AristoSys

Fossil Energy Hydrogen Research and Development Program Formulation

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Date of Submission:

12/17/2020

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Acknowledgements

We gratefully acknowledge ClearPath for funding this work in its entirety. We also would like to thank Justin Ong and Natalie Houghtalen for their insightful guidance during the formulation and preparation of this work.

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Executive Summary

Low carbon hydrogen has a versatility that lends itself to decarbonization of multiple energy consuming sectors in the United States. Hydrogen can be used as zero carbon fuel in the power and transportation sectors, and also as an energy storage medium to mitigate the variability of renewable electricity. For these reasons, hydrogen has emerged as a focal point of broad decarbonization efforts.

In order for its use in any of these sectors to be efficient and economical, research and development on its production, utilization, transport, and storage are necessary. Moreover, to fully realize hydrogen's potential carbon neutrality, the carbon footprint of its production, transport and storage must be minimized.

In the early 2000's the United States Department of Energy (DOE) engaged in hydrogen research primarily as a means to reduce reliance on foreign oil. In 2009, evaluation of the DOE Hydrogen Program in the context of the transportation sector resulted in the decision to substantially scale back further hydrogen research. The timeline to convert to a hydrogen car economy was deemed too long to be practical.

Today, multi-sector decarbonization is a critical motivating factor for both governments and industry. Thus, the market for hydrogen has been revived in a more robust manner, creating a demand for improved technology to meet climate needs. A viable hydrogen market that will enable large scale climate change mitigation requires Federal support for proper maturation.

Many ongoing Federal research and development programs are involved in efforts that can be directly leveraged to develop hydrogen technologies. However, even within DOE offices, *this work is not coordinated around a hydrogen technology development effort*. This report articulates a need to coordinate the various independent efforts that maximizes development efficiency to support hydrogen technology commercialization.

The Office of Fossil Energy is ideally positioned to lead the broad classes of research that are required to support a hydrogen economy. Multiple Fossil Energy programs contribute directly to development of hydrogen production, utilization, transportation, and storage infrastructure required to support a hydrogen economy.

Recommendations

Dedicate Office of Fossil Energy funding. This analysis of the Fossil Energy R&D programs in Coal, Natural Gas and Oil, suggests that an investment of approximately $1B over 13 years is highly likely to result in a commercialization of an advanced fossil-energy-based hydrogen system that would meet suggested R&D goals. The program would be seeded the first three years with approximately $30M per year for development of technologies currently at low Technology Readiness Level (TRL). Subsequent years require increasingly larger investments to support pilot testing, to a maximum of $132M per year.

Coordinate DOE-wide efforts. Most hydrogen-specific R&D is housed with EERE's hydrogen and fuel cell program. FE's critical mass of expertise in carbon capture, hydrogen to power technologies, and geology and pipeline infrastructure make it well-suited to further critical R&D across the hydrogen supply chain. FE's depth of expertise is further detailed within this report.

Establish Fossil Energy hydrogen technology goals. Current DOE goals are geared toward the EERE program. Goals should be established to align R&D across the DOE and specifically relate to Office of FE technology development trajectories.

I. Motivation for Fossil Energy Hydrogen Research

Holistic decarbonization of the U.S. economy relies heavily on reducing CO_2 emissions in all of our diverse energy consuming sectors. The power generation, industrial, transportation and residential sectors are all significant in their contributions to CO_2 emissions. However, the unique characteristics of each sector necessitate varying approaches to mitigate their emissions. Improved production, transport, utilization, and storage of hydrogen can play a central role in decarbonizing many of these sectors due to its impressive versatility as a carbon-zero fuel, feedstock, and energy storage medium. While hydrogen itself can be considered a zero-carbon option, in general its production, transport, and storage cannot.

Multiple routes for hydrogen production are viable: conversion of fossil fuels; splitting of water using heat or electricity; and biological approaches. All of these routes have an associated CO_2 footprint, whether through direct emissions from the production process, or from the electricity required to operate them.

Today, economics drive nearly all (99%) hydrogen in the U.S. to be derived from fossil fuels, with 95% of the total hydrogen produced by steam methane reforming of natural gas, 4% of the total from gasification of coal, and the remaining 1% not derived directly from fossil fuels is produced via electrolysis. Fossil based methods release CO_2 as part of the production process, and electrolysis requires appreciable amounts of electricity, currently with a CO_2 footprint of its own. For hydrogen to be implemented as a truly zero-carbon option for decarbonizing any sector, the full lifecycle of its production through ultimate utilization will need to be decarbonized. Research and development for methods to decarbonize hydrogen production, transport, storage, and utilization is required to fully transition to a low carbon economy.

The power sector in particular is in a transition to low carbon energy sources. This transition however is constrained by the dynamics of renewable energy sources, and thus the timing of renewable electricity supply relative to gross electrical demand. These renewable options by themselves are not guaranteed to produce electricity on demand, and as a result require viable mechanisms for low carbon dispatchable power generation and energy storage to address this variability.

For times when renewable energy supply does not meet demand, mitigation of CO_2 emissions from large, baseload fossil power is executed best by employing large scale, direct carbon capture and storage. State of the art technologies designed for this approach rely on economies of scale and the capture of CO_2 from relatively high-concentration gas streams somewhere in the electricity production process. Applying this approach to capture carbon from sectors with smaller and more diffuse CO_2 emissions such as transportation is, in general, less cost-effective. Fuel-switching to a less carbon intense fuel could be considered as an alternative to capturing CO_2 emitted from these processes; for example, between 2011 and 2019, 104 coal fired power plants were converted to natural gas, and to a lesser extent petroleum coke. Moreover, existing natural gas combustion turbine designs are viewed as options that could be retrofit to combust hydrogen in a similar manner to natural gas. Hydrogen, therefore, could be considered for similar low carbon re-fuelling efforts in both natural gas and coal related applications.

Sufficiently large-scale low-carbon energy storage options for times when renewable power would otherwise be curtailed, are not fully mature. Battery storage is technically viable; however, there exist concerns with energy density and materials cost in efforts to efficiently scale this approach to levels required for practical electricity demands. Hydrogen may have more promise to scale to sufficient levels of energy storage than current alternatives such as batteries, pumped hydro and compressed air storage.

In the industrial sector, CO_2 emissions result largely from the fossil fuel combustion used to generate the heat required to carry out the process. Cost effective generation of hydrogen can be used to supplement or replace fossil fuels as the current heat source for these processes.

Finally, fuel-switching to hydrogen has the potential to play a role in decarbonizing some elements of the transportation sector as well as the residential sector.

Hydrogen, as a solution to mitigate CO_2 emissions, can be implemented in multiple parts of the value chain of these sectors. All will require improvements in hydrogen production, and most will benefit from improved hydrogen transport, storage, and utilization. The U.S. Department of Energy's (DOE) Office of Fossil Energy (FE) is the world leader in funding carbon dioxide mitigation research for fossil fuel related applications, which includes the capture, transport, and storage of CO_2 as well as mitigating CO_2 emissions from the industrial sector. As such, FE is positioned as the logical entity to translate this research to hydrogen production, transport, storage, and utilization applications.

II. History

Historical interest in the development of hydrogen-based energy systems was highest in the early 2000s as part of the George W. Bush administration. In 2002, the FreedomCAR (Cooperative Automotive Research) initiative was launched. It was a partnership with automakers to accelerate research needed to produce practical, affordable hydrogen fuel cell vehicles. Then, in 2003 the Bush administration announced the hydrogen fuel initiative, which included $720 million in new funding over the following five years to develop the technologies and infrastructure to produce, store, and distribute hydrogen for use in fuel cell vehicles and electricity generation. Combined with FreedomCAR, a total of $1.7 billion over five years was proposed to develop hydrogen-powered fuel cells, hydrogen infrastructure and advanced automotive technologies.[i]

The motivation for the program was to relieve US dependence on foreign oil. At that time, imports accounted for 55% of oil consumed, and were projected to grow to 68% by 2025.[i] The vast majority of that oil was used for transportation. The rationale was that fuel cell vehicles offered the best hope of dramatically reducing dependence on foreign oil. The three pillars of the program were:

- Lowering the cost of hydrogen
- Creating effective hydrogen storage
- Creating affordable hydrogen fuel cells

In response to this influx of funding, the DOE Hydrogen Program was formed through integration of a number of existing activities into a coordinated, department-wide effort involving the DOE Offices of Energy Efficiency and Renewable Energy (EERE), Fossil Energy (FE), Nuclear Energy (NE), as described below.

II.1 Hydrogen Fuel Initiative/DOE Hydrogen Program

The DOE Hydrogen Program arising out of the Hydrogen Fuel Initiative consisted of the following components:[ii]

- *Production* – thermal, electric, and photolytic processes
- *Delivery* – develop a national supply network - pipelines, trucks, and other mechanisms
- *Storage* – lightweight, low-cost, high-capacity devices
- *Conversion* – focused on low-cost, reliable fuel cells
- *Tech Validation* – hydrogen use for transportation, electricity generation, and heating
- *Safety, Codes, and Standards* – develop codes/equipment standards that can be adopted in commercial and residential settings
- *Integration Education* – enhance understanding of hydrogen/fuel cell technologies to advance widespread adoption

Program funding was distributed among the various components, with the largest fractions going to production and delivery, fuel cells (conversion), basic research, technology validation and storage. Figure 1 shows the distribution associated with the FY2007 budget request.[ii] While there was some variability in the year-to-year funding distributions, the patterns shown in Figure 1 were relatively consistent throughout the first several years of the Program.

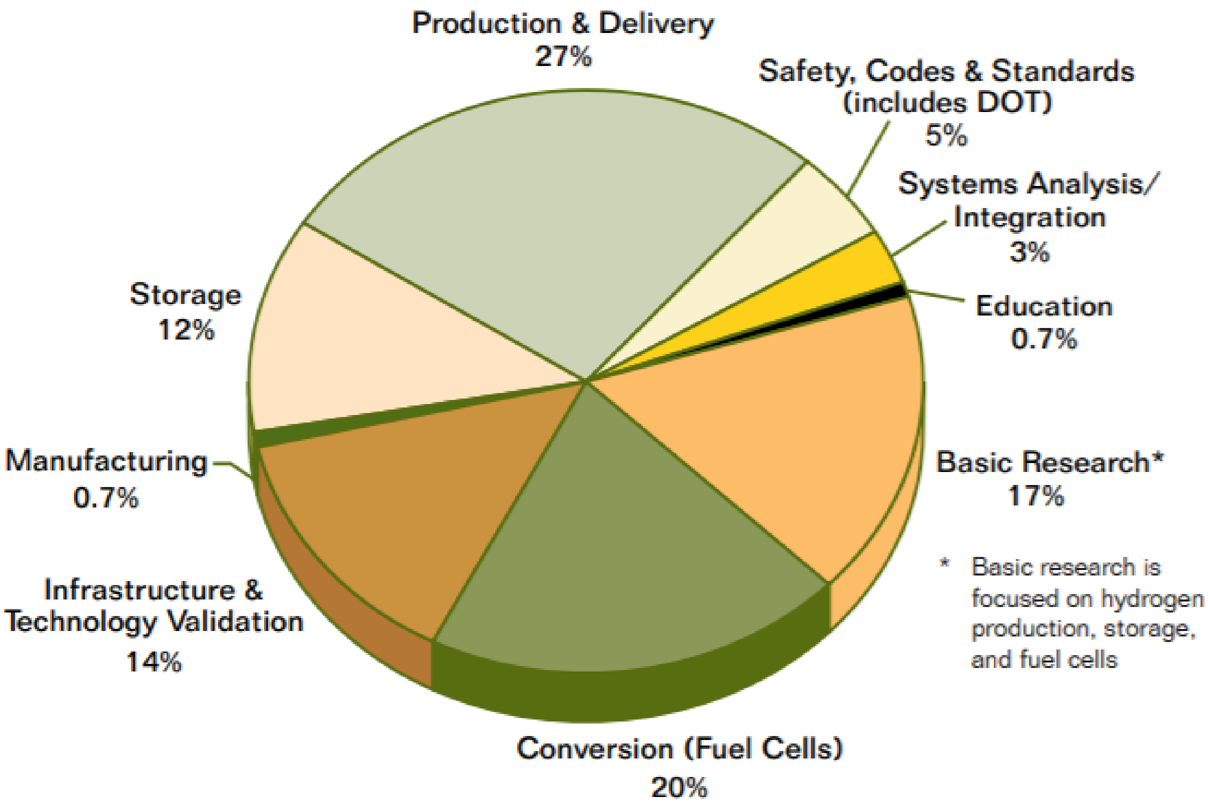

Figure 1. FY2007 Distribution of Hydrogen Program Funding Request

The hydrogen fuel initiative lasted until 2009. Significant progress was made in the development process, with highlights including but not limited to the following:[iii]

- The potential high-volume manufactured cost for an 80-kW$_{net}$ fuel cell system was reduced from $275/kW in 2002 to $61/kW in 2009. These cost reductions resulted primarily from reducing platinum (Pt) loading (decreasing capital cost) and improving power density (reducing operating cost).

- Substantial reductions in the costs associated with manufacturing chemical hydrogen carriers.

- Conversion efficiency for certain types of micro-organisms were increased by a factor of five for the production of bio-derived hydrogen.

- Electrolyzer membrane costs were reduced by nearly 75% through the development of sulfone-based materials compared to nafion-based membranes.

- Systems analyses demonstrated that hydrogen station costs for cryo-compressed fueling, using a cryopump, were 70% lower than station costs for fueling 700-bar vehicles using booster compressors.

In 2008, the Government Accounting Office (GAO) conducted an analysis of the hydrogen program.[iv] Some of the accomplishments noted in their analysis included:

- The cost of producing hydrogen from natural gas - an important source of hydrogen through the next 20 years - had been reduced

- A sophisticated model to identify and optimize major elements of a projected hydrogen delivery infrastructure had been developed

- The storage capacity of hydrogen had been increased by 50% for small scale transportation applications

- Fuel cell cost and durability had been improved

In addition, the GAO report noted that the most difficult technical challenges that the hydrogen program faced would come in the future, specifically:

- Finding a technology that can store enough hydrogen on board a vehicle to meet driving range targets

- Reducing the cost of delivering hydrogen to consumers

- Further reducing the cost and improving the durability of fuel cells

- Deploying the support infrastructure needed to commercialize hydrogen fuel-cell vehicles nationwide would require an investment of tens of billions of dollars over several decades beyond hydrogen program target dates

- The program emphasis on vehicle fuel cell technologies has resulted in neglect of stationary or portable technologies that potentially could be commercialized before vehicles

The technical challenges and hydrogen R&D budget constraints led DOE to delay some of its interim target dates.

In 2009, the incoming Obama administration evaluated the progress of the hydrogen program and the possibilities for development of a hydrogen-based energy system and concluded that the previous funding level was inappropriate. Secretary of Energy Steven Chu made the following statement regarding the Hydrogen Program:[v]

> *"We asked ourselves, 'Is it likely in the next 10 or 15, 20 years that we will convert to a hydrogen car economy?' The answer, we felt, was 'No,'"*

This resulted in a significant drop-off in funding, as reflected in Figure 2, and a change in emphasis toward other applications.

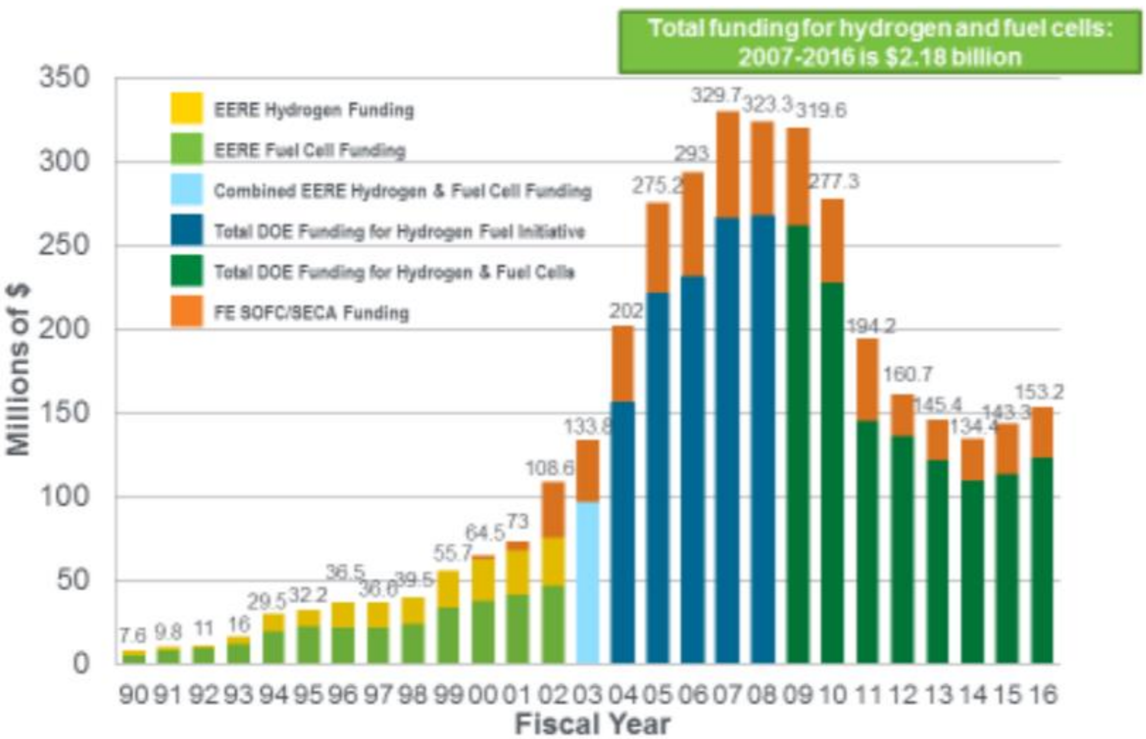

Figure 2. DOE Hydrogen R&D Funding Over Time

III. Renewed Interest

While interest in the development of hydrogen-based technologies decreased in the US after 2009, there has been a sharp increase in global interest in the latter half of the 2010s. Very recently the US has renewed its interest in hydrogen as well. The principal driver in the increased interest is decarbonization associated with the Paris Climate Agreement. Governments and industry increasingly see hydrogen as an essential element in achieving greenhouse gas emission reduction goals, and that a successful decarbonization path cannot solely rely on renewable electricity. Growing the hydrogen market will be necessary to lower costs, increase power system flexibility, and decarbonize many industries.[vi, vii]

Currently, the vast majority of hydrogen produced globally comes from reforming natural gas or gasification of coal. Hydrogen generated from these sources has a significant carbon footprint and has been designated as "Grey Hydrogen."

However, if carbon capture utilization and storage is applied to these sources, the hydrogen produced is low-carbon and can contribute to decarbonization of industries. Hydrogen generated in this manner (fossil fuel source with CCUS) is referred to as "Blue Hydrogen."

Hydrogen can also be produced by using low-carbon electricity (wind, solar, nuclear, etc.) to separate hydrogen from oxygen in water, called electrolysis. The product of this process is referred to as "Green Hydrogen."

Currently, the cost of blue hydrogen is substantially lower than the cost of green hydrogen. This is largely because green pathways rely heavily on electrolysis and require large amounts of variable renewable electricity, to the detriment of timely capital recovery.

III.1 Recent DOE Activity

With the steep drop-off in funding at the conclusion of the Hydrogen Fuels Initiative, hydrogen-based R&D efforts were substantially scaled back, focusing to a large extent on electrolysis efforts. One of the principal avenues of interest that has been pursued in recent years is the H2@Scale concept.

H2@Scale is an initiative that brings together stakeholders to advance affordable hydrogen production, transport, storage, and utilization to increase revenue opportunities in multiple energy sectors. It includes DOE funded projects and national laboratory-industry co-funded activities to accelerate the early-stage research, development, and demonstration of applicable hydrogen technologies.

In order to facilitate development of a hydrogen-based energy system, a significant influx of funding and ambition is needed to drive increased hydrogen production, delivery, storage, and use. DOE has developed a blueprint for moving toward a hydrogen-based energy system, as described in the section below.

IV. General Hydrogen R&D Needs and Plan

In November 2020, US DOE released *The Department of Energy (DOE) Hydrogen Program Plan,* which outlines the strategic high-level focus areas of DOE's Hydrogen Program. The Hydrogen Program includes activities across multiple DOE offices—including Energy Efficiency and Renewable Energy (EERE), Fossil Energy (FE), Nuclear Energy (NE), Electricity (OE), and Science (SC), and coordinates with the Advanced Research Program Agency – Energy (ARPA-E). The Program Plan includes an overview of core technology areas, challenges, and research and development (R&D) thrusts that DOE plans to pursue to enable the adoption of hydrogen technologies across multiple sectors of the US economy.

Development of any R&D program requires consideration of multiple factors. In general, advancement of technologies from concept to commercialization takes decades of research, development, and demonstration. Not all projects selected to support the commercialization effort are viable. Projects that do eventually support viable commercial offerings rely on some combination of scientific and engineering successes, market drivers and motivating policy. Projects undertaken at early stages in the development process (i.e., those at low levels of technology readiness) have a lower probability of successful outcomes than more mature projects at higher levels of technology readiness. This is because as a technology matures, the technical uncertainties diminish, which allows a more judicious selection of projects that have a higher probability of success.

When considering the historical chances that a research and development project successfully advances to the next technology readiness level, one can use binomial (i.e. project "pass" or "fail") probability to approximate the overall chances of commercial success and the required number of projects to support a desired probability of success. Moreover, with general knowledge of project costs, program budgets can then be derived.

Application of this approach is illustrated in Figure 3, which represents a program plan targeting an overall 75% chance that a technology entering technology readiness level (TRL) 3 will result in commercialization success. Each box contains the number of projects, each with the noted probability of advancing to the next TRL, required to realize at net 75% chance that one project at the earliest TRL will ultimately result in commercialization. The number of projects in each TRL group were chosen to satisfy a 90% probability that at least one will advance to the next TRL. While not a theoretically perfect application of binomial probabilities (i.e. individual project "trials" are not executed under identical conditions), this analysis provides a reasonable justification for the estimated size of research and development programs with a mission to commercialize an early stage concept.

Historical project costs and timelines can then be used to develop a multi-year program budget and schedule. Examples of how this methodology was applied to develop hydrogen program budgets are presented in sections summarizing R&D required for Production/Utilization, Transport and Storage.

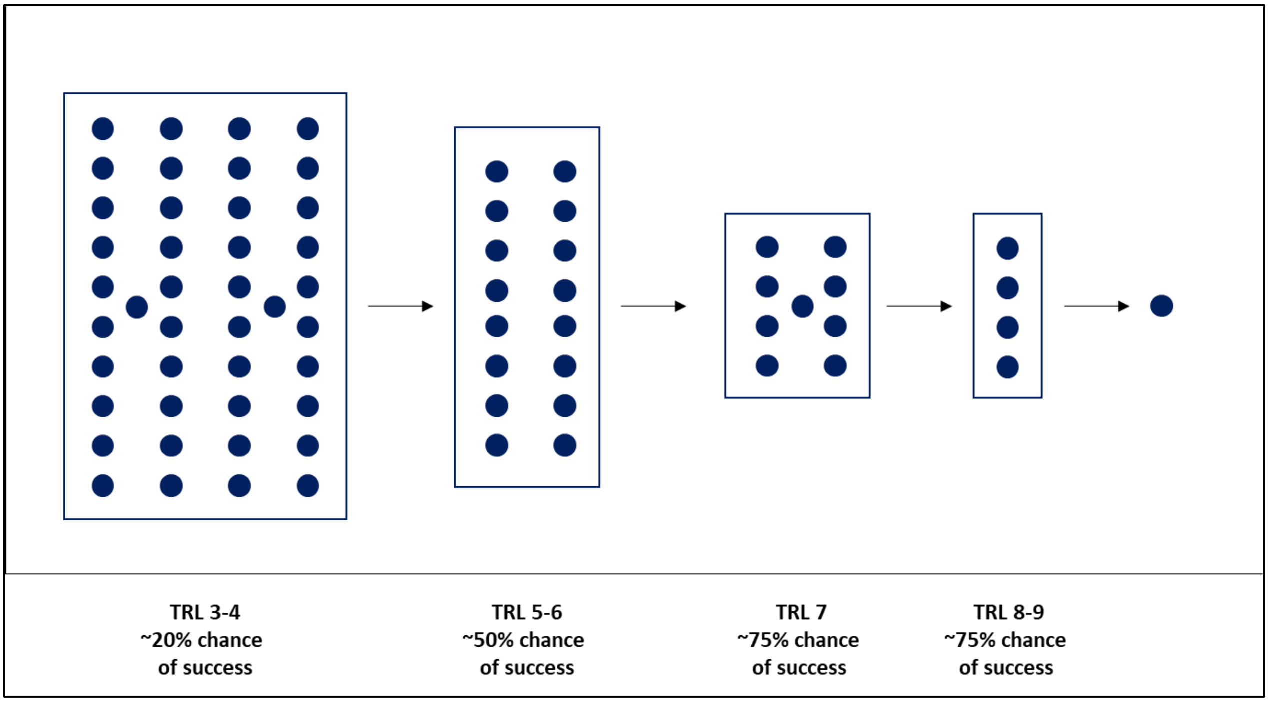

Figure 3. Notional Project Numbers Required at Varying TRLs to Ensure Commercialization Success

IV.1 Hydrogen Program Technical Challenges and R&D Focus Areas

The key technical challenges to adoption of hydrogen-based technologies relate to cost, durability, reliability, and performance, as well as the lack of hydrogen infrastructure. These technical challenges can be lumped into four broad focus areas – production, delivery, storage, and conversion/utilization – which are summarized in Table 1 and will be further described in subsequent sections.

IV.2 Timelines

Wide-scale implementation of a hydrogen-based energy system is likely to require an extended period of time for the development and deployment of both advanced technologies and supporting infrastructure. There are, however, elements that can be deployed in the near term that can serve as the groundwork for wider deployment in the future. Short-, medium-, and long-term opportunities for the four R&D focus areas described above are noted in Table 2.

Table 1. Key Technical Challenges to Adoption of Hydrogen-Based Technologies

Hydrogen R&D Focus Area	Needs and Challenges
PRODUCTION • Thermochemical processes • Electrolysis via water splitting • Reverse Solid Oxide Fuel Cells • Advanced CO_2 capture	• Lower-cost, more-efficient, and more-durable electrolyzers • Improved catalyst performance • 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 and environmentally sound carbon capture, utilization, and storage technologies
DELIVERY • Pure hydrogen • Chemical carriers • Pipelines • High-pressure tanks • Liquid tankers (trucks, rail or ships) • End-use factors/considerations	• Lower-cost and more-reliable systems for distributing and dispensing hydrogen • Advanced technologies and concepts for hydrogen distribution including liquefaction and material based chemical carriers • Rights-of-way, permitting, and reduced investment risk of deploying delivery infrastructure
STORAGE • Physical storage (e.g., high-pressure tanks and liquid hydrogen) • Material-based processes that incorporate hydrogen in chemical compounds • Geologic storage	• Lower-cost hydrogen storage systems • Higher storage capacity, with reduced weight and volume • Large-scale storage, including onsite bulk emergency supply and in geologic formations • Optimized storage strategies for co-locating stored hydrogen with end-use applications to meet throughput and dynamic response requirements and reduce investment cost
CONVERSION • Electrochemical conversion using fuel cells • Combustion using turbines or reciprocating engines • Hybrid systems	• 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

Table 2. Development Timeline for Hydrogen R&D Focus Areas

R&D Focus Area	Short-term	Medium-term	Long-term
Production	Gasification/reforming of fossil/biomass/waste feedstocks with CCUS Electrolysis		Advanced biological/ microbial conversion Advanced thermo/ photo-electrochemical water splitting
Delivery	Pressurized/cryogenic trucks and trailers	Chemical carriers	Widespread pipeline networks
Storage	Pressurized/cryogenic tanks and vessels	Geologic storage Chemical carriers	Materials-based storage
Conversion	Turbine combustion Fuel cells	Advanced combustion Next-generation fuel cells	Fuel cell/combustion hybrids Reversible fuel cells

IV.3 R&D Performance Targets

A key element in the development of any R&D plan is the establishment of performance targets. Once established, these targets guide both the R&D community and Program planners in terms of portfolio activities. DOE has established some preliminary targets for the broad hydrogen R&D effort, most of which are relevant to transportation applications and thus would be focus areas for EERE R&D efforts. These include the following:

- $2/kg for hydrogen production
- $2/kg for hydrogen delivery and dispensing for transportation applications
- Fuel cell system cost of $80/kW with 25,00-hour durability for long-haul heavy-duty trucks
- On-board vehicular hydrogen storage at $8/kWh, 2.2 kWh/kg, and 1.7kWh/l
- Electrolyzer capital cost of $300/kW, 80,000 hour durability, and 65% system efficiency
- Fuel cell system cost of $900/kW and 40,00-hour durability for fuel-flexible stationary high-temperature fuel cells

The DOE preliminary goal that is most relevant to FE R&D efforts is:

- $1/kg for hydrogen production, delivery and dispensing for industrial and stationary power applications

As the FE Hydrogen Program moves forward, additional goals will be established relating to the following:

- Hydrogen turbine cost and efficiency
- Safety, reliability, and cost of hydrogen delivery and storage systems
- Demonstration of geologic hydrogen storage hubs
- Blue hydrogen production cost targets

It is likely that these preliminary targets will evolve and be expanded-upon to include other focus areas over time based on the results of ongoing R&D.

IV.4 Research Thrust Areas

As noted above, the DOE Hydrogen Program Plan identifies four principal research focus areas:

- Production
- Conversion/Utilization
- Delivery
- Storage

For each of these focus areas, R&D thrusts are identified that will help achieve Program targets. In the subsections below, these thrusts are summarized, and the contributions of various DOE offices toward achieving overall Program goals are defined. Finally, more detailed information regarding the contributions of the Office of Fossil Energy toward meeting goals is provided along with estimates of budget requirements to do so.

Hydrogen Production

Technically viable routes for hydrogen production are: Catalytic steam methane reforming; coal gasification; partial oxidation of coal or natural gas; electrochemical and thermochemical water splitting; and biologically-based methods for hydrogen production. All of these routes have an associated CO_2 footprint, whether through direct emissions from the production process, or from the electricity required to operate them.

Combining fossil-fuel-based processes with CCUS offers a promising near-term option for carbon-neutral hydrogen production. R&D in the areas of catalysis, separations, controls, polygeneration, process intensification, and modularization with advanced design methods (e.g., parametric design) - including through the use of artificial intelligence - can reduce the cost of fossil-based hydrogen production.

Biomass can be gasified or co-fed with coal or waste plastics to produce hydrogen. It can also be processed into bio-derived liquids for subsequent reforming into hydrogen and could potentially produce carbon-negative hydrogen if coupled with CCUS. R&D needed to advance biomass-based production of hydrogen includes improvements in conversion efficiency (e.g., through advanced catalysis and separations, as well as process intensification) and reductions in the costs of pre-treating and transporting feedstocks.

Water can be split into hydrogen and oxygen using electric, thermal, or photonic (light) energy. The maturity of water splitting technologies varies widely, with some processes approaching commercial viability and others in the early stages of development. R&D needs for water splitting technologies include improvements in the efficiency and durability of electrolyzers, process integration, and improvements at the materials, component, and system levels.

The R&D thrusts established for hydrogen production focus on development of materials, catalysts, and modular/intensified equipment designs. Table 3 summarizes the R&D thrust areas and identifies the DOE offices with expertise to address the research needs.

Table 3. R&D Thrusts to Support the Development of Hydrogen Production Technologies

R&D Thrust Areas	EERE	Nuclear	Science	Fossil	OE	ARPA-E
Catalysts			●	●		●
Modularity	●			●		●
Separations				●		●
Materials			●	●		●
Degradation			●			
Capital Cost Reductions	●					
BoP	●	●				
Econ of #	●					
Fuel Cells				●		
Process Design and Optimization		●		●		
Electricity Reliability					●	

Hydrogen Delivery

A hydrogen-based energy system would include diverse modes of energy production and use. In order to accommodate that diversity, a wide range of hydrogen delivery methods will be required. These are likely to include transporting hydrogen as a gas in pipelines and high-pressure tube trailers, as a liquid in tanker trucks and ships, and using chemical hydrogen carriers. The technologies required to support these delivery methods are currently at various stages of development. Critical considerations in future development efforts include:

- Costs
- Safety
- Convenience for the end user
- Reliability
- Energy efficiency

Low volume hydrogen use is currently serviced by tube trailers carrying liquid hydrogen. Expanding small-scale hydrogen markets will likely drive the development of co-located gaseous hydrogen production and tube trailer terminals to transport both liquid and gaseous products. R&D efforts will be needed to enhance the lifetime of tube trailer pressure vessels, reduce the cost of high-pressure composite tube trailers, increase the capacity of compressors used at tube trailer terminals, and improve the energy efficiency of liquefaction approaches.

Pipelines are the most energy-efficient approach to transporting hydrogen for high-volume applications. Currently, there are more than 2,575 kilometers (1,600 miles) of dedicated hydrogen transmission pipelines in the United States. However, their high capital costs are a barrier to their deployment. R&D efforts needed to drive down costs will focus on compressors, novel materials, and demonstration of novel technologies.

Hydrogen carriers are materials that bond with hydrogen and form liquids or solids that can transport it at low-pressure and near ambient temperature but can then release the hydrogen when needed. There are two broad classes of hydrogen carriers:

- One-way carriers, such as ammonia, do not release a by-product after the hydrogen is released.
- Two-way carriers, such as methylcyclohexane/toluene, generate by-products that are typically returned for processing for reuse or disposal after the hydrogen is released.

R&D efforts are needed to increase the capacity and efficiency of these materials.

The R&D thrusts established for hydrogen delivery focus on development of materials, catalysts, liquefaction approaches, and components used in the transport process, such as compressors. Table 4 summarizes the R&D thrust areas and identifies the DOE offices with expertise to address the research needs.

Table 4. R&D Thrusts to Support the Development of Hydrogen Delivery Technologies

R&D Thrust Area	EERE	Nuclear	Science	Fossil	OE	ARPA-E
Materials - High Pressure			●	●		●
Materials - Low Temperature			●	●		●
Materials/Catalysts - Carriers			●	●		●
Liquefaction			●	●		
Components (e.g., compressors)	●			●		

Hydrogen Storage

Many of the challenges associated with storage in a hydrogen-based energy system are similar to those associated with delivery and relate to diverse modes of energy production and use. The volumetric energy density of hydrogen at ambient temperature and pressure is low, making it difficult to store in compact containers. For this reason, hydrogen storage requires high pressure, low temperature, or incorporation into higher-density molecular structures (carriers). Many low- and mid-volume storage applications involve high-pressure all-metal or composite-overwrapped vessels or cryogenic tanks. High-volume applications can potentially be best-served by geologic storage.

The R&D thrusts established for hydrogen storage are the same as those discussed for delivery in terms of development of materials, catalysts, liquefaction approaches, and components. Areas not addressed in the discussion on delivery include geologic storage, sensors, and analyses focused on storage related to specific end uses (including power production) as well as safety, durability and optimization of storage and delivery systems. Table 5 summarizes the R&D thrust areas and identifies the DOE offices with expertise to address the research needs.

IV.5 Office of Fossil Energy Hydrogen R&D Plan

The National Energy Technology Laboratory (NETL) executes multiple research and development programs for the Office of Fossil Energy that are directly relevant to near term opportunities in hydrogen production, delivery, storage, and utilization. NETL also classifies its internal expertise, which can be applied to research and development, in terms of core competencies that cross-cut programs and projects funded by FE. NETL's core competencies are also directly relevant to the needs of hydrogen R&D, as illustrated in Table 6.

Table 5. R&D Thrusts to Support the Development of Hydrogen Storage Technologies

R&D Thrust Area	EERE	Nuclear	Science	Fossil	OE	ARPA-E
Materials			●	●		●
Components (e.g., compressors)	●			●		
Liquefaction/Cryogenics	●		●	●		●
Efficiency Optimization for Carriers	●			●		
Power Production-Focused Storage	●			●	●	
Goelogic Storage				●		
End-Use Focused Analysis				●		
Sensors	●			●		●
Systems Analysis/Optimization	●			●		
Material Safety/Durability Analysis	●			●		

Table 6. NETL Programs and Competencies Relevant to Hydrogen-Based Energy System R&D

		Materials Development	Equipment Design	Process Piloting	Systems Analyses	Storage	Transport
Coal	Carbon Capture		●	●			●
	Carbon Storage					●	
	Carbon Utilization						
	STEP						
	Rare Earth						
Crosscutting	Sensors and Controls					●	
	Modeling, Simulation and Analysis				●		
	High Performance Materials		●				●
	Water Management						
	Energy Storage						
	University Training and Research		●				
Advanced Energy Systems	Fuel Cells	●	●	●			
	Turbines		●				
	Transformative Energy Systems	●	●	●			
	Coal-Biomass to Liquids						
	Advanced Coal Processing						
Core Competencies	Computational Science and Engineering				●		
	Energy Conversion Engineering	●					
	Geological and Environmental Systems					●	
	Materials Engineering and Manufacturing	●					
	Program Execution and Integration						
	Systems Engineering and Analysis				●	●	●

FE Hydrogen Production and Utilization R&D

Nearly all (99%) of hydrogen in the U.S. is derived from fossil fuels, with 95% of the total hydrogen produced by steam methane reforming of natural gas, 4% of the total from gasification of coal. CO_2 is generated as a byproduct of the steam methane reforming and gasification processes that could otherwise be captured, but today is instead released to the environment. State of the art CO_2 capture technologies can be applied to these applications, so near-term hydrogen production research should focus on costeffectively decarbonizing these processes, converting grey hydrogen approaches to blue hydrogen applications.

Capturing the CO_2 from currently implemented methods of hydrogen production is in many ways similar to previously FE-funded power applications for pre- and post-combustion CO_2 capture. For this reason, the most straightforward path to immediately decarbonizing hydrogen production is to apply CO_2 capture technology to existing hydrogen production. As outlined in Table 6, more advanced pursuits in materials/catalyst development to decrease the high reforming temperatures, more efficient equipment designs to increase heat transfer effectiveness, and piloting of advanced processes are expected to further improve performance and drive down costs. Moreover, from a lifecycle perspective, research in processing alternative feedstocks such as biomass, plastics, etc. could provide additional carbon reduction benefits. Economic projections tend to support these approaches as well; blue hydrogen costs are anticipated to be only slightly more expensive than grey hydrogen. Depending on the price of natural gas, electricity and any carbon dioxide penalty, today's grey hydrogen costs range from approximately $1.00-$1.80/kg while blue hydrogen is anticipated to cost approximately $1.40-$2.40/kg. A $30/ton CO_2 penalty is anticipated to add about $0.50/kg H2, which if applied will position blue hydrogen to be cost competitive if its anticipated range of hydrogen costs is upheld by successful research. This CO_2 penalty is within the 45Q tax credit range, so existing policy may yet sufficiently support decarbonization of the hydrogen industry. However, it is important to note that these hydrogen costs do not include the cost to transport and/or store the hydrogen product, which requires further research to fully enable and future studies to reliably estimate.

Relevance to Existing Programs

Contributing to the development of a hydrogen-based energy system requires improvements in multiple pathways for both hydrogen production and utilization. A potential breakdown of such research and development pathways that may be organized to leverage research and development ongoing at NETL is presented below, organized by relevance to existing programs:

- **Hydrogen Production Research Relevant to NETL Programs**
    - <u>Fuel Cell Program</u>
      Reverse Solid Oxide Fuel Cell (RSOFC) technology is a relatively novel approach to operate Solid Oxide Fuel cells in a mode able to accept excess electricity in times of low demand to generate hydrogen for energy storage. NETL has a mature solid oxide fuel cell program addressing R&D needs from the materials level through the systems level to improve the technology.

- Transformative Energy Systems
  The NETL Advanced Energy System program funds the Coal FIRST program through Transformative Energy Systems. Coal FIRST is currently supporting advanced electricity and hydrogen plants with a target of net zero CO_2 emissions. Coal FIRST is also exploring research and development in co-firing biomass, plastics, and other low carbon feedstocks along with coal in gasification w/CCS processes to further reduce the lifecycle CO_2 footprint of hydrogen production.

- Capture
  The Capture program leads the world in carbon capture technology development. Both post-combustion technologies and pre-combustion technologies developed over the past two decades can be directly applied to hydrogen production systems. CO_2 capture is likely the technology which will enable the nearest term decarbonization of hydrogen production.

- Crosscutting
  The focuses on developing materials that can withstand high temperatures and temperature cycling without compromising integrity. The latter becomes important when considering the high temperatures required for advanced steam methane reforming processes which may need to cycle as a means to follow renewable variability.

• Hydrogen Utilization Research Relevant to NETL Programs

- Turbines
  The NETL turbines program is focused on developing turbine components which enable efficient combustion of hydrogen, which will support a potential transition from natural gas-based power generation to hydrogen-based power generation while leveraging the efficiency of the existing Brayton cycle frameworks.

- SOFC
  Operating in their conventional mode, Solid Oxide Fuel Cells are capable of oxidizing hydrogen to produce electricity at higher efficiencies than conventional fossil fuel approaches, with no direct CO_2 emissions.

- Crosscutting
  Similar to its relevance in hydrogen production applications, High Performance Materials in utilization applications must accommodate the high temperatures required for advanced power generation processes such as SOFC and hydrogen turbines which also may need to cycle as a means to follow renewable variability.

Projected Budget

Based on an assumption that a hydrogen production R&D program would target a 75% chance of successfully commercializing one novel idea, the program project profile in Table 7 is generated by applying the aforementioned binomial probabilities of success, and on historical project costs and duration for given TRLs.

Table 7. Annual Hydrogen Production Project Profile

		# of Projects per Year @ each TRL												
TRL	**$/Project**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
3-4	**3,000,000**	9	9	9	9	6								
5-6	**15,000,000**				4	3	3	3	3					
7	**60,000,000**									2	2	2	2	1
TRL		**$M per year @ each TRL**												
3-4		27	27	27	27	18	-	-	-	-	-	-	-	-
5-6		-	-	-	60	45	45	45	45	-	-	-	-	-
7		-	-	-	-	-	-	-	-	120	120	120	120	60
	$M/yr	**27**	**27**	**27**	**87**	**63**	**45**	**45**	**45**	**120**	**120**	**120**	**120**	**60**

Actual project costs and duration will vary depending on many practical factors. Due to their similar nature as chemical process technologies, historical project budgets and duration for CO_2 capture technology development can be reasonably applied here for reliable budget and schedule estimates for hydrogen technology development. Maximum annual project awards have been assumed here to reflect limitations on the natural pace of project concept development. This limitation along with the historical project duration dictate the procurement schedule for hydrogen related R&D.

Figure 4 is a graphical representation of the annual and cumulative funding profile that results from the number of projects proposed for funding each year until a commercialization is anticipated. The profile presumes continuous funding is approved by Congress with no procurement delay.

Over thirteen years, approximately $900 million dedicated to Fossil Energy for the commercialization of a blue hydrogen production platform is proposed. The early stage of the proposed program is focused on lower TRL, lower cost, projects, resulting in a request of $27M per year for the first three years. Years 4-8 incorporate more expensive small pilot projects, while research at TRL 3-4 ramps down. With historical project duration as guidance, years 9-13 are the nearest timeframe to graduate a novel technology conceptualized in program years 1-4 to large pilot tests of blue hydrogen production systems, which is the last step before commercialization.

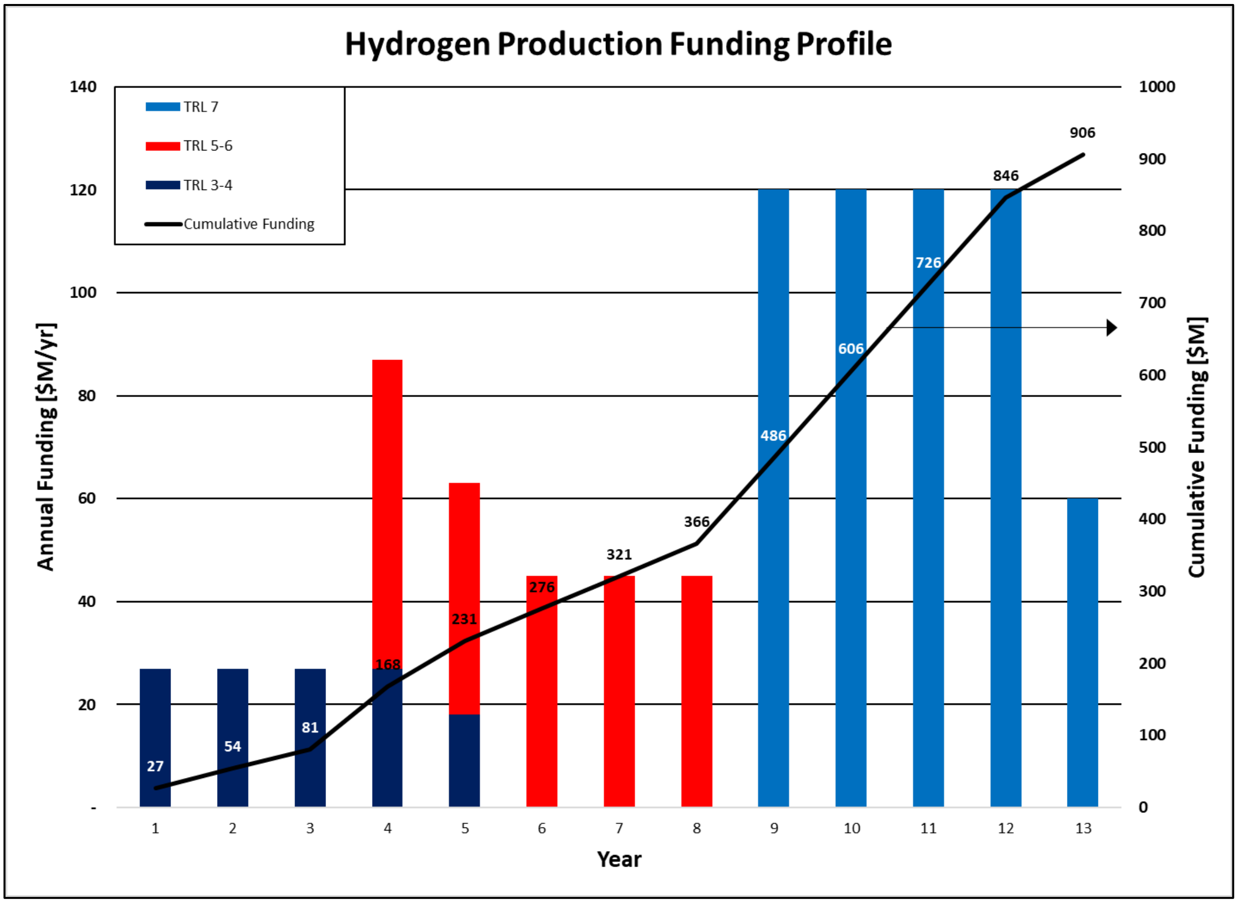

Figure 4. Hydrogen Production/Utilization Program Annual and Cumulative Funding Profile

FE Hydrogen Delivery and Storage R&D

As noted in Table 3 and Table 4, considerable overlap exists in the R&D efforts needed to support development of hydrogen delivery and storage approaches. FE expertise can be most-effectively leveraged to support technology development in the following areas:

- Materials
- Liquefaction
- Components
- Geologic Storage
- Sensors

Each of these areas is described briefly below.

Materials

In the high-pressure and low temperature materials thrust areas, FE would support computational and experimental analysis to advance the fundamental understanding of factors that influence material degradation and failure in the presence of hydrogen under extreme conditions. For example, hydrogen embrittlement can lead to catastrophic failure of pipeline and tank materials and significant safety concerns. Enhanced understanding of material properties has the potential to lead to development of delivery and storage systems that improve both cost and safety.

Materials development efforts in the carriers thrust area would focus on computational and experimental efforts to develop an enhanced understanding of the fundamental molecular characteristics that underlie the ability of compounds to serve as both one-way and two-way hydrogen carriers. Both types of carriers offer the potential for significantly higher energy density – and thus reduced hydrogen delivery and storage cost - compared to gaseous systems. Materials research aimed at determining the optimum characteristics of carriers in terms of hydrogen-carrying capacity, hydrogen uptake and release efficiency, and manufacturability will be pursued. This will include the development of catalyst materials that could potentially accelerate hydrogen uptake and release.

Liquefaction

The current process for hydrogen liquefaction involves initial cooling of gaseous hydrogen followed by multiple compression and expansion cycles until the hydrogen condenses. This process is both capital- and energy-intensive - consuming about 35% of the energy content of the liquefied hydrogen. R&D is needed to develop novel, more efficient approaches to liquefaction. An initial step in this development process is a detailed analysis of existing liquefaction technologies to identify opportunities for improvements and define R&D needs/opportunities for evolving technologies such as the use of magnetocaloric materials and processes.

Components

FE expertise is applicable to the development of components for high-volume uses of hydrogen. For example, high-throughput compressors and dispensers are needed to enable use of larger pipelines. As with liquefaction, an initial step in the component development process is an analysis of existing compressor/seal technologies to identify opportunities for improvements and to define R&D needs/opportunities for evolving technologies.

Geologic Storage

Geologic storage of hydrogen is currently practiced in a salt cavern in Beaumont, Texas. Oil refineries in the region require a large, reliable supply of hydrogen to support operations, and the storage system in place serves as a buffer for the Gulf Coast hydrogen pipeline system. Salt caverns are attractive sites for geologic storage of hydrogen because many are well-understood geologically and are relatively easy to engineer. However, as demand for hydrogen increases with the establishment of a hydrogen-based energy system, geologic storage in other types of formations (e.g., saline aquifers, depleted natural gas or oil reservoirs, and engineered hard rock reservoirs) requires evaluation to determine suitability for large-scale storage. An initial step in this evaluation process is a preliminary analysis of the viability of hydrogen storage in a range of geologic formations to identify opportunities for improvements and define R&D needs/opportunities for evolving technologies and processes.

Sensors

Given the challenging pressure and temperature environments required for hydrogen delivery and storage, development of sensors is needed to ensure that both are safe, efficient, and secure. Sensors optimized to quickly and continuously provide data regarding changes in conditions in transport and storage infrastructure and in geologic formations are essential to operations at multiple scales. As the hydrogen-based energy system evolves, the use of these sensors will become ubiquitous, so cost considerations are also essential. R&D in the sensors thrust area will involve development of sensor technologies targeted to safety and cost concerns associated with hydrogen transport and storage.

Relevance to Existing Programs

A potential breakdown of the relevance of R&D needed for advancement of a hydrogen-based energy system to ongoing at NETL efforts is presented below:

- Hydrogen Delivery and Storage Research Relevant to NETL Programs
    - Transformative Energy Systems
      The NETL Advanced Energy System program funds R&D involving gasification and oxy-combustion-based power generation through Transformative Energy Systems. Cryogenic processes for air separation play a significant role in both gasification and oxy-combustion platforms. These processes are directly relevant to R&D associated with hydrogen liquefaction.

- Capture
  In addition to the post-combustion and pre-combustion capture technologies described in the previous section, the Carbon Capture Program has been instrumental in the development of advanced CO_2 compressors that can be used to prepare captured CO_2 for transport and storage. The lessons learned as part of this development process can be extended to the development of compressors used as part of the hydrogen delivery process.

- Natural Gas Infrastructure
  The Oil and Gas Research Program funds R&D associated with delivery of natural gas through the Natural Gas Infrastructure Program. Efforts currently supported include advancing pipeline inspection and repair technologies, improving compressor system operational performance, developing smart sensor systems, and developing advanced pipeline materials. All of these efforts have direct application to hydrogen delivery as well.

- Carbon Storage
  Since 1997, the NETL Carbon Storage Program has supported R&D on advanced CO_2 storage technologies and approaches, as well as storage infrastructure. These efforts directly support R&D focused on geologic storage of hydrogen.

- Crosscutting (Materials)
  Similar to its relevance in hydrogen production and utilization applications, the High Performance Materials program is relevant to hydrogen delivery and storage in that it focuses on the development of materials that can maintain performance under a variety of extreme conditions. Materials R&D proposed for hydrogen delivery and storage would be closely aligned with the ongoing activities in this existing NETL program.

- Crosscutting (Sensors and Controls)
  The Advanced Sensors and Controls Program tests and matures novel sensor and control systems that are operable in power production settings. This expertise can be applied to hydrogen storage and delivery systems as well.

- Crosscutting (Energy Storage)
  The Energy Storage program is developing a strategy to extract maximum economic value from the Nation's fossil-fueled energy system assets. In December 2020, sixteen projects were selected as part of Funding Opportunity Announcement (FOA) DE-FOA-0002332, *Energy Storage for Fossil Power Generation* that will focus on energy storage based on hydrogen and ammonia.[viii] Half of the selected projects include subsurface hydrogen storage in salt caverns or sedimentary basins. The other half of the selected hydrogen projects focus on

large capacity, above-ground hydrogen storage to be integrated with a fossil asset.

Projected Budget

Assuming that like hydrogen production, a transport and storage R&D program would similarly target a 75% chance of successfully commercializing one novel idea, the program budget profile in Table 8 is generated by applying the aforementioned binomial probabilities of success, and on historical project costs and duration for given TRLs.

Table 8. Annual Hydrogen Transport and Storage Project Profile

		# of Projects per Year @ each TRL												
TRL	**$/Project**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
3-4	**250,000**	18	18	18	18	12								
5-6	**700,000**				7	7	6	6	6					
7	**3,000,000**									4	4	4	4	2
TRL		**$M per year @ each TRL**												
3-4		5	5	5	5	3	-	-	-	-	-	-	-	-
5-6		-	-	-	5	5	4	4	4	-	-	-	-	-
7		-	-	-	-	-	-	-	-	12	12	12	12	6
	$M/yr	**4.5**	**4.5**	**4.5**	**9.4**	**7.9**	**4.2**	**4.2**	**4.2**	**12**	**12**	**12**	**12**	**6**

Project costs associated with varying TRLs as substantially lower for delivery and storage R&D versus that of production and utilization due to differing scopes, project scale/complexity and technical challenges. The hydrogen-focused projects recently funded as part of the Energy Storage Program provide an illustration of the varying costs. The FOA included three areas of interest (AOI), each with specific funding levels and approximate TRLs:

- AOI1: Design Studies for Engineering Scale Prototypes –DOE Funding = $200,000/project – TRL ~ 4 transitioning to 5
- AOI2: Component-level Research and Development –DOE Funding = $500,000/project – TRL ~ 5 – 6
- AOI3: Innovative Concepts and Technologies – DOE Funding = $250,000/project – TRL ~ 3 - 4

Figure 5 is a graphical representation of the annual and cumulative funding profile that results from the number of projects proposed for funding each year until a commercialization is anticipated. In this representation, transport, and storage efforts, although conceptually different, are shown combined; the assumption, consistent with the premise in using the binomial distribution, is that half of the projects are transport- and half are storage-related. The profile presumes continuous funding is approved by Congress with no procurement delays.

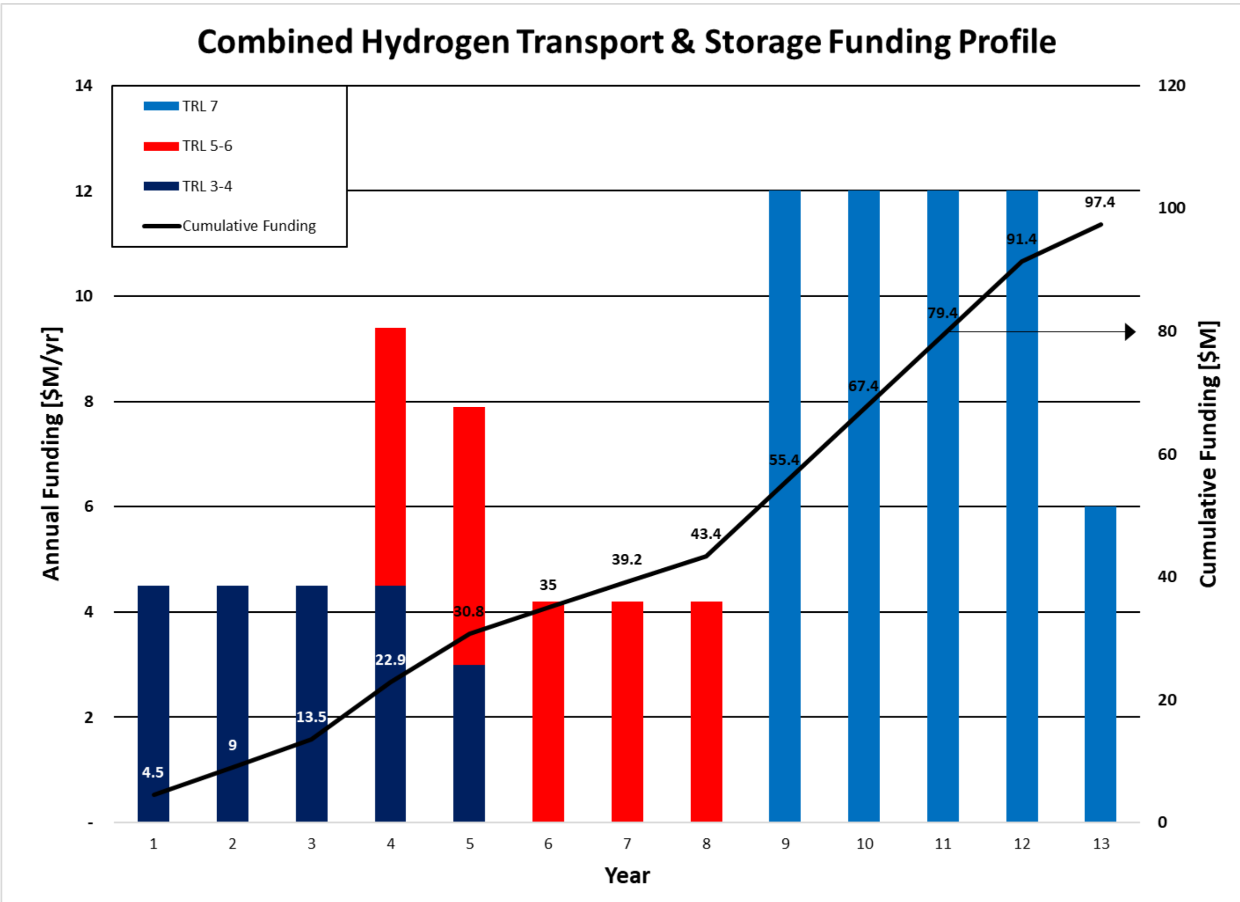

Figure 5. Combined Hydrogen Transport and Storage R&D Program Funding Profile

Over thirteen years, approximately $98 million dedicated to Fossil Energy for the commercialization of blue hydrogen transport and storage approaches is proposed. The early stage of the proposed program is focused on lower TRL, lower cost, projects, resulting in a request of $4.5M per year for the first three years. Years 4-8 incorporate more expensive projects demonstrating proof of concepts, while research at TRL 3-4 ramps down. With historical project duration as guidance, years 9-13 are the nearest timeframe to graduate a novel technology conceptualized in program years 1-4 to commercial scale tests of blue hydrogen production systems, which is the last step before deployment.

V. Conclusions

Hydrogen research relevant to maturing a low carbon hydrogen market is diffusely executed within Offices of the Department of Energy, each with independent and non-integrated program management structures. Such workflows lack the coordination of hydrogen R&D demanded by timely mitigation of large scale climate change mitigation.

The U.S. Department of Energy's Office of Fossil Energy has extensive experience in funding and deep expertise in conducting hydrogen relevant R&D. FE is uniquely positioned to coordinate DOE-wide research and development to enable a hydrogen economy that has the potential for large scale decarbonization of the power, industrial residential and transportation sectors.

An investment of approximately $1B over 13 years is likely to result in successful commercialization of low carbon hydrogen production, utilization, transport, and storage technologies that together are cost competitive with today's conventional methods with more substantial CO_2 footprints.

This report recommends maximizing the efficiency of maturing low carbon hydrogen technology by granting the Office of Fossil Energy authority to leverage its programmatic and research expertise and administer a concerted DOE-wide program on all relevant research, development, and demonstration efforts.

Bibliography

[i] George W. Bush, Fact Sheet: Hydrogen Fuel: a Clean and Secure Energy Future Online by Gerhard Peters and John T. Woolley, The American Presidency Project https://www.presidency.ucsb.edu/node/280723
[ii] US DOE. 2006. Hydrogen Posture Plan: An Integrated Research, Development and Demonstration Plan. http://171.67.100.116/courses/2015/ph240/llanos1/docs/posture-2006.pdf
[iii] US DOE. 2009. FY 2009 Progress Report for the DOE Hydrogen Program. https://www.hydrogen.energy.gov/annual_progress09.html
[iv] GAO. 2008. Hydrogen Fuel Initiative: DOE Has Made Important Progress and Involved Stakeholders but Needs to Update What It Expects to Achieve by Its 2015 Target. https://www.gao.gov/new.items/d08305.pdf
[v] Scientific American. 2009. R.I.P. hydrogen economy? Obama cuts hydrogen car funding. https://blogs.scientificamerican.com/news-blog/rip-hydrogen-economy-obama-cuts-hyd-2009-05-08/
[vi] Baker McKenzie. 2020. Shaping Tomorrow's Global Hydrogen Market Via De-risked Investments. https://www.bakermckenzie.com/-/media/files/insight/publications/2020/01/hydrogen_report.pdf?la=en
[vii] Hydrogen Council. 2020. Path to hydrogen competitiveness: A cost perspective. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf
[viii] NETL. 2020. https://www.energy.gov/fe/articles/areas-interest-doe-invests-nearly-76m-develop-energy-storage-projects