CHEMICAL ENGINEERING TRANSACTIONS

VOL. 111, 2024

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Valerio Cozzani, Bruno Fabiano, Genserik Reniers

ISBN 979-12-81206-11-3; **ISSN** 2283-9216

DOI: 10.3303/CET24111117

Green Hydrogen and the Environment: a Review of Trends and Challenges in Scientific Production (2019-2023)

Emilio J. Medrano-Sánchez[a]*, Edson Marín-Jara[b]

[a] Faculty of Engineering and Architecture, Cesar Vallejo University, Campus Ate, Km.8.2, Ate Vitarte. Lima Perú
[b] National University of Trujillo, Av. Juan Pablo II, Trujillo 13011. Trujillo-Perú
emedranos@ucvvirtual.edu.pe

This article focuses on the study of green hydrogen and its relationship with the environment, highlighting the growing importance of this topic in the context of the transition to more sustainable energy sources, noting that green hydrogen produced by renewable energy has become a fundamental resource for addressing current environmental and energy challenges. As for the methodology used to carry out this study, it is based on the review and analysis of a set of scientific articles published in journals indexed in Scopus and Web of Science for the period between 2019 and 2023, organizing the results into nine main categories covering topics such as hydrogen production with renewable energies, its climate benefit, social and economic implications, cost analysis and environmental impacts, among others. These categories represent the main research focuses in the field of green hydrogen and provide a comprehensive view of progress in this area. The analysis reveals that hydrogen production with renewable energies is a prominent research topic, closely followed by the analysis of its environmental and economic impacts. However, less explored areas are also identified, such as the use of green hydrogen and suitable water sources for its production. Finally, this article provides a comprehensive overview of recent research on green hydrogen and its environmental implications. The results highlight the importance of continuing to explore less studied areas and promote an integral approach to research on this key resource for energy and environmental sustainability.

1. Introduction

The global reliance on fossil fuels significantly contributes to greenhouse gas emissions and air pollution, posing serious environmental and health risks. Therefore, it's crucial to explore and implement alternative energy sources. Green hydrogen, produced via water electrolysis from renewable energy, offers a promising climate-neutral solution. Recent studies have increasingly focused on green hydrogen due to its potential as a clean energy alternative to fossil fuels, with water electrolysis providing a sustainable method of production (Yao et al., 2021). Hydrogen produced this way boasts a purity of over 99.9% (Terlouw et al., 2022), yet it currently accounts for only 2% of global hydrogen production (Terlouw et al., 2022). This low output is attributed to unresolved challenges, such as the operational patterns of renewable energy, policy measures, production costs, and the significant capital investment needed to address intermittency issues (Chew et al., 2023). Economic viability is key to scaling up green hydrogen, with current high costs of production, storage, and distribution making it less competitive compared to blue and grey hydrogen, or natural gas (Jovan & Dolanc, 2020). However, as nations strive for carbon neutrality by 2050, green hydrogen stands out as a vital option for reducing emissions, especially in the energy and transportation sectors, which are major sources of anthropogenic environmental pressure (Valente et al., 2021).
Bareiß et al. (2019) demonstrate that hydrogen production via electrolysis, powered by renewable energy, can reduce CO_2 emissions by up to 75%. Hauglustaine et al. (2022) highlight the climate benefits of transitioning to a 100% green hydrogen economy, with CO_2eq emissions from green hydrogen constituting only 1.2% to 11.3% of avoided CO_2 emissions. Jaradat et al. (2022) show a reduction of 3042 TnCO_2/year in a Jordanian case study using photovoltaic energy, while Mneimneh et al. (2023) suggest that increasing liquid green hydrogen power generation by 5% in the maritime industry could cut global emissions by 9%. These studies underscore the environmental significance of transitioning to a green hydrogen economy.Water consumption is also crucial in

Paper Received: 15 April. 2024; Revised: 28 July 2024; Accepted: 29 August 2024
Please cite this article as: Medrano-Sánchez E.J., Marín-Jara E., 2024, Green Hydrogen and the Environment: a Review of Trends and Challenges in Scientific Production (2019-2023), Chemical Engineering Transactions, 111, 697-702 DOI:10.3303/CET24111117

green hydrogen production. Ajanovic et al. (2022) report that 10-15L of water are required per kg of hydrogen produced. Rodríguez-Fontalvo et al. (2023) note that solar-intensive hydrogen production in Colombia requires substantial water resources, and Simoes et al. (2021) find that tap water, followed by urban wastewater, is most suitable for hydrogen production in Portugal. These findings, though limited, emphasize the critical role of water in green hydrogen production.

From this point of view and added to the premise that hydrogen is a key player in the energy of the future, this article aims to analyze the academic production in journals indexed in Web of Science and Scopus, from 2019 to 2023, on green hydrogen and its environmental implications. To address this objective, the following question is posed: To what extent does existing research on green hydrogen comprehensively explore its environmental impacts, including its contribution to climate change and its significant demand for hydrological resources?

2. Methodology

This research was based on a descriptive bibliographic review that addressed scientific articles focused on "green hydrogen" and its interaction with the environment, using the Web of Science and Scopus databases. This review was limited to publications between 2019 and May 2023. Articles were selected based on two inclusion criteria: the explicit inclusion of the terms "green hydrogen" and "environment" in the title, abstract, or keywords, and their publication within the designated period. Additionally, articles that did not qualify as scholarly articles or were not available in open access were excluded. Only open access articles were selected to ensure that the results of this review are accessible to a broader audience, including academic and professional communities. This decision facilitates the transparency and replicability of the findings presented.In total, 171 articles were identified, distributed between Scopus and Web of Science. A duplication elimination process reduced this number by removing works that appeared in both databases, leaving a total of 102 articles for the first phase of review.

The next stage involved a more detailed review, excluding 62 articles that did not specifically align with the study's objectives because they did not focus on the environmental dimensions of green hydrogen or addressed unrelated aspects such as design, costs, or technical issues not linked to environmental concerns. This reduced the sample to 40 articles, which were examined in full text.

After this evaluation, an additional six articles were discarded for deviating from the required environmental focus, leaving 34 articles for the final analysis. These articles were processed to extract substantial information about green hydrogen and its environmental implications, using Microsoft Excel to effectively organize and categorize the data.

In this process, a categorization system was established that divided the topics into nine major research areas, grouping the articles according to thematic relevance and the content of their contributions. Additionally, 36 groups of contributions and proposals were identified based on the frequency of their mention in the reviewed studies, totaling 92 instances of relevant themes that contributed to the understanding of green hydrogen from an environmental perspective.

Among the notable findings, for example, was an estimate of water consumption in the production of green hydrogen and its projected impact by 2050, highlighting the importance of considering water resource sustainability in the context of the global hydrogen economy.These compilation and analysis efforts not only allowed for a better understanding of the current situation of green hydrogen and its potential environmental impact but also helped identify gaps in the existing literature and suggest directions for future research in this critical field.

3. Results

3.1 Main research topics on green hydrogen and environment

The systematic research identified nine main categories in the field of green hydrogen and its intersection with environmental concerns. The first topic "Hydrogen production with renewable energy" has been investigated in 09 articles. Yao et al. (2021) propose a method to address environmental issues caused by urea while producing green hydrogen using solar energy, achieving a 17.3% reduction in energy consumption. Huang & Liu (2020) analyze the potential for green hydrogen production in China from solar and wind energy. Kakoulaki et al. (2021) examine the replacement of high-carbon hydrogen production in Europe with water electrolysis using renewable electricity. Guo et al. (2022) develop a solar-powered prototype to generate hydrogen from air humidity. Jaradat et al. (2022) present a case study on green hydrogen production in Jordan using Red Sea water and electrolysis. Fernández-González et al. (2022) explore green hydrogen production to boost renewable energy in Spain. Woods et al. (2022) discuss water management for the hydrogen economy, analyzing the use of desalinated water and wastewater effluents for electrolysis in Australia. Brigljević et al. (2022) address the challenge of utilizing surplus renewable electricity for centralized hydrogen production via the power-to-gas conversion

process. Finally, Pedrazzi et al. (2022) propose a sustainable energy system in an Italian fruit market, using green hydrogen to meet the energy needs of hydrogen-powered forklifts.
The second category, "Climate benefit of hydrogen," was addressed in 02 articles. Hauglustaine et al. (2022) analyzed CO_2eq emission reductions in long-term hydrogen economy scenarios, highlighting their contribution to the Paris Agreement goals. Mneimneh et al. (2023) complemented this by exploring the impact of green hydrogen on key sectors like shipping and transportation, with case studies from various global regions.
The third category, "Society and hydrogen," was addressed in 06 articles. Chew et al. (2023) explored how Process Systems Engineering (PSE) can tackle challenges related to energy security, equity, and environmental sustainability. Trattner et al. (2022) complemented this by evaluating the transition from the fossil era to the green era, both globally and in Austria. In the industrial sector, Swennenhuis et al. (2022) analyzed fairness in the transition towards climate neutrality in the steel industry, comparing technologies such as CO_2 capture and storage, biotech-based steelmaking, and green hydrogen-based steelmaking. Kochanek (2022) expanded the analysis regionally by examining the development of the hydrogen economy in the Visegrad Group countries, focusing on legislation and investments. At the European level, Ciechanowska (2020) investigated the Green Deal initiatives and hydrogen strategies in the EU, with a focus on Poland. Finally, Ibrahim et al. (2022) provided a comprehensive view of the energy transition in the United Arab Emirates, assessing efficiency from 2001 to 2020.
The fourth category, "Hydrogen production and economic-environmental analysis," was addressed in 06 articles. Ajanovic et al. (2022) discussed various forms of hydrogen production based on primary energy sources, analyzing the economic and environmental performance of the main hydrogen colors and the barriers to their adoption in fuel cell vehicles. Jovan & Dolanc (2020) studied the potential for green hydrogen production at a Slovenian hydropower plant, showing its competitiveness in the transport sector under certain fiscal conditions. Terlouw et al. (2022) quantified the current and future costs and environmental burdens of large-scale hydrogen production systems on islands with high renewable energy potential. Winter et al. (2022) evaluated the implications of electrolysis from dispersed water sources for small-scale hydrogen production from a techno-economic and life-cycle perspective. Pivetta et al. (2022) optimized the design and operation of a hydrogen production and storage system at an Italian port to meet the demand of an automobile fleet and a steel plant. Ali et al. (2022) assessed the green hydrogen potential in southern Thailand by selecting suitable sites based on technical, economic, and environmental criteria.
The fifth category, "Potential sources of water for hydrogen production," was addressed in a single article. Simoes et al. (2021) evaluated the suitability of water sources for hydrogen production through electrolysis, combining technological, economic, environmental, and social criteria at two different sites in Portugal: one in a semi-urban location on the Atlantic coast and the other in a rural area far from the coast.
The sixth category, "Environmental impacts of hydrogen production," was addressed in 05 articles. Valente et al. (2021) analyzed the environmental implications of using hydrogen in heavy transport, quantifying the impacts throughout the entire life cycle. Ceran (2020) determined the limit value for weighting the environmental criterion, showing that hydrogen production via photovoltaic-electrolyzer systems is the best option under Polish conditions. Weidner et al. (2023) evaluated the impacts of different hydrogen technologies on climate change mitigation costs, highlighting the environmental load changes when switching from gray to blue and green hydrogen. Weidner & Guillén-Gosálbez (2023) studied the decarbonization of the residential heating sector in the EU and the UK, evaluating impacts to minimize the transgression of biophysical limits. Amaya-Santos et al. (2021) compared hydrogen production from urban solid waste with blue and green hydrogen production.
The seventh category, "Climate benefit of renewable source fuels," was addressed in a single article. Dray et al. (2022) assessed how different fuel pathways, such as synthetic fuels from biomass, synthetic fuels from green hydrogen and atmospheric CO_2, and the direct use of green liquid hydrogen, could lead aviation towards a climate impact with net-zero emissions.
The eighth category, "Use of green hydrogen," was addressed in 03 articles. Digiesi et al. (2022) developed a model to minimize emissions in renewable energy systems and steel production with hydrogen. Kalchschmid et al. (2023) evaluated three uses of hydrogen: energy storage, vehicle mobility, and direct use. Awad et al. (2023) analyzed the use of hydrogen in Dubai's buses to reduce CO_2 emissions.
The ninth category, "Green hydrogen production with different energy sources," was addressed in a single article. Rodríguez-Fontalvo et al. (2023) estimated Colombia's potential to produce green hydrogen and evaluated different production alternatives, considering installed capacity, capital investment, and environmental analysis related to water use and CO_2 capture.

3.2 Main contributions and proposals on green hydrogen and the environment

The analysis of 34 articles has culminated in a compendium of significant contributions ranging from theoretical proposals to empirical findings, all focused on the interaction between green hydrogen and the environment. Among the most frequent contributions, totaling 15 mentions, are the "Measures to Implement Green Hydrogen and/or Reduce CO_2 Emissions." These contributions highlight a variety of strategies for integrating green hydrogen into different economic sectors, aimed at reducing the emission of pollutants and alleviating anthropogenic pressure on the ecosystem.

The "Costs of Producing Green Hydrogen" and "CO_2 Emissions for Different Types and/or Configurations of Hydrogen or Energy Source" both share a frequency of 10 in the reviewed literature, emphasizing both the economic challenge of producing green hydrogen compared to other types of hydrogen and the environmental impact associated with various production methodologies.

The category "Hydrogen Production from Renewable Energy through Electrolysis" reaches a frequency of six, showing interest in optimizing various renewable sources such as solar, onshore, and offshore wind, and hydroelectric for hydrogen production. Likewise, the "Geographical Location of Green Hydrogen Production Projects" with a frequency of four, highlights the importance of selecting optimal sites that not only meet environmental, technical, and economic criteria but also sociocultural and institutional considerations.

Furthermore, the analysis reveals less focus on topics such as the "Use of Green Hydrogen" and the "Climate Benefit of Hydrogen," with three and two articles respectively, marking a clear opportunity for deeper exploration in these areas. Additionally, challenges related to "Water Consumption in Hydrogen Production" and the "Analysis of Environmental Impacts of Hydrogen from a Life Cycle Perspective" are less frequently explored, emphasizing the need to address water resource sustainability and the capability to operate within planetary boundaries.

In conclusion, the spectrum of contributions gathered highlights the complexity and multidimensionality of the transition to a green hydrogen economy, urging more rigorous inquiry into less studied areas to foster a holistic understanding of its environmental implications and maximize its contribution to global sustainability goals.

4. Discussion

The increasing dependence on energy resources across all sectors of the economy, coupled with growing climate concerns, drives the search for cleaner energy sources like green hydrogen. However, its production presents environmental challenges that must be carefully addressed. Simoes et al. (2021) and Ajanovic et al. (2022) emphasize that hydrogen production, particularly green hydrogen, is highly dependent on water resources, making it vulnerable to water scarcity. This is especially critical given that gray and blue hydrogen production also requires large amounts of water, and large-scale production could place significant pressure on global water resources. These authors report that water consumption for blue and gray hydrogen is 25L and 38L/KgH2 respectively, while for green hydrogen, it ranges between 10-15L. Woods et al. (2022) highlight the importance of exploring alternative water sources, such as wastewater, to mitigate this impact and meet the projected hydrogen demand for 2050. Their study suggests that if the 1720 GL of wastewater generated per year were used, it would be sufficient to meet the projected global hydrogen demand for 2050 (530 MtH2/year).

Regarding the integration of hydrogen in industrial sectors, Digiesi et al. (2022) identify that the selection of low-energy-consuming electrolyzers, combined with a low-impact energy mix, is crucial for decarbonizing the steel sector. Awad et al. (2023), analyzing the use of hydrogen in public transportation in Dubai, conclude that a combination of green and gray hydrogen could reduce CO2 emissions by 3.5 million tons, representing a 61.7% reduction in CO_2 emissions over the next three decades. This underscores hydrogen's viability as a key solution for sustainable transportation.

Finally, Kakoulaki et al. (2021), Terlouw et al. (2022), and Digiesi et al. (2022) emphasize the importance of geographic location in the success of green hydrogen projects, highlighting that careful site selection is crucial to maximizing environmental and economic benefits.

5. Conclusions

The reviewed studies demonstrate that while green hydrogen is a viable alternative for decarbonization, its production presents significant environmental challenges, particularly regarding water resource demand. These studies highlight the need to integrate alternative water sources, such as wastewater, to minimize environmental impact and meet future hydrogen demand.

Furthermore, the implementation of green hydrogen in industry and transportation shows great potential for reducing CO_2 emissions, provided that the technology and geographic location of projects are carefully selected and optimized. Although important progress has been made, it is crucial to adopt a more holistic approach that integrates both technical considerations and environmental impacts, ensuring that green hydrogen effectively contributes to climate and sustainability goals.

Future research should consider incorporating a wider variety of sources, as the present study focused on open access articles to ensure that the findings are accessible to a broader audience, including those without access to subscription-based journals.

References

Ajanovic, A., Sayer, M. & Haas, R. (2022). The economics and the environmental benignity of different colors of hydrogen. *International Journal of Hydrogen Energy*, *47*(57), 24136–24154. https://doi.org/10.1016/j.ijhydene.2022.02.094

Ali, F., Bennui, A., Chowdhury, S. & Techato, K. (2022). Suitable Site Selection for Solar-Based Green Hydrogen in Southern Thailand Using GIS-MCDM Approach. *Sustainability*, *14*(11), 6597. https://doi.org/10.3390/su14116597

Amaya-Santos, G., Chari, S., Sebastiani, A., Grimaldi, F., Lettieri, P. & Materazzi, M. (2021). Biohydrogen: A life cycle assessment and comparison with alternative low-carbon production routes in UK. *Journal of Cleaner Production*, *319*, 128886. https://doi.org/10.1016/j.jclepro.2021.128886

Awad, M., Bouabid, A., Almansoori, A. & AlHajaj, A. (2023). Analysis of CO2 emissions reduction on the future hydrogen supply chain network for Dubai buses. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2023.04.121

Bareiß, K., de la Rua, C., Möckl, M. & Hamacher, T. (2019). Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. *Applied Energy*, *237*, 862–872. https://doi.org/10.1016/j.apenergy.2019.01.001

Brigljević, B., Byun, M., Lee, H., Kim, A., Lee, B., Moon, C., Choi, J. H., Yoon, H. C., Yoon, C. W., Ok, Y. S., Lim, D.-H., Kim, C.-H., Moon, S. & Lim, H. (2022). When Bigger Is Not Greener: Ensuring the Sustainability of Power-to-Gas Hydrogen on a National Scale. *Environmental Science & Technology*, *56*(18), 12828–12837. https://doi.org/10.1021/acs.est.1c08525

Ceran, B. (2020). Multi-Criteria Comparative Analysis of Clean Hydrogen Production Scenarios. *Energies*, *13*(16), 4180. https://doi.org/10.3390/en13164180

Chew, Y. E., Cheng, X. H., Loy, A. C. M., How, B. S. & Andiappan, V. (2023). Beyond the Colours of Hydrogen: Opportunities for Process Systems Engineering in Hydrogen Economy. *Process Integration and Optimization for Sustainability*, *7*(4), 941–950. https://doi.org/10.1007/s41660-023-00324-z

Ciechanowska, M. (2020). Europejski Zielony Ład wyzwaniem dla transformacji polskiego przemysłu naftowego i gazowniczego. *Nafta-Gaz*, *76*(10), 757–761. https://doi.org/10.18668/NG.2020.10.12

Digiesi, S., Mummolo, G. & Vitti, M. (2022). Minimum Emissions Configuration of a Green Energy–Steel System: An Analytical Model. *Energies*, *15*(9), 3324. https://doi.org/10.3390/en15093324

Dray, L., Schäfer, A. W., Grobler, C., Falter, C., Allroggen, F., Stettler, M. E. J. & Barrett, S. R. H. (2022). Cost and emissions pathways towards net-zero climate impacts in aviation. *Nature Climate Change*, *12*(10), 956–962. https://doi.org/10.1038/s41558-022-01485-4

Fernández-González, R., Puime-Guillén, F. & Panait, M. (2022). Multilevel governance, PV solar energy, and entrepreneurship: the generation of green hydrogen as a fuel of renewable origin. *Utilities Policy*, *79*, 101438. https://doi.org/10.1016/j.jup.2022.101438

Guo, J., Zhang, Y., Zavabeti, A., Chen, K., Guo, Y., Hu, G., Fan, X. & Li, G. K. (2022). Hydrogen production from the air. *Nature Communications*, *13*(1), 5046. https://doi.org/10.1038/s41467-022-32652-y

Hauglustaine, D., Paulot, F., Collins, W., Derwent, R., Sand, M. & Boucher, O. (2022). Climate benefit of a future hydrogen economy. *Communications Earth & Environment*, *3*(1), 295. https://doi.org/10.1038/s43247-022-00626-z

Huang, Y.-S. & Liu, S.-J. (2020). Chinese Green Hydrogen Production Potential Development: A Provincial Case Study. *IEEE Access*, *8*, 171968–171976. https://doi.org/10.1109/ACCESS.2020.3024540

Ibrahim, M. D., Binofai, F. A. S. & Mohamad, M. O. A. (2022). Transition to Low-Carbon Hydrogen Energy System in the UAE: Sector Efficiency and Hydrogen Energy Production Efficiency Analysis. *Energies*, *15*(18), 6663. https://doi.org/10.3390/en15186663

Jaradat, M., Alsotary, O., Juaidi, A., Albatayneh, A., Alzoubi, A. & Gorjian, S. (2022). Potential of Producing Green Hydrogen in Jordan. *Energies*, *15*(23), 9039. https://doi.org/10.3390/en15239039

Jovan, D. J. & Dolanc, G. (2020). Can Green Hydrogen Production Be Economically Viable under Current Market Conditions. *Energies*, *13*(24), 6599. https://doi.org/10.3390/en13246599

Kakoulaki, G., Kougias, I., Taylor, N., Dolci, F., Moya, J. & Jäger-Waldau, A. (2021). Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables. *Energy Conversion and Management*, *228*, 113649. https://doi.org/10.1016/j.enconman.2020.113649

Kalchschmid, V., Erhart, V., Angerer, K., Roth, S. & Hohmann, A. (2023). Decentral Production of Green Hydrogen for Energy Systems: An Economically and Environmentally Viable Solution for Surplus Self-Generated Energy in Manufacturing Companies? *Sustainability*, *15*(4), 2994. https://doi.org/10.3390/su15042994

Kochanek, E. (2022). The Role of Hydrogen in the Visegrad Group Approach to Energy Transition. *Energies*, *15*(19), 7235. https://doi.org/10.3390/en15197235

Mneimneh, F., Ghazzawi, H., Abu Hejjeh, M., Manganelli, M. & Ramakrishna, S. (2023). Roadmap to Achieving Sustainable Development via Green Hydrogen. *Energies*, *16*(3). https://doi.org/10.3390/en16031368

Pedrazzi, S., Morini, E., Nasti, M., Pizzileo, S. & Allesina, G. (2022). Green Hydrogen Powered Forklifts in Industrial Transport: Case Study of an Italian Fruit and Vegetable Market. *International Journal of Heat and Technology*, *40*(1), 145–150. https://doi.org/10.18280/ijht.400117

Pivetta, D., Dall'Armi, C. & Taccani, R. (2022). Multi-Objective Optimization of a Hydrogen Hub for the Decarbonization of a Port Industrial Area. *Journal of Marine Science and Engineering*, *10*(2), 231. https://doi.org/10.3390/jmse10020231

Rodríguez-Fontalvo, D., Quiroga, E., Cantillo, N. M., Sánchez, N., Figueredo, M. & Cobo, M. (2023). Green hydrogen potential in tropical countries: The colombian case. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2023.03.320

Simoes, S. G., Catarino, J., Picado, A., Lopes, T. F., di Berardino, S., Amorim, F., Gírio, F., Rangel, C. M. & Ponce de Leão, T. (2021). Water availability and water usage solutions for electrolysis in hydrogen production. *Journal of Cleaner Production*, *315*, 128124. https://doi.org/10.1016/j.jclepro.2021.128124

Swennenhuis, F., de Gooyert, V. & de Coninck, H. (2022). Towards a CO2-neutral steel industry: Justice aspects of CO2 capture and storage, biomass- and green hydrogen-based emission reductions. *Energy Research and Social Science*, *88*. https://doi.org/10.1016/j.erss.2022.102598

Terlouw, T., Bauer, C., McKenna, R. & Mazzotti, M. (2022). Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment. *Energy & Environmental Science*, *15*(9), 3583–3602. https://doi.org/10.1039/D2EE01023B

Trattner, A., Klell, M. & Radner, F. (2022). Sustainable hydrogen society – Vision, findings and development of a hydrogen economy using the example of Austria. *International Journal of Hydrogen Energy*, *47*(4), 2059–2079. https://doi.org/10.1016/j.ijhydene.2021.10.166

Valente, A., Tulus, V., Galán-Martín, Á., Huijbregts, M. A. J. & Guillén-Gosálbez, G. (2021). The role of hydrogen in heavy transport to operate within planetary boundaries. *Sustainable Energy & Fuels*, *5*(18), 4637–4649. https://doi.org/10.1039/D1SE00790D

Weidner, T. & Guillén-Gosálbez, G. (2023). Planetary boundaries assessment of deep decarbonisation options for building heating in the European Union. *Energy Conversion and Management*, *278*, 116602. https://doi.org/10.1016/j.enconman.2022.116602

Weidner, T., Tulus, V. & Guillén-Gosálbez, G. (2023). Environmental sustainability assessment of large-scale hydrogen production using prospective life cycle analysis. *International Journal of Hydrogen Energy*, *48*(22), 8310–8327. https://doi.org/10.1016/j.ijhydene.2022.11.044

Winter, L. R., Cooper, N. J., Lee, B., Patel, S. K., Wang, L. & Elimelech, M. (2022). Mining Nontraditional Water Sources for a Distributed Hydrogen Economy. *Environmental Science & Technology*, *56*(15), 10577–10585. https://doi.org/10.1021/acs.est.2c02439

Woods, P., Bustamante, H. & Aguey-Zinsou, K.-F. (2022). The hydrogen economy - Where is the water? *Energy Nexus*, *7*, 100123. https://doi.org/10.1016/j.nexus.2022.100123

Yao, M., Ge, J., Sun, B., Hu, J., Koh, S. W., Zhao, Y., Fei, J., Sun, Z., Hong, W., Chen, Z., Hu, W. & Li, H. (2021). Solar-driven hydrogen generation coupled with urea electrolysis by an oxygen vacancy-rich catalyst. *Chemical Engineering Journal*, *414*, 128753. https://doi.org/10.1016/j.cej.2021.128753