The 23rd IAMUC
samk
Helsinki, 19-20 Oct 2023

Proceedings of the
International Association of Maritime Universities Conference

Hydrogen Shipping Cost Evaluation for Potential Routes

Peggy Shu-Ling Chen [1,*], Hongjun Fan [1], Hossein Enshaei [1], Wei Zhang [1], Wenming Shi [1], Nagi Abdussamie [1], Takashi Miwa [2], Zhuohua Qu [3] and Zaili Yang [4]

[1] *Australian Maritime College (AMC), University of Tasmania, Australia*
[2] *Faculty of Maritime Science, Kobe University, Japan*
[3] *Liverpool Business School, Liverpool John Moores University, United Kingdom*
[4] *Liverpool Logistics, Offshore and Marine Research Institute (LOOM), Liverpool John Moores University, United Kingdom*
[*] *Corresponding author: p.chen@utas.edu.au; Tel.:* +61 3 6324 9694.

Abstract: Shipping is a critical component of international hydrogen (H2) supply chains, and H2 can be transported in various forms or media, including liquid hydrogen (LH2), ammonia, methanol, dibenzyl toluene (DBT), and methylcyclohexane (MCH). To compare the costs associated with shipping H2 in different forms or media, this study develops an evaluation model to assess the H2 shipping costs on nine potential international shipping routes. The results indicated that the Australia-East/Southeast Asia, West Africa-Europe, and Middle East-Europe routes have more competitive H2 shipping costs when compared to the Australia-Europe and Middle East-East Asia routes. Additionally, methanol has the lowest shipping cost among all H2 forms or media, followed by ammonia, DBT, MCH, and LH2. However, it is important to note that the higher cost of producing methanol may offset this advantage when considering the pricing of H2 for end users.

Keywords: maritime; hydrogen; transportation; shipping; cost

1. Introduction

The Paris Agreement signatories have submitted their Nationally Determined Contributions (NDC) to address climate change. According to the online database “Net zero Tracker” [1], as of May 2023, 128 countries had set or proposed net-zero greenhouse gas (GHG) emissions targets. Most countries set targets to achieve net-zero by 2050 or 2060. To this end, the use of hydrogen (H2) is expected to be one of the key deep decarbonisation options. The main reason is that H2 is an excellent carrier of renewable energy, such as wind, solar and hydropower, which can be released as heat through combustion, or as electricity using fuel cells, in both cases the only other input needed is oxygen, and the only by-product is water. Therefore, H2 has the potential to replace fossil fuels in several scenarios. Many countries issued their H2 strategies, for example, sixteen out of the top 20 GHG emission countries, responsible for 78.11% of global emissions [2], have clearly raised H2 to the level of national energy strategies and have formulated relatively straightforward timetables and roadmaps. According to the predictions, H2 could account for 10-18% of the global energy consumption mix by 2050 [3-5].

The worldwide H2 demand, the renewable energy resource endowments, unbalanced H2 production costs, and geopolitical factors drive the formation of international H2 trade [6, 7]. Therefore, the potential of the international H2 supply chain is vast, and it is expected to form a new international energy supply pattern. The main pillars of the H2 supply chain are production, storage, transportation, and utilisation. The H2 supply chain is more complicated than others because of numerous permutations of how H2 being produced, stored, transported, and utilised, all of which differ in technology, infrastructure, and safety.

Ports and shipping are essential in the international H2 supply chain. Some ports in such countries as Australia, Japan, South Korea, Singapore, and the Netherlands are preparing for international H2 trade. The previous study by the authors identified twenty possible early H2 ports, including twelve exporting and eight importing ports [8]. The H2 shipping routes could appear between these ports. H2 shipping cost, being a costly part of the supply chains [9], will be a key factor in determining each route’s competitiveness. The H2 shipping cost varies depending on the H2 media used. Liquid hydrogen (LH2), ammonia, methanol, and liquid organic hydrogen carriers (LOHCs), including dibenzyl toluene (DBT) and methylcyclohexane (MCH), are considered suitable H2 international transportation forms or media. This paper aims to evaluate H2 shipping costs on different potential international H2 shipping routes considering different H2 forms and media.

2. Methodology and Data

2.1 Methodology

Figure 1 illustrates the scope of the H2 shipping cost evaluation, which encompasses the costs of H2 storage and loading at the exporting port, as well as sea transport cost. The outcome of the evaluation is the levelised shipping cost of H2 prior to unloading at the importing port. To facilitate this evaluation, this study develops a cost estimation model in Figure 2. The levelised cost of H2 shipping is calculated by dividing the total annual cost by the annual quantity of H2 delivered. The total annual cost is comprised of both annualised capital expenditure (CAPEX) and operational expenditure (OPEX). The annual quantity of H2 delivered is determined by a range of factors, including the chosen H2 form or media, ship capacity, shipping route, and number of annual trips. The currency unit used in this study is US dollars ($).

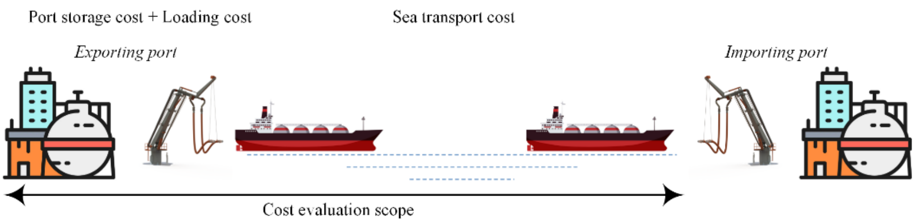


Figure 1. Hydrogen shipping cost evaluation scope.

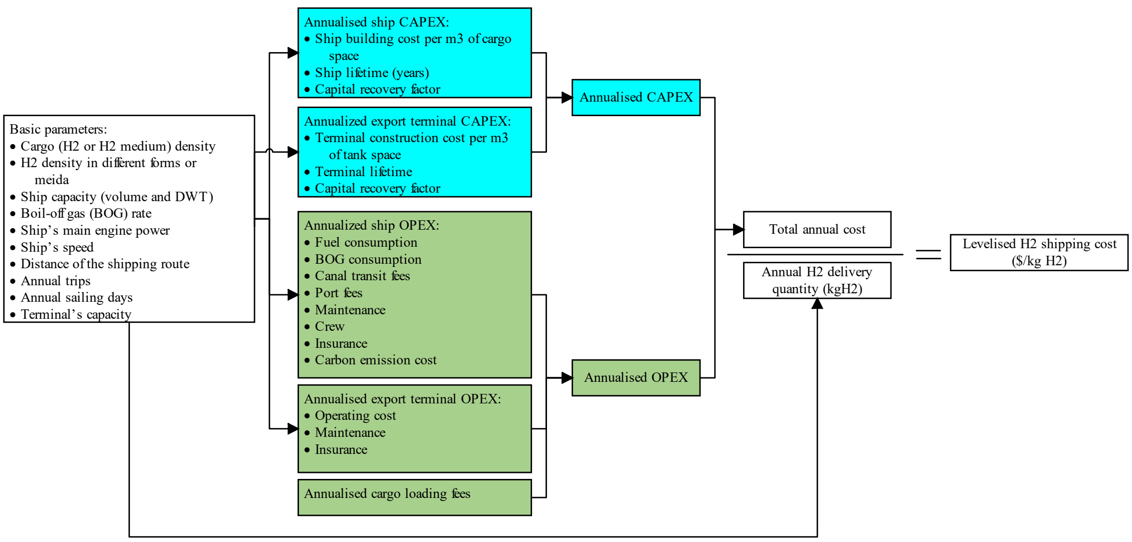


Figure 2. Hydrogen shipping cost evaluation model.

2.2 Data

This study compared the H2 shipping costs using different H2 forms and media, including LH2, ammonia, methanol, DBT, and MCH, across different shipping routes. Based on the identification of 20 potential early H2 ports in the previous study by the authors [8], nine potential H2 routes representing Australia-East/Southeast Asia, West Africa-Europe, the Middle East-Europe, and the Middle East-East Asia were selected to compare the costs. They are Hastings to Kobe, Townsville to Ulsan, Hedland to Singapore, Bonython to Rotterdam, San Antonio to Rotterdam, Nouadhibou to Rotterdam, Yanbu to Onahama, and Yanbu to Rotterdam. Figure 3 provides the information on these H2 shipping routes. Table 1 presents the basic input data for the evaluation. To ensure comparability of results, the following basic assumptions were made for the input data:

- The net cargo volume of the ships is assumed to be 100,000 m^3.
- The capacity of the port tank is also assumed to be 100,000 m^3 to match the ship's capacity.
- The ship's effective operating time is 330 days per year.
- The ships for transport H2 forms or media use marine gas oil (MGO) as a fuel.
- The economic lifespan of the ship and infrastructure is conservatively considered to be 20 years for the purpose of evaluating the annualised CAPEX.
- The discount rate is conservatively considered to be 8% in calculating annualised CAPEX.
- The storage and transportation of DBT and MCH use existing infrastructure.

Note: the green port marks represent export ports; the blue port marks represent import ports

Figure 3. Nine hydrogen shipping corridors.

Table 1. Basic input data for the evaluation.

Item	**Value**	**Ref.**
Ship capacity / terminal tank capacity (m^3)	100,000/100,000	/
Ship main engine power (kW)	PME = 0.709*DWT – 1963, for DWT < 60,000 tons PME = 0.328*DWT + 27596, for DWT > 60,000 tons	[10]
Ship speed (kn)	16	/
Ship operation days per year	330	/
LH2 ship building cost ($/$m^3$)	1355	[11]
Ammonia ship building cost ($/$m^3$)	1016	[11]
Methanol ship building cost ($/$m^3$)	750	[11]
LOHC ship building cost ($/$m^3$)	0 (using existing chemical tankers)	/
Fuel consumption (g/kWh)	190	/
MGO fuel cost ($/ton)	500	/
Canal fee ($/transit) *	25,000 (LH2); 50,000 (Ammonia, methanol, LOHCs)	/
LH2 terminal tank building cost ($/$m^3$) **	800	/
Ammonia terminal tank building cost ($/$m^3$) **	600	/
Methanol terminal tank building cost ($/$m^3$) **	440	/
LOHC terminal tank building cost ($/$m^3$)	0 (using existing infrastructures)	/
Loading costs: LH2 /ammonia /Methanol /DBT /MCH ($/$m^3$) ***	0.054/0.00303/0.00303/0.0045/0.0045	[12]
BOG rate of LH2 (%/day) ****	0.5	[13]
BOG rate of ammonia (%/day)	0.05	[14]
BOG rates of methanol, DBT, and MCH (%/day)	0	/
Carbon price ($/ton)	50	[15]

*Note: * The LH2 ship has low DWT, resulting in low canal fees; ** The data was obtained from an interview; *** The loading costs include the CAPEX of the loading facilities. **** The BOG rate of LH2 tank was estimated based on the findings of the literature.*

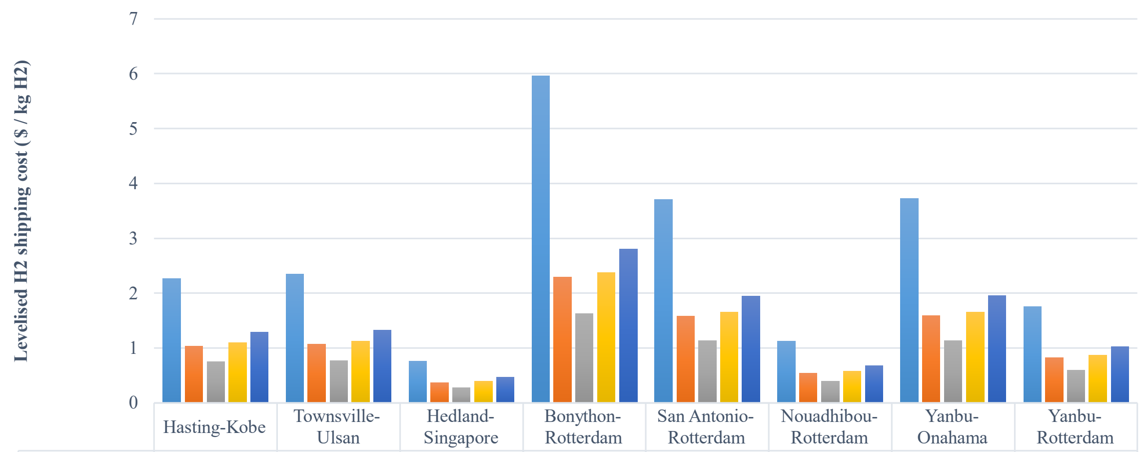
Table 2 lists the physical and chemical characteristics parameters of the H2 forms and media used in the cost evaluation process.

Table 2. Basic properties of hydrogen forms and media.

	LH2	**Ammonia**	**Methanol**	**LOHC (DBT)**	**LOHC (MCH)**
Composition	H_2	NH_3	CH_3OH	$C_{21}H_{38}$	C_7H_{14}
Molecular weight (g/mol)	2.0	17.0	32.04	290	98.2
Boiling point (°C)	-253.15	-33.15	64.5	353.85	100.85
Density (g/cm^3)	0.071	0.682	0.792	0.91	0.769
Hydrogen density by volume (kg/m^3)	71	121	99	56.4	47.3
Hydrogen density by weight (wt%)	100	17.8	12.1	6.21	6.16
Energy density (MJ/kg)	120	18.6	19.9	/	/

3. Results

Figure 4 illustrates the levelised shipping cost per kilogram of H2, influenced by the shipping distance. The Hedland-Singapore route presents the lowest cost, whereas the Bonython-Rotterdam route is the most expensive. When comparing different H2 transport options, methanol has the lowest shipping cost, followed by ammonia, DBT, MCH, and LH2. The cost of LH2 shipping ranges from 2.7 to 3.7 times higher than that of methanol shipping, and 2.1 to 2.6 times, 1.9 to 2.5 times and 1.6 to 2.1 times higher than that of ammonia, DBT and MCH, respectively.

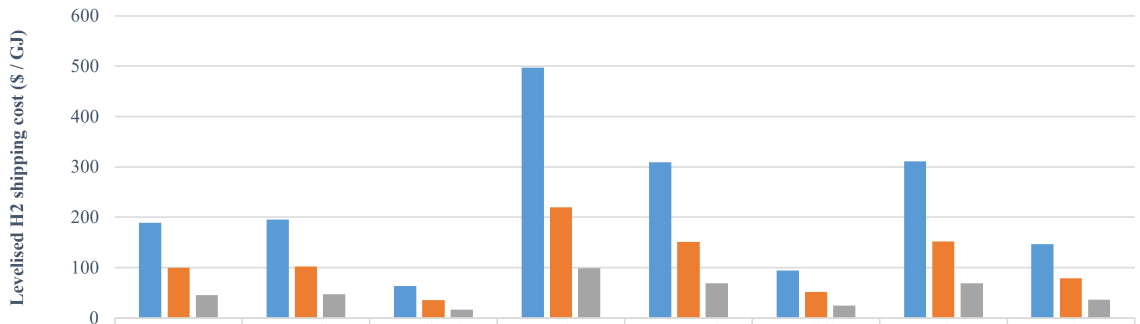


	Hasting-Kobe	Townsville-Ulsan	Hedland-Singapore	Bonython-Rotterdam	San Antonio-Rotterdam	Nouadhibou-Rotterdam	Yanbu-Onahama	Yanbu-Rotterdam
LH2	2.265545987	2.349916514	0.761260393	5.959261618	3.708676795	1.126632198	3.73269323	1.755911085
Ammonia	1.037503994	1.071700209	0.371831446	2.295111487	1.583595307	0.543935513	1.591601999	0.824239213
Methanol	0.751486974	0.775718849	0.275570777	1.629573599	1.136322568	0.399388091	1.141563304	0.599890418
LOHC (DBT)	1.092478311	1.127797456	0.398808035	2.372608652	1.653590289	0.579277438	1.661034203	0.871519005
LOHC (MCH)	1.289713298	1.331455274	0.469898277	2.802658785	1.952879635	0.683186238	1.961661838	1.028572271

Figure 4. Levelised hydrogen shipping cost per kilogram of H2.

In contrast to DBT and MCH, the benefits of using ammonia and methanol as H2 transport media are that they can be used directly as fuels. If there are ammonia or methanol users at the receiving port, there is no need to extract H2 from these media. Table 2 demonstrates that their energy densities are acceptable, despite being significantly lower than that of LH2. Figure 5 depicts the levelised shipping cost per Gigajoule (GJ) for energy delivery comparison purposes. Methanol has the lowest shipping cost, followed by ammonia and LH2. In terms of delivered energy amount, the cost of LH2 shipping is 3.8 to 5.0 times higher than that of methanol shipping and 1.8 to 2.3 times higher than that of ammonia shipping.

Overall, the H2 shipping costs in the Australia-East/Southeast Asia ($0.28-2.35/kgH2), West Africa-Europe ($0.40-1.13/kgH2), and Middle East-Europe ($0.60-1.76/kgH2) corridors are comparatively more competitive than those in the Australia-Europe ($1.63-5.96/kgH2) and Middle East-East Asia ($1.14-3.73/kgH2) corridors.



	Hasting-Kobe	Townsville-Ulsan	Hedland-Singapore	Bonython-Rotterdam	San Antonio-Rotterdam	Nouadhibou-Rotterdam	Yanbu-Onahama	Yanbu-Rotterdam
LH2	188.7954989	195.8263761	63.43836605	496.6051349	309.0563996	93.88601653	311.0577692	146.3259238
Ammonia	99.28801664	102.5605576	35.58386957	219.6397014	151.5483681	52.05404374	152.3145999	78.87880637
Methanol	45.69342909	47.16682451	16.75581109	99.08462586	69.09298028	24.28440149	69.41163811	36.47574905

Figure 5. Levelised hydrogen shipping cost per Gigajoule of energy.

4. Discussion

Production, conversion (liquification, chemical compounding, hydrogenation/dehydrogenation), storage, shipping, and distribution costs should be considered when pricing H2 for end-users. However, the cost analysis in this study is limited to H2 storage and loading costs at the exporting port and sea transportation costs. Methanol is found to have the lowest shipping cost, but its higher conversion cost due to higher electricity consumption may offset this advantage. The H2 liquefaction process requires power of 11.11-27.78 kWh/kgH2 [16]. Ammonia production via Haber-Bosch process needs 8 MWh/ton ammonia, equivalent to 44.94 kWh/kgH2 [17]. Although exothermic hydrogenation process of LOHCs needs tiny energy, the endothermic dehydrogenation at the destination requires about 9 kWh/kgH2 [18]. While methanol synthesis using H2 and carbon dioxide requires 10-11 MWh/ton methanol, or 82.6-90.9 kWh/kgH2 [19], which is about 3-8 times, 2 times, and 10 times higher than conversion electricity consumptions for LH2, ammonia, and LOHCs respectively. High electricity consumption implies high cost. In H2 exporting countries with expensive electricity, such as Australia, the drawbacks of utilising high-energy-consumption H2 transport media become apparent.

Projected cost reductions in H2 production from renewable sources, driven by falling costs of wind and solar power and water electrolysers, have the potential to significantly lower H2 production costs. BloombergNEF estimated that green H2 production costs could be as low as $0.7 to $1.6/kg in most countries by 2050, with potential exporters achieving costs as low as $1.5/kg by 2030 [20]. In H2 importing countries, by 2030, the production costs could be around €3/kg ($3.07/kg) in European countries [21], $3/kg in Japan [22], $3/kg in South Korea [23]. Therefore, imported green H2 is more expensive than domestic supply considering production, conversion and port storage and shipping costs. However, given that the domestic renewable energy sources are limited in major H2 demand countries, global H2 trading still has considerable potential.

5. Conclusion

This paper adopts the levelised cost approach to assess the H2 shipping costs on nine potential international shipping routes. The main findings show that the shipping costs for H2 in the Australia-East/Southeast Asia, West Africa-Europe, and Middle East-Europe corridors are comparatively more competitive than those in the Australia-Europe and Middle East-East Asia corridors. Besides, methanol has the lowest shipping cost among all H2 forms and media, followed by ammonia, DBT, MCH, and LH2. However, it is worth noting that the higher cost of producing methanol offsets this advantage when considering pricing H2 for end-users.

The present study is constrained by its exclusive focus on the costs associated with H2 port storage, loading, and shipping. To address this limitation, the next phase of the research will involve extending the model to account for the costs associated with H2 production, conversion, and overland transportation. Such an expanded model would permit a comprehensive analysis of H2 costs across the entire supply chain, thus providing decision-makers with valuable support for pricing H2 commodities.

Acknowledgements

The authors would like to acknowledge the support of the International Association of Maritime Universities (research project number 20220205).

References

[1] Net Zero Tracker. *Global Net Zero Covergage*. 2023 1 May 2023]; Available from: https://www.zerotracker.net/.
[2] WPR. *CO2 Emissions by Country 2022*. 2022 30 June 2022]; Available from: https://worldpopulationreview.com/country-rankings/co2-emissions-by-country.
[3] Hydrogen Council, *Hydrogen scaling up: a sustainable pathway for the global energy transition*. 2017: Brussels, Belgium.
[4] WNA. *Hydrogen Production and Uses*. 2021 20 June 2022]; Available from: https://www.world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses.aspx.
[5] IRENA, *World Energy Transitions Outlook: 1.5°C Pathway*. 2022, International Renewable Energy Agency: Abu Dhabi.
[6] IRENA, *Geopolitics of the Energy Transformation： The Hydrogen Factor*. 2022: Abu Dhabi.
[7] Pflugmann, F. and N.D. Blasio, *Geopolitical and Market Implications of Renewable Hydrogen*. 2020, Harvard Kennedy School: Cambridge, the UK.
[8] Chen, P.S.-L., et al., *A review on ports' readiness to facilitate international hydrogen trade.* International Journal of Hydrogen Energy, 2023.DOI: https://doi.org/10.1016/j.ijhydene.2023.01.220.
[9] Johnston, C., et al., *Shipping the sunshine: An open-source model for costing renewable hydrogen transport from Australia.* International Journal of Hydrogen Energy, 2022. **47**(47): p. 20362-20377.DOI: https://doi.org/10.1016/j.ijhydene.2022.04.156.
[10] Sun, X., et al., *Estimation of Vessel Emissions Inventory in Qingdao Port Based on Big data Analysis.* Symmetry, 2018. **10**(10): p. 452.
[11] Al-Breiki, M. and Y. Bicer, *Comparative cost assessment of sustainable energy carriers produced from natural gas accounting for boil-off gas and social cost of carbon.* Energy Reports, 2020. **6**: p. 1897-1909.DOI: https://doi.org/10.1016/j.egyr.2020.07.013.
[12] Kimura, S., et al., *Demand and Supply Potential of Hydrogen Energy in East Asia – Phase 2*. 2019, Economic Research Institute for ASEAN and East Asia (ERIA): Indonesia.
[13] Hendrie Derking, L.v.d.T., Marcel Keezer, *Liquid Hydrogen Storage: Status and Future Perspectives*, in *Cryogenic Heat and Mass Transfer 2019*. 2019: Enschede, The Netherlands.
[14] Belapurkar, V.C. *Boil-Off in Refrigerated Ammonia Tanks*. 2011 9 May 2023]; Available from: https://www.cheresources.com/refnh3tanks.shtml.
[15] Sean Bray. *Carbon Taxes in Europe*. 2022 28 July 2022]; Available from: https://taxfoundation.org/carbon-taxes-in-europe-2022/.
[16] Ulf Bossel, Baldur Eliasson, and G. Taylor. *The Future of the Hydrogen Economy: Bright or Bleak?* 2003 26 June 2022]; Available from: https://planetforlife.com/pdffiles/h2report.pdf.
[17] MacFarlane, D.R., et al., *A Roadmap to the Ammonia Economy.* Joule, 2020. **4**(6): p. 1186-1205.DOI: https://doi.org/10.1016/j.joule.2020.04.004.
[18] Schorn, F., et al., *Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations.* Advances in Applied Energy, 2021. **3**: p. 100050.DOI: https://doi.org/10.1016/j.adapen.2021.100050.
[19] IRENA, *Innovation outlook renewable methanol*. 2021, International Renewable Energy Agency: Abu Dhabi.
[20] BloombergNEF, *Hydrogen Economy Outlook, Key Messages*. 2020.
[21] DIERMANN, R. *Green hydrogen, blue hydrogen to reach cost parity in Europe by 2030*. 2022 26 July 2022]; Available from: https://www.pv-magazine.com/2022/02/28/green-hydrogen-blue-hydrogen-to-reach-cost-parity-in-europe-by-2030/.
[22] CSIRO, *HyResource*. 2021.
[23] S&P Global. *S Korea to provide 27.9 mil mt/year of 'clean hydrogen' by 2050*. 2021 5 July 2022]; Available from: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/112621-s-korea-to-provide-279-mil-mtyear-of-clean-hydrogen-by-2050.