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Global demand for green hydrogen-based steel: Insights from 28 scenarios

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ABSTRACT

Growing expectations are being placed on green hydrogen-based steel for decarbonising the global steel industry. However, the scale of the expected demand is dispersed across numerous case studies, resulting in a fragmented picture. This study examines 28 existing scenarios to provide a cohesive view of future global demand. In the short term, the demand for green hydrogen-based steel is expected to be limited, constituting 2% of current total steel production by 2030. However, a transformation phase is expected around 2040, marked by accelerated growth. By 2050, global demand is projected to reach 660 Mt (with an interquartile range of 368–1000 Mt), equivalent to 35% (19%–53%) of current total steel production. To meet such growing demand, green hydrogen supply and electrolyser capacity will need to increase to more than 1000 times current levels by 2050. These trends highlight both short-term limitations and long-term potential. Decarbonisation efforts will therefore require immediate emission reductions with already scalable options, while simultaneously building the enabling infrastructure for green hydrogen-based steelmaking to ensure long-term impacts.

1. Introduction

How can we decarbonise the global steel industry? Answering this simple question is a daunting task, and one that has been plaguing us for many years [1]. The main difficulty lies in the process of separating the oxygen from the iron ore, i.e., in reducing the iron. Since iron exists in the natural environment as iron oxide, reduction is essential for producing steel from iron ore. Environmentally, the problem is that one of the most cost-effective ways to reduce iron involves using carbon from coal and coke [2]. Irrespective of how low-carbon the energy supplied to this reduction process may be, carbon-based reduction inevitably produces CO_2 due to the chemical reactions involved. A consequence of these chemical reactions is the significant emission of CO_2, which accounts for ~5% of global emissions [3]. Further, this figure rises to ~8% if all CO_2 emissions from steel plants producing coke, sinter, iron and steel are considered [4].

While there are several potential solutions to this problem (e.g., installing carbon capture and storage (CCS) at the blast furnace and basic oxygen furnace (BF-BOF) process) [5], one that is attracting increasing attention is hydrogen-based reduction, where carbon is replaced with hydrogen as the reducing agent [6]. This transition is based on the principle that when hydrogen reacts with iron oxide, it produces water vapour instead of carbon dioxide as a by-product. Therefore, if hydrogen is produced without CO_2 emissions, then the process can be emission-free. A growing body of literature has examined the potential of this 'defossilisation' option, particularly in leveraging green hydrogen, which is defined as hydrogen derived from renewable sources such as wind and solar energy. For example, Vogl et al. (2018) conducted a detailed investigation of the process of green hydrogen-based steelmaking and the associated production costs [7]. Their findings showed that the economic feasibility of the hydrogen-based process is dependent upon low-cost renewable electricity. This observation corroborates the conclusions reached by Devlin et al. (2023), who proposed that green hydrogen-based steelmaking is cost-competitive when there is abundant renewable electricity and access to high-quality iron ore [8]. In this context, there is positive news on the horizon: the cost of renewable electricity is falling rapidly [9], and the cost of green hydrogen is expected to fall in the future [10]. Indeed, a growing number of studies suggest that hydrogen-based steelmaking will become cost-competitive and play a major role in the economies of iron- and steel-producing countries such as China [11], India [12], Japan [13], Germany [14], the US [15], the UK [16], South Africa [17], and Australia [18].

These findings raise a key question: What is the expected global

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demand for green hydrogen-based steel? Currently, scenarios outlining the demand for green hydrogen-based steel are dispersed across various case studies, resulting in a fragmented picture. This fragmentation hinders our ability to understand the full scale of future demand and the associated resource and infrastructure requirements, including green hydrogen, electrolysers, and renewable electricity. The objective of this study was therefore to bridge this knowledge gap by reviewing existing scenarios projecting future demand for green hydrogen-based steel. Subsequently, we translated this future demand data into quantifiable requirements for green hydrogen and its associated infrastructure. By presenting this information, we aim to provide policymakers and industry stakeholders with a clear understanding of the projected scale of green hydrogen-based steel demand and the requirements for infrastructure deployment.

2. Methods

Firstly, in order to identify relevant studies, we conducted a systematic review of global-level analyses considering green hydrogen as a decarbonisation option for the steel industry. The search was conducted in June 2023 using Scopus and Web of Science, using the keywords "steel" OR "iron" OR "industry" AND "carbon" OR "CO2″ OR "GHG" OR "climate" OR "pathway" OR "scenario" OR "hydrogen". These search engines do not include grey literature, which also provides valuable information. Thus, Google and Google Scholar were utilised as supplementary search engines to screen relevant documents. Following the initial search, relevant studies were identified and subjected to a title and abstract screening process. The selected studies were then subjected to a full text eligibility check, with specific criteria including whether the analysis was on a global scale, considered green hydrogen-based steelmaking, and presented future production scenarios. The final selection comprised 10 references covering 28 distinct scenarios [19–28]. Subsequently, we extracted hydrogen-based steel demand data up to 2050 from these selected scenarios for further analysis.

The hydrogen-based steel demand data was then converted into green hydrogen, electrolyser, and renewable electricity requirements. This conversion was facilitated by employing the process model developed by Venkataraman et al. (2022) [22]. The key assumptions include the mass of iron ore to be processed (1.43 kg-Fe_2O_3/kg-Fe), the mass of hydrogen required for reducing the ore (0.0431 kg-H_2/kg-Fe_2O_3), electrolyser efficiency (50 kWh/kg-H_2), hydrogen processing efficiency (90%), and electricity requirements for electric arc furnaces (450 kWh/t-liquid steel). Based on the International Energy Agency's scenario [26], we assume an electrolyser capacity factor of 46%, considering the variable electricity supply. These assumptions result in the following key technical factors: a green hydrogen requirement of 0.0616 kg-H_2/t-liquid steel, an electrolyser requirement of 0.849 GW/t-liquid steel, and a renewable electricity requirement of 3872 kWh/t-liquid steel.

Note that we focus specifically on green hydrogen, rather than "blue" (fossil fuel with CCS) or other hydrogen production routes. This deliberate focus is based on the assumption that anything other than green hydrogen may not be compatible with a decarbonised future. For example, Howarth and Jacobson (2021) showed that natural gas-based hydrogen with carbon capture (i.e., blue hydrogen) would be associated with significant emissions due to fugitive emissions [29]. Longden et al. (2022) concluded that establishing hydrogen supply chains on the basis of fossil fuels is likely incompatible with climate targets and raises the risk of stranded assets [30]. Bauer et al. (2022) provided a more nuanced perspective in this space by showing that blue hydrogen based on 'state of the art' technology can indeed reduce CO_2 emissions compared to conventional natural gas reforming or direct combustion of natural gas [31]. However, even under conditions favourable to blue hydrogen production, emissions are at the upper end of the green hydrogen range. In line with these established findings, our study considered only green hydrogen-based steel. This choice does not reflect an intention to oppose blue or other coloured hydrogen projects, but only an intention to focus on the main options for defossilising the steel industry.

3. Results and discussion

3.1. Growing and uncertain future demand

From 28 distinct scenarios, we obtained a total of 84 data points indicating the global demand for green hydrogen-based steel for the years 2030, 2040, and 2050. Although the future demand estimated by the individual scenarios varies markedly, all of the scenarios show an upward trend by 2050 (Fig. 1).

The widely different future demand for green hydrogen-based steel stems mainly from four factors: climate ambition, the efficacy of CCS, the uptake of scrap recycling, and total steel demand. The first factor is climate ambition – more stringent emissions reductions required in the steel industry increase the need for green hydrogen-based steel. This trend can be seen in the differences between Morfeldt et al. (2015) and other studies. Morfeldt et al. (2015) assume global temperature rise stabilisation at 2.4–3.2 °C above pre-industrial levels, a much more conservative benchmark than all other studies considering 1.5 °C or well below 2 °C [28]. The modest climate ambition of Morfeldt et al. (2015) leads to limited demand for green hydrogen-based steel, as other processes can produce steel more cheaply while continuing to emit carbon dioxide into the atmosphere [32].

The second factor is the efficacy of CCS – less effective CCS increases the need for green hydrogen-based steel. This trend is particularly well illustrated in Agora Industry (2023), which carefully considers the effectiveness of CCS and argues that the assumption of ~90% emission reduction from the BF-BOF process through CCS, as assumed in most scenarios, is optimistic due to its low economic viability and low flue gas CO_2 concentration [19]. Using a more conservative assumption of up to ~70% emission reduction from the BF-BOF process through CCS, Agora Industry (2023) expects a relatively higher demand for green hydrogen-based steel compared to other scenarios. Furthermore, Bataille et al. (2021) explicitly consider the accessibility to geological storage sites and show a clear relationship between lower accessibility and higher demand for green hydrogen-based steel [24]; Lopez et al. (2022), which do not assume CCS deployment, also shows a rapid increase in demand for green hydrogen-based steel [20]. In contrast, the future demand for green hydrogen-based steel is modest in Venkataraman et al. (2022) [22], IEA (2021) [26] and IEA (2020) [27], which assume larger scale CCS deployment for the BF-BOF process.

The third factor is the uptake of scrap recycling – limited scrap recycling increases the demand for green hydrogen-based steel. This trend is particularly evident in Pye et al. (2022), where there is little growth in scrap recycling between now and the future. This assumption contrasts with all the other scenarios, where scrap recycling is expected to at least double by 2050 due to the increasing availability of scrap [23]. Consequently, Pye et al. (2022) report the scenario with the highest demand for green hydrogen-based steel among the scenarios considered.

The fourth factor is total steel demand – growing total steel demand increases the demand for green hydrogen-based steel. This simple relationship is well illustrated in MPP (2022), where total steel demand increases to 1.3 times current levels by 2050, requiring green hydrogen-based steel along with CCS and scrap recycling [21]. In contrast, Yu et al. (2021) assume that a range of material efficiency strategies, combined with higher steel prices due to carbon pricing, will significantly reduce total steel demand, resulting in no growth in total steel demand by 2050 [25]. The limited total steel demand results in a relatively lower demand for green hydrogen-based steel than in the other scenarios.

Overall, the magnitude of the increase in green hydrogen-based steel demand depends on a number of factors and assumptions employed in each scenario, including climate ambition, the efficacy of CCS, the uptake of scrap recycling, and total steel demand. Any results should,

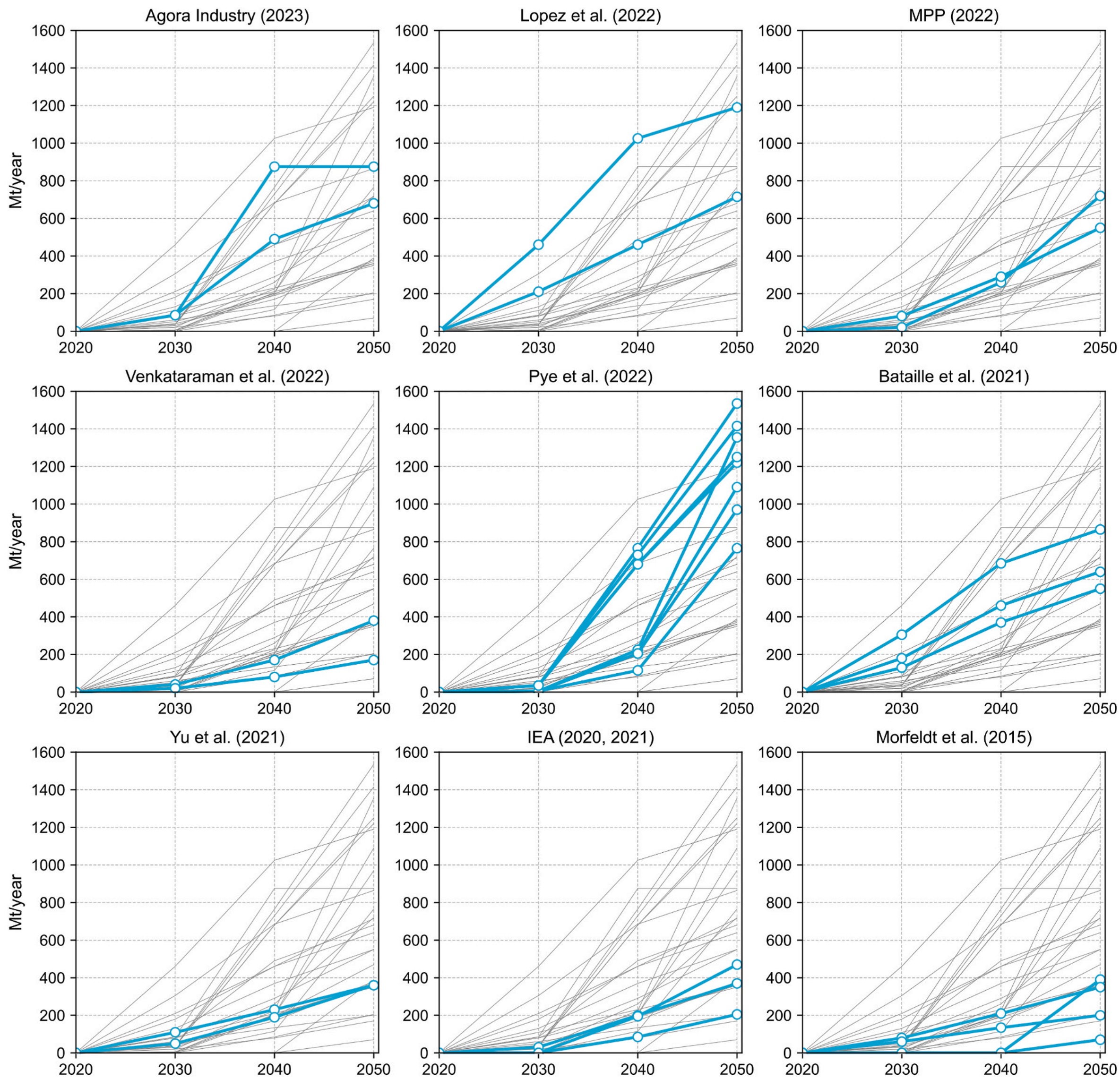

Fig. 1. Individual scenarios for the expected global demand for green hydrogen-based steel. Thin grey lines indicate all scenarios, while thick blue lines indicate scenarios in each literature. The data include 10 references covering 28 distinct scenarios [19–28]. MPP: Mission Possible Partnership; IEA: International Energy Agency. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

therefore, always be interpreted alongside these assumptions. In this context, the range of estimates reported in this study can be interpreted as potential uncertainties.

3.2. General trends – limited in the short term but significant in the long term

When all of the data are processed together, three key general trends emerge (Fig. 2). First, the demand for green hydrogen-based steel is expected to be limited in the short term. The median demand in 2030 is 35 Mt (with an interquartile range of 5–85 Mt), which corresponds to only 2% (0%–4%) of current total steel production (i.e., 1890 Mt) [33]. Second, a period of accelerated demand is expected by around 2040, with existing scenarios showing that global demand will rise to 228 Mt (185–468 Mt), or 12% (10%–25%) of the current level of total steel production. Third, the demand for green hydrogen steel is expected to continue its upward trend until 2050, albeit with a high degree of uncertainty. The global demand in 2050 is expected to rise to 660 Mt (368–1000 Mt), corresponding to 35% (19%–53%) of current levels of total steel production. To put these numbers into context, the total estimated steel demand in 2050 ranges from 1860 Mt to 2800 Mt, with a median of 2240 Mt. This means that green hydrogen-based steel is expected to meet approximately 30% of total steel demand in 2050.

Collectively, our analysis confirms that while existing scenarios do not perceive green hydrogen as a short-term solution, it is positioned as a major medium-to long-term solution within the evolving landscape of the global steel industry.

3.3. Challenging scale of resources and infrastructure requirements

Our ability to meet the aforementioned increase in demand will depend largely on essential resources and infrastructure: green hydrogen, electrolysers, and renewable electricity. The estimated resources and infrastructure requirements required for producing green hydrogen-based steel highlight significant challenges in this context (Fig. 3).

Specifically, green hydrogen demand is expected to be 2 Mt (0–5 Mt) in 2030, 14 Mt (11–33 Mt) in 2040, and 41 Mt (23–62 Mt) in 2050. To put these numbers into perspective, low-emission hydrogen production was approximately 1 Mt in 2021, mainly from fossil fuels with CCS, with

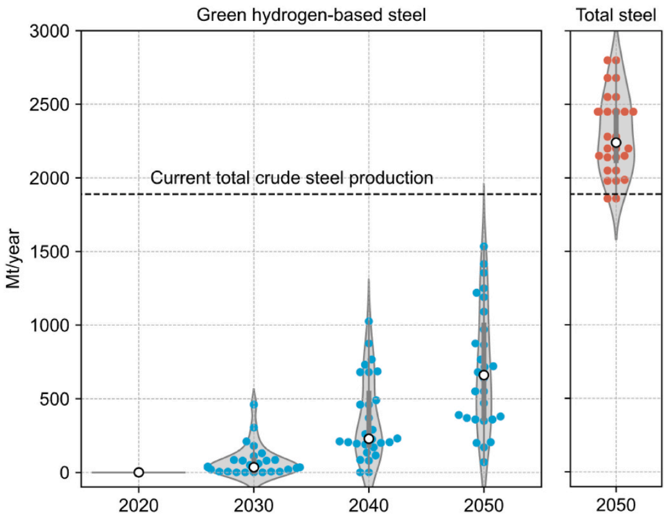

Fig. 2. Expected global demand for green hydrogen-based steel derived from 28 scenarios. White symbols represent the median of the data, while the thick grey bars represent the interquartile range. The thin grey area shows the distribution of the data using kernel density estimation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

only 35 kt produced by water electrolysis [34]. This means that the supply of green hydrogen will have to increase by more than 1000 times by 2050 for steelmaking alone.

A similar trend is evident in electrolyser requirements. The current global electrolyser capacity is ~0.5 GW [35], while the existing scenarios require 561 GW (312–849 GW) in 2050. This means that electrolyser capacity will also need to increase more than 1000 times by 2050.

Such an increase in electrolyser capacity will require a significant increase in the generation of renewable electricity needed for electrolyser operations. Specifically, the renewable electricity required for these operations is projected to increase to 2556 TWh (1423–3872 TWh) in 2050. By comparison, current annual electricity production from solar and wind is approximately 2873 TWh [35], which implies that, by 2050, the entire current output of solar and wind power will be required solely for green hydrogen-based steel production.

These results are based on our set of assumptions for standardisation purposes. Nevertheless, our findings align closely with those reported in existing studies. For example, Agora Industry (2023) reports hydrogen requirements of 45–58 Mt in 2050, while our results indicate 42–54 Mt for their scenarios [19]. Similarly, IEA (2021) estimates that 295 GW of electrolyser capacity will be required for the steel industry in 2050, which compares well with our estimate of 310 GW [26]. In addition, Yu et al. (2021) project total electricity use in the global steel industry to increase to 1900 TWh in 2050, including electricity use for 1000 Mt of scrap recycling in electric arc furnaces [25]. Adjusting for this latter electricity use using the same assumption as in our study (i.e., 450 kWh/t of liquid steel), we arrive at 1450 TWh, which closely aligns with our estimate of 1400 TWh. Obviously, actual figures may vary depending on future technological advancements and regional factors. Our intention here is to offer a reasonable indication of the scaling challenge posed by resource and infrastructure requirements, providing insights for strategic planning by government and industry stakeholders.

4. Conclusion

Our analysis provides an integrated view of the global demand for green hydrogen-based steel. In the short term, demand is expected to be limited, with a cautious start by 2030. However, a transformative phase characterised by an accelerated increase in global demand is expected by around 2040. Looking ahead to 2050, global demand is expected to reach ~660 Mt/year, which is equivalent to ~35% of current crude steel production. These trends point to green hydrogen-based steel as an important long-term solution, not a short-term fix.

This emerging perspective poses a key dual challenge for decarbonising the steel industry: on the one hand, all possible options for immediate emission reductions must be implemented now to cope with limited carbon budgets; on the other hand, infrastructure deployment and supply chain building for green hydrogen-based steelmaking must be pursued in parallel to ensure long-term impacts. Given the narrowing window of opportunity to stay within carbon budgets [36], failure to address even one of these challenges could jeopardise our ability to achieve a stable climate while providing essential services to a growing world population.

Immediate emission reduction options include improving energy and material efficiency, enhancing recycling efforts, and retrofitting existing facilities [37]. Given the long lifespan of iron and steel facilities, any of these efforts must carefully consider the risk of "committed" emissions and bridge the gap between current practices and the long-term transition to green hydrogen-based steelmaking [38]. It is vital to recognise that we do not have time to wait for 'new' technology to come online in the future and solve our problem away [39]; we must work now with what we have.

A key consideration in developing the enabling infrastructure and supply chains could be where to build what. There is an emerging body of literature discussing the energy-efficient supply chain in this context. For instance, Devlin and Yang (2022) demonstrate that exporting hydrogen-reduced iron (i.e., in the form of hot briquetted iron) is more energy-efficient and cost-competitive than exporting hydrogen and iron ore [40]. The same trend is observed in another independent study,

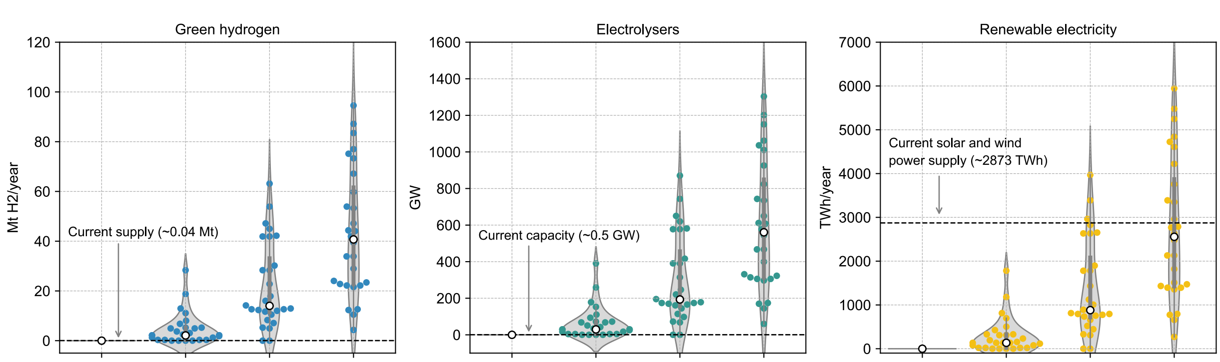

Fig. 3. Resource and infrastructure requirements for meeting the expected global demand for green hydrogen-based steel derived from 28 scenarios. White symbols represent the median of the data, while the thick grey bars represent the interquartile range. The thin grey area shows the distribution of the data using kernel density estimation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

which shows that maintaining today's production patterns by shipping hydrogen is significantly more costly, whereas trading intermediate products could save costs while retaining significant value creation in resource-poor importing regions [41]. In addition, Wang et al. (2023) demonstrate that levelised costs of green hydrogen-based steel production vary widely, even within the same countries, depending on existing infrastructure, transport distance and renewable electricity potential [42]. All of these findings underscore the need for strategic planning and international collaboration based on a detailed understanding of geography and country context. With the exception of Bataille et al. (2021) [24] and Lopez et al. (2022) [20], few existing studies provide detailed regional resolution, which is an important avenue for future research.

Overall, our analysis paints an integrated picture of the evolving landscape of green hydrogen-based steel demand, highlighting both short-term limitations and long-term potential. The road to a hydrogen-based steel industry is a long one, and considerable effort will be required to navigate the complexities and ensure successful implementation.

CRediT authorship contribution statement

Takuma Watari: Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft. **Benjamin McLellan:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.06.423.

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