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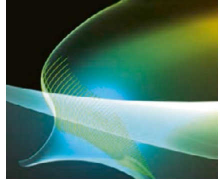

COMMENTARY

Opportunities for the materials research community to support the development of the H_2 economy

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ABSTRACT

MRS hosted a panel discussion on materials needs for growth of the clean H_2 economy. This commentary summarizes key elements from the panel discussion and addresses how the materials research community can engage more deeply with the H_2 energy transition.

The goal of decarbonizing global energy systems by 2050 is a challenge of unprecedented scope and ambition. Hydrogen has been identified as an important enabler for this effort, but its precise role in the energy transition and future energy system remains unclear. The MRS *Focus on Sustainability subcommittee* sponsored a panel discussion on the roles of and materials needs associated with hydrogen in the energy transition. This commentary summarizes key elements from the panel discussion and addresses how the materials research community can engage more deeply with the H_2 energy transition. The topics include inventing new materials with improved properties for advanced technologies, but also supporting the growth of a robust manufacturing base, improving materials corrosion mitigation, helping to de-risk supply chains, and training qualified workers across the industrial ecosystem to reinforce a culture of safety and support the evolution of commercial processes and business models.

Keywords corporate/business · outreach · society · sustainability

Discussion

While there is general agreement that a portfolio of approaches is needed for the energy transition, the exact role for clean H_2 is an area of active debate across government, industry, and academia. Although it may be too early to tell what the "final answer" to this question will be, it is the right time to move with urgency to identify and test technologies and business models for H_2 that can scale to the level needed to reach decarbonization targets. To do so, a host of materials-related challenges related to the safe use of H_2 must be addressed. In this paper, we identify some of them and call for greater materials research community engagement in the essential technical and non-technical issues that require its unique expertise to address in a timely manner.

Introduction

The decarbonization of global energy systems by mid-century is a challenge of unprecedented scope and ambition. Such a transition will require major changes in how energy is produced, delivered, and utilized, the replacement of tens of trillions of dollars' worth of equipment over two or fewer capital deployment cycles, and potentially significant rethinking and reconfiguration of attendant business models and regulatory schemes. There is no "silver bullet" which can single-handedly meet this goal. Rather, a toolkit approach using a variety of technologies will be needed. Hydrogen (H_2) has been identified as an important enabler for decarbonization.[1] Among the roles H_2 can play are: an energy carrier for transportation and for global energy trade;[2,3] a substitute for fossil fuels in industrial processes and residential heating;[4–6] and a mode of long-duration energy storage to support renewables integration onto the power grid.[7] While historical efforts to develop and deploy H_2 technologies have had limited success, the current mix of deepening societal support for decarbonization, increasing industry engagement, generationally attractive government incentives, and renewed interest from universities and the innovation community suggests the window of opportunity for the emergence of a large-scale clean H_2 economy has opened again.

On May 10, 2022, the MRS Focus on Sustainability (FoS) subcommittee hosted a panel discussion asking, "Is hydrogen the fuel of the future?" as part of its on-going series on *Materials Needs for Sustainability by 2050*. This panel featured representatives from academia, industry and government who are working on developing and deploying clean H_2 technologies. During the wide-ranging discussion, panelists offered perspectives on the potential of and current challenges facing H_2 technologies and commented on ways the materials research community can more actively engage in this area. There was common agreement between panelists and during interactive discussion with the audience that the materials research community has an important role to play in supporting the evolution and growth of H_2 technologies as part of the energy transition.

This commentary arises from the need to share this message and the insights of the event with the broader materials research community. We summarize key points from the panel discussion and further develop some of the technical and non-technical themes to provide additional context and content. While the article discusses the opportunities for new materials discovery, it also takes a broader view to include issues that extend beyond the traditional realm of materials research, such as maintenance issues during the field use of H_2 systems.

This article is organized in four parts. The first part introduces the roles H_2 could play in future low-carbon energy systems, and briefly summarizes the panelist perspectives on the overall landscape. The second part highlights different types of technical materials challenges across the H_2 ecosystem–ranging from discovery and design to engineering scale-up and manufacturing to commercialization and life-cycle management. Illustrative examples, some drawn from the panel discussion, are used to show the myriad of ways the materials research community might contribute its expertise. The third section covers ecosystem gaps related to workforce development and interactions with other stakeholder communities working on H_2. The final section offers suggestions from a holistic perspective on how to improve engagement across the various dimensions introduced in the article.

Context

H_2 is an energy carrier. Multiple pathways exist for production, storage and distribution, and utilization of H_2. Today, H_2 production is dominated by fossil fuel-based processes (*i.e.*, steam methane reforming–SMR, and coal gasification), with petrochemical refining and chemicals production as the largest end uses.

H_2 is appealing as a means of decarbonization due to its multiple modes of production compatible with low-carbon energy (via electrolysis using zero carbon energy or thermochemical conversion of fossil fuels with CO_2 capture), relatively high gravimetric energy density, and chemical stability (for long-term energy storage).[1] These features allow the use of H_2 in "hard-to-decarbonize" applications such as transportation (especially for heavy duty vehicles), the chemicals industries (as a reducing agent or effective means of zero-carbon heat), and firm power in support of deep integration of renewable power generation.[1,2,4,7]

Figure 1 shows the magnitude of the changes needed over the next thirty years to achieve various levels of transformation. The plots compare the current global production and use of H_2, by production pathway and end use, against two future scenarios modeled by the International Energy Agency (IEA)–an announced pledge scenario (APS) which reflects current commitments, and a more-aggressive net zero emissions (NZE) scenario.[8] These scenarios are indicative of the level of growth needed in various energy transition models to reach climate action targets. While not the focus of this commentary, the global picture unfolds into a diverse set of regional strategies of that emphasize the relative strengths of different countries around the world; interested readers are referred to individual national roadmaps. [9–15]

Two important trends are predicted as the transition progresses. First, the total flows of H_2 are expected to increase dramatically; the scenarios in Fig. 1 show growth in production ranging from 3 to 7 times by 2050. Second, decarbonization efforts will drive significant shifts in the modes of production and a broadening of the range of end uses that consume H_2. Large-scale deployment of electrolyzers powered by zero-carbon renewable or nuclear energy is expected, as well as a lesser degree of fossil fuel-based production with CO_2 capture and storage (CCS). Significant new uses of H_2 could include industrial metals production, fuel cell vehicles for transportation, and grid support via long-duration energy storage and firm power via fuel cells or H_2 turbines. While new forms of production could grow to significantly exceed the production from current methods based on steam reforming or coal gasification, it is important to note that the transition path will likely feature a dynamic intermediate period of a decade or longer during which multiple types of production with varying degrees of carbon intensity are used, along with efforts to repurpose or otherwise avoid stranding capital assets associated with current infrastructure.

The technical foundations for these changes have been in place for many years. The natural gas sector has been preparing for a transition to H_2 for decades; its current scale guarantees it a role during the transition and likely beyond. Industrial scale electrolysis for H_2 production was demonstrated in the late nineteenth century, with modern fuel cell systems entering into commercial service in the twentieth century.[16] H_2 burners,

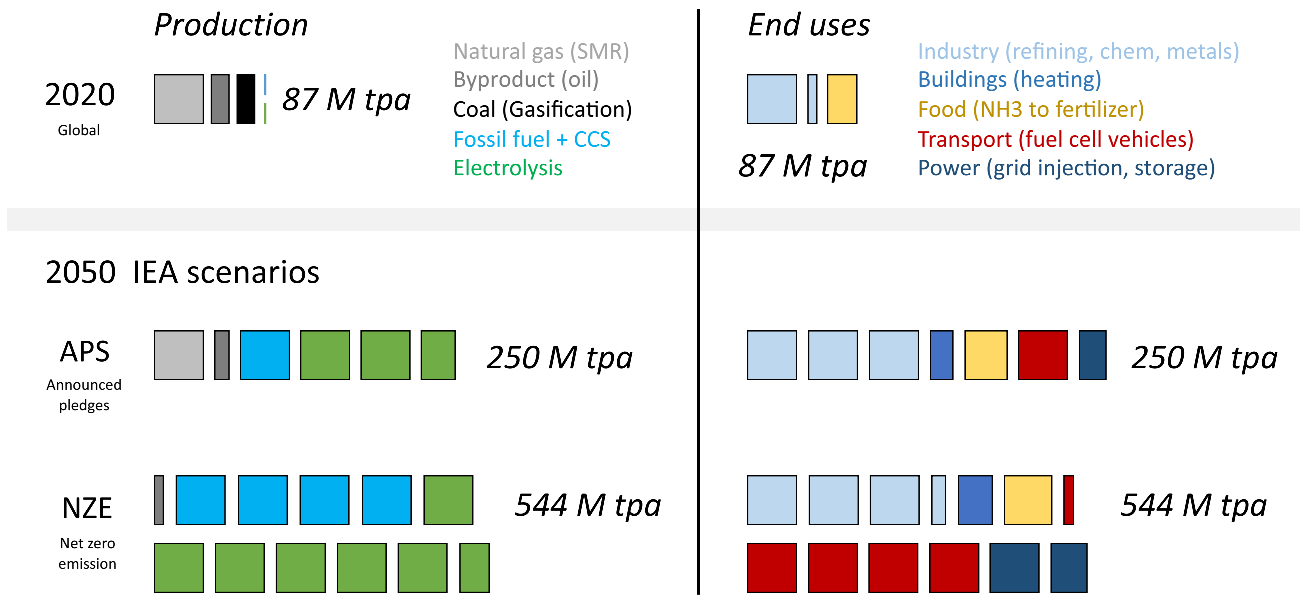

Figure 1. Changes needed in H_2 production and consumption to reduce the carbon intensity of the global economy by 2050. Production is shown on the left and end use on the right. Pathways are color-coded. Historical data from 2020 are shown, along with IEA forecasts of H_2 production and use by 2050 under the APS and NZE scenarios. Each box represents 50 million tonnes H_2 per annum (Mtpa).

H_2-compatible vessels and coatings, and industrial process alternatives using H_2 are at various stages of commercialization.[4,17] A key challenge for the emerging clean H_2 economy is that change is occurring at multiple levels. There is a lot of work on improving the performance and reducing costs of individual technologies. At the same time, the wider ecosystem (including regulatory policy and business models) is also evolving, resulting in a dynamic commercial landscape. While there is a general sense that H_2 will play a role in the future, the specific details remain difficult to predict with high confidence. The members of the panel provided their perspectives on the issues they and their organizations face at the "ground-level" as they work towards deploying H_2 into the energy system.

Box 1 shows the panelists, their organizations, and main points from their initial remarks. Together, these perspectives highlighted the evolving nature of the ecosystem. The panelists agreed on the high hopes for clean production, as well as the growing momentum for use in transportation. There remains uncertainty in the specific paths H_2 will take to scale, but general outlines of the direction are emerging. Renewed public support and private interest in fuel cells and electrolyzers suggests an inflection point in adoption at scale. At the same time, the existing infrastructure around natural gas can be evolved towards clean H_2 production, through the adoption of CCS and the repurposing of pipeline networks, in a way that allows a progressive growth of H_2 supply in conjunction with "green" hydrogen. There is a palpable sense that after several cycles that failed to get H_2 to scale over the past several decades, that this time is different. However, the path is not without materials research challenges, and that is the focus of the rest of this commentary.

Materials needs and opportunities for engagement

For H_2 to reach its potential as part of the energy transition, the challenge is not only to create new materials solutions, but also to deliver them as systems that are affordable, reliable, and manufacturable at scale. To this end, technical gaps requiring materials research can be grouped into two broad categories:

- New materials with better performance and stability
  These types of problems are in the sweet spot of the materials research community.[18,19] They include the improvement of properties and performance through the discovery and optimization of (micro)structure, and study of corrosion. This latter topic is of particular interest under the extreme pH conditions associated with electrolysis.
- Materials aspects of large-scale commercialization
  Materials-enabled systems that show promise at the pilot or limited scale will need to be deployed affordably at very large-scales as part of the H_2 energy transition. There are host of challenges that involve optimization for cost and mass production, as well as practical materials issues related to life and reliability in field operation, replacement or retrofitting of existing assets, and the maturation of supply chains.

The academic materials research community has traditionally focused on the first category, leaving the second category primarily to industrial players; conversely, industrial R&D tends to focus on problems tied to commercial impact, with some companies also supporting targeted efforts in fundamental R&D. While the second type of problems generally involve less fundamental discovery than the first type, they include many interesting yet scientific technical challenges that are just as important to overall success. To advance the H_2 economy, there is a stringent need to bring these two categories together by leveraging the fundamental understanding typical of the first category to address the technical materials challenges for large-scale commercialization.

We now present four examples that illustrate the types of technical materials challenges that will need to be overcome over the next decade. We conclude with an additional example related the "ecosystem" challenges related to human capacity development. Due to the technical expertise of the panelist group, our examples focus on electrochemical conversion; these are intended to be illustrative, rather than exclusive and comprehensive. Many additional materials-related opportunities exist across production (e.g., new materials for CO_2 capture for "blue H_2 or NH_3;" materials selection for methane pyrolysis reactors), delivery infrastructure (e.g., conversion of natural gas pipelines and risks of materials embrittlement), and end use (e.g., materials selection for H_2 turbines) that are not explored in detail here due to space limitations.

New materials

Example 1. Lower cost electrolysis

Renewable energy from wind, solar, and nuclear power is expected to be foundational in future clean energy systems. There are high hopes that zero-carbon electricity from these sources can be used to generate clean H_2 through electrolysis. Currently, the cost of H_2 from electrolysis ranges from $2.2 to $12.3/kg;[20] the key to success will be reducing these costs further. The US DOE Hydrogen Earthshot has set a heuristic goal of 1-1-1: electrolytic H_2 produced using zero-carbon electricity at a cost of $1/kg within a decade [see Box 1]. The panel event included a lively debate on the ultimate achievability of this Earthshot goal; opinions were divided among both panelists and audience participants. Ultimately, beyond the specific price target, the more relevant question is not whether the specific price target can be achieved, but rather what can be done to drive down the cost of "green" H_2 derived from electrolysis using renewable power.

Figure 2 presents a conceptual roadmap towards the Earthshot goal. The cost is broken down by energy and non-energy contributions, and a waterfall is used to illustrate different ways in which the economics can be improved. Electricity dominates the cost, and the left side of the figure shows the current situation (with ranges associated with electricity cost variability in the US) and avenues for cost reduction. Current power producer agreements for utility scale solar offer electricity at prices as low as $0.02/kWh;[21] continued growth of renewable generating capacity and improvements in grid integration over time could allow *average* costs to approach this lower bound resulting in meaningful savings. The specific energy consumption of state-of-the-art systems is 50 kWh/kg, about 50% greater than the thermodynamic limit of 33 kWh/kg. Progress on both energy consumption and energy cost is needed to create the headroom necessary to reach the ultimate u$1/kg goal. Here, we do not distinguish between different electrolyzer technologies (alkaline, proton exchange membrane, anion exchange membrane, or solid oxide electrolysis) but refer an interested reader to a number of introductory reviews on electrolyzer technology and specific research directions for reducing costs.[22-24] Active work along this theme includes direct efforts to reduce the overpotential or increase the current density through engineering of the catalytic activity or conductivity of materials, and indirect action through surface engineering to facilitate bubble removal.[25,26] Materials advances that generally contribute to lower costs in wind and solar electricity production and distribution will indirectly contribute to cost reductions for green H_2.

Savings are also possible in non-energy contributions such as capital cost recovery and operating costs. At present, the capital costs of electrolyzer systems are split evenly between the stack and balance of system, but materials-based improvements are possible by introducing alternate architectures.[27] Polymer/catalyst structure–activity relationships can benefit from fundamental understanding to optimize the overall materials and stack performance (e.g., reduce overpotential and improve current density, Fig. 2). On the operations side, attention must be paid to issues of maintenance and system life. Regarding life, a key technical metric is degradation of the stack performance. Accelerated testing methods are needed to support efforts to extend equipment service lifetimes beyond about 5 years.[28]

Example 2. Replacements for supply-constrained materials

Criticality refers to the risk of, and impact from, materials supply disruptions. There is a growing awareness of the importance of material supply due to a combination of strong expected growth rates relative to production capacity and growing geopolitical tensions.[29] While rare earth elements (e.g., Nd, Pr, and Dy for permanent magnets) and battery materials (including Li, Co, and Ni) have received the most attention, certain aspects of the H_2 supply chain are also exposed to materials supply risks (e.g., Pt or Ir catalyst materials for electrolyzers and fuel cells, carbon fiber for reinforced storage tanks, Ni in solid oxide fuel cells).

One way to reduce the risk is to develop substitutes. Direct substitutes can be introduced at the component level in equipment. An example is the search for replacements for noble metal group catalyst materials.[30] Here, new techniques and tools (e.g., machine learning techniques to accelerate the materials discovery process), building on the decades long investment by DOE in building characterization capabilities and foundational materials science understanding, have the potential to help offset the additional constraints introduced by excluding high performing, but difficult to obtain, materials.[31] Specifically, machine learning and artificial intelligence may be able to extend or challenge some of the existing paradigms of materials discovery in the areas of novel catalysts for H_2 production and water oxidation.[32] A second example is the well-recognized challenge of H_2 embrittlement in steels and alloys. This is often discussed in the context of pipelines but is also applicable throughout the supply chain wherever metals are used in H_2 equipment.

Materials-based solutions can include alternatives alloys or protective coatings, as well as the development of methods to readily assess material health.[33,34]

Substitutions can also be developed at the engineered component- or system-levels. Continuing with the example of electrolysis, a reduction in exposure to Pt or Ir demand could be achieved by switching from PEM-based stacks to alternatives such as alkaline or solid oxide electrolysis systems, but this may increase the need for other materials. Input from the materials community can help system engineers better understand and decide on trade-offs.

Materials aspects of large-scale commercialization

Example 3. Engineering systems for field use

Large-scale commercialization of H_2 technologies at the scales contemplated in the IEA scenarios would likely involve the deployment of millions of assets, designed to operate for periods approaching a decade, under a wide range of environmental conditions. For example, electrolyzer stacks are currently manufactured at the MW scale. The delivery of 50 Mtpa of green H_2 would require at least 285 GW of electrolyzer capacity, corresponding to hundreds of thousands of units.

The "hardening" of assets for field deployment is typically undertaken by industry but involves well-known materials challenges such as corrosion protection and packaging for weather. Figure 3 shows corrosion at an electrolyzer system deployed near the ocean at the HNEI. The panel discussed this as an anecdotal example of the type of engineering problems that must be overcome in the field. Although solutions to corrosion are known in industry generally, this particular case exposed a gap in communication between the system operator and the technical teams at the manufacturer, who were unaware of the problem. In addition to extreme pH used in electrolyzers and subsequent stringent requirements on materials stability and reliability, other environmental concerns include ambient temperature ranges, humidity, and ground vibrations and stability. The chlor-alkali and other mature electrochemical industries have decades of relevant experience and the nascent H_2 industry could potentially benefit from more integration with these sectors.

As companies' equipment matures and their products enter large-scale production, these gaps should naturally begin to close. During this process, there will be a need to apply the general lessons learned in the field development of energy infrastructure to these emerging systems. Competing interests among industrial players and new entrants may hinder the flow of proprietary knowledge and experience due to commercial concerns. In addition, there may be communication gaps between suppliers and their system integrators further down the supply chain. As a repository of know-how, the materials research community can help lessen these "growing pains."

H_2 component suppliers will need to overcome several issues: (1) components designed specifically for the H_2 industry are not always available; (2) commercial components with larger size may require optimization for cost and performance; and (3) components will need to be produced in commercially relevant volumes. Emerging technologies often borrow components from more mature adjacent offerings. This can occur within a sector as well; companies that have developed commercial fuel cell offerings can repurpose components for electrolyzers. However, there are limits to this approach. Despite the opposite nature of the underlying electrochemical reaction, there are aspects where the optimization needs diverge. For example, water in fuel cells must be removed from the reaction zone because of undesired flooding effects, while electrolyzers must be designed for efficient delivery of water to the stack. As a result, hydrophobic materials are favored in the design of components adjacent to the membrane in fuel cells. The converse is true for electrolyzers, but there is a need for more options among hydrophilic materials. This, and other related issues in materials and component development, can be addressed with more open communication across the ecosystem of researchers and engineers working in the field.

The second and third challenges noted above relate to the manufacturing process. As technology enters the marketplace, companies may opt to build larger systems. Increasing the size of components can sometimes have non-obvious impacts on system performance. Operational efficiency, mechanical integrity, and production consistency can all be affected by changes in physical dimension. In addition, the production of large quantities may necessitate changes in processing methods. New processes would require qualification to ensure they are able to produce components with the same properties and performance and could require substantial optimization. In both cases, the materials science and engineering can play a pivotal role in the development of appropriately scaled and cost-effective products and processes.

Example 4. Mass production and end-of-life recovery

Large-scale use of clean H_2 will also require processes for mass production and adequate end-of-life materials management. While these areas are generally considered the concern of industry, they implicitly include a host of materials-related challenges that could benefit from engagement from the broader materials research community. Recent advances in additive manufacturing and 3D printing have brought to the fore the role of materials expertise and the benefits of cross-industry and industry-academic collaboration to accelerate the development of new techniques and processes beyond what can typically be done "in-house."[35] Similar opportunities for collaboration-driven acceleration are expected for fuel cells and electrolyzers, storage and distribution systems, and specialty H_2 equipment.[36,37] Since most roadmaps for cost reduction-depend significantly on manufacturing scale-up, faster progress towards mature mass production should accelerate the adoption of H_2 technologies.

Materials recovery and reuse at the end of service life can improve economics and mitigate life-cycle environmental impacts. While the scale of recycling of fuel cell or electrolyzer stacks is not likely to approach the magnitude of lithium-ion batteries, activity by market leaders is already underway to identify readily recoverable high-value materials and move up the learning curve to take advantage of these opportunities.[38] This presents the materials science community with an opportunity to engineer and introduce novel materials and designs conducive to end-of-life recovery and recycling. As commercial experience is gained and more H_2 technology enters the market, more opportunities are expected to emerge. Private companies will be motivated by commercial considerations, but there will be ample opportunity for strategic collaborations across industry, policymakers, and the research community to address the end-of-life materials questions.

Ecosystem needs

Example 5. Skills and workforce development

On one hand, the maturation and scale-up of a clean H_2 industry with decarbonization impacts across energy, transportation, and commercial sectors will not be possible without an adequate, skilled, and secure workforce. On the other hand, the natural gas sector has long considered its skillset to be complementary to H_2, which could limit the retraining necessary to evolve the workforce. In addition, the growing H_2 sector will create considerable job opportunities.[39]

Steps are well underway with a growing number of training and retraining initiatives across both public and private sectors[40–43] to cover skills ranging from technology and engineering to operations and manufacturing to commercial business development. As was noted during the panel discussion, it is crucial to encourage a broad and versatile preparation of scientists and engineers for new technology development to overshadow efforts to develop an appropriate number of operators, technicians, and maintenance staff to ensure effective commercial operations and technology deployment.

In the near term, there are two areas where expertise from the materials community is particularly needed: safety and standards development. The track record of existing industrial H_2 operations suggests safe operation at scale is possible, but continued vigilance will be needed as H_2 expands into new applications. A clear understanding of the materials aspects of H_2 handling will need to be incorporated into safety protocols. More broadly, standards are needed to encode the expert knowledge into a form that can drive consistency, safety, and efficiency across different applications and support engagement by non-specialists, and the materials community can engage with existing groups such as the Center for Hydrogen Safety on questions about materials selection, capability, and maintenance.[44] See Box 2 for additional information on materials implications for safety and training programs.

The human aspect also has implications for energy justice and global coordination. In response to differences in political and strategic priorities, underlying infrastructure, and resource constraints, the strategic roadmaps to clean H_2 economies vary by country. Engineered products and the commercial ecosystem in different parts of the world may reflect regional preferences. Since scientific and engineering principles are universal, cooperative exchanges across the technical and local communities can be a valuable complement to government-led efforts to promote compatible technical ecosystems and commercial standards across borders. Attention from the materials community to these issues in education, training, and human capacity-building at the local community, regional, and international level will help ensure strong foundations on which the clean H_2 industry will be built.

Moving forward

The next decade offers tremendous opportunity and challenge in scaling up the technologies, commercial ecosystems, and business models that will enable a sustainable energy system by 2050. The materials research community has much to contribute, both broadly and specifically related to H_2. We conclude with two suggestions going forward:

- Look for opportunities across the entire H_2 value chain to apply materials expertise.

  There are a host of materials R&D challenges to be solved across the H_2 value chain. Fundamental questions receive more scientific attention since academic researchers typically have more ability to publish, while applied problems addressed by industry can more often remain locked behind proprietary firewalls. Efforts are needed from both researchers and industry to close this gap, focus on use-inspired science that extends to demonstration projects, and scale-up deployment. Through legislation and funding opportunities, government can promote this type of cooperation, and agencies such as the DOE and other national entities are increasing their efforts in this direction. Likewise, elsewhere in the world, governments are leading efforts to increase deployment of H_2 from clean energy sources, such as the European Union (EU) hydrogen strategy, part of the European Green Deal which plans for increasing production of green hydrogen starting at one million tons per year in 2024, to ten million in 2030 and increasing scale through 2050.[11] Given the urgency of energy transition efforts, there is an opportunity for members of the materials research community in industry to explore additional creative approaches needed to unlock public–private cooperation in a way that accelerates progress while also aligning with corporate interests.
- Engage the wide range of stakeholders across the H_2 ecosystem.

  The energy transition has many moving parts and involves decision-making under uncertainty by a myriad of interests across government, industry, and the R&D community, as well as broader social and economic interests. Although general outlines for region-specific paths are emerging, there will likely be adjustments and pivots needed between now and 2050. Good-faith engagement is needed to understand how to leverage competing objectives

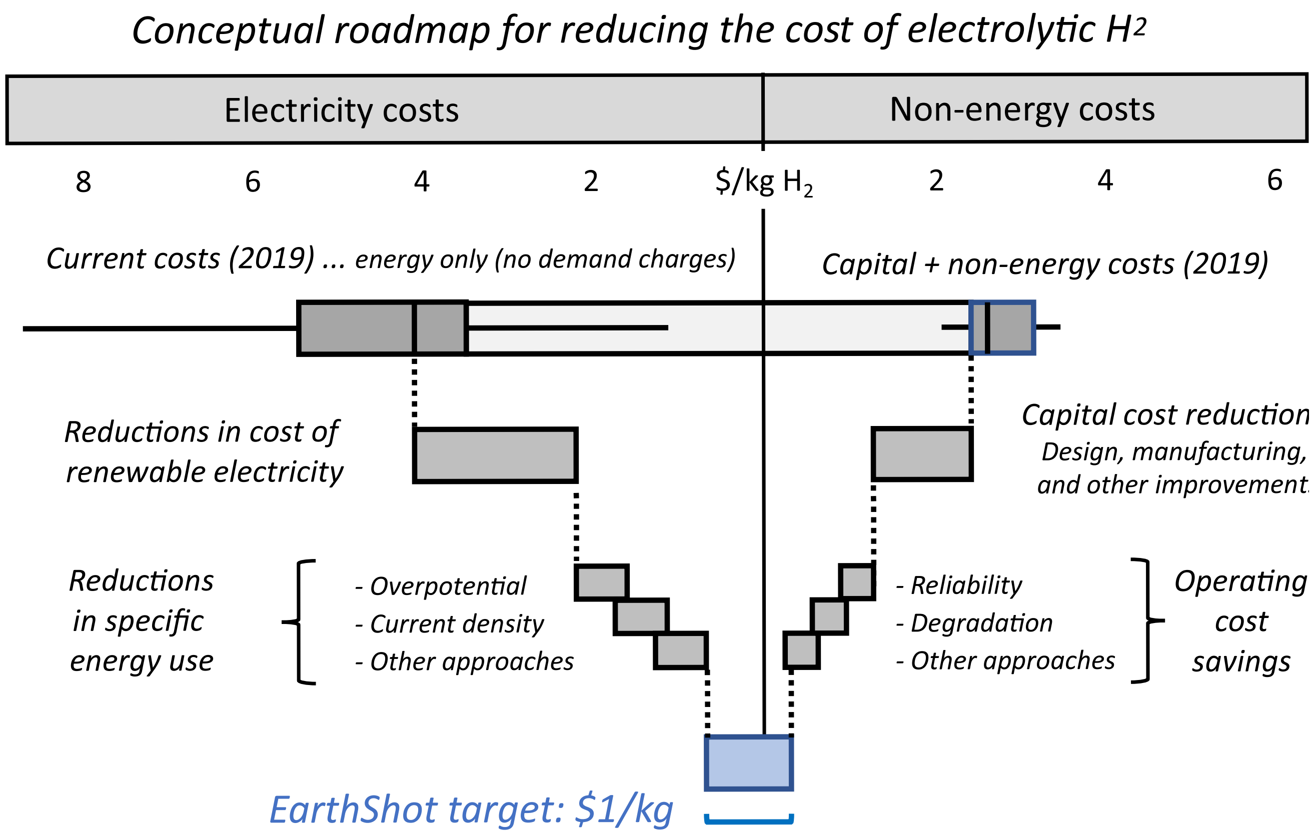

Figure 2. Conceptual roadmap for reducing the cost of green H_2 production in the United States. Current costs (estimated from[20]) and cost ranges are shown, along with potential paths for reducing the cost of H_2 towards an eventual target of $1/kg.

and constraints to find practically implementable solutions for the H_2 economy.[45,46]

Returning to the question from the panel discussion on whether the H_2 Earthshot 1:1:1 target is achievable, opinions differed but agreement was reached that the goal is worthwhile to raise awareness and move things forward in a meaningful way. Focus should remain on making progress across the full range of challenges that will need to be overcome to reach global decarbonization goals and finding pathways to scalable deployment, rather than iterating on the "right" or "wrong" way to move forward.

Afterword—Hydrogen's role in a just energy transition

There is an unprecedented commitment and investment in environmental and energy justice in the United States and globally.[47] The energy sector is pivoting to and advancing cleaner solutions, setting the stage for aligning deployment of low-carbon solutions with societal needs, and presenting this emerging imperative as a "must" in ensuring a just and equitable energy transition. Simply stated, it is important to keep in mind the goal of "just outcomes" alongside the long-term potential in decarbonizing hard-to-abate sectors, when working towards deploying H_2 technologies. Its potential to offer low-cost, scalability, and low-carbon footprint can support efforts to reach multiple goals for a just energy transition. The resulting economic, environmental, and societal benefits include improved public health, reduced pollution, and revitalized communities that have been historically marginalized, underserved, and overburdened by pollution.[48]

Targeted deployment of clean energy solutions such as hydrogen can advance disadvantaged communities through infrastructure investment, job creation, and other economic development measures. Measurable outcomes and benefits to communities and customers could include decreasing energy burden, creating parity and access to clean energy, decreasing exposure to pollutants and environmental burdens, and increasing access to low-cost capital, enterprise creation, clean energy job pipeline and job training, energy resilience and energy democracy. Championing hydrogen deployment in disadvantaged communities prioritizes environmental justice, maximizes economic benefits, and drives decarbonization. To reach net-zero by midcentury, the public and private sector must continue to announce new policies, projects, and

Figure 3. Corrosion in electrolyzer systems located near the ocean. Metal corrosion in the equipment housing (left), H_2 storage tanks (middle), and chiller (right) presents a maintenance challenge. Photos courtesy of HNEI.

investments critical for hydrogen deployment. The time is now, but the where and how of hydrogen will be deployed will determine how its benefits–economic, environmental, and societal–will be realized.

The U.S. DOE HFTO is actively engaged in every aspect of the H_2 ecosystem–production, utilization, storage, infrastructure, policy, and workforce development.

- Its tentpole initiative–the H_2 Energy Earthshot–seeks to reduce the cost of H_2 by 80% to a target cost of $1 for one (1) kilogram of clean hydrogen in one (1) decade.
- H2@Scale supports the scale-up of low-cost clean H_2 from diverse domestic resources including renewables, nuclear, and some fossil paired with carbon capture, utilization, and storage (CCUS). A large part of the vision includes understanding the multitude of pathways for H_2 use: offsetting peak charging on the electricity grid; transportation; synthesis of fuels and fuel upgrading; ammonium fertilizer production; metals production; and chemical feedstock.
- The recent Bipartisan Infrastructure law has allocated $9.5 billion for clean H_2. This includes $1 billion for clean electrolysis R&D, $500 million for clean H_2 manufacturing and recycling R&D, and finally $8 billion toward the development of H_2 hubs. In addition, the Inflation Reduction Act has implemented tax credits for clean H_2 production.
- Funding efforts from the office include $10 million for solar fuels and $2.5 million for perovskite as photo-absorbers, catalysts, and catalyst supports for H_2 production.
- DOE is very committed to workforce development activities, safety codes and standards, and environmental justice priorities, including the Biden administration's goals for Justice40, which ensures that 40% of the benefits of all future clean energy deployment are realized by historically disadvantaged and underserved communities. The office also hosts H2IQ, a series of monthly webinars focused on increasing awareness and knowledge about H_2, as well as a H_2 tools website, and safety training in partnership with the American Institute of Chemical Engineers (AIChE).

GTI Energy solves important energy challenges worldwide, turning technology and insights into solutions that create exceptional value for our customers in natural gas and broader clean energy systems by embracing a vision for integrated, low-carbon, low-cost energy systems that leverage gases, liquids, infrastructure, and efficiency to meet the urgent challenges presented by climate change and global energy access.

As an established leader in hydrogen and fuel cell technology, GTI Energy has cross-cutting research, product development, and demonstration projects, focused on clean hydrogen production, storage, delivery, and use. Initiatives include:

- H2@scale in Texas and Beyond–A public-private collaboration with Frontier Energy and the University of Texas to design, build and operate one of the largest collections of renewable hydrogen production and end-use technologies ever assembled at one site. A H_2 "proto-hub" in Austin includes multiple clean hydrogen production technologies such as the conversion of renewable natural gas, wind, and solar to H_2 for use in a fuel cell for critical power generation applications, for passenger vehicle fuel and even for powering fuel cell aerial drones.
- Open H_2 initiative–A consortium working to define benchmarks for the carbon intensity of H_2 production at the asset level.
- Next-generation Energy Storage for Clean power–A GTI Energy-led team, including Southern Company, Pacific Gas & Electric, and the Electric Power Research Institute recently completed a DOE-funded project on the feasibility of using stored "blue" H_2 for load-following in an existing natural gas combined cycle plant with a H_2-fired duct burner. The project is entering Phase 2 to conduct a pre-FEED study for a 54 MWh project.

Founded in 1974, HNEI is a research unit of the School of Ocean and Earth Science and Technology (SOEST) at the University of Hawai'i at Mānoa (UHM). It conducts research of state and national importance to develop, test, and evaluate novel renewable energy technologies. The Institute leverages its in-house work with public–private partnerships to demonstrate real-world operations and enable integration of emerging technologies into the energy mix.

HNEI has been working on several major projects that address infrastructure challenges with H_2 in transportation systems:

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Lessons learned from these projects include:

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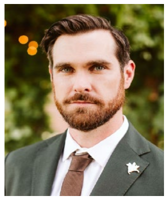
Nel, headquartered in Norway, has over 90 years of experience in electrolyzer technology with its alkaline electrolyzer division headed in Norway, fueling division based in Denmark and PEM electrolyzer division in the United States. Nel focuses on producing, storing, and distributing H_2 from renewable energy, and provides large-scale electrolyzer and fueling technology to industrial customers in the energy and gas sectors. It is Nel's vision to empower generations with clean energy forever, with technology that allows people and businesses to make everyday use of H_2, while continuing to unlock the potential of renewables and enable global decarbonization.

From a materials science perspective, characterization of new materials is critical for continued advancement in H_2 technologies. Many existing materials for electrolysis are not ideal given they are borrowed from legacy technologies and modified to work for electrolysis. Materials designed specifically for electrolyzers would enable increased efficiency along with reduced capital cost. Materials R&D is critical to identifying next generation materials through subscale testing which includes pre- and post-operations testing to address any potential pitfalls of a new material. Nel works on H_2 challenges at the materials development stage through to prototype building and integration into our large-scale electrolyzers. In addition to internal R&D Nel also frequently participates in collaborative work through DOE funded projects that will advance the H_2 industry at large. For example, "Benchmarking Advanced Water Splitting Technologies: Best Practices in Materials Characterization" (DOE-DE-EE0008092) involves collaboration with universities, national labs and private companies to create standardized protocols for materials characterization, an area lacking standardization within the electrolyzer community.

Box 1. Highlights from May 10, 2022 panel presentations



Dr. James Vickers
Technology Manager
US Department of Energy (DOE)
H_2 and Fuel Cell Technologies Office

The U.S. DOE HFTO is actively engaged in every aspect of the H_2 ecosystem - production, utilization, storage, infrastructure, policy, and workforce development.

- Its tentpole initiative - the H_2 Energy Earthshot - seeks to reduce the cost of H_2 by 80% to a target cost of $1 for one (1) kilogram of clean hydrogen in one (1) decade.
- H2@Scale supports the scale-up of low-cost clean H_2 from diverse domestic resources including renewables, nuclear, and some fossil paired with carbon capture, utilization, and storage (CCUS). A large part of the vision includes understanding the multitude of pathways for H_2 use: offsetting peak charging on the electricity grid; transportation; synthesis of fuels and fuel upgrading; ammonium fertilizer production; metals production; and chemical feedstock.
- The recent Bipartisan Infrastructure law has allocated $9.5 billion for clean H_2. This includes $1 billion for clean electrolysis R&D, $500 million for clean H_2 manufacturing and recycling R&D, and finally $8 billion toward the development of H_2 hubs. In addition, the Inflation Reduction Act has implemented tax credits for clean H_2 production.
- Funding efforts from the office include $10 million for solar fuels and $2.5 million for perovskite as photo-absorbers, catalysts, and catalyst supports for H_2 production.
- DOE is very committed to workforce development activities, safety codes and standards, and environmental justice priorities, including the Biden administration's goals for Justice40, which ensures that 40% of the benefits of all future clean energy deployment are realized by historically disadvantaged and underserved communities. The office also hosts H2IQ, a series of monthly webinars focused on increasing awareness and knowledge about H_2, as well as a H_2 tools website, and safety training in partnership with the American Institute of Chemical Engineers (AIChE).

Brian Weeks
Senior Business Development Director
Gas Technology Institute (GTI Energy)

GTI Energy solves important energy challenges worldwide, turning technology and insights into solutions that create exceptional value for our customers in natural gas and broader clean energy systems by embracing a vision for integrated, low-carbon, low-cost energy systems that leverage gases, liquids, infrastructure, and efficiency to meet the urgent challenges presented by climate change and global energy access.

As an established leader in hydrogen and fuel cell technology, GTI Energy has cross-cutting research, product development, and demonstration projects, focused on clean hydrogen production, storage, delivery, and use. Initiatives include:

- H2@scale in Texas and Beyond – A public-private collaboration with Frontier Energy and the University of Texas to design, build and operate one of the largest collections of renewable hydrogen production and end-use technologies ever assembled at one site. A H_2 “proto-hub” in Austin includes multiple clean hydrogen production technologies such as the conversion of renewable natural gas, wind, and solar to H_2 for use in a fuel cell for critical power generation applications, for passenger vehicle fuel and even for powering fuel cell aerial drones.
- Open H_2 initiative - A consortium working to define benchmarks for the carbon intensity of H_2 production at the asset level.
- Next-generation Energy Storage for Clean power - A GTI Energy-led team, including Southern Company, Pacific Gas & Electric, and the Electric Power Research Institute recently completed a DOE-funded project on the feasibility of using stored “blue” H_2 for load-following in an existing natural gas combined cycle plant with a H_2-fired duct burner. The project is entering Phase 2 to conduct a pre-FEED study for a 54 MWh project.

Mitch Ewan
H_2 Systems Program Manager
Hawaii Natural Energy Institute (HNEI)

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Dr. Jennifer Glenn
Materials Scientist
Nel

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Box 2. Safety: Materials selection considerations and education resources

Guidance for hydrogen for material selection

General guidelines for material selection for H_2 applications are available. For example, Technical Report ISO/TR 15916 (Basic considerations for the safety of hydrogen systems) lists selected materials and their suitability for hydrogen use [45]. For compressed hydrogen, embrittlement is the main deciding factor in material selection. For liquid hydrogen, the fragility of the material at cryogenic temperatures is the critical factor in material selection. Moretto and Quung provide a detailed review of the available guidelines for material selection in hydrogen applications [46]. One particular challenge is that hydrogen embrittlement depends on various complex interactions that are affected by environment, mechanical parameters, design parameters, material microstructure, and hydrogen purity. This explains why standards for hydrogen only provide general guidelines for design.

Specific guidance is also available for material selection in leading applications. The National Renewable Energy Laboratory (NREL) has published a safety guide for hydrogen and lists the design standards that can be used for component and material selection for applications, including H_2 refueling stations [47]. The blending hydrogen into the natural gas pipelines is also an active area of research [48]. Due to a diversity of materials across the piping infrastructure, the retrofitting of natural gas pipelines for H_2 must be considered on a case-by-case basis.

Hydrogen Safety Education – AIChE's Center for Hydrogen Safety (CHS)

CHS is a global, neutral and nonprofit resource that supports and promotes the safe handling and use of hydrogen across industrial and consumer applications in the energy transition. The CHS facilitates access to hydrogen safety experts; develops comprehensive safety guidance, outreach and education materials and activities; and provides a forum to partner on worldwide technical solutions. CHS is delivering educational products to help the industry build the safety skills needed to meet the demands of the growing hydrogen marketplace.

Fundamental Hydrogen Safety Credential

Reducing risk, liability and exposure is essential to the long-term growth and development of the H_2 and fuel cell industries. CHS offers a Fundamental Hydrogen Safety Credential that certifies an employee's understanding of hydrogen's properties and best practices for handling it safely. The credential also exemplifies an organization's preparedness to work safely and underpins stakeholder and public confidence. The topics covered in the 9 h online course include:

Hydrogen as an Energy Carrier	Properties and Hazards	Safety Planning
Facility Design	Equipment and Components	Liquid Systems
Material Compatibility	System Operation	Inspection & Maintenance

CHS First Responders Micro Training Learning Plan

Increasing availability and adoption of fuel cell electric vehicles presents new safety challenges for First Responders. The Center for Hydrogen Safety (CHS) in collaboration with AIChE has developed a micro training learning plan as part of the Hydrogen Safety for First Responders training. This 4-part multimedia course aims to better inform incident responders and support the safe handling and use of hydrogen in a variety of fuel cell applications. Apart from these courses, there are numerous hydrogen-safety related webinars on the AIChE-CHS website.

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