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A green hydrogen economy for a renewable energy society

Alexandra M Oliveira, Rebecca R Beswick and Yushan Yan

A hydrogen economy has long been promoted as a ground-breaking aspect of a low-carbon future. However, there is little consensus on what this future entails, with some overly concerned about lack of demand and others disregarding hydrogen's limitations. Here, we fill the need for a comprehensive definition of the 'hydrogen economy' and illustrate a vision in which hydrogen will primarily be used for decarbonization where no alternative exists. We propose a three-phase implementation plan for hydrogen into the industrial sector as a chemical feedstock, the transportation sector for long-range, heavy-duty vehicles, the buildings sector for heat, and the power sector for seasonal storage. We find that hydrogen will not be the largest energy economy, but with a projected need of 2.3 Gt H_2 annually, it can decarbonize around 18% of energy-related sectors. In the long-term, hydrogen can complement renewable electricity and be the keystone to a 100% renewable future.

Address
Department of Chemical and Biomolecular Engineering, Center for Catalytic Science and Technology, University of Delaware, Newark, DE 19716, United States

Corresponding author: Yan, Yushan (yanys@udel.edu)

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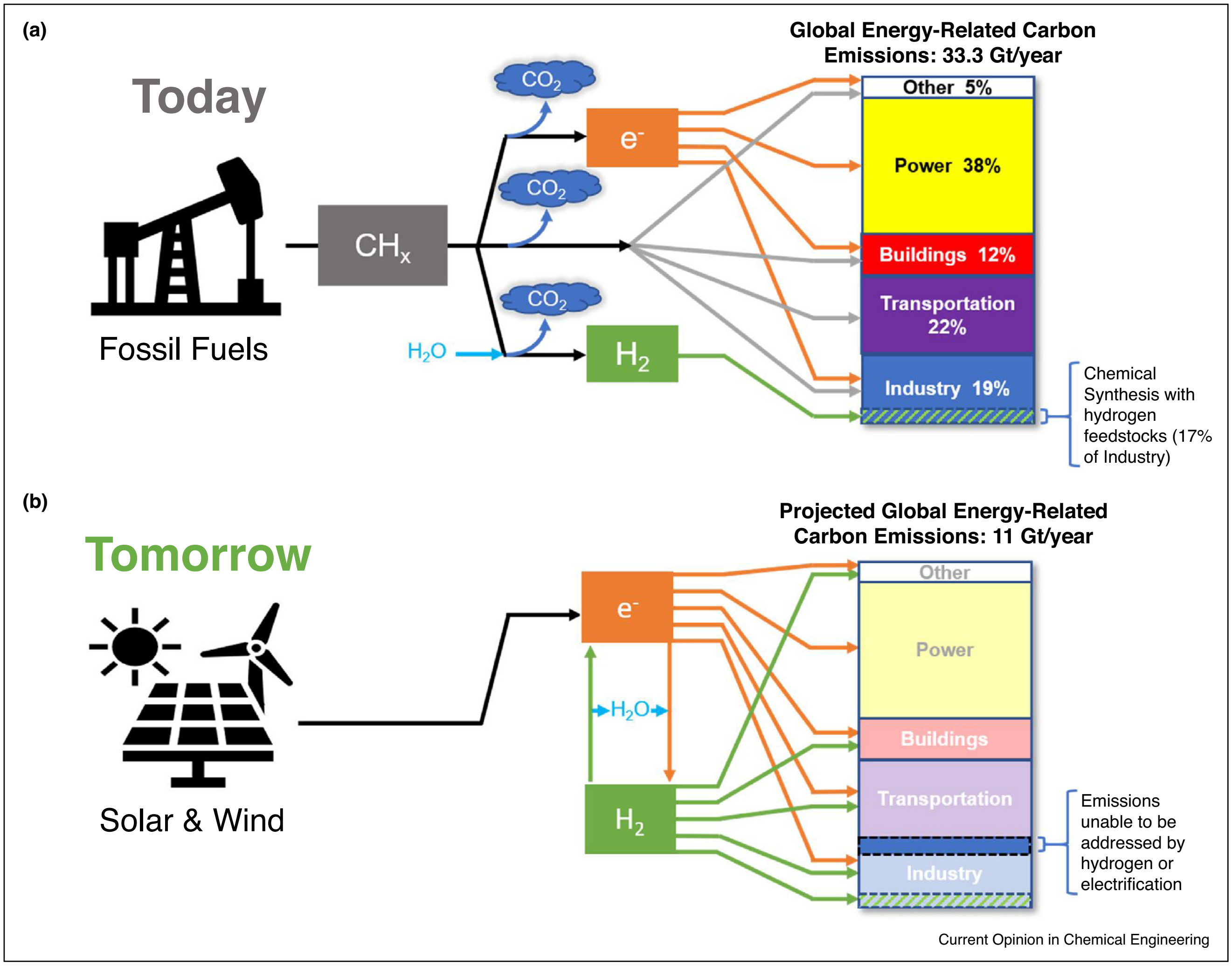
Introduction

In 2019, global energy-related CO_2 emissions reached 33.3 metric gigatons (Gt) annually, growing at a rate that is expected to raise Earth's temperature by several degrees without intervention [1]. The difficulty in reducing emissions in energy-related sectors is largely due to a global dependence on fossil fuels, which contribute to the majority of CO_2 emissions, especially in the power, buildings and heating, transportation, and industry sectors shown in Figure 1a. As such, many countries have been pushing toward the implementation of renewable energy technologies, which could lead to the electrification of many end-use processes with power derived from clean sources. However, due to the diverse applications of fossil fuels, there remain many sectors that are difficult to decarbonize by electricity alone.

One alternative to fossil fuels is 'green' hydrogen, which can be produced through water electrolysis by using an electric current to split water into hydrogen and oxygen with no greenhouse gas emissions, provided the electricity used to power the process is entirely from renewables. Hydrogen's high mass energy density, light weight, and facile electrochemical conversion allow it to carry energy across geographical regions through pipelines or in the form of liquid fuels like ammonia on freight ships [2]. Across sectors as it can be used as a chemical feedstock, burned for heat, used as a reagent for synthetic fuel production, or converted back to electricity through fuel cells. Furthermore, hydrogen's long-term energy storage capacity in tanks or underground caverns [3] makes it one of the only green technologies that can store energy across seasons.

This drove many prominent scientists and economists to suggest a future in which the gas will be the main solution in the battle against climate change [4•,5]. Some believe hydrogen will serve as the primary energy storage technology, the central heating fuel, and the leading transportation fuel for cars, trucks, airplanes, and more. The staunchest opponents to this philosophy counter that hydrogen will have no practical place as a future energy technology due to high production costs and inefficiencies in its conversion to and from electricity [6–8]. These scientists argue that innovative efforts should focus directly on renewable energy and battery technologies, cutting out hydrogen as a middleman. We find the most practical philosophy lies in between these two extremes. The inherent inefficiencies of hydrogen production and conversion indicate that anything that can be electrified using renewable energy will be. However, there are a vast number of areas that renewable energy cannot reach without a bridge. Hydrogen has the potential to fill these gaps in the decarbonization effort because it possesses an inherent flexibility as both a chemical and a non-emissive energy carrier. In our following calculations, we project that the global hydrogen demand could reach over 2.3 Gt annually, compared to the 88 Mt per year used today [9•]. This leads us to propose a new 'green hydrogen economy in a renewable energy society', framing hydrogen as a significant player with a strong market value in a 100% renewable future.

Figure 1



Energy sectors of today and tomorrow.

Energy sources and annual carbon dioxide emissions from various sectors compared for the society of 2021 and a future society which utilizes electrification and green hydrogen production from renewable energy to the highest extent. Hydrogen will play a role in sectors that are difficult to decarbonize, whereas electrification will be the predominant green solution where possible. The remaining 11 Gt CO_2 per year is due to chemical byproducts where carbon capture is the only currently developed solution. Future increases in demand are also taken into account.

The concept of ‘hydrogen economy’ was originally created by John Bockris in the 1970s. It described a vision in which hydrogen is produced via water electrolysis and through pipelines to factories, homes, and fueling stations where it would be converted back to electricity in on-site fuel cells [4•]. Nations like Japan have put forth plans for a ‘hydrogen society’, in which hydrogen is the major component of the nation’s secondary energy framework illustrated in their Strategic Energy Plan [10]. Researchers at the National Renewable Energy Laboratory of the U.S. Department of Energy have proposed a vision defined as H2@Scale, in which hydrogen is incorporated into sectors such as grid power, industry, and transportation but provides additional benefits like energy security [11].

In examining the colloquial and professional use of these terms for a hydrogen future within publications, there is little agreement as to what exactly these terms mean. In the vision that follows, we will define an energy ‘economy’ to describe the production, consumption, distribution, and dispensation network of a particular energy carrier and its dependent sectors, including the resultant business, economic, and environmental impacts. An energy ‘society’ is supported upon several of these economies, where a particularly dominant economy can define a society by being deeply integrated into its culture and lifestyle. Our analysis shows that hydrogen will not be the largest player in the global energy infrastructure. Instead, we foresee a green hydrogen economy in which hydrogen will fill a secondary role as the keystone that is necessary to enable a 100% renewable energy society. As shown in Figure 1b, hydrogen and electricity will work in tandem to service all energy-related sectors.

The hydrogen economy is not a distant concept; rather, the current hydrogen economy will scale up to sustain future demand. Below is our qualitative vision for the integration of green hydrogen into the industry, transportation, buildings and heating, and power sectors in a three-phase process. First, green hydrogen must be implemented in sectors such as the chemical synthesis industry, where there is currently a significant demand for hydrogen globally, 96% of which is 'gray' hydrogen produced from oil, coal, and steam methane reforming [12••]. Soon after, hydrogen could help decarbonize the transportation sector with heavy-duty and long-range fuel cell vehicles, as well as the buildings and heating sector through blending with natural gas pipelines for heating. In the long-term, hydrogen could have an increased presence in the transportation sector if it is used to produce electrofuels (e-fuels) for aviation applications, and it could be used to generate high-grade heat for industrial processes. At this point, it will also penetrate the power sector, serving as a method of seasonal energy storage and reducing the curtailment of renewable energy to allow for near-total decarbonization of the energy sector.

Phase 1: Hydrogen as a chemical feedstock

The hydrogen economy is here today, but it is not yet green. Of the 6.3 Gt of global energy-related carbon emissions that come from the industrial sector each year [12••], around 17% (1.1 Gt) is due to the production of gray hydrogen feedstocks for chemical synthesis and other industrial processes [9•]. 'Blue' hydrogen, which combines gray hydrogen with carbon capture and storage (CCS) technologies, is a low-carbon alternative, but electrolysis is the only entirely green pathway to meet the current hydrogen demand of 88 Mt in this sector for chemical synthesis involving hydrogen feedstocks, since electrification cannot directly impact these processes [9•]. Gray and blue hydrogen currently cost between \$1.20 and \$2.40/kg depending on the cost of CCS, compared to green hydrogen's \$4.85/kg at an electricity cost of \$53/MWh and an efficiency of 65% of the lower heating value at nominal capacity. However, decreasing renewable electricity prices and improvements in electrolyzer efficiency and capital cost are projected to drive the cost of green hydrogen down to less than \$2.00/kg by 2030, which is deemed competitive with gray hydrogen for industrial and all other sectors [13•].

The emissions impact that green hydrogen can bring to the current chemical feedstock industry is often overlooked when the focus is centered upon fuel cell vehicles and energy storage. Yet processes which use hydrogen feedstocks such as oil refining, ammonia synthesis, and methanol production are already firmly established and are growing. The need of hydrogen for refining will continue to grow for the next 10 years to approximately 41 Mt per year following current trends [9•], and ammonia and methanol demand is expected to increase considerably for many years to come, both for agriculture and as a viable energy carrier [14••]. Feedstock hydrogen can also penetrate other chemical synthesis processes which produce CO_2, most notably steel production, one of the largest carbon-emitters in the world, making up nearly 6% of all emissions [12••]. A new process can produce direct reduced iron (DRI) with green hydrogen as the reducing agent and lead to 740 Mt of atmospheric carbon dioxide reduction per year by 2050 when accounting for the growth of the steel industry [9•]. Further current uses for hydrogen also include rocket fuels, glass production, hydrogenation of consumable fats, and applications which use hydrogen for its physical properties, all of which can use green hydrogen to mitigate carbon dioxide emissions.

Replacing fossil fuel-based hydrogen with green hydrogen is the only solution to decarbonizing many large-scale chemical synthesis processes. The simple switch can reduce projected carbon dioxide emissions by 1.6 Gt annually by 2050. Additionally, chemical synthesis provides a reliable beachhead market for introducing green hydrogen, since it presents a targeted, reliable opportunity to sell green hydrogen and even produce it onsite at chemical plants while additional and affordable green hydrogen technologies are developing. To implement green hydrogen for chemical synthesis, research and development of large-scale water electrolysis should be given the highest priority.

Phase 2: A transition fuel for transportation and buildings and heating

With innovations in infrastructure and energy technologies, hydrogen will begin to find new markets in the mid-term transition toward a 100% renewable energy economy. In particular, hydrogen can aid in the decarbonization of heavy-duty and long-range transportation, as well as the heating of buildings.

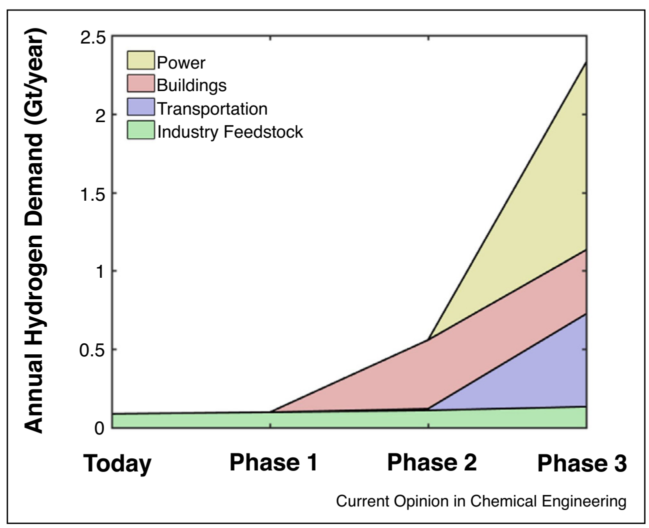
In 2015, 22% of energy-related CO_2 emissions were produced in the transportation sector [12••], and finding replacements for the internal combustion engine (ICE) is necessary to reduce this carbon footprint. Fuel cell electric vehicles (FCEVs), which consume only hydrogen and oxygen from the air and release only water vapor, are already commercially available as passenger vehicles. As of 2019, there were over 23 000 total FCEVs on the road, including cars, buses, and trucks [15]. However, as battery electric vehicles (BEVs) emerge as a competitive commercial technology for green transportation, hydrogen fuel cells will have the most impact in heavy-duty and long-range vehicles, while battery vehicles will likely be the preferred technology for small short-range vehicles especially when fast charging becomes available. This is in part because it is more expensive to extend the range of a BEV by adding battery packs than it is to extend the range of an FCEV by adding hydrogen storage, making FCEVs the more cost competitive option past 300 km [14••]. For longer journeys, FCEVs have a shorter refuel time of about 5 min [16] compared to BEV charging, which can require 8 hours or longer for long-distance charging from the most common home and commercial chargers [17]. Fast refueling times are important for vehicles such as long-range freight trucks, which account for around 25% of transportation-related CO_2 emissions [14••], but require a technology that will not interrupt travel time or driving range. Current predictions show that fuel cell trucks could replace 25% of the fleet by 2050 [14••]. Buses could also be powered by fuel cells during the transition, both as long-range vehicles or, in the case of city buses, as vehicles with fixed routes and high operating times. City buses and materials handling vehicles — such as the 15 000 fuel cell forklifts that are already in operation today [14••] — often run for many hours per day, leaving little time for battery-powered equivalents to recharge. Fuel cell vehicles could alleviate this burden provided a refueling network is developed. Therefore, it is advantageous for transportation research to focus predominantly on long-range and heavy-duty vehicles and leave the decarbonization of passenger vehicles largely to electrification.

In the buildings and heating sector, CO_2 emissions are generated from space and water heating, cooking, and district heating and cooling. In 2015, these applications contributed to 12% of global CO_2 emissions [12••]. Unlike some of the other sectors discussed in this report, the buildings and heating sector does have decarbonization alternatives to hydrogen such as solar heating and electric heating. Although electric heating is not yet cost competitive with heating oil, propane, or natural gas in many areas, it is unlikely that hydrogen will be more cost competitive than electrification for low-grade heat in the long term. However, if it is blended into the existing natural gas grid, hydrogen can serve as a transition fuel to begin to reduce CO_2 emissions in the buildings and heating sector until electric heating becomes cost competitive. Blending of up to 20% hydrogen can be achieved without significant modifications of the existing infrastructure [18], which could lead to the abatement of 145 Mt of CO_2. However, the burning of pure hydrogen for low-grade and mid-grade heat is unlikely due to hydrogen embrittlement damage with the current gas pipeline network. An alternative technology for low-grade heat under 100°C is the use of fuel cells for combined heat and power. While the efficiency of using direct grid electricity is higher than that of a fuel cell, combining the fuel cell power and heat production increases the overall energy efficiency to as high as 80% [19].

While low-grade heat that cannot be satisfied by natural alternatives such as solar heating will eventually be fully electrified, in the industry sector electrification cannot always serve the need for high-grade heat, specifically for processes that require temperatures over 400°C. Cement production, for example, is responsible for 7% of global CO_2 emissions, and 40% of this comes from the combustion of fuels needed to heat kilns to 1450°C [20]. While some processes, such as steel making described in Phase 1, have possible electrochemical alternatives, thermal processes without alternatives will still require high-grade heat, which can be generated from the combustion of pure hydrogen, as long as furnaces and boilers are retrofitted for hydrogen use.

It is important to note that Phase 2, along with the other proposed phases, does not follow a strict timeline in our analysis. Rather, implementation plans for hydrogen into Phase 2 can overlap with Phases 1 and 3. Figure 2 shows a total hydrogen demand of 558 Mt is expected with the implementation of Phase 2.

Figure 2



Projections of hydrogen demand.
Our vision for the changing annual hydrogen demand for each sector today and for the three phases of our implementation plan. In Phase 1, chemical synthesis applications can be fulfilled entirely by green hydrogen. Phase 2 shows the role of hydrogen in the transition of heating and heavy-duty and long-range transportation sectors to green alternatives. In phase 3, hydrogen will be used in tandem with electrification for a 100% renewable energy society enabled by hydrogen energy storage and hydrogen-derived e-fuels. While each phase does not have a precise start date, and some phases may overlap in a practical timeline, much of the Phase 2 data is based on 2030 projections, and Phase 3 relies on predictions out to at least 2050.

Phase 3: Energy security through seasonal storage

In our vision, the final target is a society whose energy needs are met entirely by renewables. This will likely involve electricity and hydrogen working as complementary technologies, storing and converting energy between them. To realize this goal, hydrogen will be especially important in the power sector, where electricity generation by renewables is intermittent and uncertain. Energy storage solutions will be crucial for demand during off-peak periods, and though battery technologies may alleviate hourly fluctuations throughout the day, hydrogen is the one of the only green technologies that can meet seasonal energy storage requirements. Currently, the demand for seasonal storage is low, and fluctuations in renewable energy can be satisfied by fossil fuel-based electricity generation. However, as renewables are responsible for an increasing share of electricity production, the demand for seasonal energy increases exponentially to anywhere from 5 to 20% of total energy production [21•,22,23]. Based on EIA predictions of the total electricity load in 2050, this is equivalent to around 14–67 trillion kWh of seasonal storage annually, which equates to a hydrogen demand of 1.2 Gt [24]. In a Germany-based study, the integration of around 80% renewables with 15% storage equated to around 17 days of long-term storage [21•]. While this is predominantly due to the unpredictability of renewables, there will also be an uptake in seasonal fluctuations as low-grade building heating is provided increasingly by electric heating. Green hydrogen can be produced directly from the grid during peak periods and stored in tanks or underground caverns, where losses to leakage are minimal, even over seasonal durations [3]. This is in comparison to leading battery technologies, including lithium-ion and redox flow batteries, which are effective for up to 12 hours of storage before they incur significant losses [25,26], after which hydrogen is uniquely cost competitive to fulfill this need. However, it is important to note that energy storage, while one of the most prominent proposed applications for hydrogen, will be the last application to come to fruition.

There are some projections that the future of the energy system lies not with an interconnected grid, but in many smart microgrids. Hydrogen will still have a prominent role in any microgrids, as current microgrids often require fossil fuel generators. On average, a single mid-sized generator in a microgrid will emit 2.8–4.5 t of CO_2 per year [27]. Hydrogen fuel cells can easily take the place of generators to supply intermittent power and ensure resiliency.

In the transportation industry, there are several cases where electrification is simply not possible, such as aviation applications, where kerosene-based jet fuels are currently used. These jet fuels currently contribute 918 Mt CO_2 emissions per year, which is likely to increase to 2.6 Gt CO_2 annually as air transport for freight is predicted to grow by 2.4% per year until 2050 and passenger aviation is expected to triple [28,29•]. Converting this sector to green technologies is difficult because volumetric energy density and light weight are particularly important. Battery and fuel cell technologies cannot currently satisfy the power needs of large, long-haul commercial and military aircraft, since the inclusion of more batteries would significantly increase the weight, and hydrogen tanks would consume too much storage space [30]. Hydrogen can still meet the green energy needs of this sector by being converted to e-fuels. In one possible pathway, hydrogen and carbon monoxide can undergo Fischer-Tropsch conversion to form synthetic jet and diesel fuels in a carbon-neutral process if captured CO_2 is converted to CO [31]. The resulting e-fuel would be compatible with the current infrastructure in place in the aviation industry, as long as production pathways are further developed. In the marine sector, e-fuels could also be used to decarbonize larger freight ships, while smaller passenger vessels will likely use fuel cells to replace current fuels and diesel-based power generators. With these new markets for hydrogen in the power and transportation sectors, Figure 2 shows an expected increase in annual hydrogen demand to a total of 2.3 Gt by Phase 3.

In the 100% renewable future, the only decrease in hydrogen production will be due to a reduction in the need for the refining industry, as fossil fuels are used less and less for energy. However, there will still be a need for petroleum-based products industries, which will be responsible for some of the remaining 11 Gt of annual CO_2 emissions in Figure 1b. Other contributions to the remaining emissions are chemical processes that yield unavoidable CO_2 byproducts, such as the cement industry, where 60% of CO_2 emissions are due to non-energy related processes such as the decomposition of calcium carbonate [20]. For these applications, CCS technologies can help abate CO_2 emissions [32], but electrification and hydrogen can work together to alleviate all other CO_2 emissions.

Conclusion

Here we have outlined a viable path by which hydrogen can infiltrate each of four sectors — industry, transportation, buildings and heating, and power — to reduce carbon emissions in applications that are otherwise difficult to decarbonize. Green hydrogen should first be introduced into chemical synthesis applications in the industry sector, where there is a market available now that would cut CO_2 emissions by almost 1.1 Gt annually. In the mid-term energy transition, hydrogen's physical similarity to the current fossil fuel infrastructure will help abate CO_2 emissions in the transportation and buildings and heating sectors by 95 Mt and 3.1 Gt per year, respectively. Finally, hydrogen is one of the few green technologies that can fill the 15% seasonal storage demand of the power sector that is required to enable a 100% renewable energy society. In all, the total need for hydrogen is 2.3 Gt each year, giving room for a large, scalable, and complex future green hydrogen economy that could decarbonize around 18% of energy-related sectors.

Hydrogen will not be the largest energy economy. Because of inevitable energy losses when converting electricity to hydrogen, it is most productive to directly use electricity when possible. However, hydrogen is conveniently suited to decarbonize applications which renewable electricity cannot. Therefore, academic and industrial efforts should target green hydrogen not as the sole solution to decarbonization nor as an infeasible idea to cast aside, but instead as the linchpin economy that works with electrification and other technologies to make possible a society supported entirely by renewable energy.

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Conflict of interest statement

The senior author Y.Y. is cofounder and CEO of Versogen which is a University of Delaware startup for green hydrogen generation.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.coche.2021.100701.

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