&D programmes in Korea



Further examination of programs relevant for only production and storage & transportation that are highly relevant to hydrogen supply plans in Korea including the one for renewable energy to hydrogen supply plans, including renewable energy, revealed 13 programs(see Table XX) with a funding of KRW 49 billion, constituting approximately 36.3% of hydrogen R&D budget[4]. Four ministries are in charge of this area, the MSIT, MOLIT, MOTIE, and MOF. Here, only the MSIT and MOF are focusing on hydrogen production technologies, and MOLIT and MOTIE are more into storage & transportation part. Also, it is noteworthy that the stage of research stated is highly biased to development research which is the final stage to systematically use the knowledge gained from basic and applied research toward production or improvement of products, services, processes or methods (National Science Foundation, 2016). On the other hand, basic research is applicable to only two programmes and applied research for 5 of those. However, a detailed overview of each program was conducted to specify their focus of research in more detail as already shown in Table XX for Germany's case.

3.3.1 Ministry of Science and ICT

First of all, the MSIT appears to be only involved in basic research on hydrogen production and storage & transportation technologies, which highly aligns to the MSIT's roles. MSIT's hydrogen R&D programmes include:

- **Hydrogen Energy Innovation Technology Development** aims to establish a foundation for hydrogen economy by developing core technologies of high-efficient production and stable hydrogen storage. It supports next generation innovative technologies such as ALK & PEM electrolysis and liquid organic compound hydrogen storage that can be demonstrated within five years. This programme also supports international conferences, seminars, etc. to strengthen the research infrastructure for joint R&D. Project duration spans from 43 to 55 months, and government funding is KRW 2.1 billion;
- **Future Hydrogen Core Technology Development** programme is to discover and nurture future-leading technologies that are challenging but impactful, e.g., proton-based water electrolysis, thermochemical production linked to renewable energy, ammonia-based hydrogen storage and transport etc. It supports KRW 6.2 billion for 54~66 months.

[4] The renewable energy programme is not included in the budget summation.

3.3.2 Ministry of Land, Infrastructure, and Transport

Following four programmes are managed by the MOLIT which are as follows:

- The MOLIT is in charge of hydrogen pilot cities in Korea of which **Hydrogen Pipeline Technology Localization and Demonstration for Cities** is a programme for developing a renewable energy integrated system of hydrogen energy supply, storage, and utilization to achieve 100% of renewable energy self-sufficiency rate. The budget is KRW 1.8 billion for 45 months;
- **Hydrogen Production Technology Development and Commercialization Using Petroleum Coke** is the only programme for production under the MOLIT. It seeks to construct and operate a demo plant for synthetic gas production, advanced refining, gas conversion, and high-purity hydrogen production (3tons/day) using petroleum cokes(20tons/day). Projects are funded for 57 months with KRW 5.6 billion;
- Lastly, technologies for hydrogen liquefaction plant are funded by **Commercial-grade Liquid Hydrogen Plant Core Technology Development** and **Commercial-grade Liquid Hydrogen Plant Compressors Core Technology Development and Demonstration**. The goal is to promote a trial run and performance evaluation of pilot level (0.5tons/day) hydrogen liquefaction plant utilizing LNG cold heat and develop experimental design for key components for configuring a refrigerant compressor system for a large-scale plant (5tons/day). Budgets and duration account for KRW 2.8 billion for 57 months and KRW 3.8 billion for 69 months, respectively.

3.3.3 Ministry of Trade, Industry and Energy

Next, MOTIE is in charge of four hydrogen programmes and the renewable energy programme. Among the programmes under MOTIE, storage & transportation technologies are more in attention than production technologies, and programmes for enhancing competitiveness and establishing standards occupies big part.

- **Green Hydrogen Production and Storage System Technology Development** is to support demonstration of 3MW renewable energy linked electrolysis system, which is the largest at the moment in Korea, and operation of a test bed for comparison of Korea's and foreign electrolysis stacks of over 1MW and systems for securing stable hydrogen energy supply system. It spends KRW 4.3 billion for 35 months;
- **Hydrogen Co-firing Gas Turbines Technology Development and Demonstration** is for developing core technologies to demonstrate gas turbine hydrogen co-firing conversion retrofit and establishing test evaluation and performance verification system. The budget is KRW 3.8 billion and funded for 57 months;
- **Liquified Hydrogen Charging Core Components and Facilities Safety Technology Development** is meant to establish safety standards appropriate for introduction of liquefied hydrogen equipment in Korea. It spends KRW 6.4 billion for 45 months;
- Another programme called **LNG Pipeline Hydrogen Blending Safety Technology Development** focuses on institutionalization of safety standards for hydrogen blending in LNG pipeline for up to 20Vol%. The budget is KRW 2.8 billion for 36 months;
- In addition, the renewable energy programme, Renewable Energy Core Technology Development is funded a considerable amount of government budget, KRW 274 billion, from 36 months to 60 months to develop future-leading core technologies of solar PV, wind, hydrogen, and fuel cell and enhance energy independency.

3.3.4 Ministry of Oceans and Fisheries

The MOF focuses on hydrogen production technologies along with the MSIT. The programmes include:

- **Green Hydrogen Production Technology from Marine Renewable Energy** aims to develop and demonstrate Korea's first marine energy linked fixed green hydrogen production system. KRW 6.5 billion is invested for 24~48-month projects;
- **Commercialization of Marine Biohydrogen Production Technology** supports KRW1.9 billion for 33 months to establish an optimised system for commercialization of marine biohydrogen plant that has been developed utilising Korea's domestic technology.

Ministry	Programme	Stage[1]	Duration (months)	Budget (KRW 100million)	Basic research, Innovation, Manufacturing	Piloting, Demonstration, Upscaling, Market uptake, Infrasutreture	Competitiveness, Standardization	Techno-economics, Scenario development	Public, Int'l Cooperation, Governance, Regulatory environment
MIST	Hydrogen energy innovation technology development	BR, AR	43-55	21	O				O
MSIT	Future hydrogen core technology development	BR, AR	54-66	62	O				
MOLIT	Hydrogen Pipeline Technology Localization and Demonstration for Cities	DR	45	26		O	O		
MOLIT	Hydrogen Production Technology Development and Commercialization Using Petroleum Coke	DR	57	56		O			
MOLIT	Commercial-grade liquid hydrogen plant core technology development	DR	57	10		O	O		
MOLIT	Commercial-grade liquid hydrogen plant compressors core technology development and demonstration	DR	69	38		O			
MOTIE	Green hydrogen production and storage system technology development	DR	35	43		O			
MOTIE	Liquefied hydrogen charging core components and facilities safety technology development	DR	45	64			O		
MOTIE	Hydrogen Co-firing Gas Turbines Technology Development and Demonstration	DR	57	38	O	O	O		
MOTIE	New and renewable energy core technology development	AR, DR	36-60	2,737	O			O	
MOTIE	LNG Pipeline Hydrogen Blending Safety Technology Development	DR	36	28		O	O		
MOF	Green Hydrogen Production Technology from Marine Renewable Energy	DR	24-48	65.16	O	O			
MOF	Commercialization of Marine Biohydrogen Production Technology	AR, DR	33	19			O	O	

Table 5: Korea's Hydrogen-focused R&D Programmes in Production and Storage & Transporation Technologies

[1] Basic research (BR), Applied research (AR), Development research (DR）

Overall, Korea's hydrogen-focused R&D programmes in production and storage & transport seems to lack in the number of programmes, especially in production technologies. It was only the MSIT and MOF focusing solely on production part with four programmes, and those programmes had limited duration, less than 6 years at most, compared to those in Germany and EU that span over phases, which would prevent research continuity. Also, unlike multiple ministries running R&D programmes in Germany, Korea's programmes are managed by individual ministries. In this regard, there should be large-scale programmes that would support developing core hydrogen supply technologies and trials for cross-ministerial programmes that promote integrated projects covering from technology development, demonstration, and to commercialization.

Moreover, it was challenging to find any programmes targeting international cooperation activities such as joint technology development or demonstration, export or import cooperation, joint research for global regulatory environment, etc., while it is crucial for Korea to participate in international cooperation to meet its hydrogen supply goal. Notably, only one programme under the MSIT suggested that it supports holding international conferences and seminars to lay a foundation for R&D joint research. This observation prompts consideration of potential future opportunities for international cooperation in R&D and the securing of hydrogen energy supply for Korea.

4 Conclusion

According to the PtX import potential assessment, 54 countries were mapped for comparison. The findings identified Australia, Norway, Canada, Ireland, Chile, UK, USA, New Zealand, Denmark, and Malaysia as high-potential countries. These countries fall into two categories: PtX import or export countries. European nations such as Belgium, France, Germany, Italy, and the Netherlands, as well as other countries like China, Japan, and Israel, exemplify PtX import countries. On the other hand, Australia, Norway, Canada, Ireland, Chile, UK, USA, New Zealand, Denmark, and Malaysia represent PtX export countries.

The PtX export countries can be further categorized into pipeline countries and shipping countries. Among the listed export countries, Norway, UK, Ireland, and Denmark fall under the pipeline category, while Australia, Canada, Chile, USA, New Zealand, and Malaysia are shipping countries. For South Korea, focusing on shipping countries is paramount, as these nations become primary cooperation partners for PtX import.

Beyond the high-potential shipping export countries, South Korea can explore collaboration opportunities with lower potential shipping export countries in the form of research, development, and demonstration (RD&D). This strategy involves demonstrating PtX value chain technologies in countries with high cost benefits but relatively lower geopolitical assessments due to lack of infrastructure.

An illustrative example is Namibia, where Germany and France are actively involved in green hydrogen projects. Germany's Hyphen Hydrogen Energy, through a 10 billion USD project financing agreement with the Namibian government, aims to produce 2 million tonnes of green ammonia annually by 2030. France's HDF Energy plans to generate electricity from its green hydrogen plant, starting in 2024, providing 142GWh of electricity annually. South Korea can participate as a collaborative partner in such projects, leveraging its R&D results, acting as an engineering, procurement, and construction partner, or collaborating with import countries like Germany for large-scale demonstration projects. This strategic approach enables South Korea to establish a track record as a provider of hydrogen production technology.

Shared focus to collaborate between Korea and Germany lies in the progression of low-carbon hydrogen markets, particularly emphasized by Germany's commitment to fostering these markets through the creation of green lead markets reliant on procurement quotas. In a more confined manner, Korea employs a comparable strategy with its Clean Hydrogen Energy Portfolio Standards, mandating the incorporation of clean hydrogen in specific sectors.

H2Global, Germany's trade system is designed as a dual auction system for hydrogen supply and demand sectors, addressing the imbalance between demand and supply through the utilization of subsidies. In case of South Korea, similar mechanism called the Hydrogen Power Generation Bidding Market is developed as a system that involves the purchase and supply of electricity produced from hydrogen compounds such as hydrogen or ammonia. It is based on Article 25-6 of the Hydrogen Act. Buyers, such as the Korea Electric Power Corporation (KEPCO) and regional electric power business operators, must purchase a certain amount of hydrogen power based on the guidelines specified by the MOTIE considering the basic electricity supply plan. Hydrogen power generation operators, acting as suppliers, competitively bid through auctions to supply the purchased hydrogen power to buyers. The bidding volume for the year 2023 was set at 650 GWh, which is 50% of the total bidding volume of 1,300 GWh.

Even though the strategies have some differences, the common challenge provides a good opportunity for mutual collaboration. This collaboration can focus on sharing ideas about how to put in place rules and policies that encourage the use of low-carbon hydrogen.

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