



Technology and economic perspective of hydrogen as a green fuel on ship

B Ariani^{1*}, F M Felayati², M A Batutah¹ and M Rosyadi¹

¹ Universitas Muhammadiyah Surabaya, Surabaya, Indonesia

² Universitas Hang Tuah Surabaya, Surabaya, Indonesia

*Corresponding author email: betty.ariani@ft.um-surabaya.ac.id

Abstract

The maritime industry is currently navigating a critical juncture with the imperative goals of de-carbonization and achieving zero carbon emissions, driven by increasingly stringent environmental regulations. As the world grapples with the escalating depletion of fossil fuels, the industry is compelled to explore alternative energy sources. Green hydrogen, produced through electrolysis and devoid of carbon emissions, emerges as a promising solution for the maritime sector's sustainable future. Despite the potential benefits, the development of hydrogen as a viable marine fuel faces numerous technical and economic challenges. This article provides a thorough examination of the technical and economic aspects of hydrogen's development, offering insights that can inform evaluations, propose solutions, and catalyze new research initiatives. By addressing these challenges, the maritime industry can pave the way for the widespread adoption of hydrogen technology, contributing significantly to the sector's commitment to environmental sustainability. This comprehensive analysis aims to facilitate in-formed decision-making, foster innovation, and accelerate the integration of hydrogen as a clean and efficient fuel for ships.

Keywords

Hydrogen, Green fuel, Ship

Introduction

In global economic development, the maritime and shipping industry plays a crucial role. The flow and transportation of goods, as well as the mobility of people from one place to another, lead to a significant increase in energy demand. Energy is one of the many fundamental needs that govern all structures of human life on Earth. Naturally, energy demand is closely linked to population and economic growth. The world's population and economy continue to grow, coupled with advancements in industry and transportation, resulting in a significant increase in energy demand (Figure 1) [1].

As mentioned [2], [3] the human population has increased sixfold while energy consumption has reached 80 times. Our dependence on fossil energy has reached its

Published:

October 20, 2024

This work is licensed
under a [Creative
Commons Attribution-
NonCommercial 4.0
International License](#)

Selection and Peer-
review under the
responsibility of the 5th
BIS-STE 2023 Committee

peak, leading to a gap between fuel availability and the level of fuel consumption needs [4], [5]. This is certainly a concerning issue, aside from the non-renewable nature of fossil fuels, which means they can be depleted. The impact of increasing global emissions, particularly greenhouse gases, will have significant consequences for the sustainability of life on Earth [6]–[8]. The effects of greenhouse gases manifest in the form of increased global warming and global climate change.

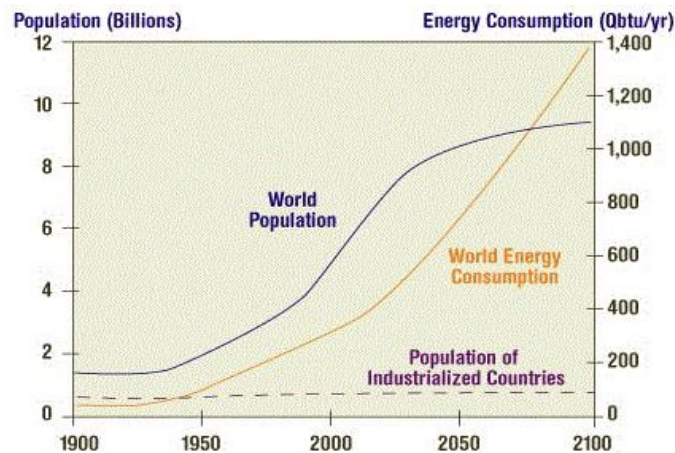


Figure 1. Population & energy consumption growth

In the maritime sector, as a response and effort to mitigate greenhouse gases, significant decarbonization efforts are underway towards achieving zero carbon emissions by 2050 [9]–[11]. Based on data [12]–[14] it is stated that in 2018, global shipping emissions accounted for 2.9% of global emissions caused by human activities, a trend that is projected to increase to 130% by 2050 if left uncontrolled. Data from 2021 indicates that sea transportation contributes 3 - 4% of total CO₂ emissions. Significant steps have been taken through the International Maritime Organization (IMO) via various regulations and policies as concrete measures in the commitment to reduce greenhouse gas emissions towards zero carbon emissions by 2050 [13], [15]. One of the efforts involves implementing measures to provide environmentally friendly alternative fuels for ships.

The use of hydrogen is beginning to attract the attention of various groups as an alternative to reduce greenhouse gas emissions [16], [17]. Hydrogen is significantly different from fossil fuel energy in general, where combustion exhaust gas produces CO₂, while hydrogen actually produces water as a by-product. This makes hydrogen a projection of future energy [17]–[20]. Statements from [21], [22] suggest that the use of hydrogen can reduce carbon emissions by 20% in the form of fuel cells

This article will discuss technological and economic perspectives regarding the projections for the future use of hydrogen in the shipping sector. Through reviews conducted in many journals, we will technically discuss hydrogen production and storage technology as a basis for planning infrastructure that supports its operations and usage on ships. In terms of economic overview, we will explain the changes that

have arisen after the conversion from fossil fuels to hydrogen and the global view on this matter. Through reviews conducted in many journals.

Method

The initial stage involves grouping articles based on keywords, namely hydrogen production technology, hydrogen storage design, technology for converting fossil fuels into hydrogen, economic impacts after the application of hydrogen, as well as economic reviews related to preparations and global impacts after the application of hydrogen in transportation in general and shipping in particular. The information obtained from the journal review will then be used as a reference for writing technological and economic perspectives on the discourse of using hydrogen fuel for shipping.

Results and discussion

Hydrogen production process

In a statement made by [23] There are almost a hundred hydrogen production technologies. To facilitate the process of classifying hydrogen based on its origin of production and the characteristics of each type of hydrogen, a hydrogen taxonomy was created with color coding, as stated in Table 1 [24].

Table 1. Hydrogen taxonomy based on emission potential

Color Code	Method	Feed Stock	Emission	Maturity Level	Literature
Green H ₂	Electrolysis	Water	Low	9 - 10	[25]-[28]
Gray H ₂	Steam Reform	NG	High	10	[24], [29], [30]
Blue H ₂	Steam Reform	NG	Low	10	[31]-[34]
Brown H ₂	Gasification	Coal	High	10	[35]
Turquoise H ₂	Pyrolysis Thermal	NG	Low	8 - 10	[36], [37]

As the name suggests, green hydrogen is obtained through an environmentally friendly process where water electrolysis utilizes electricity from renewable energy sources [25], [26]. The electrochemical separation process of water into oxygen and hydrogen is a commonly used method that leaves no carbon footprint at all [27], [28]. In contrast to gray hydrogen, this type of hydrogen is produced from fossil fuels, namely natural gas, through steam reforming which generates CO₂ exhaust gas that enhances the greenhouse effect. In its statement [24] In the production of 1 ton of hydrogen, it will produce around 10 tons of CO₂ or 10 times as much. Although currently reforming methane into hydrogen has relatively affordable production costs, namely around €1.5/kg or €0.045/kWh, this will be abandoned along with the development of economic scale and the application of renewable energy [29], [30]. Unlike blue hydrogen, additional applications in the form of carbon capture and storage make emissions more controlled compared to gray hydrogen, although this statement [31], the level of carbon emissions produced by blue hydrogen is only 9 - 12% lower than gray hydrogen, this is not surprising due to the use of natural gas in carbon capture. What is surprising is that the greenhouse gas footprint of blue hydrogen is 20% greater than that of burning

natural gas or coal and 60% greater than that of burning diesel fuel. Meanwhile, hydrogen production originating from the coal gasification process or more commonly known as brown hydrogen is stated to be the least environmentally friendly method due to the high CO₂ emissions produced in the range of 18 - 20 times more than the amount of hydrogen produced. Turquoise hydrogen [24], [36], [37] is produced through pyrolysis of methane from natural gas, This thermal decomposition method breaks down methane into hydrogen and carbon molecules at temperatures ranging from 600 to 1200 – 1400 °C. However, this high-temperature process is not very effective in reducing the CO₂ emissions produced, thus resulting in emissions not lower than those from methane reforming processes. It is crucial to utilize renewable energy in high-temperature reactor operations, ensure long-term binding or storage of solid carbon, and implement conditions that support CO₂ neutrality.

From Table 2 can be obtained that electrolysis is a method used to produce hydrogen by passing a direct current through an electrolyzer, which drives electrochemistry based on the principle of oxidation-reduction, thus breaking water into hydrogen and oxygen [39]. Power plants can utilize fossil fuels or renewable energy such as solar or wind power. As mentioned by [41] there are three models of electrolysis: low-temperature electrolysis, high-pressure electrolysis, and high-temperature steam electrolysis. According to [47] water thermolysis in the hydrogen production process requires heating at high temperatures, necessitating efficient reactor performance and power. Photolysis, on the other hand, requires light penetration into water, posing a challenge in designing the optimal reactor [43]. Hydrogen can also be obtained through hydrocarbon pyrolysis, partial oxidation, auto thermal processes, or steam reforming using natural gas or other fossil fuels [48], [51], [52]. Additionally, biomass can serve as a material for hydrogen production through processes such as bio-photolysis, dark fermentation, photo-fermentation, or biomass gasification and pyrolysis [44]–[46]. However, the production process from biomass is less reliable due to its slow and low yields. Moreover, biomass conditioning requires specific attention to stages of collection, transfer, and processing, which need to consider certain spatial and size constraints not necessarily proportional to the production capacity.

Table 2. Efficiency of hydrogen production method

Process	Feed Stock	Technology	Efficiency	References
Electrolysis	Water	AEM	62-82	[19][38][39]
	Brine	PEM	67-84	[40][41]
Photolysis	Water, alga	Photosynthesis	1,6-5	[42][43]
Biolysis	Microorganism	Dark ferment	60-80	[44]
	Fermentive bacterias	Hydrolysis	-	[45]
	Biomass, water	Aqua reform	35-55	[46]
	CO+water	Bio shift ref	-	[45]
Thermolysis	Water	Water thermo	20-55	[47]
	Biomass no O ₂	Pyrolysis	35-50	[48]
	Biomass	Gasification	35-50	[49][50]
	Coal	Gasification	74-85	[35]
	Fuels	Steam reform	60-85	[51][24]
	Methane + CO ₂	Auto-thermal	60-75	[52]

Discourse on hydrogen storage

The most important aspect that requires attention in the utilization of hydrogen, besides its production, is the issue of storage and transportation. Security and efficiency requirements are absolute prerequisites to ensure that hydrogen can be utilized anywhere and anytime [51]. According to [53] in its pure form, hydrogen is characterized by low volumetric energy density and high gravimetric energy density. However, in practice, hydrogen storage is closely associated with the medium used. In its application as a transportation fuel, for instance, gravimetric density is crucial, where the hydrogen storage system must be tailored to the size of the user's vehicle without adding extra load and ensuring efficiency in vehicle operation. As mentioned by [53] generally, there are three common approaches to hydrogen storage, namely physical storage in the form of compressed gas and cryogenic liquid hydrogen, as well as material-based or solid-state storage. Storage in compressed gas and liquid methods is the most widely utilized compared to the third method, which is still in the research and development stage. As a form of liquid hydrogen, the challenges faced by the industry are more significant compared to others, including when compared to LNG handling, thus limiting the number of people able to transport liquid hydrogen on a large scale (Table 3) [53], [54].

Table 3. Storage hydrogen method

Storage Method	Advantage	Weakness	References
Compressed gases	The technology has been widely embraced and firmly established, with a rapid handling and filling process.	It experiences energy losses of approximately 15%, is less secure and susceptible to leaks, and its distribution involves high-pressure systems.	[3], [54], [55]
Liquid Hydrogen	Effective compression, high density and efficiency, operates at low pressure, and offers lower storage costs compared to alternative methods.	Storage needs low temperature or high pressure, 30% energy losses, boil off in days and need cooling syst	[53], [54], [56]
Solid-State	Only a minimal storage volume is required to accommodate a substantial amount of hydrogen, with the potential for high density at moderate temperature and pressure.	Specific weight & volume of storage	[57], [58]

Economic aspect of hydrogen as alternative fuel on ship

According to [59] from an economic perspective, there are four cost categories that can be used to evaluate the feasibility of implementing hydrogen in the shipping sector. The four cost categories are as follows at Table 4.

From an economic perspective, there are several considerations in the implementation of hydrogen in the shipping sector, particularly, and transportation or other industries in general. According to [60][29] the cost of hydrogen production varies depending on

the method used. The cost of hydrogen production is a primary economic consideration before other factors such as intervention costs to advance the use of hydrogen in the transportation and industrial sectors, technical target development costs, costs to guide research and development (R&D), costs of identifying legal and regulatory barriers and surveying safety codes and standards, costs of increasing global collaboration focus, and infrastructure costs that support hydrogen applications.

Table 4. Breakdown of hydrogen implementation costs on ships

Category	The Definition	Items
Capital Cost	One-time costs of starting business	Ship hull weight, engine output power, number of azimuthal pods as part of the propulsion system, cost of hydrogen cargo, fuel tanks and ship engines.
Annual Cost	Variations and fluctuation of routine expenses	Fuel prices and crew costs
Emission Cost	Emission taxes	Assumed no emission taxes
Investment	Additional cost required to prepare and run the project	Design, research & develop tanks and ship hull materials, manufacturing, engineering & supervision, consulting, contingencies & science technology.

Conclusion

In general, hydrogen can be proposed as an alternative fuel for ships, with green hydrogen emerging as a possible discourse at this time due to its lowest emission potential and easily obtainable raw materials. However, there are still long-standing challenges ahead, especially concerning the supporting systems related to hydrogen handling and conversion that need to be addressed for ships to be converted into hydrogen-powered vessels. Nonetheless, even though hydrogen is not the sole alternative solution, research indicates significant potential regarding the future of hydrogen energy.

References

- [1] H. G. PhD, T. Boravelli, J. D. S. PhD, and H. R. Safarpour, "Production of Syngas from Biomass Using a Downdraft Gasifier," *International Journal of Engineering Research and Applications*, vol. 07, no. 06, 2017, doi: 10.9790/9622-0706026171.
- [2] M. Genovese and P. Fragiaco, "Hydrogen refueling station: Overview of the technological status and research enhancement," *Journal of Energy Storage*, vol. 61, 2023, doi: 10.1016/j.est.2023.106758.
- [3] L. Van Hoecke, L. Laffineur, R. Campe, P. Perreault, S. W. Verbruggen, and S. Lenaerts, "Challenges in the use of hydrogen for maritime applications," *Energy and Environmental Science*, vol. 14, no. 2, 2021, doi: 10.1039/d0ee01545h.
- [4] H. Canton, "International Energy Agency—IEA," in *The Europa Directory of International Organizations 2021*, 2021, doi: 10.4324/9781003179900-103.
- [5] S. Wang *et al.*, "Decarbonizing in Maritime Transportation: Challenges and Opportunities," *Journal of Transportation Technologies*, vol. 13, no. 02, 2023, doi: 10.4236/jtts.2023.132015.
- [6] S. Sharma, S. Agarwal, and A. Jain, "Significance of hydrogen as economic and environmentally friendly fuel," *Energies*, vol. 14, no. 21, 2021, doi: 10.3390/en14217389.
- [7] O. Boucher, P. Friedlingstein, B. Collins, and K. P. Shine, "The indirect global warming potential and global temperature change potential due to methane oxidation," *Environmental Research Letters*, vol. 4, no. 4, 2009, doi: 10.1088/1748-9326/4/4/044007.
- [8] S. Gössling, C. Meyer-Habighorst, and A. Humpe, "A global review of marine air pollution policies,

- their scope and effectiveness,” *Ocean and Coastal Management*, vol. 212, 2021. doi: 10.1016/j.ocecoaman.2021.105824.
- [9] Z. Domachowski, “Minimizing Greenhouse Gas Emissions from Ships Using a Pareto Multi-Objective Optimization Approach,” *Polish Maritime Research*, vol. 28, no. 2, 2021, doi: 10.2478/pomr-2021-0026.
- [10] A. Romano and Z. Yang, “Decarbonisation of shipping: A state of the art survey for 2000–2020,” *Ocean and Coastal Management*, vol. 214, 2021, doi: 10.1016/j.ocecoaman.2021.105936.
- [11] A. S. Alamoush, A. I. Ölçer, and F. Ballini, “Ports’ role in shipping decarbonisation: A common port incentive scheme for shipping greenhouse gas emissions reduction,” *Cleaner Logistics and Supply Chain*, vol. 3, 2022. doi: 10.1016/j.clscn.2021.100021.
- [12] DNV GL - Maritime, “Assessment of Selected Ternative Fuels and Technologies,” *Imo*, vol. 391, no. June, 2019.
- [13] International Maritime Organization, “IMO 2020 : consistent implementation of MARPOL Annex VI.,” *OMI*, 2020.
- [14] European Commission, “Reducing emissions from the shipping sector | Climate Action,” *Climate Action Committee*. 2016.
- [15] Second IMO GHG study, “Second IMO GHG study, 2009. International Maritime Organization (IMO),” ... *Maritime Organization (IMO ...)*, 2009.
- [16] A. Al-Enazi, E. C. Okonkwo, Y. Bicer, and T. Al-Ansari, “A review of cleaner alternative fuels for maritime transportation,” *Energy Reports*, vol. 7, 2021. doi: 10.1016/j.egy.2021.03.036.
- [17] F. Dawood, M. Anda, and G. M. Shafiullah, “Hydrogen production for energy: An overview,” *International Journal of Hydrogen Energy*, vol. 45, no. 7, 2020. doi: 10.1016/j.ijhydene.2019.12.059.
- [18] O. B. Inal, B. Zincir, and C. Dere, “Hydrogen as Maritime Transportation Fuel: A Pathway for Decarbonization,” in *Energy, Environment, and Sustainability*, 2022. doi: 10.1007/978-981-16-8344-2_4.
- [19] S. Dunn, “Hydrogen futures: Toward a sustainable energy system,” *International Journal of Hydrogen Energy*, vol. 27, no. 3, 2002, doi: 10.1016/S0360-3199(01)00131-8.
- [20] S. M. M. Ehteshami and S. H. Chan, “The role of hydrogen and fuel cells to store renewable energy in the future energy network - potentials and challenges,” *Energy Policy*, vol. 73, 2014, doi: 10.1016/j.enpol.2014.04.046.
- [21] J. Nowotny and T. N. Veziroglu, “Impact of hydrogen on the environment,” *International Journal of Hydrogen Energy*, vol. 36, no. 20, 2011, doi: 10.1016/j.ijhydene.2011.07.071.
- [22] I. Dincer, “Environmental and sustainability aspects of hydrogen and fuel cell systems,” *International Journal of Energy Research*, vol. 31, no. 1, 2007, doi: 10.1002/er.1226.
- [23] K. Salikhov, N. D. Stoyanov, and T. V. Stoyanova, “Using optical activation to create hydrogen and hydrogen-containing gas sensors,” in *Key Engineering Materials*, 2020, vol. 854 KEM. doi: 10.4028/www.scientific.net/KEM.854.87.
- [24] M. Dvoynikov, G. Buslaev, A. Kunshin, D. Sidorov, A. Kraslawski, and M. Budovskaya, “New concepts of hydrogen production and storage in Arctic region,” *Resources*, vol. 10, no. 1, 2021. doi: 10.3390/resources10010003.
- [25] G. Squadrito, G. Maggio, and A. Nicita, “The green hydrogen revolution,” *Renewable Energy*, vol. 216, 2023, doi: 10.1016/j.renene.2023.119041.
- [26] C. B. Agaton, K. I. T. Batac, and E. M. Reyes, “Prospects and challenges for green hydrogen production and utilization in the Philippines,” *International Journal of Hydrogen Energy*, vol. 47, no. 41, 2022. doi: 10.1016/j.ijhydene.2022.04.101.
- [27] S. Shiva Kumar and H. Lim, “An overview of water electrolysis technologies for green hydrogen production,” *Energy Reports*, vol. 8, 2022. doi: 10.1016/j.egy.2022.10.127.
- [28] M. Ostadi, K. G. Paso, S. Rodriguez-Fabia, L. E. Øi, F. Manenti, and M. Hillestad, “Process integration of green hydrogen: Decarbonization of chemical industries,” *Energies*, vol. 13, no. 18, 2020, doi: 10.3390/en13184859.
- [29] A. Ajanovic, M. Sayer, and R. Haas, “The economics and the environmental benignity of different colors of hydrogen,” *International Journal of Hydrogen Energy*, vol. 47, no. 57, 2022, doi: 10.1016/j.ijhydene.2022.02.094.
- [30] M. Willuhn, “Green hydrogen to reach price parity with grey hydrogen in 2030,” *pv magazine International*. 2020.
- [31] R. W. Howarth and M. Z. Jacobson, “How green is blue hydrogen?,” *Energy Science and Engineering*, vol. 9, no. 10, 2021, doi: 10.1002/ese3.956.
- [32] S. Mantilla and D. M. F. Santos, “Green and Blue Hydrogen Production: An Overview in Colombia,” *Energies*, vol. 15, no. 23, 2022. doi: 10.3390/en15238862.
- [33] A. O. Oni, K. Anaya, T. Giwa, G. Di Lullo, and A. Kumar, “Comparative assessment of blue hydrogen

- from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions,” *Energy Conversion and Management*, vol. 254, p. 115245, 2022, doi: <https://doi.org/10.1016/j.enconman.2022.115245>.
- [34] C. Bauer *et al.*, “On the climate impacts of blue hydrogen production,” *Sustainable Energy and Fuels*, vol. 6, no. 1, 2022, doi: [10.1039/d1se01508g](https://doi.org/10.1039/d1se01508g).
- [35] Y. Han, J. Liao, W. Li, H. Ma, and Z. Bai, “Insight into the interaction between hydrogen bonds in brown coal and water,” *Fuel*, vol. 236, 2019, doi: [10.1016/j.fuel.2018.09.119](https://doi.org/10.1016/j.fuel.2018.09.119).
- [36] M. McConnachie, M. Konarova, and S. Smart, “Literature review of the catalytic pyrolysis of methane for hydrogen and carbon production,” *International Journal of Hydrogen Energy*, vol. 48, no. 66, 2023, doi: [10.1016/j.ijhydene.2023.03.123](https://doi.org/10.1016/j.ijhydene.2023.03.123).
- [37] S. Anwar and X. Li, “Production of hydrogen from fossil fuel: A review,” *Frontiers in Energy*, vol. 17, no. 5, 2023, doi: [10.1007/s11708-023-0886-4](https://doi.org/10.1007/s11708-023-0886-4).
- [38] F. Shariatzadeh, P. Mandal, and A. K. Srivastava, “Demand response for sustainable energy systems: A review, application and implementation strategy,” *Renewable and Sustainable Energy Reviews*, vol. 45, 2015, doi: [10.1016/j.rser.2015.01.062](https://doi.org/10.1016/j.rser.2015.01.062).
- [39] F. Mneimneh, H. Ghazzawi, M. Abu Hejjeh, M. Manganeli, and S. Ramakrishna, “Roadmap to Achieving Sustainable Development via Green Hydrogen,” *Energies*, vol. 16, no. 3, 2023, doi: [10.3390/en16031368](https://doi.org/10.3390/en16031368).
- [40] S. Shiva Kumar and V. Himabindu, “Hydrogen production by PEM water electrolysis – A review,” *Materials Science for Energy Technologies*, vol. 2, no. 3, 2019, doi: [10.1016/j.mset.2019.03.002](https://doi.org/10.1016/j.mset.2019.03.002).
- [41] İ. Dinçer and C. Zamfirescu, *Sustainable energy systems and applications*. 2012, doi: [10.1007/978-0-387-95861-3](https://doi.org/10.1007/978-0-387-95861-3).
- [42] M. Amin *et al.*, “Hydrogen production through renewable and non-renewable energy processes and their impact on climate change,” *International Journal of Hydrogen Energy*, vol. 47, no. 77, 2022, doi: [10.1016/j.ijhydene.2022.07.172](https://doi.org/10.1016/j.ijhydene.2022.07.172).
- [43] S. F. Ahmed *et al.*, “Biohydrogen production from wastewater-based microalgae: Progresses and challenges,” *International Journal of Hydrogen Energy*, vol. 47, no. 88, 2022, doi: [10.1016/j.ijhydene.2021.09.178](https://doi.org/10.1016/j.ijhydene.2021.09.178).
- [44] S. K. Bhatia *et al.*, “Wastewater based microalgal biorefinery for bioenergy production: Progress and challenges,” *Science of the Total Environment*, vol. 751, 2021, doi: [10.1016/j.scitotenv.2020.141599](https://doi.org/10.1016/j.scitotenv.2020.141599).
- [45] S. E. Hosseini, M. Abdul Wahid, M. M. Jamil, A. A. M. Azli, and M. F. Misbah, “A review on biomass-based hydrogen production for renewable energy supply,” *International Journal of Energy Research*, vol. 39, no. 12, 2015, doi: [10.1002/er.3381](https://doi.org/10.1002/er.3381).
- [46] Y. Amekan, D. S. A. P. Wangi, M. N. Cahyanto, Sarto, and J. Widada, “Effect of different inoculum combination on biohydrogen production from melon fruit waste,” *International Journal of Renewable Energy Development*, vol. 7, no. 2, 2018, doi: [10.14710/ijred.7.2.101-109](https://doi.org/10.14710/ijred.7.2.101-109).
- [47] E. B. Agyekum, C. Nutakor, A. M. Agwa, and S. Kamel, “A Critical Review of Renewable Hydrogen Production Methods: Factors Affecting Their Scale-Up and Its Role in Future Energy Generation,” *Membranes*, vol. 12, no. 2, 2022, doi: [10.3390/membranes12020173](https://doi.org/10.3390/membranes12020173).
- [48] M. Shahabuddin, B. B. Krishna, T. Bhaskar, and G. Perkins, “Advances in the thermo-chemical production of hydrogen from biomass and residual wastes: Summary of recent techno-economic analyses,” *Bioresour. Technol.*, vol. 299, 2020, doi: [10.1016/j.biortech.2019.122557](https://doi.org/10.1016/j.biortech.2019.122557).
- [49] J. C. Elauria, M. L. Y. Castro, and D. A. Racelis, “Sustainable biomass production for energy in the Philippines,” *Biomass and Bioenergy*, vol. 25, no. 5, 2003, doi: [10.1016/S0961-9534\(03\)00089-8](https://doi.org/10.1016/S0961-9534(03)00089-8).
- [50] J. C. Elauria, M. L. Y. Castro, M. M. Elauria, S. C. Bhattacharya, and P. Abdul Salam, “Assessment of sustainable energy potential of non-plantation biomass resources in the Philippines,” *Biomass and Bioenergy*, vol. 29, no. 3, 2005, doi: [10.1016/j.biombioe.2005.03.007](https://doi.org/10.1016/j.biombioe.2005.03.007).
- [51] C. Tarhan and M. A. Çil, “A study on hydrogen, the clean energy of the future: Hydrogen storage methods,” *Journal of Energy Storage*, vol. 40, 2021, doi: [10.1016/j.est.2021.102676](https://doi.org/10.1016/j.est.2021.102676).
- [52] P. J. Megia, A. J. Vizcaino, J. A. Calles, and A. Carrero, “Hydrogen Production Technologies: From Fossil Fuels toward Renewable Sources. A Mini Review,” *Energy and Fuels*, vol. 35, no. 20, 2021, doi: [10.1021/acs.energyfuels.1c02501](https://doi.org/10.1021/acs.energyfuels.1c02501).
- [53] F. Zhang, P. Zhao, M. Niu, and J. Maddy, “The survey of key technologies in hydrogen energy storage,” *International Journal of Hydrogen Energy*, vol. 41, no. 33, 2016, doi: [10.1016/j.ijhydene.2016.05.293](https://doi.org/10.1016/j.ijhydene.2016.05.293).
- [54] T. Zhang, J. Uratani, Y. Huang, L. Xu, S. Griffiths, and Y. Ding, “Hydrogen liquefaction and storage: Recent progress and perspectives,” *Renewable and Sustainable Energy Reviews*, vol. 176, 2023, doi: [10.1016/j.rser.2023.113204](https://doi.org/10.1016/j.rser.2023.113204).

- [55] J. Zheng, X. Liu, P. Xu, P. Liu, Y. Zhao, and J. Yang, "Development of high pressure gaseous hydrogen storage technologies," *International Journal of Hydrogen Energy*, vol. 37, no. 1, 2012, doi: 10.1016/j.ijhydene.2011.02.125.
- [56] L. Pu, H. Yu, M. Dai, Y. He, R. Sun, and T. Yan, "Research progress and application of high-pressure hydrogen and liquid hydrogen in storage and transportation," *Kexue Tongbao/Chinese Science Bulletin*, vol. 67, no. 19, 2022, doi: 10.1360/TB-2022-0063.
- [57] E. Boateng and A. Chen, "Recent advances in nanomaterial-based solid-state hydrogen storage," *Materials Today Advances*, vol. 6, 2020, doi: 10.1016/j.mtadv.2019.100022.
- [58] R. Chandra Muduli and P. Kale, "Silicon nanostructures for solid-state hydrogen storage: A review," *International Journal of Hydrogen Energy*, vol. 48, no. 4, 2023. doi: 10.1016/j.ijhydene.2022.10.055.
- [59] A. N. Alkhaledi, S. Sampath, and P. Pilidis, "Economic analysis of a zero-carbon liquefied hydrogen tanker ship," *International Journal of Hydrogen Energy*, vol. 47, no. 66, 2022, doi: 10.1016/j.ijhydene.2022.06.168.
- [60] J. R. Bartels, M. B. Pate, and N. K. Olson, "An economic survey of hydrogen production from conventional and alternative energy sources," *International Journal of Hydrogen Energy*, vol. 35, no. 16, 2010, doi: 10.1016/j.ijhydene.2010.04.035.