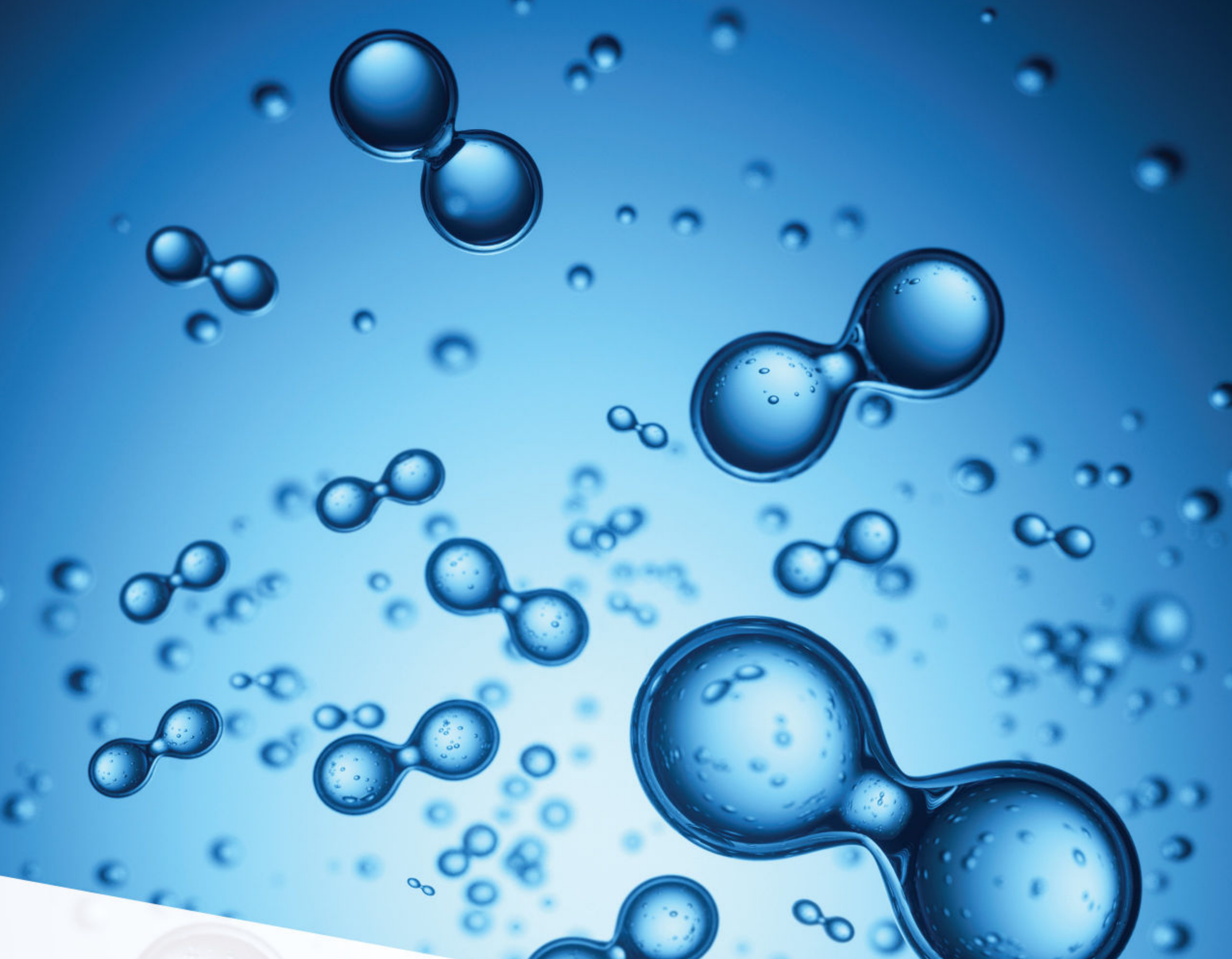


Institute of Clean Air Companies

Recommendations for Rapidly Establishing a Thriving Hydrogen Ecosystem in the United States

October 2023

Contents

1. EXECUTIVE SUMMARY

According to the Department of Energy, hydrogen is currently in widespread commercial use with annual consumption around 10 million metric tons domestically, and 90 million metric tons globally. Building a comprehensive strategy for hydrogen deployment based on existing commercial-scale production and distribution infrastructure and emerging solutions will allow for its further utilization as an alternative fuel and a critical component of the energy transition.

The Infrastructure Investment and Jobs Act (IIJA) and Inflation Reduction Act (IRA) provide exceptional incentives and programs to accelerate the production of hydrogen. However, several challenges remain that could hinder the scale of the role of hydrogen in the energy transition. Without demand for low-carbon hydrogen scaling equal to production, the required project economic thresholds will not be achieved. Both regulatory and future incentive program efforts will be required to overcome this challenge. Additionally, swift deployment of existing solutions is needed to begin achieving greenhouse gas reductions in the near-term, but without a technology-neutral approach to hydrogen production, there will be delays and valuable projects will not materialize.

For over 60 years, the members of the Institute of Clean Air Companies (ICAC) have met the challenge of eliminating harmful emissions from process and waste gas streams. Armed with this know-how and the capabilities to enable large-scale technologies and system design, ICAC members are focused on addressing greenhouse gas emissions in support of both hydrogen production and carbon capture systems.

To further solve the hydrogen ecosystem's decarbonization puzzle, ICAC offers these recommendations to DOE and other interested stakeholders:

- **Support demand development and creation.** DOE has undertaken efforts to establish a demand-side initiative to accelerate commercial liftoff of the Regional Clean Hydrogen Hubs program. Additional work is critical across all existing programs, and new mechanisms should be considered to achieve market balance. For example, the California Low Carbon Fuel Standard (LCFS) could be replicated elsewhere in the U.S. to accelerate the demand and use of hydrogen as an energy source and lower regional carbon emissions.
- **Establish regulatory standards for carbon intensity.** ICAC believes the establishment of regulatory standards for hydrogen and carbon dioxide are needed to provide ongoing reporting of climate impacts based on robust science. Guidance for determining the carbon intensity of produced hydrogen will be critical in maintaining a credible and equitable program and life cycle analysis and validation will be required to clearly understand the product's full contribution to decarbonization.
- **Support a portfolio approach to hydrogen deployment.** ICAC member companies understand that each type of hydrogen production technology has both beneficial and challenging attributes. The path to fully realized clean hydrogen deployment will need to leverage all production solutions and consider regionality in project planning in a portfolio approach.

This paper dives further into these recommendations and includes ICAC member companies profiling many of the key technologies and projects that are progressing rapidly within the market.

2. OVERVIEW OF ICAC AND MEMBERS' HYDROGEN TECHNOLOGY EXPERTISE

The Institute of Clean Air Companies (ICAC) members are first and foremost technology innovators. We have a track record of conceiving and commercializing environmentally beneficial technologies that stretches back to the 1960s when our organization was formed. ICAC member companies are engaged in developing many technology solutions, including methane reformation, renewable natural gas, methane management, carbon capture, storage of captured carbon, water electrolysis and storage of hydrogen. With this expertise, ICAC is uniquely positioned to serve as an unbiased and technical education resource that can provide validated information to support programs and rulemakings at the Department of Energy (DOE), Environmental Protection Agency (EPA), and other federal and state agencies.

Today, the member companies of ICAC are prepared for scaling up hydrogen and carbon capture technologies. This work includes leveraging existing manufacturing capabilities using proven technologies, along with the engineering of rapidly evolving technologies. ICAC provides first-hand insight needed for the development of hydrogen as a decarbonization tool.

TECHNOLOGY SOLUTIONS FOR DEVELOPING A HYDROGEN ECOSYSTEM

We know that technology innovation is an uneven and unpredictable process, and climate change is a pressing issue, demanding the most rapid possible deployment of decarbonizing technologies. Our industry's extensive experience in deployment of environmental innovations directly informs our view that over-reliance on a single, not yet commercially viable technology pathway is a fragile strategy fraught with unnecessary risk and challenged with achieving beneficial operation and outcome.

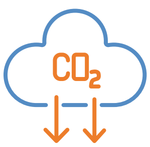
ICAC supports technology-neutral and flexible policies that enable cost-competitiveness and a diverse set of technologies to compete in the market. The following describes some of the critical technology solutions needed for a rapid and effective energy transition. ICAC member companies have leading experience working on each of these solutions.

Methane Reformation: Most hydrogen production in use today relies on steam-methane reforming (SMR) or autothermal reforming (ATR), which separates hydrogen from a methane compound at elevated temperatures by applying heat. Historically, fossil methane (natural gas) is the most common feedstock used in hydrogen production.

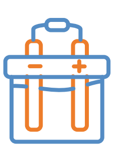
The presence of carbon results in multiple adverse climate emissions that must be addressed. Both SMR and ATR systems separate the carbon from the hydrogen and require concentration of the carbon in the hydrogen containing gas for capture. Reformers generally are powered by onsite combustion for heat and power, resulting in an opportunity for additional CO_2 emissions capture that can reduce the overall GHG emissions of the fossil-based hydrogen production by more than 90%.

Fugitive Emissions Management: Fugitive methane emissions resulting from fossil methane-based hydrogen production can occur anywhere along the supply chain. The application of measurement and monitoring equipment, in combination with appropriate capture solutions and maintenance practices, is key to identifying and controlling sources of emissions. Various methane detection technologies, such as small handheld devices, mobile and stationary monitors, and aerial and satellite systems, are commercially available today and currently in use. ICAC member companies have experience in Europe with more robust methane management systems directly applicable to the challenges experienced in the U.S. market.

Renewable Natural Gas: Supplementing fossil methane with renewable natural gas (RNG) in combination with carbon capture and storage (CCS) can produce hydrogen with net negative GHG emissions. However, this option might be challenging on a very large scale due to the limited supply of RNG compared to fossil natural gas. RNG development is on a similar track to that of H_2 with respect to supply and infrastructure needs. As noted, RNG is produced on a relatively small scale and unless that effort is increased substantially, it may only provide marginal CI reductions.



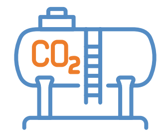
Carbon Capture: Adding carbon capture systems to existing methane reforming technology and associated site cogeneration technologies can rapidly decarbonize existing hydrogen production through further investment in this existing infrastructure. Although some process integration challenges will need to be addressed, carbon capture systems can enable both speed and scale of deployment, providing another technology solution. ICAC member companies are leaders in this market supplying equipment and design for many of the facilities referenced by the DOE.



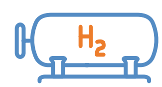
Water Electrolysis: Hydrogen production from electrolysis extracts hydrogen from water. Since electrolyzers run on electricity, the cost and carbon intensity of the power supply is the key factor in determining the electrolysis hydrogen production cost. ICAC member companies have estimated in production modeling that around 70% of the cost of electrolyzer hydrogen is related to power costs. The key to realizing cost reductions will be driven by more efficient electrolyzers that use less energy. Besides improving efficiency, which is being pursued by all the different electrolysis technologies, improved manufacturing, power conversion equipment, and auxiliaries also will add significant cost reductions.

Despite significant production cost challenges, ICAC members are actively involved in this area and are overall bullish on the long-term prospects for electrolysis-based hydrogen production. The members of ICAC are working on a variety of innovative solutions to reduce the cost and improve the efficiency of water electrolysis.

Storage of Captured Carbon:



EPA Class VI well permitting and grants for state primacy have created positive momentum for the geological storage of CO_2. Protocols and technologies for measurement and monitoring of CO_2 sequestration sites along with associated pipelines still need further attention and refinement. The geology in some areas of the U.S. has already been proven to sequester CO_2 while other regions need further development work to characterize the geology for porosity and permeability of CO_2 and ultimate sequestration capacity.



Storage of Hydrogen: There are multiple ways to store hydrogen. Some of these methods are listed in order of lower to higher costs.

- Geological formations, including salt cavern and hard rock cavern storage
- Pipeline storage
- Underground vertical silos
- Pressure vessel storage, including Hydril tubes, spherical, and composite materials
- Conversion to other compositions or states, such as liquefaction, H_2 derivatives such as ammonia, or liquid organic hydrogen carriers.

Each method of storage has positive and negative implications, depending on size and application. For larger hydrogen storage requirements, such as for a hydrogen hub, geological storage has the lowest costs per unit of H_2 stored. For smaller volume applications, such as transportation, high pressure tanks or liquefaction is often best suited if remote from a hydrogen hub location. Conversion to ammonia involves additional costs but is the most economical method today for transporting hydrogen long distances without a pipeline.

In addition to the cost of the storage itself, compression costs (both CAPEX & OPEX) are important to consider. Compressing hydrogen has challenges due to it having the lowest molecular weight, but also due to its characteristics. Improving compressor technology and manufacturing capacity is key to overall cost reduction.

Figure 1 provides a high-level view of the technologies under consideration across the hydrogen ecosystem and their current levels of development. ICAC members can provide expertise on all of the solutions listed.

ICAC MEMBER TECHNOLOGY EXAMPLES

HyCOgen Process for H_2 Utilization

Johnson Matthey's HyCOgen process uses clean hydrogen and atmospheric or waste CO_2 to produce syngas, which can be upgraded into sustainable aviation fuel, for example, and dropped into existing supplies.

Johnson Matthey CLEANPACE Technologies

Johnson Matthey's suite of CLEANPACE technologies addresses today's emissions and enables the revamp of steam methane reformers with existing, proven technology to achieve CO_2 emission reductions of up to 95%. Such retrofitted low-carbon hydrogen plants have a key role to play in expanding the hydrogen market in which new low-carbon hydrogen plants, and water-electrolysis hydrogen facilities, can then thrive.

KS-21 Solvent for CO_2 Capture

This solvent was developed jointly by Mitsubishi Heavy Industries Engineering and Kansai Electric Power Company for greatly improved performance in CO_2 capture rates. The KS-21 solvent will be supplied within the U.S. market by MHI Americas. Demonstration testing of the technology was completed at the Technology Centre Mongstad (TCM) in Norway, one of the world's largest carbon capture demonstration facilities.

Figure 1. Status of Commercial Hydrogen Technologies

	Technical Support	Commercialization Support	Commercially Available	ICAC Expertise
PRODUCTION TECHNOLOGY*				
Lower-cost, more-efficient, and more-durable electrolyzers	✓			✓
Advanced designs for reforming, gasification, and pyrolysis		✓		✓
Advanced and innovative hydrogen production techniques from renewable, fossil, and nuclear energy resources, including hybrid and fuel-flexible approaches	✓			✓
Lower-cost and more-efficient technologies for producing hydrogen from water, fossil fuels, biomass, and waste		✓		✓
Low-cost/environmentally sound carbon capture, utilization, and storage technologies			✓	✓
CONVERSION TECHNOLOGY*				
Lower-cost, more-durable, and more-reliable fuel cells that can be mass-produced		✓		✓
Turbines that can operate on high concentrations of hydrogen or pure hydrogen		✓		✓
Development and demonstration of large-scale hybrid systems		✓		✓
END-USE APPLICATIONS & INTEGRATED ENERGY SYSTEM TECHNOLOGY*				
Systems integration, testing, and validation to identify and address the challenges unique to each application			✓	✓
Demonstration of end-use applications, including steel manufacturing, ammonia production, and techniques for producing synthetic fuels from hydrogen and carbon dioxide		✓		✓
Demonstration of grid-integration to validate hydrogen energy storage and grid services	✓			✓

**Technological advancements needed for hydrogen, as identified by DOE in its 2020 Hydrogen Program Plan report.*

3. DEMAND FOR CLEAN HYDROGEN IS CRITICALLY LINKED WITH PRODUCTION

The most central question posed for any capital investment decision is: **will there be demand for this product?** While there is some demand for decarbonization driven by voluntary corporate sustainability commitments, little of that has translated into clear long-term demand for clean hydrogen. "Build it and they will come" might seem like a great baseball field strategy; however, it isn't going to satisfy the scrutiny of the financial investment community and their fears of a potentially stranded asset.

Current grants and funding only extend approximately 10 years in the future. It is very likely that much of the infrastructure necessary to support full energy transition will not be completed in that time period. The only current location with any existing infrastructure for hydrogen development is California. There are ongoing projects but producing the amount of hydrogen needed to support use within transportation and industrial sectors (development, design, buildout and subsequent generation of clean hydrogen) is likely to take 15 to 20 years. If funding is terminated midway through that process, as noted, the risk may be larger than many are willing to take on.

To ensure sustained growth in clean hydrogen production, sustained demand for clean hydrogen from customers is essential. ICAC member companies are significantly involved in many of the proposed Department of Energy (DOE) Regional Clean Hydrogen Hubs (H2Hubs). The program does allow the potential for demand generation within the hubs; however, production can be readied in short order while non-oil refining hydrogen demand is very challenged. In order to create a thriving domestic market, more work needs to be done to go beyond the capital support provided by the H2Hubs program to balance supply and demand.

DOE has announced an effort to establish sufficient demand for clean hydrogen for the H2Hubs program through a demand-side support mechanism and ICAC commends the agency for this step. Establishing a demand-side support mechanism with a longer term (5-10 years) authorization will allow hydrogen producers to meet the required economic proforma thresholds.

As a whole, the U.S. needs to continue with policy focusing on demand generation for low-carbon products to economically produce hydrogen and move towards a balanced market. The most significant driver of clean hydrogen demand thus far has been California's Low Carbon Fuels Standard (LCFS). Through technology-neutral regulatory requirements for transportation fuel carbon intensity, the LCFS establishes a dependable revenue stream for fuels that are less carbon-intensive than conventional fossil fuels. The lower the carbon intensity of a given fuel, the larger its revenue stream will be under the program. If this carbon-intensity weighted model were more broadly applied to all hydrogen applications, it would provide a strong investment signal for all hydrogen production, infrastructure, and utilization strategies.

ICAC supports DOE's efforts on this topic and recommends the agency, and other entities working on hydrogen deployment programs, continue with robust opportunities for stakeholder engagement. Public acceptance for clean hydrogen applications will be critical to ensure investments in hydrogen production move forward. **Understanding the needs and concerns of communities local to potential hydrogen projects is essential to a just energy transition.**

4. PATH TO A CLEAN HYDROGEN PORTFOLIO

ICAC recommends consideration of the following elements as part of establishing effective pathways to the vast expansion of hydrogen production within the U.S. market. Experience tells us that utilizing lifecycle assessments to support a technology-neutral, carbon intensity-based (i.e., colorblind) hydrogen production portfolio is necessary to achieve the greatest carbon reductions with the least cost. Taking a portfolio approach is the only available option for achieving the speed and scale of clean hydrogen deployment needed to materially reduce climate risks in a relevant timeframe.

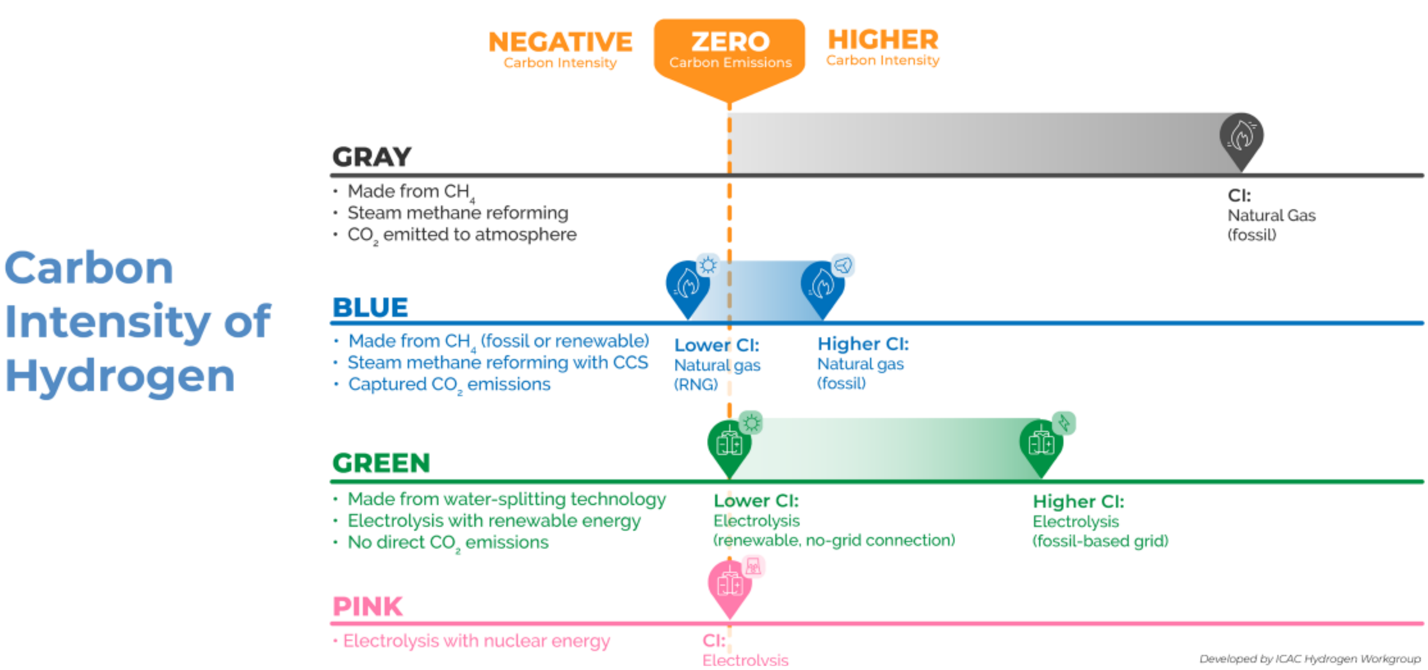
CARBON INTENSITY RATHER THAN COLOR DESIGNATION

ICAC applauds the technology-neutral, carbon intensity (CI) focused approach used in the IRA. DOE has also been consistent in its consideration of the CI of hydrogen, as opposed to naming preferred approaches based on certain color designations.

Though this naming convention might be a memorable way to classify what is, ironically, a colorless gas, ICAC believes a continued focus on the CI of hydrogen production is a much better approach. By keeping the focus on CI, it encourages continual identification of more efficiencies rather than choosing color "winners". Please refer to Figure 2 for observed CI ranges of hydrogen production paths.

LIFECYLE ANALYSIS AND VALIDATION

Frameworks to improve the accuracy, completeness, and transparency of lifecycle analysis and validation will be required to clearly understand the end product's full contribution to decarbonization and will help drive emissions reductions. ICAC member companies are active in monitoring and verification equipment and services for hydrogen production, transportation, and storage. This equally applies to carbon capture, transportation, storage, utilization, and disposal.



Comprehensive verification is a particularly challenging issue. Lifecycle emissions include emissions from the entire supply chain of a product, from the extraction of raw materials to the manufacturing, transportation, and disposal of the product. It can be challenging to accurately measure and verify these lifecycle emissions, and there are several different approaches that can be taken.

A **lifecycle assessment (LCA)** is a tool that can be used to estimate the environmental impact of a "product" throughout its lifecycle. LCAs can be used to estimate lifecycle emissions, as well as other environmental impacts, such as water use, waste generation, and air pollution. LCAs are often seen as the most comprehensive way to assess the environmental impact of a product, but they can also be complex and time-consuming. One common approach to LCA uses ISO14040 series standards.

Another approach is to use a **carbon footprint "label."** A carbon footprint "label" is assigned to a product indicating the amount of CO_2 that was emitted in the product's production. For consumer goods, this could even be physically identified on the product.

Carbon footprint labels will be a more user-friendly way to inform consumers about the environmental impact of a product. New standards and potentially even regulatory guidance will be needed to ensure high-quality reporting. We have already seen emerging companies starting to do this by certifying natural gas production emissions. For this approach to be credible in the market, there can't be competition simply just reporting a smaller number. A recognized standard, either by a trade organization or government guidance, will be needed if this information is to be factored into environmental, social, and governance (ESG) performance reporting.

PORTFOLIO APPROACH

There are multiple reasons why a portfolio approach to hydrogen technology deployment will be the most beneficial in the U.S. First, each method for low-carbon intensity hydrogen production has its advantages and its limitations.

For example:

- Conventional SMR or ATR combined with CCS has lower costs, is readily scalable to the level of energy demands, and likely has significant near-term deployment potential in many regions of the country with significant oil and gas experience. CCS is limited to regions where geology is favorable, though, and there are additional permitting and routing challenges associated with CO_2 pipelines. If the CO_2 source and the sequestration site are in different states, that adds another level of complexity. EPA is actively addressing the management of fugitive methane emissions through rulemaking.
- Use of RNG feed in SMR or ATR combined with CCS may be an obvious strategy, but its current scale is limited by the availability of RNG and its associated feedstocks.
- Water electrolysis eliminates waste gas management problems associated with both methane and CO_2, but is hampered by the availability and production costs of its electricity and availability of water resources.

Each of these limitations needs to be addressed, but deployment of low-carbon solutions is needed now. Therefore, ICAC strongly recommends that a technology-neutral, portfolio approach is the best path forward for limiting risk.

Additionally, the U.S. market for hydrogen projects is extremely diverse, considering the wide range of availability of natural resources. This regionality will drive technology choice. While matching supply with demand might seem like

Moving forward with a portfolio approach to hydrogen deployment will allow the U.S. to implement existing, commercially available solutions in the near-term while continuing to work to address the challenges with other medium- to long-term solutions.

a simple exercise, many project examples in the market today fail to fully understand and integrate resource and offtake availability and affordability into their ambitious plans.

Access to and construction of pipeline networks, transmission lines, suitable land and geology, location on the electric grid, water availability, public acceptance, regulation, and numerous other aspects can impact the optimal technology choice for a project. With too much focus afforded to the designated hydrogen color, both project developers and governments fail to approach hydrogen as a decarbonization tool in the most effective manner.

The planning effort leading to a technology and site selection also requires engagement of numerous stakeholders including local governments, permitting boards, electrical utilities, gas producers, pipeline, water resource suppliers, hydrogen off-takers, non-governmental organizations, communities, and project development professionals.

Moving forward with a portfolio approach to hydrogen deployment will allow the U.S. to implement existing, commercially available solutions in the near-term while continuing to work to address the challenges with other medium- to long-term solutions.

THE IMPORTANCE OF REGIONALITY

The availability and cost of carbon-free power supplying water electrolysis varies significantly throughout the U.S.

Furthermore, hydrogen development is occurring concurrently with multiple other efforts to mitigate climate impacts, including:

- the electrification of vehicle fleets,
- an EPA rulemaking intended to limit the utilization of fossil fuels for power generation,
- the addition of massive data center and crypto-mining electrical loads,
- and commercial and residential building electrification.

All these new electrical users are competing for the same MWh on the grid, stretching the limits with initial indications of a critical reliability risk that could be catastrophic to stability of a region.

While renewable energy solutions may add a considerable amount of the MWh needed by these users, unfortunately, grid resilience will be challenged in an even greater way by many of these capacity additions. There are significant challenges to accomplishing this in a responsible manner, scale, and pace.

5. EXAMPLES OF GLOBAL HYDROGEN PROJECTS ICAC MEMBERS SUPPORT

Learn more about the global hydrogen projects with which ICAC member companies have been actively engaged.

1. Advanced Clean Energy Storage (ACES) Hub

The first project to combine utility and industrial-scale renewable hydrogen production, storage, and transmission, the ACES hub in Delta, Utah, will support the Intermountain Power Agency as an 840 MW hydrogen-capable gas turbine combined cycle power plant.

The project will initially run on a blend of 30% green hydrogen and 70% natural gas starting in 2025 and will incrementally expand to 100% electrolytic hydrogen by 2045. Nearly doubling worldwide electrolysis capacity, the project will use Utah's unique geological salt domes to store 150-gigawatt hours of electrolytic hydrogen, with additional storage capacity available. From this initial project, ACES Delta will deploy hydrogen hubs across the United States to accelerate and support the clean energy transition.

2. Georgia Power at Plant McDonough-Atkinson

Teaming with Georgia Power, Southern Company R&D, and EPRI, **Mitsubishi Power** achieved a historic first-of-a-kind demonstration of large advanced-class gas turbine in combined cycle operation on blends of over 20% hydrogen with natural gas.

The first-of-a-kind hydrogen co-fire demonstration project at Georgia Power's 2,520MW McDonough-Atkinson power station, comprising three 2-on-1 M501-G combined cycle units, resulted in significant achievements:

- Highest hydrogen fuel blend (20.9%) on any advanced class 1,500°C TIT gas turbine;
- 7% reduction in CO_2 emissions while maintaining advanced-class high thermal efficiency;
- Improved turndown, lowering minimum emIssions compliance load (MECL);
- Successfully integrated H_2 flow control and measurement within the turbine control system; and
- Results achieved without hardware changes to the gas turbine.

3. H2H Saltend Project

Equinor, a Norway-based petroleum refining company, will use **Johnson Matthey**'s LCH™ technology in their H2H Saltend project. This is a 600-megawatt low-carbon hydrogen production plant with carbon capture. The plant design will use Linde Engineering's hydrogen and air separation technologies, which will be combined with the Johnson Matthey LCH™ technology.

Due to be operational by 2027, it will help to reduce the park's emissions by up to one-third. To achieve this, low-carbon hydrogen will directly replace natural gas in several industrial facilities, reducing their products' carbon intensity. The amount of CO_2 stored will be around 890,000 tons per year.

4. H2Med Project

The H2Med project will connect Portugal and Spain with France and Germany to supply about

10% of the European Union's anticipated hydrogen demand by 2030. The pipeline under the Mediterranean Sea will carry green hydrogen, made from water via electrolysis using renewable energy. The Spanish government estimates that H2Med will begin operations in 2030 and will be able to supply some two million metric tons of hydrogen annually.

5. H2NorthEast

The Kellas Midstream H2NorthEast hydrogen project in Teesside utilizes **Johnson Matthey** LCHTM technology. This initial phase is a 500 MW low-carbon hydrogen production plant with carbon capture. The project will deliver low-carbon hydrogen through synergies with the UK CATS terminal, industrial customers, UK domestic sourced gas feedstock, and reuse of existing distribution and storage infrastructure. Upskilling existing jobs and creating a similar portion of new operational jobs will contribute further to the local economy.

Front-end engineering design work on the project has begun, and Kellas has announced they are partnering with both Worley and Johnson Matthey, The project has been working towards this key milestone since it was awarded funding in March 2023 through the Net Zero Hydrogen Fund, a dedicated UK government initiative to support the commercial deployment of low-carbon hydrogen projects.

The H2NorthEast project is part of the East Coast Cluster, which has been named as one of the UK's first carbon capture, usage, and storage clusters following a successful bid to the Department for Business, Energy & Industrial Strategy. Once complete, the scale of this project will produce low carbon hydrogen volumes equivalent to heating over one million households (or around 10% of the UK's target hydrogen capacity).

6. Hellesylt Hydrogen Hub

Norwegian Hydrogen AS to establish water-electrolysis produced hydrogen at Hellesylt, Norway, for use as a zero-emission fuel solution for ferries, cruise vessels, and high-speed vessels. While a smaller-scale production hub, operations are anticipated in Q4 2023.

7. HyNet Project

The HyNet consortium of **Johnson Matthey**, SNC-Lavalin, Essar Oil UK, and Progressive Energy will develop the UK's first hydrogen and carbon capture facility in Cheshire. Johnson Matthey is providing a Low Carbon Hydrogen (LCH) technology that includes carbon capture, meaning that over 97% of CO_2 emissions produced can be efficiently sent for storage.

It will be the first example of a technology that has been proven in other sectors, being deployed to produce clean hydrogen. The facility will deliver low-cost, low-carbon bulk hydrogen at scale and high efficiency and with a very high carbon capture rate. When operational, the facility will capture 600,000 tons of CO_2 emissions a year. This project will take a phased approach, with an initial production phase targeting 2025 for commercialization.

8. MCH2 Hydrogen Hub

The MCH2 hydrogen hub application consisted of the states of Iowa, Nebraska, and Missouri. 1898 & Co (a subsidiary of **Burns & McDonnell**) developed a Linear Programming model, commonly used for petrochemical process optimization, for the prime recipient, Nebraska Public Power District.

The LP model results provided a financial basis for hydrogen production, demand, and utilization and also integrated a new carbon dioxide transport and sequestration hub. Clearly understanding the entire value chain allowed for optimizing the MCH2 hub technology and project engagement strategy.

9. NEOM Project

Saudi Arabia's bountiful solar and wind resources will produce 1.2 million tons of water-electrolysis-produced hydrogen for conversion to ammonia, anticipated by 2026. This will be used for export to both Europe and SE Asian countries.

10. Petra Nova

The Petra Nova CCS demonstration project became operational in January 2017, utilizing a proven carbon capture process developed by **Mitsubishi Heavy Industries, Ltd**. and the Kansai Electric Power Co. The technology uses a high-performance solvent for CO_2 absorption and desorption. The project is designed to capture approximately 90% of the CO_2 from a 240 MW slipstream of flue gas, after which the captured CO_2 is compressed and transported to be utilized for enhanced oil recovery and sequestration near Vanderbilt, Texas. The project aims to use and sequester approximately 1.4 million metric tons of CO_2 annually. Petra Nova was shut down in May 2020 and resumed operations in September 2023.

11. Takasago Hydrogen Park

Mitsubishi Power's Takasago Hydrogen Park is the world's first center for validating hydrogen-related solutions, from production to power generation. When developing new gas turbine technologies and digital solutions, Mitsubishi Power undergoes long-term operation of at least 8,000 hours of validation, which is equivalent to nearly one year of normal operation. Validation tests will be conducted in the same way for hydrogen power generation. Commercial operations will commence in 2023 and will be used to commercialize small and large gas turbines on a path to 100% hydrogen utilization starting in 2025.

6. CONCLUSIONS

ICAC members represent a significant market segment of the capable technologies needed to decarbonize the U.S. energy market. Armed with experience and a long history of cleaning up waste gas streams, ICAC members are prepared, today, to rapidly scale up the production of technologies in existing manufacturing facilities. We stand ready to enable hydrogen production through a vast suite of proven and established technologies.

Many of our member companies are focused on rapid low-carbon intensity hydrogen production. For these efforts to be realized, the demand for low-carbon intensity hydrogen will need to expand proportionally. The grants and tax credits included in the IIJA and IRA, respectively, are a significant step forward but will only influence a portion of the supply and demand equation to achieve financeable business cases driving the overall hydrogen economy.

ICAC believes DOE and other federal and state agencies working on hydrogen deployment should continue to ramp up focus on demand-side efforts to balance the currently more aggressive efforts on rapid production expansion.

Additionally, judging the value of a hydrogen product by a color designation will not enable effective strategies that maximize the dollars invested in achieving incremental decarbonization of the economy. The efforts toward centering programs around carbon intensity metrics need to continue.

The IRA provides a strong basis for establishing carbon intensity as the primary indicator for securing the tax credit, and forthcoming guidance from the Department of Treasury should further clarify the technical basis.

Finally, multiple considerations, including available local resources and regional and project differences, should help inform the choice of technology solutions. This will reduce risk and help optimize investments.

ICAC member companies look forward to engaging in the significant contributions hydrogen solutions can make toward continued decarbonization efforts.

ICAC

APPENDIX I

Commercial Hydrogen Production Technologies

Technology	Feedstock (Source of H_2)	Carbon Intensity Range	Recognized Color
Steam Methane Reforming	Methane (natural gas, RNG, steam)	9.4 NG 0.2 LFG Manure RNG is not approved	**Gray**
Auto Thermal Reforming	Methane (natural gas, RNG, steam)	Similar to SMR	**Gray**
Steam Methane Reforming w/CCS	Methane (natural gas, RNG, steam)	3.4 NG -5.8 LFG Manure RNG is not approved	**Blue**
Auto Thermal Reforming w/CCS	Methane (natural gas, RNG, steam)	Similar to SMR	**Blue**
Electrolysis using Fossil Electricity	Water	26 – U.S. Grid Mix 29 – NG 61 - Coal	**Gray**
Electrolysis using Zero Carbon Renewable Electricity	Water	0.0	**Green**
Electrolysis using Nuclear Power	Water	0.4	**Pink**
Pyrolysis	Methane	Not Commercial	**Turqoise**
Hard Rock Mining	Naturally-occurring H_2		**White**

APPENDIX II

ICAC Member Companies' expertise can contribute to the necessary Hydrogen Technology RD&D technology advancements identified by DOE in its 2020 Hydrogen Program Plan report.

RD&D THRUSTS FOR HYDROGEN PRODUCTION
New catalysts and electrocatalysts with reduced platinum group metals
Modular gasification and electrolysis systems for distributed and bulk power systems
Low-cost and durable membranes and separations materials
Novel, durable, and low-cost thermochemical and photoelectrochemical materials
Accelerated stress tests and understanding of degradation mechanisms to improve durability
Reduced capital costs for reforming technologies, including autothermal reforming (ATR)
Improved balance-of-plant components and subsystems, such as power electronics, purification, and warm-gas cleanup
Component design and materials integration for scale-up and manufacturability at high volumes
Reversible fuel cell systems including for polygeneration of electricity and hydrogen
System design, hybridization, and optimization, including process intensification

COMMON RD&D THRUSTS FOR HYDROGEN STORAGE
Reduced costs at the material-based, component-, and system-level
Low-cost, high-strength carbon-fiber for high-pressure tanks
Materials compatible with hydrogen for durability and safety
Cryogenic RD&D for liquid hydrogen and cold/cryo-compressed storage
Discovery and optimization of hydrogen storage materials to meet weight, volume, kinetics, and other performance requirements
Optimization for round-trip efficiency using chemical hydrogen carriers
Storage of hydrogen in the form of a chemical energy carrier that can be used in hydrogen turbines
Identification, assessment, and demonstration of geologic storage of hydrogen
Systems analysis for the export of hydrogen and hydrogen carriers
Analysis to refine targets for a broad range of storage options and end-uses
Sensors and other technologies needed to ensure hydrogen storage is safe, efficient, and secure

COMMON RD&D THRUSTS FOR HYDROGEN DELIVERY
Materials compatibility with hydrogen at high pressures and/or low temperatures
Innovations in hydrogen liquefaction
Carrier materials and catalysts for hydrogen storage, transport, and release
Innovative components for low-cost distribution/dispensing (compressors, storage vessels, dispensers, nozzles)

COMMON RD&D THRUSTS FOR HYDROGEN AND RELATED TECHNOLOGY APPLICATIONS
Development of rigorous application-specific targets for hydrogen utilization
Materials compatibility issues in diverse end-uses
Reduced cost and improved durability and efficiency in industrial-scale electrolyzers, fuel cell systems, combustion turbines and engines, as well as in hybrid systems
Component- and system-level integration and optimization, including balance of plant systems
Optimized controls of integrated systems, including cybersecurity
Manufacturing and scale-up, including process intensification
Harmonized codes and standards, including refueling protocols
Capacity expansion models to identify value propositions for use of hydrogen in new applications

2022-2023 Institute of Clean Air Companies Members

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