

ADVANCED SENSORS FOR HYDROGEN TECHNOLOGY

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ACRONYMS AND ABBREVIATIONS

3D	Three dimensional	OEM	Original equipment manufacturer
AEO	Annual Energy Outlook		
AI	Artificial Intelligence	PEMFC	Proton exchange membrane fuel cells
AM	Additive manufacturing		
ASME	American Society of Mechanical Engineers	PSA	Pressure swing adsorption
		R&D	Research and development
BTU	British thermal unit	RH	Reheater
CO ₂	Carbon Dioxide	SCR	Selective catalytic reduction
CCUS	Carbon Capture, Utilization, and Storage	SH	Superheater
		SOFC	Solid Oxide Fuel Cells
CAPEX	Capital expenditure	TWh	Terawatt-hours
DMW	Dissimilar-metal welds	U.S.	United States
DOE	Department of Energy		
EIA	Energy Information Administration		
EMAT	Electromagnetic Acoustic Transducer		
EPRI	Electric Power Research Institute		
FE	Fossil energy		
FOH	Force outage hours		
GADS	Generating Availability Data System		
GW	Gigawatt		
GWh	Gigawatt-hour		
HPA	High performance alloy		
Hrs	hours		
HRSG	Heat recovery steam generator		
IGT	Industrial gas turbines		
IoT	Internet of Things		
kW, kWe	Kilowatt electric		
kWh	Kilowatt-hour		
LHV	Lower heating value		
LOHC	Liquid organic hydrogen carrier		
m	Meter		
MESA	Mission Execution and Strategic Analysis		
ML	Machine Learning		
Mt	Megatonne		
IGT	Industrial gas turbines		
NETL	National Energy Technology Laboratory		
Ni	Nickel		
ODS	Oxide dispersed strengthening		

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EXECUTIVE SUMMARY

As with much federally-funded research, a requirement of the Sensors and Controls program is to make a positive impact on society, demonstrate an exceptional return on taxpayer investment, as well as building the brand of the program and the United States as a technology leader in the field. One of the primary ways that NETL can fund impactful projects is to identify challenges that persist in industry and that are expensive or complex to execute. Many large companies are reluctant to invest in these projects, especially when product margins are thin, or when companies are faced with pressure from shareholders. Nonetheless, government research fills an important gap of foundational knowledge generation and exploring new ideas from a first principles approach.

This gap analysis study included all parts of the hydrogen value chain, from hydrogen generation, to storage, and end use, with the exception of transportation applications. While these research projects are not always commercially viable, they are important in advancing technology, and especially in reaching goals such as improved efficiency and reducing emissions. Without emissions targets enforced by the government, or incentives for industry for emissions reduction, investing in advanced technology and manufacturing system upgrades can be exceedingly difficult to justify. This analysis identifies and prioritizes sensor R&D development areas that are critical to enable the hydrogen economy.

While all areas noted in this analysis are important, the Sensors and Controls program at NETL should prioritize R&D areas that scored high in “Improvement Over Incumbent in Target End Use Market” and “Opportunity for Adjacent End Users & Markets,” but low in “Ease of Technological Integration.” These are indicative of opportunities with market high-upside, but that require prolonged and focused R&D to raise the TRL, which federally-funded research can provide. Such areas included:

- Sensors supporting catalyst development to enable the improvement of chemistry of hydrogen release in liquid hydrogen carriers;
- Sensors that can help optimize current compressors or that can be integrated into new compressor stations tailor-made for hydrogen to help mitigate the increased power requirements (and subsequent emissions) of compressors for transport of high-hydrogen gas blends;
- Sensors to aid in the materials discovery process to uncover new, hydrogen embrittlement resistant materials; and
- Sensors that enable real-time material degradation analysis.

Targeted investment in these areas offer the highest-reward opportunities to advance the hydrogen economy and fulfil U.S. goals to reduce the cost of clean hydrogen by 80% to \$1 per 1 kilogram by 2030.

1 INTRODUCTION

1.1 NETL CROSSCUTTING SENSORS AND CONTROLS

The Crosscutting Sensors and Controls (hereafter, “Sensors and Controls”) program at the United States (U.S.) National Energy Technology Laboratory (NETL) focuses on improving fossil energy power generation using sensors, distributed control systems and increased security, including maturing novel technologies for commercialization that can optimize plant performance, and increase reliability. Because hydrogen technologies are an increasingly important part of a carbon neutral future, the Sensors and Controls program is highly motivated to improving its commercial viability. The development of technologies to aid in bridging major gaps in the industry is a strategic investment area for this program. For this research to benefit U.S. taxpayers and other stakeholders, it must uniquely address challenges that are persistent to the hydrogen economy. Challenges arise when technology is not solving the right set of issues, or it is prohibitively expensive to implement in a commercial application.

Much of the research that NETL funds is early-stage developmental research. The portfolio addresses a wide range of technical challenges and includes projects from early discovery research as well as higher maturity technologies. The portfolio of funded research does not include technologies that are fully ready for commercial deployment, but there is a programmatic value in aiding connections with industry that will eventually result in commercial adoption.

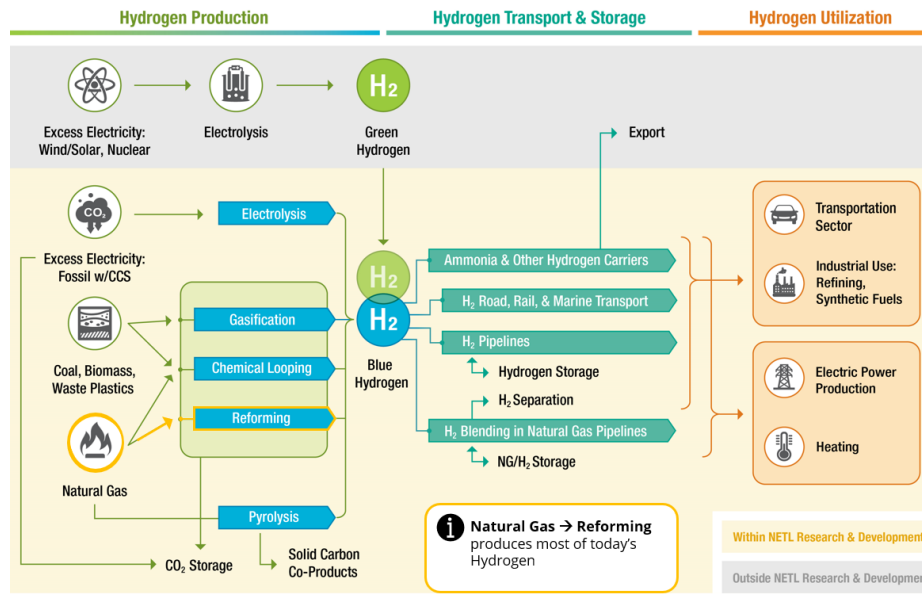
As with much federally-funded research, a requirement of the Sensors and Controls program is to make a positive impact on society, demonstrate an exceptional return on taxpayer investment, as well as building the brand of the program and the United States as a technology leader in the field. One of the primary ways that NETL can fund impactful projects is to identify challenges that persist in industry and that are expensive or complex to execute. Many large companies are reluctant to invest in these projects, especially when product margins are thin, or when companies are faced with pressure from shareholders. Nonetheless, government research fills an important gap of foundational knowledge generation and exploring new ideas from a first principles approach.

1.2 HYDROGEN VALUE CHAIN

This gap analysis study will include all parts of the hydrogen value chain, from hydrogen production, to logistics (transport and storage), and utilization, with the exception of transportation applications such as fuel use in hydrogen vehicles. While these research projects are not always commercially viable, they are important in advancing technology, and especially in reaching goals such as improved efficiency and reducing emissions. Without emissions targets enforced by the government, or incentives for industry for emissions reduction, investing in advanced technology and manufacturing system upgrades can be exceedingly difficult to justify. An illustration of the hydrogen value chain that will be used for purposes of this analysis can be found in **Exhibit 1-1** below.

ADVANCED SENSORS FOR HYDROGEN TECHNOLOGY

Exhibit 1-1. Hydrogen Value Chain.



This analysis took a systematic approach to identify key opportunities to develop novel sensor technology within the hydrogen value chain and to determine where there is already activity within the Crosscutting portfolio. This framework included an initial research landscaping, segmentation, expert interviews, and a gap analysis.

2 KEY BARRIERS IN THE HYDROGEN ECONOMY

Based on previous research conducted to understand the hydrogen economy, several key barriers have been identified which impede the adoption and growth of hydrogen technologies. These barriers have been identified as follows:

- **Cost and Equipment Longevity:** Each stage of the hydrogen value chain contributes to the high cost of hydrogen technology. It is largely influenced by efficiency of production, storage costs, and product quality and value. Production efficiency is impacted by combustion kinetics, temperature control and the condition of the catalyst material, in processes which use a catalyst. Options for hydrogen storage are diverse, but they all have costs associated with capital expense as well as maintenance. Product quality is impacted by purity of the hydrogen that is produced.
- **Safety:** Safety challenges are associated with the innate tendency of hydrogen gas to leak, as well as its flammability. Hydrogen can become explosive at relatively low levels of concentration, so it is important to monitor using sensors that are accurate and provide rapid responses.
- **Emissions:** Emissions reductions remain a driver behind the desired transition to hydrogen across many sectors. The challenges associated with this relate to the fact that many feedstocks used to produce hydrogen are still fossil based, necessitating a need to develop carbon capture and storage technology and infrastructure.

These barriers relate to challenges which span the breadth of the hydrogen value chain, from production to utilization; this section will explore the intersection of these barriers with the hydrogen value chain. **Exhibit 2-1** below illustrates a summary of the findings of this section.

Exhibit 2-1. Key Barriers Across the Hydrogen Value Chain.

	Production	Transport & Storage	Utilization
Cost & Equipment Longevity	CAPEX, OPEX, efficiency, material degradation	Complexity of storage solutions (i.e., liquifying, pressurizing, etc.)	Challenges in impurities and design relative to natural gas turbines
Safety	False alarms caused by hydrogen leaks	Leakage and possible explosion risk	Leakage and possible explosion risk
Emissions	Fossil energy use (SMR) and inability to capture 100% of process CO ₂	Storage of captured CO ₂ and H ₂ compressor energy requirements	NOx emissions in combustion applications

2.1 PRODUCTION

Blue hydrogen is defined as any hydrogen produced with net-negative carbon emissions from fossil fuels, biomass, and wastes including recoverable plastic, waste coal, and municipal solid waste (MSW). By nomenclature, fossil fuel-based hydrogen is “grey” hydrogen. If the byproduct carbon dioxide (CO₂) produced is removed using carbon capture, storage and utilization (CCUS) hydrogen produced from fossil fuels is called “blue” hydrogen. Hydrogen produced from electrolysis of water using electricity from renewable resources such as wind and solar is called “green” hydrogen. That being said, the carbon intensity of each process has a range affected by unique variables and the color schematic used is deployed for its simplicity in this report (**Exhibit 2-2**) [1]

Exhibit 2-2. Hydrogen Colors Summary.

Color	Description	Carbon efficiency (#H/#C)	Energy efficiency (KJ/mol H ₂)	Technology maturity
Brown	Coal/biomass gasification	Average (6/1)	Low (118)	Mature
Grey	Steam methane reforming + water gas shift	Very high (8/1)	Very high (27)	Mature
Blue	Brown/Grey + CCUS	Very high (8/1, CO ₂ -neutral)	Low (150)	Pre-commercial
Teal	Methane pyrolysis	Low (4/1, CO ₂ -free)	High (37)	Pilot demonstration
Green	Renewable driven water electrolysis	Very high (C- and CO ₂ -free)	Very low (286)	Pre-commercial
Pink	Nuclear driven water electrolysis	Very high (C- and CO ₂ -free)	Very low (286)	Development

Technologies for blue hydrogen production include steam reforming and autothermal reforming of natural gas; partial oxidation of a range of hydrocarbons (natural gas and heavier); gasification of coal waste, waste materials (e.g., plastics, and other abundant low-cost materials like MSW), and co-fed biomass, all with CCUS technologies. Hydrogen is used as an input into many key chemical processes and today 95% of the hydrogen produced in the U.S. is made through methane reforming in large, centralized plants [2]. Blue hydrogen can also be produced by electrolysis—a process that splits hydrogen from water using an electric current—with electricity generated by any fossil fuel power plant with CCUS. All blue hydrogen pathways require CCUS, and multiple technology options exist for each area—capture, storage, and utilization. **Exhibit 2-2** provides an overview of various hydrogen production options, their cost and greenhouse gas footprints, as well as their technology readiness level (TRL) [3].

Exhibit 2-3. Comparison of potential commercial hydrogen production pathways.

Pathway name	Input material	TRL ^a	kg CO ₂ e per kg of H ₂ ^b
Electrolysis - solar	Water	9	2.21
Electrolysis - wind	Water	9	0.88
Electrolysis - nuclear	Water	9	0.76
Biomass gasification with carbon capture and storage (CCS)	Biomass	3-5	-14.58
Coal gasification with CCS	Coal	6-7	2.11/6.2 ^c
Biomass gasification	Biomass	5-6	2.6
Steam methane reforming with CCS (Blue H ₂)	Natural gas	7-8	5.61
Thermochemical water splitting cycle	Water	3-4	1.2
Methane pyrolysis (Solid Carbon + H ₂)	Natural gas	3-5	3.1
Coal gasification	Coal	9	19.78/23.85 ^c
Steam methane reforming (Gray H ₂)	Natural gas	9	13.24

2.1.1 Cost and Equipment Longevity

Levelized Cost of Hydrogen (LCOH) ranging from circa US\$1.00 to US\$2.50 per kg, whereas Green Hydrogen's LCOH is currently estimated to range between US\$2.50 to US\$10.00 per kg depending on technologies. For Blue Hydrogen, the addition of CCUS to Brown/Grey Hydrogen facilities adds incrementally to the LCOH, typically US\$0.50 to \$1.00 per kg, and thus an overall Blue Hydrogen levelized cost between US\$1.50 and US\$3.50 per kg [4].

The high cost of hydrogen production, both from a capital expense (CAPEX) and operating expense (OPEX) perspective, remains a significant barrier to implementation of hydrogen across sectors.

^a Technology readiness levels (TRL) are a method for estimating the maturity of technologies.

^b These values incorporate lifecycle emissions, not solely point-of-use emissions.

^c First value represents total life cycle emission (LCE) estimates from surface mined coal and the second value total LCE estimates from underground mined coal.

Efficiency limitations resulting from combustion kinetics, temperature control, condition of catalysts all contribute to the overall efficiency of the production of hydrogen. The lower the overall efficiency of the hydrogen production process, the more input materials are needed for the same level of output production, thus increasing OPEX costs. One potential solution is through integration of separation unit operations within the reactor to enable continuous byproduct removal. This may be achievable, using ATR as an example, with a sorbent injection to capture CO₂ continuously as it is formed or with a hydrogen-selective membrane to allow continuous removal of hydrogen products. This will cause a shift in the equilibria of the system, driving the reaction further towards the products and potentially altering the process energy requirements.

The most common method of hydrogen production, Steam methane reforming (SMR) has high hydrogen yield efficiency (~ 74%) [5]. This method uses a catalyzer, typically nickel, to facilitate the thermochemical reaction of natural gas and water at temperatures of around 850 °C and a pressure of 2.5 MPa [5]. SMR energy needs when coupled with carbon capture are 1.91 kilowatt-hour (kWh) per kg of hydrogen produced if natural gas is the feedstock, or 3.48 kWh per kg of hydrogen if coal is the feedstock [6]. Labor costs are a significant contributor to OPEX costs; engineers with specialized knowledge and skills drive up the overall cost of developing and maintaining systems.

Economies of scale to reduce capital cost can be a solution, along with optimal plant design to better utilize high-cost materials, and new materials and technologies for catalysts. Networked temperature sensors and improved plant design to maximize thermal efficiency, combustion analyzers using artificial intelligence (AI), machine learning (ML), and Internet of Things (IoT) integrated system predictive modeling capabilities built into systems, intelligent alarms, sensors on assets to monitor and optimize plant operations, energy consumption, plant performance, production rates, purity are all opportunities for improvement.

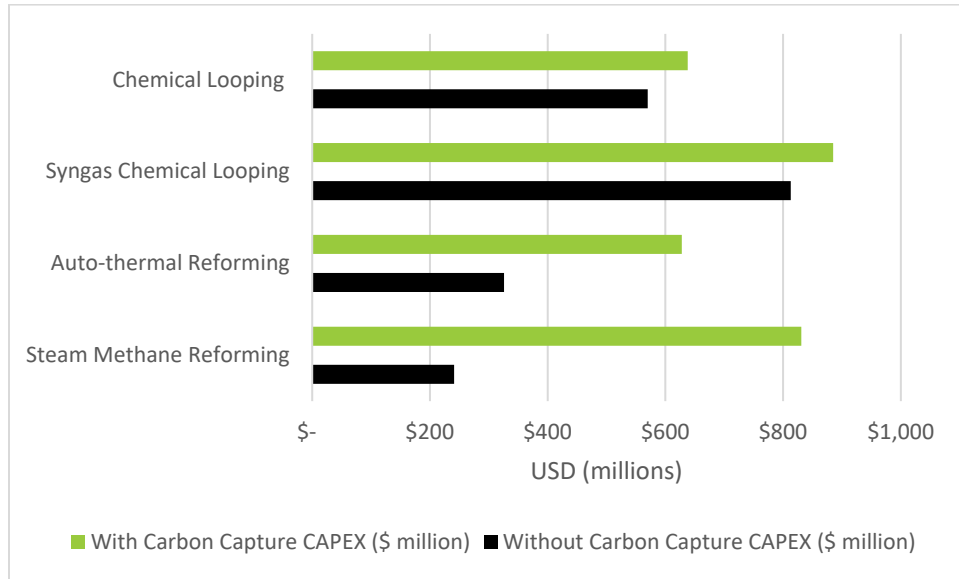
Equipment

Depending on method of hydrogen generation, the equipment used in the “Production” step of the value chain will be susceptible to a number of degradation mechanisms.

The total capital cost on a per megatonne^d (Mt) basis for steam methane reforming, auto-thermal reforming, syngas chemical looping, and the chemical looping reforming without carbon capture is estimated as \$241 million, \$326 million, \$813 million, and \$570 million, respectively. With carbon capture, these capital costs rise to \$831 million, \$628 million, \$885 million, and \$638 million, respectively [7]. These costs are illustrated in **Exhibit 2-3** below.

^d One megatonne is equal to one million (10⁶) metric tons, or one billion (10⁹) kilograms.

Exhibit 2-4. CAPEX per Mt Production Capacity for Various Hydrogen Production Processes from Natural Gas.

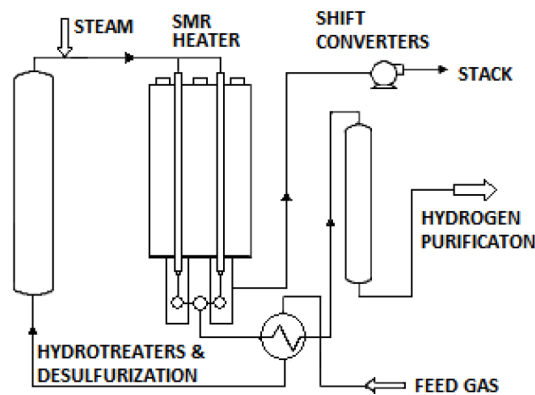


Additionally, having to shut-down and start-up units for maintenance or repair adds significant OPEX expenses and utilizes a significant amount of energy. With such high capital and operating costs, it is essential to ensure that the equipment producing hydrogen is operable throughout its intended design life with minimal downtime – this is essential to ensuring the economic competitiveness of a hydrogen economy.

Using SMR as an example, bulk hydrogen production in a petroleum refinery by SMR reforming utilizes high temperatures, moderate pressures, and catalyst – filled tubes which generate high tube temperatures of up to 1,690 °F [920 °C] imposing relatively harsh performance demands on system components which are not usually encountered in other refinery or petrochemical plant equipment [8]. The need for high temperatures to drive the reaction results in high metal temperatures within the catalyst tubes and downstream piping including outlet “pigtailed.”

Exhibit 2-4 provides a simplified schematic of the process equipment involved in SMR.

Exhibit 2-5. Schematic of SMR Process Equipment.



Creep rupture and high temperature cycling place a severe service duty on the catalyst tubes, tube outlet pigtailed, the sub header train and the downstream steam generator leading to

ruptured pigtails, cracking in sub-headers and breakup of the ceramic tube sheet ferrules at the steam generator inlet tube sheet. Although the industry has developed specific fit-for-purpose design practice standards augmented with detailed technical reports, reliability issues persist and regularly force premature shutdown of the reformer heater and downstream heat recovery equipment. Among these practices are API Standard 530 and API TR 942-A. API 530 assists designers in the selection of materials and determination of pressure design thickness of heater tubes while API TR 942-A attempts to reconcile the contradictory industry experience where some operators have little or no problems while others suffer premature degradation and cracking of outlet pigtails and manifold components [8]. High reliability reformer heaters, meeting a design life of 100,000 hours without creep rupture and cracking are possible. Selection of upgraded material for pigtails will help, along with sensors that enable real-time degradation analysis [8].

2.1.2 Safety

Since hydrogen is an output at many petroleum refineries and has been for decades, safety enabling procedures and technologies in the “Production” step of the value chain are quite well-developed and would only need to be minimally adjusted if CCUS becomes widely applied in these facilities as hydrogen production transitions from “grey” to “blue.”

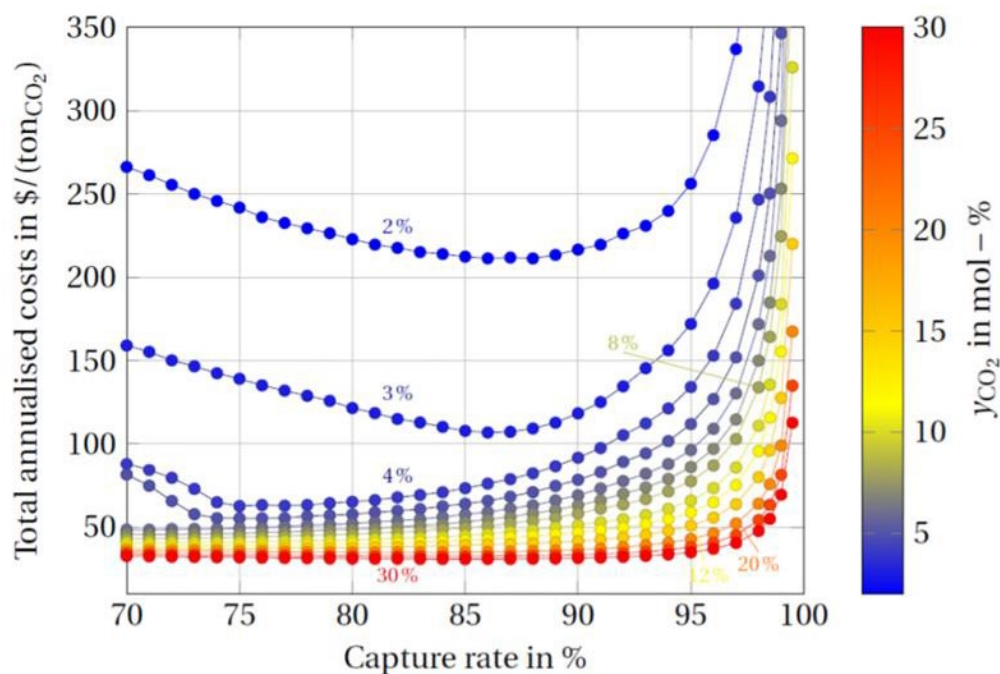
Detection layers themselves encompass different detection techniques that either improve scenario coverage or increase the likelihood that a specific type of hazard is detected. Such fire and gas detection layers can consist of catalytic sensors, ultrasonic gas leak monitors, and fire detectors. Ultrasonic gas leak detectors can respond to high-pressure releases of hydrogen, such as those that may occur in hydrocracking reactors or hydrogen separators. In turn, continuous hydrogen monitors like catalytic detectors can contribute to detecting small leaks, for example, due to a flange slowly deformed by use or failure of a vessel maintained at close to atmospheric pressure. To further protect a plant against fires, hydrogen-specific flame detectors can supervise entire process areas. Such wide coverage is necessary because with hydrogen cloud movement, a fire may be ignited at a considerable distance from the leak source [9].

An ancillary concern to those above are false alarms. Other process gases (common in refineries) can trigger sensors, resulting in false alarms and lack of confidence in the sensor. Safety will be compromised if a hydrogen leak detection system sets off frequent false alarms. False alarms are a problem when they stop production or require unnecessary evacuations; as workers experience the inconvenience, frustration, and loss of productivity from alarms that turn out to be inaccurate, they will begin to ignore them, stop responding to them, and sometimes even turn off the detection system completely [10]. This increases the chance of a real leak being missed and severe damage being done. A common strategy to avoid false alarms is to deploy multiple sensor types for a particular room or vessel to achieve a wide range of alarm set points, detection ranges, and mitigate the cross-sensitivities that certain sensor types have to non-hydrogen gases. Gas sensor arrays powered by artificial intelligence present another opportunity. Continued optimization of different hydrogen sensor combinations represents an opportunity to mitigate this challenge and can be enabled by emerging technologies like artificial intelligence and machine learning.

2.1.3 Emissions

For hydrogen produced from fossil sources to be considered low in emissions, the carbon dioxide from process emissions first need to be captured and stored. This process of CCUS is enabled by certain chemicals that function in capturing carbon that would otherwise be a waste product. Knowledge of these chemicals and their associated processes is of critical importance for the natural gas industry because of their associated capital and operating expenditure (CAPEX and OPEX) costs and significant energy requirements – another challenge for industry. **Exhibit 2-5** below provides an illustration of the cost per ton of CO₂ captured, differentiated by different desired capture rates (x-axis) and different output carbon dioxide stream concentrations (color scheme). It can be observed from the figure that attempting to capture close to 100 percent of carbon dioxide emissions in any scenario is extremely cost-intensive [11].

Exhibit 2-6. Cost per ton of captured CO₂.



The majority of capture agents in commercial use today are based on liquid systems, either pure liquids, mixtures, or solutions in solvents such as water. The CAPEX and OPEX associated with these chemical capture agents play a large role in the costs observed in the figure above.

As CO₂ capture rates exceed 90 percent, the total annualized cost of capture on a per ton basis exponentially increase. As the concentration of CO₂ in the emitted stream becomes more dilute, capture becomes less cost-effective on a per ton basis; low purity CO₂ streams are currently prohibitively expensive to capture. Sensor development can play an important role in improving the cost-effectiveness of carbon capture, including in separation processes to improve CO₂ purity before capture.

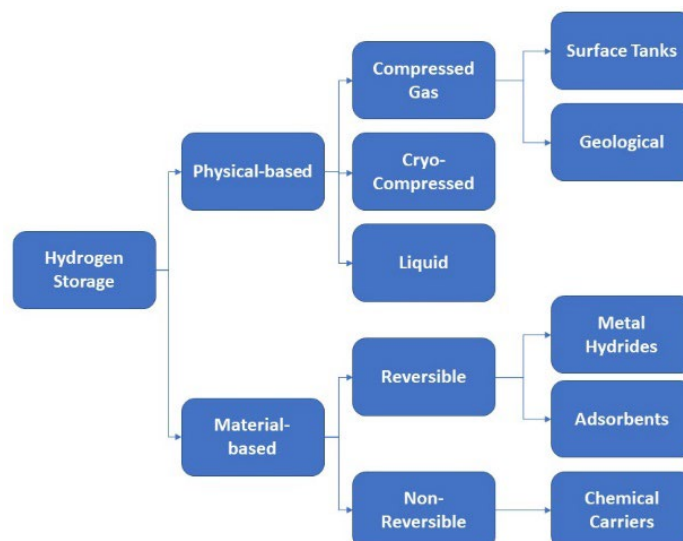
2.2 TRANSPORT AND STORAGE

A productive and valuable hydrogen economy will depend on efficient transport and storage of hydrogen once it is produced. For dedicated transport and storage infrastructure to make economic sense, high volumes of hydrogen and significant infrastructure to deliver it from where it is produced to where it will be used are required. Typically transported and stored under very high pressure as a compressed gas, these logistical factors can influence the viability of hydrogen production. For example, logistical considerations of transportation and storage may offset economies of scale that come from producing hydrogen at a large, centralized facility.

2.2.1 Cost and Equipment Longevity

There are several methods to approach the storage of hydrogen. Because of the inherent volatile characteristics of hydrogen, virtually all involve a physical or chemical transformation of the component into a more stable form. Storage of hydrogen as a mixed gas or liquid, such as natural gas blended with pure hydrogen (known as “hythane”), is also a viable option. However, such a mixture can only accommodate up to 20 percent by volume hydrogen to remain compatible with current infrastructure and pipelines [12]. An overview of the various approaches can be found in **Exhibit 2-6** below.

Exhibit 2-7. Illustration of hydrogen storage approaches.



A national hydrogen infrastructure could require geologic (underground) bulk storage to handle variations in demand throughout the year. In some regions, naturally occurring geologic formations, such as salt caverns and aquifer structures, might be used, while in other regions, specially engineered rock caverns are a possibility. Geologic bulk storage is common practice in the natural gas industry and there are four existing salt caverns used for hydrogen storage today. Storing fuel in salt caverns is not a new technology, as the U.S. Strategic Petroleum Reserve has long stored emergency crude oil in underground salt caverns on the Gulf Coast, and notes they cost 10 times less than aboveground tanks and 20 times less than hard rock mines.

The Reserve has 60 large caverns, typically 200 feet in diameter and 2,500 feet tall [13]. The use of geologic storage for hydrogen used in fuel cell electric vehicles and other applications requires further investigation into the possible impurities that could be introduced by underground storage. Sensors that could accurately detect and distinguish between such impurities would help mitigate this risk. Additional opportunities exist in automated or robotic sensor-enabled assessment of underground storage options.

Although the storage of gaseous hydrogen in salt caverns already is used on a full industrial scale, the approach is not fully applicable in all regions due to varying geological conditions. Therefore, other storage methods are necessary. On-site hydrogen storage is used at central hydrogen production facilities, transport terminals, and end-use locations. Storage options today include insulated liquid tanks and gaseous storage tanks. The four types of common high-pressure gaseous storage vessels are shown in **Exhibit 2-7** below [13].

Exhibit 2-8. Four types of high-pressure gaseous storage vessels.

Type I	All-metal cylinder
Type II	Load-bearing metal liner hoop wrapped with resin-impregnated continuous filament
Type III	Non-load-bearing metal liner axial and hoop wrapped with resin-impregnated continuous filament
Type IV	Non-load-bearing, non-metal liner axial and hoop wrapped with resin-impregnated continuous filament

Type I cylinders are the most common. Currently the costs of Type III and Type IV vessels are greater than those of Type I and II vessels. It is expected that with additional cost reductions in carbon fiber and improved manufacturing methods these technologies could ultimately cost less than the traditional metal Type I cylinders [13]. Sensors that augment and streamline the manufacturing process of these vessels could help accelerate this cost reduction.

Cryogenic liquid storage tanks, also referred to as dewars, are the most common way to store large quantities of hydrogen. Super-insulated low-pressure vessels are needed to store liquid hydrogen at -253°C (-423°F). The pressure of liquid hydrogen is no more than 5 bar (73 psig). Regardless of the quality of the insulation, however, some heat will reach the tank over time and cause the liquid hydrogen to boil. The result is that hydrogen gas accumulates at the top of the liquid tank and causes the pressure inside the tank to increase. To keep the pressure from rising above the limits of the tank, the gaseous hydrogen must be vented from the liquid tank and either released or recompressed by a boil-off compressor to be stored as gaseous hydrogen. Cryogenic storage maximizes the density of hydrogen but does impose some significant operational constraints on the fuel system [14]:

- It requires an airtight insulation system to reduce the boil-off of the liquid hydrogen and maintain it at cryogenic temperatures.

- Liquid hydrogen handling requires specialized equipment and procedures. Also, the storage of liquid hydrogen is time limited (due to boil-off) so the fuel usually needs to be manufactured on site or at a nearby location.
- The fuel tanks need to be maintained at a constant pressure, usually around 21 psia to minimize boil-off. This requires a venting system and procedure to be implemented.
- Liquid hydrogen tanks and lines must be sealed off from the atmosphere. If air enters the tanks it will freeze solid and can block the flow lines. Only helium can be used as a purge gas.

The main components for storing liquid hydrogen are the tank and insulation. Sensors can support cryogenic storage in three ways. First, pressure sensors can be deployed to help inform operators when venting is needed to maintain constant pressure. Second, sensors can be deployed to ensure there is no air entering the tank or lines of the cryogenic storage tank. Since there are wide variety of industrial and bioprocessing applications that require operation in a vacuum, commercially available sensors already exist to detect air bubbles – ultrasonic sensor technology is typically deployed in this respect. A potential challenge would be to tailoring these sensors to applications of hydrogen storage, primarily ensuring the sensors are able to withstand contact from low-temperature hydrogen. Lastly, fast-response temperature sensors can be deployed to help ensure that cryogenic conditions are being maintained – essential for minimizing boil-off events.

Hydrogen Carriers

Liquid carriers are built to store hydrogen in a chemical state different from molecular hydrogen. As a result, it can be transported conventionally without any compression or cryogenic conversion. At the delivery sites, hydrogen is extracted from these carriers for usage. The liquid carrier is then recycled and prepared for another delivery. Thus, liquid carriers are a sustainable solution for delivery of hydrogen in bulk. Liquid organic hydrogen carriers (LOHCs), a subset of liquid carriers, have proved to be promising for the transportation and storage of hydrogen. The concept of LOHCs is based on hydrogenation and dehydrogenation reactions. Ammonia, along with a diverse range of organic compounds are being researched as suitable liquid carriers of hydrogen. They are also less energy-intensive as the heat generated during hydrogenation can be used for dehydrogenation. A disadvantage with liquid carriers, however, is the extra purification required after extracting hydrogen which adds to the overall delivery cost. This is an area that sensors could be developed to help optimize.

While the synthesis costs of ammonia and LOHCs compare well with the cost of liquefying hydrogen, use of these liquid carriers introduces an extra step of converting the carrier back to hydrogen; the cost and efficiency losses associated with this reconversion step remain a barrier to commercial adoption. As such, much R&D in this area has focused on improving the chemistry of hydrogen release through catalyst development – an area sensors could be deployed to support.

Equipment

Ensuring equipment longevity in transport and storage will be critical to the growth of a hydrogen economy and the large-scale adaptation of hydrogen technology. If large CAPEX

hydrogen-related investments cannot be made with confidence due to concerns related to the inability to storage and transport hydrogen, this will stifle growth and innovation in the hydrogen economy.

Material failures related to hydrogen embrittlement and stress corrosion cracking are two common material failures that result from exposure to hydrogen – especially relevant in storage and transport of hydrogen due to extended exposure. Hydrogen embrittlement is a process resulting in a permanent loss of ductility in a metal or alloy due to the presence of atomic hydrogen in combination with a stress, either externally applied or internal residual stress [15]. This loss of ductility and load-bearing capacity is responsible for numerous cracking and catastrophic failures at stresses below the yield stress of susceptible materials. It is most encountered in high-strength steels, but also occurs in other metal alloys such as nickel, titanium, aluminum, and copper. The three primary types of hydrogen embrittlement are: Internal Reversible Embrittlement, Hydrogen Environment Embrittlement, and Hydrogen Reaction Embrittlement [16].

Related to materials failures is pressure cycling; high pressures (up to 700 bar) and pressure fluctuations can induce stresses into the material. As pressure increases, the embrittling effects of hydrogen are generally found to increase as well, but the results vary significantly depending on the material. Some high yield strength steels have demonstrated cracking threshold values that reach a limit at about 60 MPa (600 bar). If pressures are increased from the 100-200 bar range to a value of 700 bar, high-yield strength steels could pose a risk if used in equipment or storage [17]. In order to minimize risk, austenitic steels are currently one of the safest options. It remains unclear whether a threshold pressure value (beyond which properties become pressure-independent) exists, although this has been observed in a few steels studied to date. In particular, steel types 316 and A286 have demonstrated successful behavior during testing in hydrogen environments at pressures near 700 bar [18]. Sensors that can aid in the materials discovery process to identify materials best-suited to prevent hydrogen embrittlement could help address this challenge.

Operating conditions are another key consideration; low temperatures (-253 °C) required for hydrogen storage can cause embrittlement of materials and safety device failures. Related is operation compatibility; material groups respond differently to gas versus liquid hydrogen. For example, aluminum alloys are susceptible to degradation from liquid hydrogen whereas they are more resistant to gaseous hydrogen.

The most common tests performed for hydrogen embrittlement evaluation are [19]:

- Slow strain rate test (SSRT): ASTM G142, ISO 7539-7, ASTM G129, NACE TM0198;
- Hydrogen induced cracking (HIC) test: NACE TM0284, NACE TM0177;
- Stress orientated hydrogen induced cracking (SOHIC) test: NACE TM0103, NACE TM0177;
- C-Ring (CR) test: ASTM G 38, NACE TM0177, ASTM F519, ASTM F1624 and NACE TM0177;
- Four-point bend (4PB) tests: NACE TM0177, NACE TM0316, ISO 16540, ISO 7539; and
- Threshold stress-intensity factor: ASTM E1681.

Detection of embrittlement through the listed test procedures is typically a time-intensive process, and often does not allow for rapid adjustment in the case there is embrittlement occurring. While they would not replace the use of the current testing standards, the development of advanced sensors that could be deployed to provide operators real-time indication of mechanical properties of materials in contact with hydrogen could potentially allow for preemptive equipment maintenance [20].

2.2.2 Safety

The leakage of hydrogen stands at the top of the list of safety concerns in regard to the transport and storage of hydrogen. Liquefied hydrogen release can cause immediate loss of toughness of container and result in complete rupture. Hydrogen is flammable in the range of 4-to-75 percent in air by volume and release of compressed hydrogen contains tremendous energy. Hydrogen gas has a high propensity to leak due to its very small size and its low density (0.09 g/L at NTP of 0 °C / 1 atm) which corresponds to a high buoyancy. Any leakage that occurs not only diminishes efficiency, but also raises costs and introduces potential hazards such as flammability and asphyxiation. Hydrogen has a Lower Explosive Limit of just 4 percent volume, meaning even tiny quantities of hydrogen can cause explosions when mixed with atmospheric air; even a spark of static electricity from a person's finger is enough to trigger an explosion when hydrogen is present [21]. Additionally, because hydrogen is odorless and is not visible when burning, odorants and flame enhancement additives are likely to be needed before hydrogen enters any pipeline system.

Continued development of new sensors technologies that can detect hydrogen at low concentrations are critical. Using solid-state technology developed at Sandia National Laboratory and funded by DOE, H₂Scan LLC is now commercializing hydrogen-specific sensing systems that can detect hydrogen against virtually any background gases. These sensors have a low hydrogen sensitivity of about 5 ppm in air and less than 1 ppm in nitrogen and are hydrogen specific with no cross-sensitivity to other gases [22].

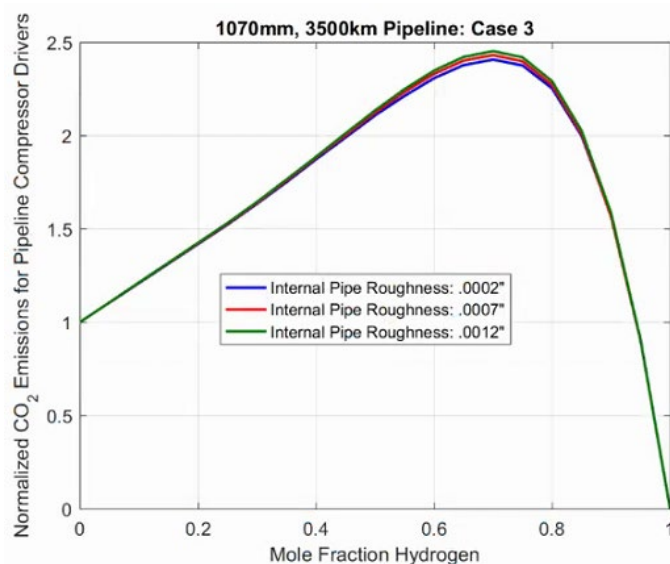
2.2.3 Emissions

Transport and storage of CO₂ emissions has an impact on total cost of production. Accessing pore space for geological storage of carbon dioxide is not yet a routine process, increasing complexity. Reports indicate that there is adequate storage options for CO₂ capture and storage needs, but there is a need to identify them in locations where blue hydrogen production is available e.g., locations near access to coal or gas. CCUS hubs where multiple facilities utilize shared CO₂ transport and storage infrastructure can help lower the overall infrastructure investment needed. Integrated plant carbon dioxide capture systems can improve heat integration and waste heat recovery. Improved plant design for reduced use of high-cost materials like stainless steel and alloys, chemical looping processes, membrane separation for removing CO₂ from other gases are all potential opportunities. The confirmation of subsurface volume capacity for CCUS requirements and assessment of the potential uncertainty range can be enabled by sensors.

To compress the hydrogen to the operating pressure of the pipeline, compressor stations are required along the way of pipeline systems. If hydrogen is mixed with methane and the existing

compressors for natural gas are kept in place, some parts might need to be adapted, depending on the admixture of hydrogen. If the share of hydrogen exceeds 40 percent, the compressors will need to be replaced. A complete switch to a 100 percent hydrogen pipeline requires installing new and more turbines or motors and more powerful compressors to deliver the three-times higher volume flow of hydrogen compared to natural gas [23]. An ancillary but critical concern related to using existing compressors with mixtures of hydrogen and natural gas is the power requirements for compressors to effectively transport hydrogen. The density of hydrogen in both gas and liquid form is a fraction of that of natural gas, necessitating more compression power for transportation of the gas. Assuming compressors are powered by grid electricity or gas-fired engines (as the majority are today), blending hydrogen into natural gas actually initially increases emissions related to gas compression in pipeline transport, as shown in **Exhibit 2-8** below [24].

Exhibit 2-9. Compressor-related CO₂ emissions for blended gas.^e



To illustrate the capital expenditures and energy requirements of compressors stations, the compressor stations just in the states that make up the Appalachian region of the United States have a capital cost of more than \$13 billion, and currently use more than 112 thousand dekatherms of gas and 2,320 gigawatt hours (GWh) of power for compression [25]. A transition to high-percentage hydrogen blended gas would have significant implications for necessary capital investment and net energy use for compression. Sensors that can help optimize current compressors or that can be integrated into new compressor stations tailormade for hydrogen could potentially help mitigate this issue.

Challenges related to compressions, transport, and storage of hydrogen has prompted significant R&D interest in other liquid carriers with moderate requirements. Most attention has been given to two carriers in particular: ammonia and liquid organic hydrogen carriers (LOHCs), including cyclic alkane compounds (e.g., cyclohexane, methylcyclohexane and decalin); both

^e "1" on the vertical axis represents the baseline compressor emissions of 100 percent natural gas.

have more moderate storage requirements than liquid hydrogen which results in significantly lower projected transportation and storage costs [26]. The properties of ammonia compared to hydrogen and natural gas are shown in **Exhibit 2-9** below [27].

Exhibit 2-10. H₂ Transportation and Storage Energy Sources Comparison.

Product	Boiling Point °F (°C)	Density (at 900 psig, 60 °F) lb/ft ³ (kg/m ³)	Energy Density (at 900 psig, 60 °F) BTU/ft ³ (kJ/m ³)	Specific Energy BTU/lb (kJ/kg)	Mass Flow Rate [†] lb/hr (kg/hr)	Pipeline size (in)	Power Required HP [‡] (kW)	Relative Costs
Natural Gas	-260 °F at 0 psig (-160 °C at 0 barg)	3.39 (54.3)	75,600 (2,814,000)	22,300 (51,820)	310,400 (140,800)	16	4,820 (3,600)	Base
Ammonia	84 °F at 150 psig 213 °F at 900 psig (29 °C at 10 barg) (101 °C at 62 barg)	38.5 (616)	372,700 (13,860,000)	9,680 (22,500)	716,500 (325,000)	12	1,610 (1,200)	0.5
Hydrogen	-423 °F at 0 psig (-253 °C at 0 barg)	0.32 (5.16)	19,360 (721,110)	60,130 (139,750)	113,650 (51,550)	18	17,850 (13,320)	2.2

Important to highlight in **Exhibit 2-9** is that relative to hydrogen and natural gas, ammonia can exist as a liquid at modest temperature and pressure conditions and require a fraction of the compression and pumping power for transport. If deployed correctly, this could help mitigate the compression-related emissions of utilizing blended hydrogen-natural gas mixtures. As previously discussed, the use of these liquid carriers such as ammonia introduces an extra step of converting the carrier back to hydrogen; the cost and efficiency losses associated with this reconversion step remain a barrier to commercial adoption. As such, much R&D in this area has focused on improving the chemistry of hydrogen release through catalyst development – an area sensors could be deployed to support.

2.3 APPLICATIONS AND END USE

Hydrogen is a gas widely used in a number of industrial applications. Hydrogen usage will be expanding as it is a primary component in fuel cell technology, as a replacement for generating process heat in industrial applications, for industrial on-site power, and as a chemical process

[†] Equivalent to 1,200 MW power generation fuel supply at 60% efficiency.

[‡] Based on 100 km pipeline.

feedstock. Critically, it is used to store the excess energy generated by renewable sources such as solar and wind.

2.3.1 Cost and Equipment Longevity

In applications such as the manufacture of microprocessors, LEDs, and solar cells the degree of hydrogen purity is crucial and advanced purification systems guarantee the purity. These low-volume, high-value applications will be critical to enabling the hydrogen economy. Achieving high purity of product is necessary for many end use applications, but the separation operations needed to achieve such high purity can be cost-prohibitive.

Hydrogen is widely used to grow epitaxial layers to make silicon devices and is also used in compound semiconductor manufacturing. An increase in hydrogen use is also taking place for the adoption of extreme ultraviolet lithography (EUV) to define smaller geometrical patterns. The purity of hydrogen needed for these processes is typically down to 10 ppb or preferably 1 ppb; thus, gas purifiers at bulk, area, or at the point of use are needed to achieve this very high degree of purity [28]. The use of purification maintains the same quality of gas over time and also eliminates any impurity contribution coming from the gas distribution system, eliminates variation in gas batch quality, and mitigates impurities introduced during the replacement of gas batches and other random sources of contamination. Hydrogen has the potential to become a significant source of clean energy in the automobile and heavy-duty transport sector. Several major car manufacturers have developed cars powered by proton exchange membrane fuel cells (PEMFC). A requirement for the mass adoption of this new vehicle technology is the development of a suitable infrastructure capable of filling car tanks at high pressure, 700 bars, with high-purity hydrogen. The specification limits for some impurities, such as carbon monoxide (CO) and sulphur compounds, are very tight, down to 200 ppb or even less, because of their ability to deplete the lifetime of the fuel cells. Due to the chemical and physical properties of hydrogen, several purification technologies have been developed over the years. **Exhibit 2-10** below illustrates common technologies used to improve hydrogen quality down to at least 6 nines (6N) quality, explaining where each technology has advantages [28].^h

^h "6N" implies a purity of 99.999999% (6 nines after the decimal place).

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Exhibit 2-11. Hydrogen Purity Technology Comparison.

Technology	Inlet Gas Purity	Impurities Removed	Impurities Not Removed	Flow Range	Operating Temperature	Pressure Drop	Maintenance	Comment
Adsorber	5N	O ₂ , H ₂ O, CO, CO ₂ , NO _x , S	N ₂ CH ₄ , rare gases	0.1 – 120 m ³ /h	Room Temperature	Low	Regeneration every 1-3 years	The better the inset gas purity, the longer the lifetime. Less expensive technology with limited performance.
Regenerable Adsorber	4.5N	O ₂ , H ₂ O, CO, CO ₂ , NO _x , S	N ₂ CH ₄ , rare gases	10 – 1,000 m ³ /h	Room Temperature	Low	None	Suitable for very high flow rate. Low running cost. No N ₂ removal.
Getter	6N	O ₂ , H ₂ O, CO, CO ₂ , N ₂ , CH ₄ , NO _x , S	Rare gases	0.1 – 300 m ³ /h	300-600 °C (572-1,112 °F)	Low	Getter column replacement every 3-8 years	Good for when the gas is relatively clean. Removes most impurities, N ₂ included.
Cryogenic	4N	O ₂ , H ₂ O, CO, CO ₂ , N ₂ , CH ₄ , NO _x , S	Helium	20 – 1,000 m ³ /h	- 180 °C (-292 °F)	Low	None	Requires complex infrastructure to manage liquid N ₂ . High running cost. Removes all impurities except helium. Competitive for high flow rates.
Palladium Membrane	3.5N	O ₂ , H ₂ O, CO, CO ₂ , N ₂ , CH ₄ , NO _x , S, rare gases	None	0.1 – 100 m ³ /h	400 °C (752 °F)	High	None	Removes all impurities, rare gases included. Very compact. Compatible with high inlet gas purity. Sensitive to sulfur contamination.
Supported Palladium Membrane	3.5N	O ₂ , H ₂ O, CO, CO ₂ , N ₂ , CH ₄ , NO _x , S, rare gases	None	0.1 – 500 m ³ /h	400 °C (752 °F)	Medium-low	None	Removes all impurities, rare gases included. Very compact. Compatible with high inlet gas purity. Sensitive to sulfur contamination.

Typically, such high purities of hydrogen are not needed for combustion applications like that of hydrogen boilers and turbines. Technologies also widely used in gas purification, like pressure swing adsorption (PSA) and polymeric membrane separation, are more suitable to handle a

lower degree of hydrogen purity. PSA is generally the purification method of choice for steam reforming units because of its production of high-purity hydrogen and is also used for purification of refinery off-gases, where it competes with membrane systems. Many hydrogen plants that formerly used a wet scrubbing process for hydrogen purification are now using PSA for purification. The PSA process is a cyclic process that uses beds of solid adsorbent to remove impurities from the gas and generally produces higher-purity hydrogen (99.9 percent purity compared to less than 97 percent purity by volume for wet scrubbing technology) [29].

CO, H₂O and S are the key impurities with a significant impact on end-users at the levels found in production; some purification is needed to address these. Solid Oxide Fuel Cells (SOFC), Proton-exchange membrane fuel cells (PEMFC), and similar end-use applications require further purification which adds to cost for these applications. **Exhibit 2-11** illustrates the impacts of these impurities in various applications [30].

Exhibit 2-12. Impact of Impurities Found for Various Hydrogen Applications.

Impact of impurities found at levels present after production

Reformation reactions:		Impurity	Combustion	SOFC	PEMFC
1	$CH_4 + H_2O \rightleftharpoons CO + 3H_2^*$	CO	Unsafe		Catalyst poison
2	$CO + H_2O \rightleftharpoons CO_2 + H_2$	CO ₂	Hydrogen dilution		
Impurities intrinsic to reformation produced hydrogen		CH ₄		Potential carbon deposition	Hydrogen dilution
		H ₂ O	No condensation in pipes at -10°C		
Impurities in natural gas and introduced in ATR O ₂ source		N ₂	Hydrogen dilution		
		Ar			
Impurities in natural gas , reduced to 50 ppb before reformer		S compounds		Catalyst poison (no impact at this level)	Catalyst poison
		O ₂			Degradation
Electrolysis impurities		H ₂ O (electrolysis)	No condensation in pipes at -10°C		

Sensors that can both detect these impurities and aid in pre-utilization separation will be critical to the widespread adoption of hydrogen.

The lower heating value (LHV) of hydrogen is 10.8 MJ/Nm³ (274.7 BTU/scf) or 120 MJ/kg (51,593 BTU/lb). In comparison, the LHV of 100 percent methane is 35.8 MJ/Nm³ (911.6 BTU/scf) or 50 MJ/kg (21,515 BTU/lb) [31]. On a mass basis, hydrogen is two times more energy dense than methane. But, on a volume basis, hydrogen is one third less energy dense than methane. Therefore, it takes three times more volume flow of hydrogen to provide the same heat (energy) input as methane. Thus, operating a gas turbine on 100 percent hydrogen requires a fuel accessory system configured for the required flow rates [31].

In a combustion reaction, the flame velocity or flame speed is the velocity at which the unburned gases propagate into the flame. The flame speed of hydrogen is an order of

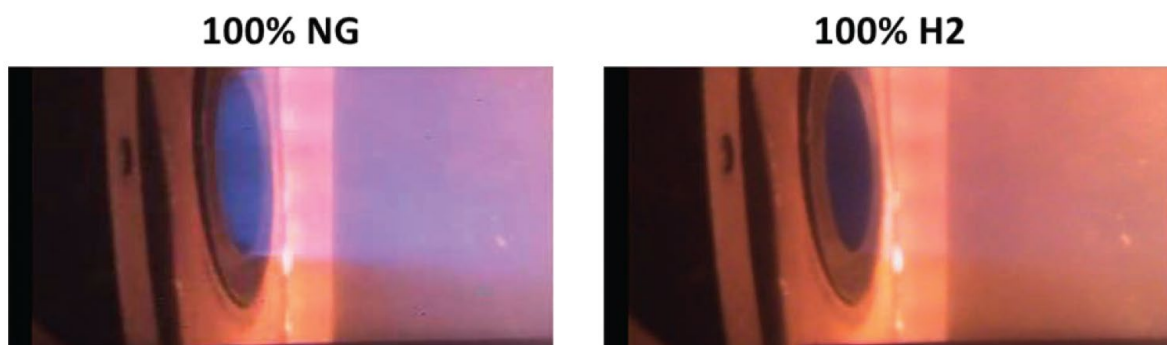
magnitude faster than many hydrocarbon fuels. From a gas turbine perspective, flame speed is an important property used in determining if a combustor may have issues with the flame propagating upstream from the combustion zone into the premixing zone (near the fuel nozzles). Typically, combustion systems are configured to operate on a set of fuels that have a defined range of flame speeds. Due to the significant difference in the flame speeds of methane and hydrogen, combustion systems configured for operating on methane (or natural gas) may not be suitable for operating on a high hydrogen fuel. In many cases, operating on a high hydrogen fuel requires a combustor specifically configured for the different combustion conditions [31].

When considering a hydrogen for on-site power, existing gas turbine assets should be included as part of the evaluation, as they can be converted to operation on fuels with hydrogen. An advantage to gas turbines is that they can be re-configured for operation on new fuels, including fuels with increased levels of hydrogen. Changing to a fuel with increased levels of hydrogen may require making changes to the gas turbine, gas turbine accessories, and/or the balance of plant. The magnitude of the required changes is a function of the amount of hydrogen in the fuel. If the new fuel will be a blend of hydrogen in natural gas, the required changes might be limited controls updates along with new combustor fuel nozzles. Given that there are many variations on fuel, combustor configurations, etc., the required scope must be evaluated on a case-by-case basis. If the conversion is to a high hydrogen fuel, the scope could include changes to numerous gas turbine system. This type of fuel conversion may require switching to a new combustion system, which would require new fuel accessory piping and valves. It may also require new fuel skids, as well as enclosure and ventilation system modifications. Other changes include upgrading to flame detectors capable of detecting hydrogen flames and upgrading gas sensors to models configured to detect gases with reduced levels of hydrocarbons. Aside from physical changes, switching to a high hydrogen fuel may require changes to the gas turbine sensors and controls, which might impact gas turbine performance, both output and heat rate [31].

2.3.2 Safety

There are additional operational challenges with hydrogen that relate to overall safety. First, a hydrogen flame has low luminosity and is therefore hard to see visually, as shown in **Exhibit 2-12** [31]. This requires flame detection systems specifically configured for hydrogen flames. Secondly, hydrogen can diffuse through seals that might be considered airtight or impermeable to other gases. Therefore, traditional sealing systems used with natural gas may need to be replaced with welded connections or other appropriate components. Thirdly, hydrogen is more flammable than methane; the lower flammability limit for methane (in air) is five percent, while for hydrogen it is four percent. Therefore, hydrogen leaks could create increased safety risks requiring changes to plant procedures, safety / exclusions zones, etc. In addition, there may be other plant level safety issues that merit review [31].

Exhibit 2-13. Comparison of natural gas and hydrogen flames.



Sensors that can detect flames in hydrogen combustion will be essential to deploy in these applications.

2.3.3 Emissions

When burning 100 percent hydrogen in combustion systems, there are zero CO₂ emissions. However, the technology is not without its drawbacks in combustion applications. Combusting hydrogen in gas turbine can produce harmful nitrogen oxides (NO_x). Several European studies have found that burning hydrogen-enriched natural gas in an industrial setting can lead to NO_x emissions up to six times that of methane [32]. There are numerous studies in the scientific literature about the difficulties of controlling NO_x emissions from hydrogen combustion in various industrial applications. The higher adiabatic flame temperature of hydrogen is typically the root cause of higher NO_x emissions. Long-term exposure to NO_x increases the risk of respiratory conditions and heightens sensitivity to allergens. NO_x is also a precursor to the formation of fine particles and ground-level ozone, which are both associated with severe adverse health effects. There are turbines commercially available that mitigate NO_x emissions, but most are constrained by the amount of hydrogen that can be included in the fuel mix [31]:

- **Dry low emission (DLE) and dry low NO_x (DLN) combustors:** DLE and DLN combustion systems are capable of operating with limited amounts of hydrogen in the fuel (limited to 5 percent by volume hydrogen).
- **Next generation high hydrogen combustion systems:** As part of the U.S. Department of Energy's Advanced IGCC/Hydrogen Gas Turbine program, GE developed a low-NO_x hydrogen combustion system.ⁱ This new combustion system was based on the operating principle of small-scale jet-in-crossflow mixing of the fuel and air streams. The miniaturized tubes function as “fast” mixers, enabling premixed combustion for gaseous fuels with higher reactivity (ethane, propane, hydrogen, etc.). Results of preliminary testing indicated that this combustion system has entitlement to operate on fuels containing up to 50 percent by volume hydrogen.

ⁱ This effort was sponsored by the U.S. Department of Energy under Cooperative Agreement DE-FC26-05NT42564.

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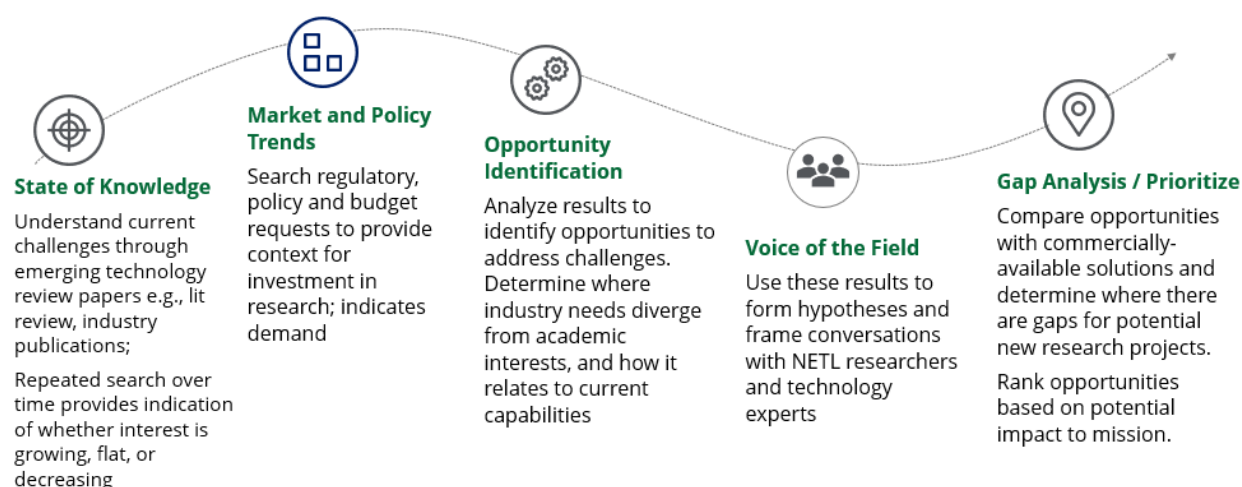
Sensors can be deployed to optimize hydrogen combustion to reduce NOx emissions, as well as in the design and testing of new combustion turbines that can handle higher blends of hydrogen with lower NOx emissions.

3 METHODOLOGY

3.1 WAYFINDER FRAMEWORK

To understand the Key Barriers and identify underlying discrete challenges that contribute to these systemic barriers, this analysis used Deloitte's Wayfinder framework. The Wayfinder methodology identifies high impact research areas by mapping trends over time, building hypotheses to guide interviews with industry representatives, and finally using insights to estimate potential impacts of current research investments. **Exhibit 3-1** illustrates this high-level approach.

Exhibit 3-1. Wayfinder framework.



Wayfinder is a systematic approach intended to remove bias and prior awareness of the field, resulting in a new understanding of relevant technology activity based on empirical evidence.

3.1.1 State of Knowledge

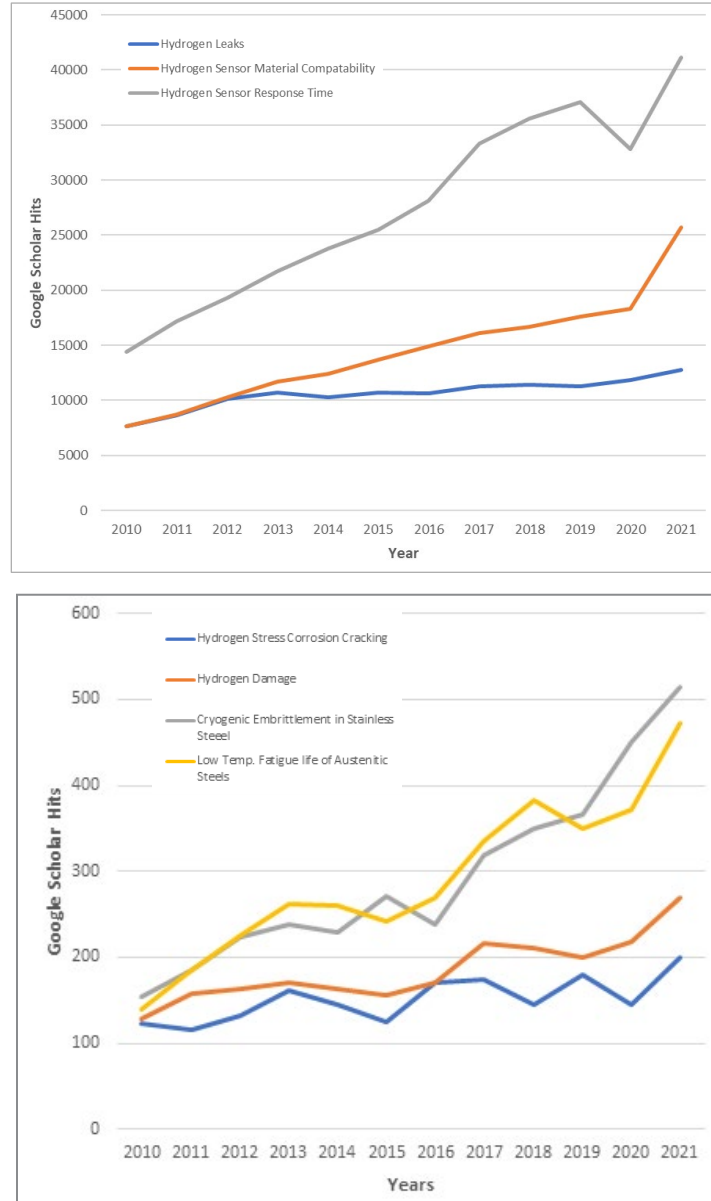
The first step in evaluating the research landscape is to identify key terms and research topics that could address the Key Barriers to hydrogen technology that are known to be of high interest by the Sensors and Controls program. Patent review indicates novel technologies that are in advanced stages of development. Review of journal articles can highlight more current academic research and may indicate topics of high interest. This type of research landscaping can provide a snapshot of interest levels at a current point in time, and can increase understanding of state of the art, contribute to funding decisions, portfolio representation, as well as a diverse range of ideas for solutions.

To get an accurate sense of the trends of certain topics, this analysis turned to academia to observe trends of interest that are relevant to advanced sensors for hydrogen technology. Rather than manually going through Google Scholar, a concise piece of R-Code was implemented to help in web scraping. The code requests the user to input the topic of interest to search and the time frame. By iterating through each year, it outputs a small data table with

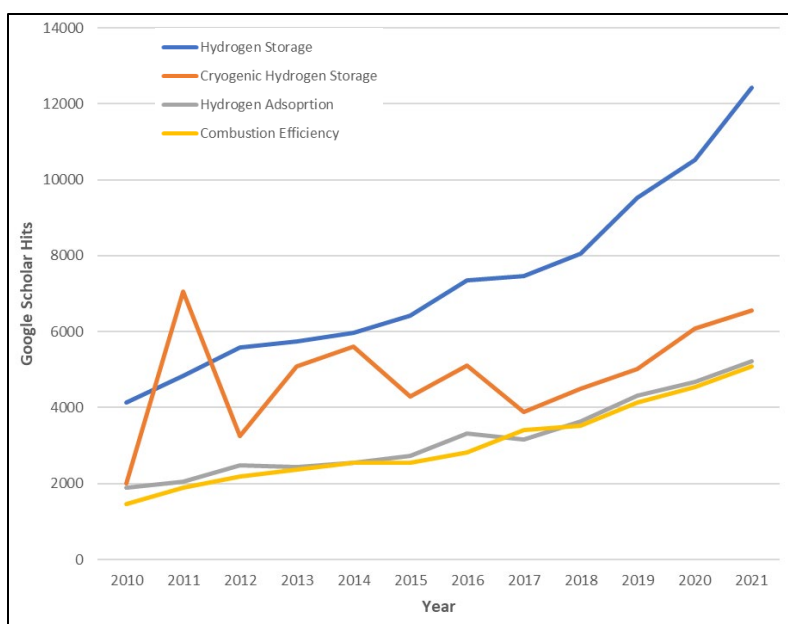
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year and number of Google Scholar “hits.” Extracting that data into Microsoft Excel and creating a simple line graph allows one to visualize the trends of interest. Some of the topics that were considered in this phase of the horizon scanning process are illustrated in **Exhibit 3-2** below.

Exhibit 3-2. Scholarly Journal Publications for Specified H₂ Concepts.



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Tracking the number of peer-reviewed publications over the last five years provides a good understanding of whether interest in these areas is increasing, decreasing, or remains stagnant. An overall summary of relevant sensor research in academia and industry can be found in **Exhibit 3-3** below.

Exhibit 3-3. Current Research Projects.

Project Description	Company / Organization	Type of Sensor	Hydrogen Measurement Range	Response Time	Primary Application
-	DOE EERE	gas analyzer	-	-	detection of impurities in fuel, which can contaminate catalyst
2D materials	-	hydrogen detector	0.1 ppm	<1 s	hydrogen detection in energy storage
Optical nanosensor	Chalmers University of Technology	plasmon visible light technology	0.1% hydrogen in air	<1 s	fastest detection rate, meeting performance targets set by auto industry
ANN approach to modeling production rate	Institute of Energy Policy and Research, Malaysia	predictive modeling using Leven-Marquardt algorithm	-	-	predicted rate of CO and H ₂ production

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Gas sensor array	Chinese Institute of Electronics	robotic olfactory system, including catalytic combustion, mass-sensitivity transducer, electrochemical, optical absorption, gas adsorption, acoustic emission	-	-	leverages automated pattern recognition algorithms and powerful AI tools
Pd nanoparticle-based optical sensor	University of Georgia, SRNL	optical array sensing	2.5 ppm	~0.8 s	spark -free leak detection, with good stability, high sensitivity, rapid response time
Low-temperature hydrogen sensor	RMIT University of Melbourne	Photoactive colloidal crystals	3.5 ppm	-	high selectivity for H ₂ over other VOCs

The hypothesis is that projects of low interest that had been growing over the past five years would be good opportunities for NETL investment. Projects that are currently of high interest may signal a crowded field or overlapping technology goals. Project areas with low but increasing interest represent emerging fields that have relatively little current research investment, but that are gaining momentum. These projects could have the potential to make significant impact in the commercial technology space, as companies are less likely to invest research budgets in early-stage technologies.

According to technical publications from NASA, commercial hydrogen sensors can be segmented into four categories, with each category having its own set of applications, detection methods, and accuracy [33]. These categories are as follows:

1. **Catalytic Combustion:** The sensing element, often referred to as a "pellistor", consists of a platinum (Pt) wire covered with a catalyst-coated alumina bead that serves as a heater and as a resistance thermometer. The heat flux generates changes in the Pt wire resistance that can be converted into a signal to give the concentration of the hydrogen gas. Sensitivity is limited by detection mechanism (resistance changes in the Pt wire)
2. **Electrochemical:** Components of a two-electrode electrochemical cell include a working (or sensing) electrode and a counter electrode that is connected through an electrolyte. In gas-sensing applications a chemical reaction occurs at the surface of the sensing electrode. The design and operation of CO and hydrogen sensors are very similar. Their reliance on diffusion for operation implies a dependence on maintaining ambient temperature.
3. **Semiconducting Oxide:** Hydrogen gas is detected through a surface reaction reactions with chemisorbed O₂. Although this sensor is operable in a range of hydrogen/O₂ concentrations, the presence of some ambient oxygen is essential for its operation and

large hydrogen concentrations would saturate the semiconductor surface and leave it insensitive to increases in hydrogen concentration.

4. **Thermal Conductivity:** Senses hydrogen gas composition by comparing the conductivity of a sample gas with that of either a flowing or stationary reference gas. Primary advantage it is measuring a property of the gas and not relying on its disassociation for measurement, while challenges include its dependency on temperature and gas flow control for accuracy.

As part of assessing the State of Knowledge in the Wayfinder approach, this analysis also did a survey of commercially available sensors that both directly detect hydrogen, as well as other ancillary properties that are critical to various aspects of the hydrogen value chain outlined in this report. The survey was organized by the sensor categories identified by NASA above. This survey of commercially available sensors is available in the Appendix of this report.

3.1.2 Market and Policy Trends

As many countries chart towards a path of net-zero economies, hydrogen has become an attractive energy source and seen a wave of political support. Hydrogen is seen as a key contributor to achieving carbon neutrality, to the extent that Bloomberg stated, “hydrogen could meet up to 24 percent of the world's energy needs by 2050.” In president Biden’s Executive Order on Tackling the Energy Crisis at Home and Abroad, President Biden laid out the government’s approach for the United States to achieve net-zero emissions by 2050. Hydrogen will be a vital part of achieving this goal in parallel with other renewable energy resources [34]. With government support, hydrogen technology can reach sufficient scale for widespread commercial utilization.

In the recent bipartisan infrastructure bill, \$9.5 billion was appropriated for clean hydrogen research, development, and demonstration programs. Of that, \$8 billion is devoted for the development of four regional clean hydrogen energy hubs which will help accelerate commercialization of, and demonstrate the production, processing, delivery, storage, and end-use of, clean hydrogen. The remaining funding will go towards developing a clean hydrogen electrolysis program and the clean hydrogen manufacturing initiative. The clean hydrogen electrolysis program will aim to lower the cost of producing clean hydrogen to less than \$2 per kilogram by 2026 [35].

In effort to reach the administration’s goal of net-zero carbon emissions by 2050, the Department of Energy has developed the Energy Earthshot Initiative. This initiative aims to accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions. The first Energy Earthshot is focused on hydrogen and was launched June 7th, 2021. The goal of the Hydrogen Energy Earthshot is to reduce the cost of clean hydrogen by 80%. Hydrogen is currently priced around \$5 per kilogram and the initiative hopes to reduce it to \$1 per 1 kilogram in 1 decade. The Hydrogen Earthshot goals are also aligned with the DOE’s Hydrogen Program plan which is a strategic framework for the Department’s hydrogen research, development, and demonstration activities [36].

3.1.3 Opportunity Identification

Combining insights from literature review, trend analysis, as well as market and policy trends, revealed research opportunities and white space that could benefit from technology development. These needs could represent the most pressing challenges identified with the hydrogen economy (**Exhibit 3-4**).

ADVANCED SENSORS FOR HYDROGEN TECHNOLOGY

Exhibit 3-4. Summary of Opportunities.

Industry Need	Addressable Challenge Area	Available Solution	Features Lacking
Hydrogen detection at low concentration	Safety	Solid-state hydrogen-specific sensing systems, in early commercialization phase	
Networked gas sensors for volumetric gas detection	All	GSA combined with AI, packaged as chip-scale electronic nose in early commercialization phase	Need to mitigate influences of ambient temperature and humidity
Material Degradation	Safety, Equipment longevity, Cost	Postmortem analytical testing	Real-time, on-site analysis
High pressure, fatigue sensor	Equipment longevity	Limited hydrogen-specific solutions available.	
Automated or robotic pore volume measurement	Cost	Early R&D phase	
Combustion analyzer	Cost	Gas calorimetry for combustion efficiency	Better detection of trace gases and improved detection windows
Emissions sensor	Emissions	Several options available.	Better detection of trace gases and improved detection windows
Predictive analytics	Cost	Early R&D phase - current research projects using ANN to model production rates	Technology only in research phase, needs Pilot scale testing

This method of grouping projects helps to segment the Sensors and Controls portfolio as it aligns with industry's most persistent challenges. It reflects that the program has a high awareness of what is needed in industry, and that there is good opportunity for high impact projects. Using the focus of these research areas aids 1) understanding of what is necessary to address the unique challenges that industry is facing and 2) estimation of what the impact of a successful research program may have on the hydrogen value chain.

3.1.4 Voice of the Field

To validate initial assumptions relating to major challenges and barriers to hydrogen production and use, the team met with industry experts familiar with historical challenges, state of the art technologies, current research of technologies in development. This phase of the analysis provides practical context for what is discovered during the literature review and trend analysis.

Industry experts agree that material compatibility with hydrogen production and use will be a major challenge to expanded use of hydrogen. Solutions for monitoring material and component health are critical to the viability of hydrogen infrastructure. Networked, distributed sensors and smart materials with embedded micro sensors are of high interest to industry.

Achieving exceptionally high purity, as well as monitoring for greenhouse gas emissions is another area of primary concern for commercial hydrogen producers. Facilities using carbon capture systems to reduce emissions will need reliable methods to prove their efficacy. Sensors to facilitate the qualification of product and process are critical to the success of these markets.

3.1.5 Gap Analysis

As the final part of the *Wayfinder* approach, this analysis compared the industry needs identified in Section 2 of this report with survey of commercially available sensors conducted in the Opportunity Identification step. **Exhibit 3-5** below provides a summary and ranking of priority opportunities for sensors R&D to enable the growth of the hydrogen economy.

ADVANCED SENSORS FOR HYDROGEN TECHNOLOGY

Exhibit 3-5. R&D Prioritization Matrix.^j

R&D Priorities			Criteria and Score*		
Value Chain	Barrier	Sensor Opportunity (<i>except from report in quotations</i>)	Improvement Over Incumbent in Target End Use Market	Ease of Technological Integration	Opportunity for Adjacent End Users & Markets
Production	Cost & Equipment Longevity	<i>“Networked temperature sensors and improved plant design to maximize thermal efficiency, combustion analyzers using AI / ML IoT integrated system predictive modeling capabilities built into systems, intelligent alarms, sensors on assets to monitor and optimize plant operations, energy consumption, plant performance, production rates, purity are all opportunities for improvement.”</i>	3	3	3
Production	Cost & Equipment Longevity	<i>“Selection of upgraded material for [SMR] will help, along with sensors that enable real-time degradation analysis.”</i>	3	1	3
Production	Safety	<i>“A common strategy to avoid false alarms is to deploy multiple sensor types for a particular room or vessel to achieve a wide range of alarm set points, detection ranges, and mitigate the cross-sensitivities that certain sensor types have to non-hydrogen gases. Gas sensor arrays powered by artificial intelligence present another opportunity. Continued optimization of different hydrogen sensor combinations represents an opportunity to mitigate this challenge and can be enabled by emerging technologies like artificial intelligence and machine learning.”</i>	2	3	3

^j Note: Score scaling is from 1 to 3, with 3 implying the highest return-on-investment for that criteria area, and 1 implying the lowest.

ADVANCED SENSORS FOR HYDROGEN TECHNOLOGY

R&D Priorities			Criteria and Score*		
Value Chain	Barrier	Sensor Opportunity (<i>except from report in quotations</i>)	Improvement Over Incumbent in Target End Use Market	Ease of Technological Integration	Opportunity for Adjacent End Users & Markets
Production	Emissions	<i>"Sensor development can play an important role in improving the cost-effectiveness of carbon capture, including in separation processes to improve CO₂ purity before capture."</i>	3	2	3
Transport & Storage	Cost & Equipment Longevity	<i>"Sensors that could accurately detect and distinguish between such impurities [from geologic hydrogen storage] would help mitigate this risk. Additional opportunities exist in automated or robotic sensor-enabled assessment of underground storage options."</i>	3	3	3
Transport & Storage	Cost & Equipment Longevity	<i>"Sensors that augment and streamline the manufacturing process of high-pressure hydrogen gas storage vessels could help accelerate this cost reduction."</i>	3	2	3
Transport & Storage	Cost & Equipment Longevity	<i>"Sensors can support cryogenic storage in three ways. First, pressure sensors can be deployed to help inform operators when venting is needed to maintain constant pressure. Second, sensors can be deployed to ensure there is no air entering the tank or lines of the cryogenic storage tank. Since there are wide variety of industrial and bioprocessing applications that require operation in a vacuum, commercially available sensors already exist to detect air bubbles – ultrasonic sensor technology is typically deployed in this respect. A potential challenge would be to tailoring these sensors to applications of hydrogen storage, primarily ensuring the sensors are able to withstand contact from low-temperature hydrogen. Lastly, fast-response temperature sensors can be deployed to help ensure that cryogenic conditions are being maintained – essential for minimizing boil-off events."</i>	2	3	3

ADVANCED SENSORS FOR HYDROGEN TECHNOLOGY

R&D Priorities			Criteria and Score*		
Value Chain	Barrier	Sensor Opportunity (<i>except from report in quotations</i>)	Improvement Over Incumbent in Target End Use Market	Ease of Technological Integration	Opportunity for Adjacent End Users & Markets
Transport & Storage	Cost & Equipment Longevity	<i>"A disadvantage with liquid carriers, however, is the extra purification required after extracting hydrogen which adds to the overall delivery cost. This is an area that sensors could be developed to help optimize. As such, much R&D in this area has focused on improving the chemistry of hydrogen release through catalyst development – an area sensors could be deployed to support."</i>	3	1	3
Transport & Storage	Cost & Equipment Longevity	<i>"Sensors that can aid in the materials discovery process to identify materials best-suited to prevent hydrogen embrittlement could help address this challenge."</i>	3	1	3
Transport & Storage	Cost & Equipment Longevity	<i>"While they would not replace the use of the current testing standards, the development of advanced sensors that could be deployed to provide operators real-time indication of mechanical properties of materials in contact with hydrogen could potentially allow for preemptive equipment maintenance."</i>	3	1	3
Transport & Storage	Safety	<i>"Continued development of new sensors technologies that can detect hydrogen at low concentrations are critical."</i>	2	3	3
Transport & Storage	Emissions	<i>"The confirmation of subsurface volume capacity for CCUS requirements and assessment of the potential uncertainty range can be enabled by sensors."</i>	3	2	3
Transport & Storage	Emissions	<i>"Sensors that can help optimize current compressors or that can be integrated into new compressor stations tailored for hydrogen could potentially help mitigate [increased compressor power requirements for high hydrogen blends]."</i>	3	1	3

ADVANCED SENSORS FOR HYDROGEN TECHNOLOGY

R&D Priorities			Criteria and Score*		
Value Chain	Barrier	Sensor Opportunity (<i>except from report in quotations</i>)	Improvement Over Incumbent in Target End Use Market	Ease of Technological Integration	Opportunity for Adjacent End Users & Markets
Transport & Storage	Emissions	<i>"As such, much R&D in this area has focused on improving the chemistry of hydrogen release through catalyst development – an area sensors could be deployed to support."</i>	3	1	3
Utilization	Cost & Equipment Longevity	<i>"Sensors than can both detect these impurities and aid in pre-utilization separation will be critical to the widespread adoption of hydrogen."</i>	3	3	3
Utilization	Cost & Equipment Longevity	<i>"High hydrogen [content] requires changes to the gas turbine sensors and controls, which might impact gas turbine performance, both output and heat rate."</i>	3	2	3
Utilization	Safety	<i>"...flame detectors capable of detecting hydrogen flames and upgrading gas sensors to models configured to detect gases with reduced levels of hydrocarbons."</i>	3	3	3
Utilization	Emissions	<i>"Sensors can be deployed to optimize hydrogen combustion to reduce NOx emissions, as well as in the design and testing of new combustion turbines that can handle higher blends of hydrogen with lower NOx emissions."</i>	3	2	3

4 CONCLUSION

As with much federally-funded research, a requirement of the Sensors and Controls program is to make a positive impact on society, demonstrate an exceptional return on taxpayer investment, as well as building the brand of the program and the United States as a technology leader in the field. One of the primary ways that NETL can fund impactful projects is to identify challenges that persist in industry and that are expensive or complex to execute. Many large companies are reluctant to invest in these projects, especially when product margins are thin, or when companies are faced with pressure from shareholders. Nonetheless, government research fills an important gap of foundational knowledge generation and exploring new ideas from a first principles approach.

This gap analysis study included all parts of the hydrogen value chain, from hydrogen production, logistics, and utilization, with the exception of transportation applications. The analysis matrixed this value chain with the most critical barriers that exist across the hydrogen ecosystem: Cost & Equipment Longevity, Safety, and Emissions.

Cost & Equipment Longevity

In regard to sensors, the most impactful opportunities include combustion analysis, materials compatibility, and gas composition analyzer. Sensors need to be designed using materials that can withstand high temperatures and pressures in operation. Sensors should be able to detect ongoing damages to continue to improve maintenance schedules. Finally, sensor networks that can determine where localized hotspots contribute to premature equipment failure. In regard to sensors for challenges related to equipment, the most impactful opportunities to address the challenges noted above include materials compatibility, predictive capabilities, and networking. Sensors need to be designed using materials that can withstand the high temperatures and pressure in operation. Additionally, sensors should be able to detect ongoing damage to continue to improve maintenance schedules. Lastly and arguably most critical in the digital era are sensor networks that can determine where localized hotspots are that contribute to premature equipment failure.

Safety

In regard to sensors, the most impactful opportunities to overcome the challenges noted above include improved sensor response time, reduced false alarms, and improved sensor longevity. Faster sampling rate from sensors will be essential to enable quick response remediation. Increase sensitivity to hydrogen detection, without triggering from other interferents, such as methane, or compounds used in refrigerated conditions, such as ammonia or Freon, and reducing sensor poisoning or contamination from process gases will be necessary to ensuring sensor performance and reducing false alarms.

Emissions

In regard to sensors, the most impactful opportunities to overcome the challenges noted above include integrated plants, sequestration volume, and gas composition analyzers. Technology gaps to design CCUS enabled plants. Sensors to accurately estimate available volumes and

reasonable uncertainty of calculations. Sensor networks that can determine where localized hotspots contribute to premature equipment failure.

While all areas noted above and scored in **Exhibit 3-5** are important, the Sensors and Controls program at NETL should prioritize R&D areas that scored high in “Improvement Over Incumbent in Target End Use Market” and “Opportunity for Adjacent End Users & Markets,” but low in “Ease of Technological Integration.” These are indicative of opportunities with market high-upside, but that require prolonged and focused R&D to raise the TRL, which federally-funded research can provide. Such areas included:

- Sensors supporting catalyst development to enable the improvement of chemistry of hydrogen release in liquid hydrogen carriers;
- Sensors that can help optimize current compressors or that can be integrated into new compressor stations tailor-made for hydrogen to help mitigate the increased power requirements (and subsequent emissions) of compressors for transport of high-hydrogen gas blends;
- Sensors to aid in the materials discovery process to uncover new, hydrogen embrittlement resistant materials; and
- Sensors that enable real-time material degradation analysis.

Targeted investment in these areas offer the highest-reward opportunities to advance the hydrogen economy and fulfil U.S. goals to reduce the cost of clean hydrogen by 80% to \$1 per 1 kilogram by 2030.

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6 APPENDIX - COMMERCIALLY AVAILABLE SENSORS

Product Name	Company	Type of Sensor	Detection Method	Hydrogen Measurement Range (%)	resolution	Response Time	Temp. Range (°C)	Primary Application	Price
Explosion Proof Hydrogen Gas Detector	Larson Electric	leak detection	solid state sensor	1-2%	1ppm	4 seconds	-10 °C to 40 °C	Battery-charging rooms, paint spray booths, aircraft maintenance, oil drilling rigs, refineries, solvent and cleaning areas, gas processing plants, chemical manufacturing, wastewater treatment plants,	\$990
D-16 PortaSens III Gas Detector- Hydrogen 0-4%	Gas Sensing	leak detection	electrochemical sensor	Min Range-0-1%, Max Range-0-10%	0.01%	Immediately	-25 – 55 °C	multi-gas sensor to test for variety of gases on the same device	\$1,725
Electrochemical Hydrogen Sensor (H2 Sensor) 0~1000ppm - ME3-H2	Isweek	leak detection	electrochemical sensor	0~1000ppm	2ppm	≤90s	- 20°C~50 °C	high precision, high sensitivity gas detection	

HGD-2000 Hydrogen and Combustible Gas Detector	Eagle Eye Power Solutions	leak detection	Solid state sensor	1-2%	100ppm LEL	about 4 seconds	-10 – 40 °C	Utilities and Power Plants UPS Power Systems Fuel Cell Test Stations Nuclear Waste Reforming Hydrogen Refueling	\$875
Storage Battery Systems SBS-H2 Hydrogen Gas Detector with Visual and Audible Alarms	Storage Battery Systems	leak detection		1-2%		60 seconds	-20-80 °C	hydrogen backup power systems, battery cabinets	\$995
RKI PS 2 Combustible Single Point Stand Alone Monitor	PK Safety	leak detection	Metal Oxide Semi-Conductor	10%-30% LEL		60 seconds	35-120 °C	hydrogen detection in battery rooms, or for LEL level detection of a variety of flammable or solvent vapors in general industry	\$425
Fixed Combustible Gas Detector, 0 to 100%LEL	ATO	leak detection	Catalytic Combustion	0-1000 ppm	0.1ppm/1ppm	≤10s	-20°C~50 °C	monitor leakage of combustible gas In confined space, gas pipeline area, gas station, material	\$526.67

								spraying workshop, chemical industry, and other flammable and explosive gas storage area.	
Hydrogen Detector	Forensics Detectors	leak detection	Electro-chemical cell sensor	0-1000ppm	1ppm	30 seconds	0-122 °F	Detect hydrogen gas for hydrogen vehicles, hydrogen fuel cells, hydrogen storage tanks	\$345
GX-3R Pro Gas Detector with Wireless Communication	RKI Instruments	leak detection	Electro-chemical cell sensor	0 ~ 2,000 ppm		30 seconds	-20 °C ~ 50 °C	Personal monitoring, Confined spaces, Refineries/Petrochemical, Utilities, Oil and Gas, Water/Wastewater, Fire Services, Construction	\$799
Protisen Hydrogen Sensor	Protisen	leak detection	Catalytic sensory with VOC filter	0-40,000 ppm in air	200 ppm	2 seconds	-40 – 80 °C	space sensitive applications	\$395
Hydrogen Sensor and Monitoring System	Storage Battery Systems	leak detection		1-2%			-4 - 176 (°F)	hydrogen leaks from lead-acid storage batteries	\$995

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