REQUEST FOR INFORMATION

H2@Scale (Hydrogen at Scale): Determining Opportunities to Facilitate Wide-Scale Hydrogen Adoption for Energy Security and Economic Growth

[DE-FOA-0001965]

DATE POSTED: August 1, 2018

SUBJECT: Request for Information (RFI) - H2@Scale (Hydrogen at Scale): Enabling affordable, reliable and secure energy options across multiple sectors [DE-FOA-0001965]

RESPONSE DUE DATE: October 31, 2018 at 5:00 PM Eastern Time

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DESCRIPTION

The U.S. Department of Energy (DOE)'s vision of the H2@Scale initiative is to enable affordable, reliable and secure energy through hydrogen production from diverse domestic resources and utilization across multiple sectors. Through this initiative, the DOE aims to incentivize the research and development (R&D) of transformational technologies that reduce the cost of hydrogen production and distribution technologies, diversify the feedstocks available for affordable hydrogen production, enable new end uses of hydrogen, enhance the flexibility of the electric power grid, reduce emissions through novel uses of affordable hydrogen, generate jobs in growing industries, and provide global technology leadership for export of next-generation energy solutions. The objective of this Request for Information (RFI) is to identify and quantify domestic resources compatible with large-scale hydrogen production, and to identify pathways to enable effective near- and long-term leveraging of these resources in major industries requiring affordable, secure, domestic, and scalable hydrogen supplies. This RFI complements the DOE Fuel Cell Technologies Office's (FCTO's) early-stage R&D activities and is intended to leverage the private sector to identify technical, cost and infrastructure barriers to deployment and widespread adoption of hydrogen and fuel cell technologies. This RFI also complements FCTO's RFI titled *Identifying Priorities for Reducing Barriers to Deployment of Hydrogen Infrastructure* which was released on June 13, 2018 (found HERE)[1].

PURPOSE

The DOE FCTO within the Office of Energy Efficiency and Renewable Energy (EERE) is seeking information to quantify the increasing industrial demand for hydrogen; to identify and quantify the available domestic resources (such as renewable, nuclear and fossil energy) that could be leveraged to generate sufficient hydrogen to sustainably meet the demand in the near- to long-terms; and to identify opportunities to better leverage current hydrogen supply options to meet growing industrial demands. Building upon prior H2@Scale workshops[2] and related stakeholder engagement efforts (e.g., the 2016 and 2017 Annual Merit Reviews,[3] the 2016 Sustainable Transportation Summit,[4] and 2016 Intermountain Energy Summit[5] among others), this RFI seeks additional input from existing and emerging hydrogen supply and demand sectors with the goal of identifying the most promising opportunities to address the technical and economic challenges to widespread adoption of hydrogen, consistent with the H2@Scale vision. This goal includes early stage R&D in diverse hydrogen production, transport, and storage and utilization technologies to enable the performance and durability advances needed to reduce costs and enhance affordability. The RFI solicits specific feedback, project ideas, and other guidance on the H2@Scale-related topics outlined in the TOPIC AREAS section of this document and detailed in the RFI QUESTIONS section. ***Note: stakeholders should feel free to respond only to those topics relevant to their experience and expertise; it is not necessary to respond to all topics/questions. Please ensure you read and follow the* RFI RESPONSE GUIDELINES *included in this document.***

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ACKNOWLEDGEMENTS

This RFI was developed by FCTO and received substantial expert input from numerous Offices within EERE, including: the Advanced Manufacturing Office, the Bioenergy Technologies Office, the Geothermal Technologies Office, the Solar Energy Technologies Office, the Water Power Technologies Office, and the Wind Energy Technologies Office within EERE; as well the DOE Offices of Nuclear Energy and Fossil Energy. FCTO is indebted to these Offices for their invaluable contributions.

H2@SCALE BACKGROUND

Hydrogen is an essential feedstock in the U.S. oil refining and ammonia production industries and is emerging in other applications, such as transportation. While much of this hydrogen is currently produced from low-cost natural gas, the long-term resilience of industries to price volatility can be enhanced by diversifying the approaches available for affordable hydrogen production from domestic feedstocks and energy resources. The H2@Scale initiative aims to develop and enable transformational technologies that can sustainably produce and efficiently utilize large quantities of affordable hydrogen to collectively enable energy storage, energy security, grid resiliency, domestic employment, and American dominance in energy innovation.

Hydrogen is a unique and versatile energy carrier due to the diversity of domestic options for large-scale hydrogen production (including utilization of natural gas, coal, water, biomass, nuclear power, electricity, and direct sunlight) as well as the broad spectrum of industrial end uses, as shown in the H2@Scale vision illustrated in Figure 1. One option for large-scale hydrogen production being leveraged in H2@Scale is the use of abundant renewable, nuclear and fossil energy resources in the U.S. to split water (e.g., by grid-based electrolysis, or other direct electrochemical, thermochemical, or photolytic methods).

It is important to emphasize that across industrial sectors, H2@Scale should be viewed as an enabler and not a direct competitor to other energy pathways. For example, hydrogen: is essential to petroleum refining, biomass upgrading, and ammonia production; can enable synthesis of renewable fuels using captured carbon dioxide (CO_2); can support grid stability under higher penetrations of renewable generation resulting in greener/cleaner battery charging for electric vehicles (EVs); can provide clean power through hydrogen turbines/fuel cells either at scale or through distributed generation and combined heat and power (CHP); and can fuel advanced zero-emission technologies for light-, medium-, and heavy-duty transportation.

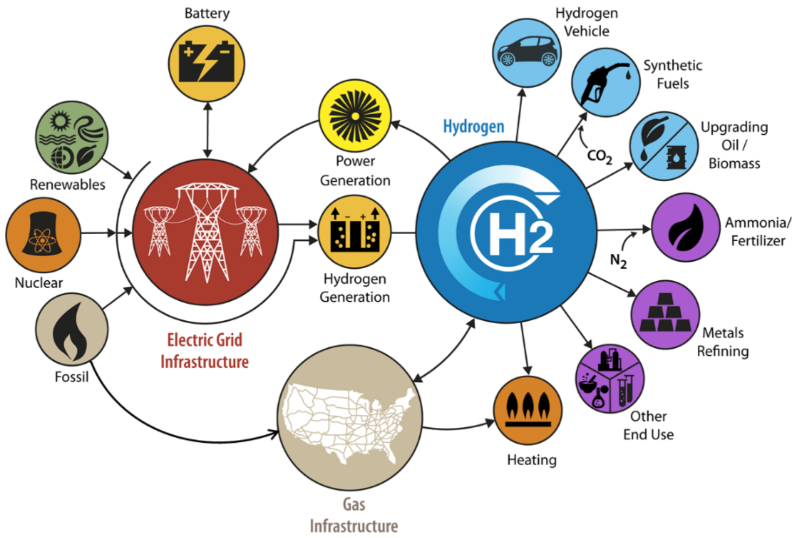

Figure 1: The H2@Scale Vision- Hydrogen can be produced from diverse domestic resources and is a central input to many important end uses in the industrial, chemical and transportation sectors

Significant benefits that H2@Scale can enable include:

- Maintaining U.S. leadership in hydrogen technologies, including innovation, manufacturing, and exports.
- Creating domestic jobs in emerging industries, such as hydrogen and fuel cells.
- Using stranded/underutilized domestic energy resources, such as stranded natural gas reserves or remote wind and solar resources, for production of hydrogen and/or chemical H_2 carriers.
- Reducing the frequency of power curtailment in regions of the country with growing non-dispatchable generation (e.g., wind and solar power).
- Enhancing utilization of baseload power by enabling production of both electricity and hydrogen.
- Diversifying the energy resources available for hydrogen production, thereby freeing domestic resources (e.g. natural gas) for other applications.
- Supplying growing domestic demands for advanced transportation technologies, stationary power and low-emission industrial processes.

Techno-economic challenges remain in the development and implementation of the diverse technologies and infrastructure needed to enable affordable hydrogen production, transport, storage and utilization at scales consistent with the H2@Scale vision. These technical and economic challenges can be mitigated by diversification of hydrogen supply options through expanded utilization of domestic resources that are currently stranded, underutilized, or completely untapped; and through leveraging of current energy and industrial technologies and infrastructure to accommodate services for hydrogen production, storage, distribution, and/or utilization. Stakeholders from industry, government, laboratories and academia all have important roles in the enabling of H2@Scale.

TOPIC AREAS

This RFI seeks information on the five topics below. DOE is pursuing input from diverse stakeholders with varying interests ranging from foundational research to demonstration and deployment of technologies and infrastructure for hydrogen production, storage, distribution, and utilization at scales consistent with the H2@Scale vision. Opportunities and strategies for expanding and diversifying current hydrogen supply options and for leveraging and repurposing current industrial infrastructure to accommodate widespread hydrogen usage are of particular interest. General strategies for promoting H2@Scale are also of interest.

I. **Hydrogen Supply Expansion/Diversification:** Identifying opportunities to better leverage and/or monetize stranded, underutilized, and/or untapped domestic energy resources through large-scale production of affordable hydrogen that can service diverse demand sectors and end uses. Additional information on this topic, including examples and case studies, can be found in Appendices A and D. DOE is specifically seeking input on:

   - Near- and long-term region-specific opportunities to leverage underutilized energy resources (including solar, wind, geothermal, natural gas, and hydro- and marine-power, among others) that can be used directly or indirectly to produce large quantities of affordable hydrogen in support of existing and emerging demand sectors.

II. **Demand-Sector Market Expansion:** Identifying opportunities for expansion in current and emerging markets requiring hydrogen as a chemical and/or energy feedstock. DOE is interested in identification of end-uses that would benefit from growth in hydrogen supply, and create market incentives for diversification of the supply sources currently used (e.g. natural gas, water, electricity, etc.). Examples include industrial-scale demands in chemical, energy and transportation sectors (typically >500,000 kilograms (kg)/day-H_2), as well as demands from small-scale niche hydrogen consumers (individually requiring ~10-100,000 kg/day-H_2) that have potential for regional aggregation. Additional information on this topic can be found in Appendix A, Chapter 2. DOE is seeking input on:

   - Near- and longer-term expansion opportunities in existing and emerging end uses with high hydrogen demand (e.g., petroleum refining; ammonia and methanol production; steel production; fuel cell electric vehicles, etc.) that could benefit from hydrogen supply chain expansion and diversification.
   - Opportunities for aggregation of regionally co-located small-scale hydrogen consumers (e.g., electronics fabrication, glassmaking, food processing, etc.), with the potential to create value propositions for novel distributed hydrogen production approaches.

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III. **Leveraging Industries and Infrastructure:** Identifying opportunities to develop, leverage or repurpose industries and/or infrastructure to enable the cost-effective production, storage and/or distribution of hydrogen, including opportunities to monetize sources of byproduct hydrogen from current industrial-scale processes. Additional information and examples on this topic can be found in Appendix E. Topics of interest include:

- Specific opportunities to leverage existing infrastructure, such as repurposing natural gas/oil pipelines for hydrogen energy storage/transport, leveraging existing rights-of-way for electricity and other infrastructure in the deployment of new hydrogen infrastructure, the use of retired geological caverns for large scale energy storage, multi-purposing- of nuclear/coal plants, etc.
- Relevant industrial-scale processes with byproduct hydrogen including chlor-alkali plants, petrochemical crackers, hydrocarbon waste-streams processors, and processes that involve boil-off from liquid hydrogen, among others.
- Local opportunities to co-locate industrial facilities requiring large quantities of hydrogen at or near hydrogen-producing resources to maximize energy utilization and minimize transport cost.

IV. **H2@Scale H-Prize Competition Concepts:** Identifying appropriateness of a DOE-sponsored H-Prize competition (e.g., similar to the recent successful "H2 Refuel H-Prize") to promote the widespread adoption of hydrogen as a viable energy storage/transport/utilization option for large-scale energy- and/or chemical-sector applications; and potential competition topics.

- A previous example of a successful H-Prize was the H2 Refuel Competition where the SimpleFuel Team was awarded $1M for their design, development, and demonstration of a commercial-ready appliance for refueling hydrogen fuel cell electric vehicles in home/community settings. Further information can be found in Appendix F.

V. **Innovative Approaches for Enabling H2@Scale**: Identifying effective innovative approaches, strategies, and/or opportunities to address technical and economic barriers to widespread hydrogen adoption in cross-sectoral applications. Example topics for which DOE is seeking information include:

- Addressing barriers that inhibit businesses, including small businesses from participating in emerging technologies relevant to H2@Scale.
- Identifying challenges that industry stakeholders are best equipped to take on.
- Identifying challenges that Federal agencies are best equipped to take on.
- Identifying ways that Federal agencies, states, industry, research organizations, and other stakeholders can better work together to enable the H2@Scale vision.
- Identifying ways that hydrogen can complement bioenergy technologies to make fuels, chemicals and other products from cellulosic biomass, algae, waste, and CO_2.

RFI QUESTIONS

The DOE is seeking stakeholder feedback relevant to the five H2@Scale topic areas above through information requested in the RFI Response Templates below. While preparing your responses, please review the background information and case studies related to your area of interest/expertise in APPENDICES A-E. **WHEN SUBMITTING YOUR FEEDBACK, IT IS IMPORTANT THAT YOU FOLLOW THE DETAILED INSTRUCTIONS FOR THE DIFFERENT SUBMISSION OPTIONS PROVIDED IN THE RFI RESPONSE GUIDELINES.** As described in the guidelines, you have the option to complete the form-fillable response templates and submit these via email; you also have additional online and write-in submission options, also described in the guidelines. For all options, you **DO NOT NEED TO RESPOND TO EVERY QUESTION OR FILL IN EVERY FIELD IN THE RESPONSE TEMPLATES**. Please only provide responses in topic areas related to your interests, experience, and expertise.

RFI Response Templates

Please provide your feedback by supplying information requested in the fields of the RESPONSE TEMPLATES below. Provide contact information about yourself and/or organization in the CONTACT INFORMATION TEMPLATE, and indicate your organization's primary areas of interest related to this RFI in the RFI-RELATED INTERESTS TEMPLATE. Provide feedback related to the five H2@Scale topic areas by supplying information requested in the TOPIC I-V RESPONSE TEMPLATES, respectively. Please note the following:

- The response templates in this pdf document are form-fillable. If you choose to submit your feedback using the *FORM-FILLABLE RESPONSE COLLECTION* option described in the RFI RESPONSE GUIDELINES, you can enter your responses directly in the template fields, re-save the pdf document, then submit via email as per the guidelines.
- Several of the response templates include special fields marked with a menu bar . In these fields, please consider using suggested response selections provided following each associated template. These responses are also selectable from drop-down menus in the field. If none of the suggested responses apply, please enter your alternative information directly into the template field.
- If possible, please avoid including confidential, proprietary, or privileged information in your responses. Please refer to page 19 for instructions on how to mark business sensitive, proprietary, or otherwise confidential information.
- All template fields are limited to a maximum of 5,000 characters, and all submission files (regardless of the submission option) should be limited to 10MB. Multiple submissions are allowed if a single submission is not sufficient to cover all the topics you wish to address.

Contact Information: Please provide contact information about yourself and your organization using the template below:

CONTACT INFORMATION: RESPONSE TEMPLATE				
Name	Email Address	Phone Number	Organization	
Address	City/Town	State/Province	Country	ZIP/Postal Code

Interests Relevant to RFI: Please indicate your organization's primary interests in areas relevant to this RFI in the template below:

RFI-RELATED INTERESTS: RESPONSE TEMPLATE *(check all that apply) optional*			
☐	Hydrogen generation technologies	☐	Hydrogen infrastructure
☐	Hydrogen use in power generation	☐	Hydrogen use in transportation
☐	Hydrogen use in chemical production	☐	Hydrogen use in industrial processes
☐	Nuclear or fossil based power	☐	Wind, solar, geothermal, water power, or bioenergy
☐	Gas and/or Electric Utilities	☐	State or Local Government Programs
☐	National laboratory research	☐	Academic/industry research
Other *(please specify)*			

General Comments: Please feel free to provide general comments on this RFI:

GENERAL COMMENTS: RESPONSE TEMPLATE *optional*

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<u>TOPIC I: Hydrogen Supply Expansion/Diversification:</u> Please provide your input relevant to **Topic I** using the template below. The purpose of this topic is to identify areas of the country where available energy is underutilized, and has potential for use in hydrogen production. For instance, in the U.S., approximately 18 million megawatt-hours (MWh) of wind energy were produced in 2016[6], of which about 2% was curtailed.[7] The wind energy curtailed can be estimated to represent approximately 367 million MWh of energy, which could be used to produce about 7,460 tonnes of hydrogen.[8]

TOPIC I: RESPONSE TEMPLATE				
Please identify a specific local/regional opportunity to better leverage and/or monetize stranded, underutilized, and/or untapped domestic energy resources. *Respond in as many or as few applicable fields as you wish. Please refer to page 19 for instructions on how to mark business sensitive, proprietary, or otherwise confidential information.*				
(1.1) Energy Resource	**(1.2) U.S. Region**	**(1.3) Current Nameplate Capacity**	**(1.4) Current Annual Energy Production**	**(1.5) Current Annual Curtailment**
(1.6) Levelized Cost of Electricity	**(1.7) Expected Nameplate Capacity Growth in 5-10+ yrs**	**(1.8) Prime Barrier to Expanded Resource Leveraging**		**(1.9) Unconstrained Expansion Potential**
(1.10) Regional Opportunity: Provide additional information on current and planned efforts to leverage the domestic energy resource, as well as options being considered to best monetize the resource (including potential opportunities offered by current and/or emerging hydrogen markets).				
(1.11) Technoeconomic Barriers: Provide additional information about the technical and/or economic barriers that are currently limiting the expanded and/or optimized utilization of the domestic resource.				
(1.12) Potential Solutions: Describe potential strategies for overcoming technoeconomic barriers, including possible innovative energy management approaches using H_2 production, storage, distribution, and/or utilization. If applicable, include information on current or planned research projects for enabling solution strategies.				

Suggested responses for requested information in Response Template I; feel free to use these, or alternate responses of your choice (or N/A if not applicable).

1.1 Energy Resource/ Feedstock *(see [Appendix A for details on some specific options)](#)*
- Wind
- Solar
- Hydro/Marine
- Geothermal
- Nuclear
- Biomass
- Fossil
- Municipal Solid Waste
- Industrial Waste
- CO_2
- Multiple
- Other

1.2 U.S. Region Options
- CT, ME, MA, NH, RI, VT
- NJ, NY, RP, Virgin Islands
- DE, DC, MD, PA, VA, WV
- AL, FL, GA, KY, MS, NC, SC, TN
- IL, IN, MI, MN, OH, WI
- AR, LA, NM, OK, TX
- IA, KA, MS, NE
- CO, MT, ND, SD, UT, WY
- AZ, CA, HI, NV, Island Terr.
- AK, ID, OR, WA
- Other

1.3 Current Nameplate Capacity
- <20 kW
- >20 to 200 kW
- >200 to 2000 kW
- >2 to 20 MW
- >20 to 200 MW
- >200 to 2000 MW
- >2 GW

1.4 Current Annual Energy Production
- <100 MWh
- >100 to 1,000 MWh
- >1 to 10 GWh
- >10 to 100 GWh
- >100 to 1000 GWh
- >1 to 10 TWh
- >10 TWh

1.5 Current Estimated Annual Curtailment
- < 1 MWh
- > 1 to 10 MWh
- > 10 to 100 MWh
- > 100 to 1000 MWh
- > 1 to 10 GWh
- > 10 to 100 GWh
- > 100 to 1000 GWh

1.6 Levelized Cost of Electricity per year per kWh
- < 2 ¢/kWh
- > 2 to 4 ¢/kWh
- > 4 to 6 ¢/kWh
- > 6 to 10 ¢/kWh
- > 10 to 15 ¢/kWh
- > 15 to 20 ¢/kWh
- > 20 ¢/kWh

1.7 Expected Nameplate Capacity Growth Over 5-10 years
- < 10%
- > 10 to 30%
- > 30 to 100%
- > 100 to 300%
- > 300 to 1000%
- > 1000%

1.8 Prime Barrier to Expanded Resource Leveraging
- Non-competitive LCOE
- Availability of Energy Transmission Infrastructure
- Land Availability
- Excessive Curtailment
- Multiple
- Other

1.9 Unconstrained Expansion Potential
- < 10%
- > 10 to 30 %
- > 30 to 100 %
- > 100 to 300 %
- > 300 to 1000 %
- > 1000 %

TOPIC II: Demand-Sector Market Expansion: Please provide your input relevant to **Topic II** using the template below. The purpose of this topic is to characterize the quantities, purities, and price points of hydrogen used in various sectors throughout the U.S., from small-scale consumers (e.g. laboratories or glassmaking plants) to large-scale consumers (e.g. petroleum refineries). The price of hydrogen in industry varies widely depending on the quantity of hydrogen being consumed and purity requirements, both of which influence the method of supply (gaseous tube trailers, liquid tankers, or pipelines).[9] When the quantity of hydrogen demanded exceeds 10 million scf/mo (23,623 kg/mo), customers may find it is more economical to install an onsite steam methane reformer to produce hydrogen, instead of having it delivered from remote production facilities.

TOPIC II: RESPONSE TEMPLATE				
Please identify a regional/local demand sector for hydrogen with growth potential tied to feedstock availability, and that is expected to provide market incentives for an expanded/diversified hydrogen supply. *Respond in as many or as few applicable fields as you wish. Please refer to page 19 for instructions on how to mark business sensitive, proprietary, or otherwise confidential information.*				
(2.1) Hydrogen Demand Sector	**(2.2) U.S. Region**	**(2.3) Estimated H_2 Demand**	**(2.4) H_2 Purity Requirement**	**(2.5) H_2 Pressure Requirement**
(2.6) Current H_2 Cost	**(2.7) Expected Growth in 5-10+ years**	**(2.8) Barriers Limiting Expansion**		**(2.9) Unconstrained Growth Potential**
(2.10) Hydrogen Demand Sector: Provide additional information on the demand sector for H_2, including details about the price points, price sensitivities, and H_2 purity requirements of the end use. Also comment on any expected impacts of growth and diversification of hydrogen supply on the end use.				
(2.11) Technoeconomic Barriers: Provide additional information about the technical and/or economic barriers that are currently limiting market expansion of the end use. If applicable, comment on expected evolutions in the sector's consumption of hydrogen under different market scenarios.				
(2.12) Potential Solutions: Describe potential strategies for overcoming technoeconomic barriers, including possible innovative approaches in diversification/expansion of the supply chain of affordable hydrogen. If applicable, include information on current or planned research projects for enabling solution strategies.				

Suggested responses for requested information in Response Template II; feel free to use these, or alternate responses of your choice (or N/A if not applicable).

2.1 H_2 Demand Sector *(see [Appendix A for information on these specific end uses)](#)*

- Petroleum Refining
- Chemicals/Fertilizer
- Synthetic Fuel
- Bio-Fuel
- Material Upgrading
- Power to Gas
- Electricity Services
- Light Duty Transport.
- Heavy Duty Transport.
- Electronics Fab
- Metals Annealing
- Glassmaking
- Power Gen Cooling
- Food Processing
- Specialty Chemical
- Jewelry Fabrication
- Cosmetics
- Material Handling
- Laboratories
- Other

2.2 U.S. Region

- CT, ME, MA, NH, RI, VT
- NJ, NY, RP, Virgin Islands
- DE, DC, MD, PA, VA, WV
- AL, FL, GA, KY, MS, NC, SC, TN
- IL, IN, MI, MN, OH, WI
- AR, LA, NM, OK, TX
- IA, KA, MS, NE
- CO, MT, ND, SD, UT, WY
- AZ, CA, HI, NV, Island Terr.
- AK, ID, OR, WA
- Other

2.3 Estimated H_2 Demand

- < 10 kg/d
- > 10 to 100 kg/d
- > 100 to 1000 kg/d
- > 1 to 10 tonne/d
- > 10 to 100 tonne/d
- > 100 tonne/d

2.4 H_2 Purity Needed

- < 99.99%
- 99.99%
- 99.995%
- 99.999%
- 99.9997%

2.5 H_2 Pressure Needed

- ambient
- > 150 psi (10 bar)
- > 500 psi (35 bar)
- > 1500 psi (100 bar)
- > 5000 psi (350 bar)
- > 10,000 psi (700 bar)
- Liquid Hydrogen

2.6 Current H_2 Cost

- < 1 $/kg
- > 1 to 1.5 $/kg
- > 1.5 to 2 $/kg
- > 2 to 3 $/kg
- > 3 to 5 $/kg
- > 5 to 10 $/kg
- > 10 $/kg

2.7 Expected Growth in 5-10 years

- < 10%
- > 10 to 30 %
- > 30 to 100 %
- > 100 to 300 %
- > 300 to 1000 %
- > 1000 %

2.8 Barriers Limiting Production Expansion

- High cost of hydrogen
- High cost of hydrogen delivery
- Hydrogen infrastructure
- Other

2.9 Unconstrained Growth Potential

- < 10%
- > 10 to 30 %
- > 30 to 100 %
- > 100 to 300 %
- > 300 to 1000 %
- > 1000 %

<u>TOPIC III: Leveraging/Repurposing Industries and Infrastructure:</u> Please provide your input relevant to **Topic III** using the template below. The purpose of this topic is to identify near-term leveraging opportunities to advance H2@Scale. Several examples provided in *APPENDIX E: Leveraging Industries and Infrastructure for H2@Scale* include leveraging pipelines, caverns, sources of byproduct hydrogen, nuclear heat, and solid carbon production.

TOPIC III: RESPONSE TEMPLATE				
Please identify a specific near-term opportunity to repurpose or better leverage industries, facilities and/or infrastructure to enable the cost-effective, industrial-scale production, storage and/or distribution of hydrogen. *Respond in as many or as few applicable fields as you wish. Please refer to page 19 for instructions on how to mark business sensitive, proprietary, or otherwise confidential information.*				
(3.1) Leveraging Opportunity	**(3.2) U.S. Region**	**(3.3) H_2 Production/ Distribution Scale**	**(3.4) Hydrogen Storage Scale**	**(3.5) Deployment Timeframe**
(3.6) Opportunity: Provide additional information on the opportunity to leverage/repurpose industries, facilities, and/or infrastructure, including price points and sensitivities.				
(3.7) Technoeconomic Barriers: Provide additional information about the technical and/or economic barriers that are currently limiting the leveraging/repurposing opportunity.				
(3.8) Potential Solutions: Describe potential strategies for overcoming technoeconomic barriers to deployment of the leveraging/repurposing opportunity. If applicable, include information on current or planned research projects for enabling solution strategies.				

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Suggested responses for requested information in Response Template III; feel free to use these, or alternate responses of your choice (or N/A if not applicable).

3.1 Leveraging Opportunity

- Pipeline
- Energy Storage
- Ethylene Byproduct H_2
- Chlor-alkali Byproduct H_2
- Other

3.2 U.S. Region

- CT, ME, MA, NH, RI, VT
- NJ, NY, RP, Virgin Islands
- DE, DC, MD, PA, VA, WV
- AL, FL, GA, KY, MS, NC, SC, TN
- IL, IN, MI, MN, OH, WI
- AR, LA, NM, OK, TX
- IA, KA, MS, NE
- CO, MT, ND, SD, UT, WY
- AZ, CA, HI, NV, Island Terr. AK, ID, OR, WA

3.3 H_2 Production/ Distribution Scale

- <10 kg/d
- > 10 to 100 kg/d
- > 100 to 1000 kg/d
- > 1 to 10 tonne/d
- > 10 to 100 tonne/d
- > 100 tonne/d

3.4 H_2 Storage Scale

- <10 kg
- > 10 to 100 kg
- > 100 to 1000 kg
- > 1 to 10 tonne
- > 10 to 100 tonne
- > 100 tonne

3.5 Deployment Timeframe

- Current
- Within 2 years
- Within 5 years
- Within 10 years
- Beyond 10 years

<u>TOPIC IV: H2@Scale Prize Competition Concepts</u>: Please provide your input relevant to **Topic IV** using the template below:

TOPIC IV: RESPONSE TEMPLATE
Please comment on the appropriateness of a DOE-sponsored prize competition (e.g., similar to the recent successful "H2 Refuel H-Prize") to promote the widespread adoption of hydrogen as a viable energy storage/transport/utilization option for large-scale energy and/or chemical-sector applications; and if appropriate, please provide information on a potential H2@Scale prize topic. *Respond in as many or as few applicable fields as you wish. Please refer to page 19 for instructions on how to mark business sensitive, proprietary, or otherwise confidential information.*
(4.1) Indicate whether an H2@Scale prize competition would be appropriate, and if so, suggest a potential prize topic with high-impact potential:
(4.2) Provide examples of targeted stakeholders that would participate in the competition:
(4.3) Suggest specific requirements, evaluation metrics, and/or judging criteria for the competition:
(4.4) Describe the potential economic impact of a successful competition:

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<u>TOPIC V: Innovative Approaches for Enabling H2@Scale:</u> Please provide your input relevant to **Topic V** using the template below:

TOPIC V: RESPONSE TEMPLATE
Please identify general approaches, strategies and/or opportunities for addressing specific technical and economic barriers to widespread hydrogen adoption in cross-sectoral applications. *Respond in as many or as few applicable fields as you wish. Please refer to page 19 for instructions on how to mark business sensitive, proprietary, or otherwise confidential information.*
(5.1) Suggest approaches for addressing barriers that inhibit small businesses from participating in emerging technologies relevant to H2@Scale:
(5.2) Identify challenges that industry stakeholders are best equipped to take on themselves:
(5.3) Identify challenges that Federal agencies are best equipped to take on themselves:
(5.4) Identify ways that Federal agencies, states, industry, research organizations, and other stakeholders can better work together:
(5.5) Please describe other relevant technical and/or economic challenges as well as strategic approaches for enabling H2@Scale:

RFI Response Guidelines

Responses to this RFI must be submitted online or by email in accordance with the submission options detailed below. The submission must be received no later than 5:00 pm (ET) on October 31, 2018.

SUBMISSION OPTION 1: ONLINE RESPONSE COLLECTION

- Complete and submit responses using the ONLINE RESPONSE COLLECTOR found HERE*. This option provides a streamlined process for respondents to provide information requested in this RFI. *(*full link: https://www.surveymonkey.com/r/H2_at_Scale_RFI)*

SUBMISSION OPTION 2: FORM-FILLABLE RESPONSE COLLECTION

- Enter your responses in the fields of the PDF form-fillable templates in the RFI RESPONSE TEMPLATE section of this RFI document, and save the PDF document to your computer.
- Email the saved PDF document with your filled-in responses to fy18fctostrandedresources@EE.DOE.Gov and include "H2@Scale RFI" in the subject line of the email.

SUBMISSION OPTION 3: WRITE-IN RESPONSE COLLECTION

- Prepare written responses to the information requested in the RFI RESPONSE TEMPLATES clearly indicating which topic areas and requested information you are addressing, in a Microsoft Word (.docx) file limited to 10MB.
- Email your written responses to fy18fctostrandedresources@EE.DOE.Gov and include "H2@Scale RFI" in the subject line of the email.

In your submission, please identify your answers by responding to a specific question or topic if applicable. Respondents may answer as many or as few questions as they wish. All submission files (regardless of the submission option) should be limited to 10MB. Multiple submissions are allowed if a single submission is not sufficient to cover all the topics you wish to address.

The DOE will not respond to individual submissions or publish publicly a compendium of responses. A response to this RFI will not be viewed as a binding commitment to develop or pursue the project or ideas discussed.

Respondents are requested to provide the following information at the start of their response to this RFI (i.e., the information requested in the CONTACT INFORMATION RESPONSE TEMPLATE and PRIMARY INTERESTS RESPONSE TEMPLATE:

- Contact's address, phone number, and e-mail address.
- Company / institution name.
- Organization's primary interest relevant to the RFI topics.

This is a Request for Information (RFI) only. The DOE will not pay for information provided under this RFI and no project will be supported as a result of this RFI. This RFI is not accepting applications for financial assistance or financial incentives. The DOE may or may not issue a Funding Opportunity Announcement (FOA) based on consideration of the input received from this RFI.

On behalf of the H2@Scale Team, thank you in advance for providing your input on this important topic and contributing to the DOE's success in achieving its objectives.

Disclaimer and Important Notes

This RFI is not a Funding Opportunity Announcement (FOA); therefore, the DOE is not accepting applications at this time. The DOE may issue a FOA in the future based on or related to the content and responses to this RFI; however, the DOE may also elect not to issue a FOA. There is no guarantee that a FOA will be issued as a result of this RFI. Responding to this RFI does not provide any advantage or disadvantage to potential applicants if the DOE chooses to issue a FOA regarding the subject matter. Final details, including the anticipated award size, quantity, and timing of the DOE funded awards, will be subject to Congressional appropriations and direction.

Any information obtained as a result of this RFI is intended to be used by the Government on a non-attribution basis for planning and strategy development; this RFI does not constitute a formal solicitation for proposals or abstracts. Your response to this notice will be treated as information only. The DOE will review and consider all responses in its formulation of program strategies for the identified materials of interest that are the subject of this request. The DOE will not provide reimbursement for costs incurred in responding to this RFI. Respondents are advised that the DOE is under no obligation to acknowledge receipt of the information received or provide feedback to respondents with respect to any information submitted under this RFI. Responses to this RFI do not bind the DOE to any further actions related to this topic.

Proprietary Information

Because information received in response to this RFI may be used to structure future programs and FOAs and/or otherwise be made available to the public**, respondents are strongly advised to NOT include any information in their responses that might be considered business sensitive, proprietary, or otherwise confidential.** If, however, a respondent chooses to submit business sensitive, proprietary, or otherwise confidential information, it must be clearly and conspicuously marked as such in the response.

Responses containing confidential, proprietary, or privileged information must be conspicuously marked as described below. Failure to comply with these marking requirements may result in the disclosure of the unmarked information under the Freedom of Information Act or otherwise. The U.S. Federal Government is not liable for the disclosure or use of unmarked information, and may use or disclose such information for any purpose.

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If your response contains confidential, proprietary, or privileged information, you must include a cover sheet marked as follows identifying the specific pages containing confidential, proprietary, or privileged information[1]:

Notice of Restriction on Disclosure and Use of Data:

Pages [List Applicable Pages] of this response may contain confidential, proprietary, or privileged information that is exempt from public disclosure. Such information shall be used or disclosed only for the purposes described in this RFI [DE-FOA-0001655]. The Government may use or disclose any information that is not appropriately marked or otherwise restricted, regardless of source.

In addition, (1) the header and footer of every page that contains confidential, proprietary, or privileged information must be marked as follows: "Contains Confidential, Proprietary, or Privileged Information Exempt from Public Disclosure" and (2) every line and paragraph containing proprietary, privileged, or trade secret information must be clearly marked with double brackets or highlighting.

Cover sheet for confidential, proprietary or privileged information ***if appropriate***

Evaluation and Administration by Federal and Non-Federal Personnel

Federal employees are subject to the non-disclosure requirements of a criminal statute, the Trade Secrets Act, 18 USC 1905. The Government may seek the advice of qualified non-Federal personnel. The Government may also use non-Federal personnel to conduct routine, nondiscretionary administrative activities. The respondents, by submitting their response, consent to the U.S. DOE providing their response to non-Federal parties. Non-Federal parties given access to responses must be subject to an appropriate obligation of confidentiality prior to being given the access. Submissions may be reviewed by support contractors and private consultants.

[1] For submission option 1 please complete the cover sheet field provided in the online collector; for submission option 2, please use the fillable field on this page; for submission option 3, please include the cover sheet in your submitted .docx document.

APPENDIX A: Hydrogen Supply Resources and Demand Sectors

The U.S. currently produces ~10 million metric tons (MMT) of hydrogen per year, mainly used in petroleum refining and ammonia production.[10] Natural gas consumption associated with this level of production is approximately 35 MMT. With aggressive growth of hydrogen use in fuel cell vehicles, heating, power generation, ironmaking, and biofuels production, the technical potential of domestic hydrogen demand is estimated at >60 MMT/year,[11] and the economic potential at 20-40 MMT/year.[12] The economic potential of hydrogen supply and demand are heavily dependent on prices of feedstock for hydrogen production technologies (e.g., natural gas, electricity, heat from nuclear plants), as well as research advancements that improve the affordability of hydrogen production and utilization technologies. Case studies completed under H2@Scale analysis projects to date have estimated that grid electrolysis is viable for hydrogen at power prices of $18/megawatt hour (MWh)-$24/MWh, and by using heat from nuclear plants with operating costs of about $25/MWh, assuming innovations in R&D.[13] The tables below provide techno-economic information on various domestic options for wide-scale hydrogen production as well as industrial sectors with hydrogen demand. Each table also includes technology-specific examples of techno-economic questions that could be addressed through responses to this RFI.

Chapter 1: Domestic Energy Resources for Large-Scale H_2 Supply: Techno-economic Background

TABLE A1: WIND ENERGY RESOURCES
The technical potential of onshore and offshore wind power in the U.S. has been estimated at 15,000 gigawatts (GW). [14] The U.S. added 8,203 MW of new wind power capacity in 2016, representing 27% of all energy capacity additions in 2016 and bringing wind's cumulative total to over 82 GW, producing more than 250 terawatt hours (TWh)/year. Thirty-seven states had over 100 MW of wind power capacity at the end of 2017.[15] Many potential sites with high quality wind energy resources have minimal or no access to electrical transmission facilities. This creates a bottleneck to cost-effective wind deployment. Collaboration is needed to increase market access to U.S. wind resources through improved power system flexibility and transmission expansion, technology development, streamlined siting and permitting processes, and environmental and competing use research and impact mitigation. Power Purchase Agreements (PPAs) for interior wind projects approach $20/MWh. The levelized cost of wind electricity for plants entering service in 2019 is expected to vary from $22.6/MWh – $51.6/MWh, depending on the region of the country, and including tax credits; without the tax credit, costs are expected to vary from $40.4/MWh-$69.4/MWh.[16] The cost of onshore wind power has fallen over 40% since 2008.[17]

Hydrogen Production Opportunities: Strategies for coupling wind-generated electricity with water electrolysis offer near-term options for large-scale hydrogen production. Please see relevant case studies included in Appendix D.

Example Techno-economic Considerations:

- Can direct coupling of remote generation wind turbines with water electrolysis open more high quality wind resources to economically viable development?
- What is the minimum sustainable price of electricity from wind plants?
- Can integration of wind power plants with variable load electrolyzers support the viability of these plants? If so, how?
- Can technologies that convert wind electricity into storable chemical fuel help in developing offshore wind projects?

TABLE A2: SOLAR ENERGY RESOURCES
Solar power provided more than 1% of the annual electricity supply in the U.S. (and for the world as a whole) in 2016, and the Energy Information Administration (EIA) projects that solar will grow to 5% of U.S. electricity by 2030.[18] The total technically available solar energy in the U.S. has been estimated as high as 400,000 TWh/year.[19] Solar electricity generation paths include photovoltaics (PV) and concentrated solar power (CSP). Installed domestic PV-powered electricity generation currently exceeds 50 GW, producing more than 50 TWh/year. Significant technological advancements have enabled solar electricity to become price-competitive with conventional utility sources; however, more work is needed to make solar a reliable, on-demand and more impactful energy resource. Curtailment resulting from PV power generation levels exceeding demand and negatively affecting the economics, along with grid integration issues, are significant challenges. Low-cost energy storage options combined with further technology advancements could increase the performance and reliability of solar power, allowing for better grid integration and reduced PV curtailment. CSP offers more dispatchability than PV because of the relative ease of incorporating thermal energy storage, but faces cost challenges. Strategies are being pursued to reduce the capital costs of plant (particularly for the reflector field) and to increase energy conversion efficiency by raising the operating temperature of the thermal transport system and turbine generator. As solar and energy storage technologies continue to improve, solar energy can supply larger amounts of our nation's electricity demand. According to EIA, the levelized cost of solar electricity for plants entering service in 2019 is expected to vary from \$0.0413/kWh – \$0.0964/kWh for PV and \$0.122/kWh – \$0.258/kWh for CSP, depending on the region of the country, and including tax credits; without the tax credit, costs are expected to vary from \$0.0535/kWh – \$.0964/kWh for PV and \$0.159/kWh – \$0.335/kWh for CSP.[20] The targets for the unsubsidized cost of electricity at the point of grid connection in a location with average U.S.

solar resource are $0.03¢/kWh for utility-scale photovoltaics by 2030 and $0.05/kWh for CSP with ≥ 12 hours of thermal energy storage by 2030.[21]

Hydrogen Production Opportunities: Solar hydrogen production options include PV and CSP-coupled electrolysis in addition to emerging technologies based on direct thermochemical and photoelectrochemical water-splitting. Please see relevant case studies Included in Appendix D.

Example Techno-economic Considerations:

- Are there any emerging technologies, business models, and/or markets in the utility sector that could take advantage of H2@Scale for enabling higher penetrations of PV while improving grid reliability/resiliency?
- Can direct coupling of remote generation solar electricity with water electrolysis or other emerging technologies which convert solar energy into storable chemical fuel open more high quality solar resources to economically viable development, such as in the regions that offer the land and sun necessary for CSP, but where CSP for electricity production may not be warranted?
- How critical is longer term energy storage (one day to seasonal) to the planning of future solar installations? What are the most important grid ancillary services (e.g., frequency regulation, voltage support) that an energy storage solution can supply and how impactful is that capability on utility scale solar installation economics?

TABLE A3: HYDRO / MARINE ENERGY RESOURCES

Hydropower provided 6.2% of net U.S. electricity generation and 48% of all U.S. renewable power in 2015. The current technical potential for conventional hydroelectricity generation in the U.S. is estimated at over 12 GW with the potential to generate more than 45 TWh/year. Emerging marine and hydrokinetic power generation technologies have the potential to tap into an estimated resource potential of over 1,500 TWh/year. The Hydropower Vision analysis finds that U.S. hydropower capacity could grow from 101 GW to nearly 150 GW by 2050.

Meeting the long-term potential for growth at potential sites that are not developed for hydropower is contingent upon continued commitment to innovative technologies and strategies to increase economic competitiveness while meeting the need for environmental sustainability.

The levelized cost of electricity (LCOE) for large hydropower projects typically ranges from $0.02 to $0.19/kWh assuming a 10% cost of capital. The LCOE range for small hydropower projects for a number of real world projects is between $0.02 and $0.10/kWh,[22] making small hydro a very cost competitive option to supply electricity to the grid, or to supply off-grid rural electrification schemes.

Hydrogen Production Opportunities: Hydro and marine-based power can be coupled with water electrolysis to produce hydrogen, facilitated by the co-location of electricity generation and the water feedstock. Please see relevant case studies Included in Appendix D.

Example Techno-economic Considerations:

- Can direct coupling of remote generation hydropower and marine power generators with water electrolysis open new resources to economically viable development? How low can the LCOE be to still make such projects profitable for hydropower stakeholders?
- What is the scale of hydropower resources that are still undeveloped?
- Can technologies that convert marine generated electricity into storable chemical fuel help in developing offshore marine energy projects? If so, how?

TABLE A4: GEOTHERMAL ENERGY RESOURCES
As of the end of 2015, the U.S. had 2.7 GW of net geothermal capacity. [23] The potential for geothermal power in the U.S. has been estimated at 40 GW, including discovered and undiscovered resources. A technology in early stages of research is "enhanced geothermal systems" (EGS), wherein geothermal reservoirs are engineered in regions that are not otherwise conducive to geothermal power generation. The potential for power generation from EGS has been estimated to be over 500 GW.[24] In contrast with wind and solar, geothermal energy is dispatchable, capable of providing base-load power with a capacity factor exceeding 90%. Geothermal resources and power plants in the U.S. are located largely in the central and western states.[25] Growth of geothermal power generation is restricted by the high capital costs and financial risks of initial exploratory drilling for wells. Research is needed to reduce both cost and risk through: 1) technologies that characterize reservoirs (e.g., permeability, heat) prior to drilling, 2) advanced drilling technologies that can withstand the conditions in geothermal reservoirs, 3) subsurface engineering of reservoirs to enable their use in geothermal power generation, and 4) integration of geothermal fluids with other value-add applications, such that they are further utilized downstream of power generation. Geothermal fluids are typically 40-100°C after their use in power generation. There is potential for their integration with hydrogen production technologies, given use of heat recuperation.[26,27] The capital cost of a geothermal power plant is about $2,500-$5,000/kW, depending on plant capacity. Operating costs are about $0.01-$0.03/kWh. The price of power from a geothermal plant built today can be expected to be about $0.05/kWh.[28] **Hydrogen Production Opportunities:** Geothermal electricity can be coupled with water electrolysis to produce hydrogen, while geothermal heat can be utilized in enhanced-efficiency high-temperature electrolysis or in direct thermochemical production. Please see relevant case studies Included in Appendix D.

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Example Techno-economic Considerations:

- In what regions do hybrid geothermal systems integrated with other heat sources (e.g., solar power) and/or value-add applications (e.g., desalination, hydrogen production) have a value proposition?
- Are there areas of the country where extraction of high-temperature (>500°C) geothermal steam (e.g., from molten rock) is being pursued? What is the value proposition and/or outlook for this approach?
- Are there other opportunities to capture high-temperature (>500°C) heat from geothermal reservoirs for use in other applications (e.g., hydrogen production)?

TABLE A5: NUCLEAR ENERGY RESOURCES

The capacity of the U.S. fleet of 99 commercial nuclear power reactors across 30 states currently exceeds 100 GW, producing more than 800 TWh/year dispatchable power. This represents almost 20% of America's total electrical output and about 60% of our carbon-free electricity. All commercial nuclear plants in the U.S. are lightwater reactors, wherein the temperature of the coolant reaches a maximum of 300°C.[29]

Low prices of natural gas, along with growing penetrations of renewable wind and solar energy onto the electric grid have challenged the economics of baseload nuclear reactors in certain regions of the U.S. Since 2012, over 4,600 megawatt electricity (MWe) of nuclear power generation (5 plants) retired early (prior to the license expiration date) and over 6,500 MWe (6 plants) have announced plans to retire early over the next eight years.[30] Many utilities are now considering a "hybrid" approach, integrating nuclear plants with industrial processes that can utilize a plant's thermal or electrical output when its use in commercial power generation is unprofitable. Such an approach may enable continued optimal use of thermal and/or electrical output of nuclear plants.

Hydrogen Production Opportunities: Advanced reactor concepts are developed by industry and DOE. Many of these concepts offer benefits in terms of safety, modularity, cost, ease of installation, and utilization of fuel, as well as potential for integration with industrial processes. Many of these concepts operate at >500°C, and are therefore compatible to integrate with high-temperature hydrogen production technologies (in the hybrid manner described above).[31] Please see relevant case studies Included in Appendix E.

Example Techno-economic Considerations:

- Would technologies that convert nuclear thermal and/or electrical energy into storable chemical fuel help make operating reactors more profitable? In what geographic regions would this be most advantageous?
- Can operating reactors in non-regulated markets be economically configured to supply thermal and direct electrical power to energy demands of a co-located electrolyzer?

- What technical, operational, or regulatory issues could be barriers to profitable implementation?
- Would deploying small modular reactors be more attractive to utilities if such reactors were designed to be coupled with technologies to convert nuclear thermal and/or electrical energy into storable chemical fuel?

TABLE A6: BIOMASS ENERGY RESOURCES

Biomass from wood, wood waste, straw, manure, sugarcane, and others stores chemical energy derived from sunlight that can be converted to useable forms such as heat, biofuels, and electricity. Current installed capacity for energy production from biomass in the U.S. exceeds 16 GW. Biomass electricity generation accounted for 12% of all renewable electricity generated in the U.S. in 2016, and 1.6% of electricity generation as a whole.[32]

Current costs for hydrogen from bio-derived renewable liquids (high temperature ethanol reforming) were estimated to be 6.60 $/kg in 2011 with a 2025 target of 2.30 $/kg. The 2011 status of biomass gasification/pyrolysis for hydrogen production is 2.20 $/kg.[33]

Hydrogen Production Opportunities: There are several strategies for producing hydrogen from biomass. The first involves pyrolyzing biomass into an intermediate mixture of organic compounds called bio-oil. The bio-oil can then be subjected to catalytic steam reforming to generate hydrogen. Another strategy involves generating a chemical intermediate from biomass, such as ethanol, followed by steam reforming. The challenges associated with these strategies include identifying durable and low-costs catalysts for the relevant reactions, incorporating efficient and cost-effective separations into these systems, and consolidating the number of process steps involved. The biggest challenges here are the high costs of biomass feedstocks and bio-derived intermediates. The reforming technologies for these processes also have prohibitively high capital costs.

Other strategies include engineering organisms to produce hydrogen. This includes developing new strands of green algae, cyanobacteria, and dark fermentative microorganisms for hydrogen production as well as developing biochemical process methods and reactor designs alongside these systems. These systems are in the early-stages of development and require new microorganisms with improved light utilization, increased rate of hydrogen production, and hydrogen molar yields. Please see relevant case studies Included in Appendix D.

Example Techno-economic Considerations:

- Are there areas in the country where biomass can be used to produce cost competitive hydrogen through biomass gasification, reforming, algae, or other methods?
- Are there any processes that utilize biomass as a feedstock that produce hydrogen as a by-product? What is the scale of the biomass consumption and the hydrogen produced?

TABLE A7: FOSSIL ENERGY RESOURCES
The vast majority of hydrogen consumed today is produced from fossil fuels. Steam methane reforming (SMR) of natural gas is the technology having the greatest advantage in terms of the lowest cost and highest energy efficiency and is the preferred choice of industry today. SMR is used industrially to produce ~95% of the H_2 consumed in the United States.[34] Coal gasification, also known as "clean coal" technology, can also be used for hydrogen production. In this technology coal is converted into a mixture of H_2 and CO_2 in a gasifier, and then pure hydrogen is separated using pressure swing adsorption (PSA) units. Coal gasification is significantly more expensive than SMR and therefore, only practiced in places where natural gas is not readily available. While SMR is a mature technology, large quantities of CO_2 are released from hydrogen production. Depending on the energy sources used and efficiency of the process, SMR generates 9–14 kg CO_2/kg H_2. If CO_2 capture is considered as part of a SMR technology option, this presents additional cost. Modifications to SMR technology have been considered to improve the efficiency and to lower the cost of CO_2 capture. These include various types of membrane reactors or reactors that incorporate CO_2 absorption in order to shift the process equilibrium to lower pressure and temperature and to separate pure CO_2 stream for downstream sequestration. Technologies that decompose natural gas (NG) into H_2 and solid carbon offer another area of development for production of CO_2-free hydrogen.[35] The cost of natural gas represents the major fraction in the H_2 production cost; therefore, prices of H_2 strongly correlate with the market price of NG. At current low NG prices resulting from recent shale gas development, the cost of H_2 production from SMR is between about $1-1.5/kg.[36] Please see relevant case studies Included in Appendix E **Example Techno-economic Considerations:** • What improvements to the existing SMR or coal gasification technologies can produce lower cost H_2 and lower greenhouse gas (GHG) emissions from hydrogen production? • What improvements to SMR technology are required to allow cost competitive distributed on-site, on-demand production of hydrogen?

TABLE A8: PETROLEUM REFINING
Hydrogen is a critical feedstock in oil refining. It is used in hydro-treating, dearomatization, hydro-isomerization, and hydrocracking. Hydrogen use in North American petroleum refineries has steadily grown over the past several years due to increased demand for diesel fuels, sulfur regulations, and availability of sour crudes. As of 2017, U.S. hydrocracking capacity was at 2.4 million barrels per stream per day, a growth of 4% over the previous year. [37] Most hydrogen used by refineries is either delivered from a centralized SMR plant, recovered from waste streams at the refinery, or produced onsite via SMR. SMR is currently the lowest cost hydrogen production method at industrial scale. The cost of large-scale hydrogen production from renewable energy sources (e.g., through water electrolysis), must be reduced for such emerging technologies to penetrate these markets. The current cost of hydrogen production from centralized SMR is currently < $2/kg and strongly depends on the price on natural gas.[38] **New Hydrogen Opportunities:** An emerging source of low-cost hydrogen is from industrial processes such as ethylene cracking and chlorine production, where hydrogen is a by-product.[39] Emerging technologies to reduce the cost of transporting by-product hydrogen to end users could increase their use. In regions with growing large-scale hydrogen demand, use of by-product hydrogen has potential for growth. Additionally, in California, the Low Carbon Fuel Standard (LCFS) incentivizes the use of electrolysis for refinery hydrogen rather than SMR. Electrolytic hydrogen therefore has potential in the California markets, or in locations where low-cost electricity is available. Several European refinery projects (e.g., Shell and H&R Group) have been announced which will use low-cost power to make hydrogen to supplant SMR hydrogen, thereby increasing the renewable content of the products made. Please see relevant case studies Included in Appendix E **Example Techno-economic Considerations:** • What are the main barriers to using hydrogen as a feedstock in current and future major industrial processes? How significant are production vs. transport costs for hydrogen at the needed scales? What R&D would help address these barriers? • What regions of the country may have growing large-scale hydrogen demand and where use of by-product hydrogen may enable faster growth? • What partnerships (e.g., within industry) could support production and utilization of renewable and by-product hydrogen as a means of utilizing stranded renewable resources? • Do you see a market for oxygen generated by electrolyzers, for instance for operating oxyfuel combustion power plants to enable carbon capture and sequestration projects? Are there other end-users of oxygen that could bring value to H2@Scale?

TABLE A9: AMMONIA PRODUCTION
Global production of ammonia in 2017 was 150 million metric tons.[40] Ammonia is produced on a large scale through the Haber-Bosch process that combines hydrogen and nitrogen over a catalyst at pressures of 250-300 bar and temperatures of 450-500°C. The primary use of ammonia is as fertilizer in agriculture. Other uses include refrigerants, industrial cleaners, or chemical intermediates in many industrial processes. Ammonia can also be used as an energy carrier for fuel in engines or fuel cells or be dehydrogenated to supply hydrogen. As with petrochemical uses, hydrogen for ammonia production is normally made via SMR, at similar costs. As with the petrochemical industry, electrolysis or supply from other industrial processes at lower cost is a potential opportunity. Natural gas is the energy source for hydrogen in ammonia production. The price of hydrogen and ammonia strongly depend on the price of the natural gas. **New Hydrogen Opportunities:** Interest in ammonia as an energy carrier is growing. Ammonia could be produced at moderate scales using hydrogen from stranded renewable resources. Ammonia could then then be distributed as a liquid under mild pressure (~20 bar). Liquid ammonia is about 70% as dense in equivalent H_2 as liquid hydrogen (37.8 kilomoles (kmol) H_2/cubic meter (m^3) for ammonia vs. 53.1 kmol H_2/m^3). Safety, handling, and distribution challenges need to be addressed. Please see relevant case studies Included in Appendix D **Example Techno-economic Considerations:** • What are the options for converting the renewable hydrogen to high-value energy carriers, (e.g., ammonia or methanol production)? What other chemicals may present an attractive option? • In what regions of the country could by-product hydrogen be co-located with by-product nitrogen from air separation for oxygen production? • What R&D would help to scale down and intensify the existing Haber-Bosch technology to match ammonia production scale to distributed renewable energy resources?

TABLE A10: METHANOL PRODUCTION
About 80 million metric tons (MMT) of methanol was produced globally in 2016. Production is expected to grow to 100 MMT by 2020.[41] Methanol is used in a broad range of chemical and energy applications. Methanol is produced primarily from natural gas that is reformed into syngas (a mixture of hydrogen, carbon monoxide, and carbon dioxide) using steam. The syngas is then converted to methanol in a reactor operating at 20-30 bar and 180-200°C. No separation of clean hydrogen is needed when methanol is produced from natural gas. Internationally, syngas is also produced from

coal; in this case, excess CO_2 is present in syngas and addition of imported hydrogen can help achieve the appropriate proportions for methanol synthesis.

Methanol can also be produced from CO_2 captured from industrial sources and hydrogen from stranded renewable resources. Availability of cheap renewable hydrogen can make the renewable methanol competitive with the methanol produced from natural gas and coal.

The price of methanol varies between about $0.80 and $1.90 per gallon[42] (~$50-120/MWh) and strongly depends on the price on feedstock natural gas.

New Hydrogen Opportunities: Methanol is finding increasing use in energy applications as a transportation, marine, and fuel cell fuel. Methanol can also be converted into hydrogen in small scale distributed reforming units close to the point of use. Please see relevant case studies Included in Appendix D

Example Technoeconomic Considerations:

- What are the options for converting the renewable hydrogen to high-value energy carriers, (e.g., ammonia or methanol production)? What other chemicals may present an attractive option?
- In what regions of the country are there stranded renewable resources for hydrogen production that may coincide with available sources of captured CO_2?
- What R&D would help to scale down and intensify methanol synthesis technology to match methanol production scale to distributed renewable energy resources?

TABLE A11: BIO- AND SYNTHETIC FUEL PRODUCTION
Hydrogen is an important component in the biomass to biofuels conversion process. A 2015 National Renewable Energy Laboratory (NREL) report estimates hydrogen demand at 0.54 kg H_2 per gallon gasoline equivalent (GGE) of produced biofuel. The NREL report indicates that the cost of produced biofuel is significantly lower when low-cost hydrogen is imported from outside sources than when it is produced in situ through hydrolysate carbon reforming reactions, or through biomass gasification process ($4.05/gge, $5.48/gge and $4.95/gge respectively). Availability of low-cost sources of hydrogen co-located with biorefineries is needed to advance the adoption biofuel production technologies. The report shows that the minimum fuel selling price (MFSP) for produced biofuel varies between $3.80 - $5.40/gge when the price of hydrogen varies between $1 and $4/kg. Please see relevant case studies Included in Appendix D

Example Techno-economic Considerations:

- Are there existing or planned biofuel projects that would benefit from availability of inexpensive sources of hydrogen?
- In what regions of the country are there stranded renewable resources for hydrogen production that may coincide with inexpensive sources of biomass for economically viable conversion to biofuels?
- What R&D would help to scale down and intensify biomass conversion technology to take advantage of distributed stranded hydrogen resources?

TABLE A12: INDUSTRIAL UPGRADING PROCESSES

Up to 16% of U.S. crude oil consumption is used to make chemicals and products, such as plastics for industrial and consumer goods, contributing a value added to the U.S. economy of $812 billion. Many products derived from petrochemicals could be replaced with biomass-derived materials. Biofeedstocks can be converted into intermediates such as crude bio-oils, gaseous mixtures such as syngas, sugars, and other chemical building blocks. These products can then be chemically upgraded to commercial products.

Upgrading processes involve a variety of technologies related to process, catalysis, and product separation all of which need improvement to make this a more cost-competitive pathway. Microorganisms (including, but not limited to, bacteria, yeast, and cyanobacteria) can convert sugar or gaseous intermediates into fuel blendstocks and chemicals. Delivering hydrogen from a centralized large scale SMR plant to the consumer may dramatically increase the cost of hydrogen needed for these processes.

Hydrogen Use Opportunities: Regardless of the feedstock or desired product, hydrogen sourcing and cost have been identified as a challenge. Having a hydrogen source, or co-locating a hydrogen production plant would be critical to advancing material upgrading and chemical technologies. BIOENERGY TECHNOLOGIES OFFICE, Multi-Year Program Plan, March 2016. https://energy.gov/sites/prod/files/2016/07/f33/mypp_march2016.pdf. Please see relevant case studies included in Appendix E

Example Techno-economic Considerations:

- Are there opportunities for industrial applications where accessible low-cost hydrogen would strengthen regional market penetration?
- In what regions of the country are there industries that require hydrogen in the technological process that may also coincide with stranded hydrogen resources?

TABLE A13: POWER TO GAS SERVICES
An emerging application for water splitting in regions with an abundance of low-cost power (e.g., from wind or solar), is the concept of power-to-gas (P2G).[43] P2G systems use otherwise excess wind or solar power to make hydrogen, or alternately synthetic methane through a methanation process, that is then injected into local natural gas pipelines.[44] From there, the hydrogen can either be burned as a fuel, mixed into the natural gas, or it can be transmitted long distances, separated from the pipeline and used as hydrogen.[45] There are a number of these projects in Europe that are either planned or have recently completed. See the HyDeploy project in the U.K., for example, where impacts of hydrogen blends up to 20% on appliances is being evaluated, or the EnergiePark Mainz Project in Germany which uses wind turbines to power 6-MW worth of electrolyzers.[46] In Mainz, the resulting hydrogen is injected into the City of Mainz gas network and can fill tube trailers.[47] Studies indicate that hydrogen concentrations can be in the range of 5-20% of the gas in a pipeline without causing major impacts on end-use systems, such as household boilers, furnaces, and similar industrial equipment.[48] Growth of P2G is challenged by cost-competitiveness, regulatory barriers, concerns about the impacts of hydrogen on end users, and hydrogen leakage from existing natural gas pipelines.[49] Hydrogen generated by current polymer electrolyte membrane (PEM) technology costs approximately \$5/kg using electricity at \$0.061 cents per kWh.[50] The cost of electricity is the dominant factor in the cost of hydrogen so produced.[51] Wind PPA prices as of 2017 are below \$20/MWh (\$0.02/kWh) which, if accessed by electrolyzers, would result in much lower hydrogen costs.[52] **New Hydrogen Opportunities:** California Independent System Operators (ISO) alone curtailed 380 GWh of wind and solar power in 2017, mostly due to oversupply and transmission or distribution congestion.[53] That energy could have generated 7,600 metric tonnes of hydrogen.[54] If used to power FCEVs, that would translate to over 120,000 vehicle miles travelled.[55] Please see relevant case studies included in Appendix D **Example Techno-economic Considerations:** • Are there other regional opportunities in the near-term to exploit underutilized renewable resources for hydrogen production/storage/transport/utilization in industrial or grid applications? • What partnerships (e.g., within industry) could support the recovery and distribution of by-product hydrogen?

TABLE A14: ELECTRIC GRID SERVICES
The majority of U.S. power generation today is in the form of natural gas turbines and baseload coal-fired power plants.[56] As the costs of wind and solar decline, however, growing amounts of the grid mix are being supplied by intermittent renewable generation.[57] Nationally, wind and solar power averaged nearly half of the newly added U.S. generating capacity between 2010 and 2017 and accounted for 6.7% of total electricity generation in 2016.[58] Grid operators (ISOs/Regional Transmission Organizations (RTO) manage markets for energy, capacity, and a host of ancillary services including frequency and voltage regulation.[59] This intermittent nature of wind and solar resources makes participation in some of these markets difficult. The growth in intermittent generation is driving the market for energy storage, which grew 500% between 2013 and 2016.[60] Pumped hydropower is the leading storage technology deployed today;[61] however, other technologies, such as flywheels, flow batteries, and lithium ion batteries are seeing rapid growth The market for non-pumped hydro storage is dominated by lithium technologies.[62] As of the end of 2017, the median price for non-pumped hydro storage (2-hour rating) was $750/kWh, and $850 per kW for 30 minute storage.[63] **New Hydrogen Opportunities:** Hydrogen systems have the ability to participate in energy, capacity, and ancillary service markets. Electrolyzers alone can act as a dispatchable load with sub-second response capabilities.[64] When paired with a fuel cell and storage, the combined system can participate in energy and capacity markets. The recent issuance of the Federal Energy Regulatory Commission (FERC) Order 841 directs ISOs to adopt rules for storage technologies that could enable the deployment of hydrogen in this role.[65] Please see relevant case studies Included in Appendix E. **Example Techno-economic Considerations:** • What are the main barriers to using hydrogen as an energy carrier in current and future grid applications? How significant are production vs. transport costs for hydrogen at the needed scales? What R&D would help address these barriers? • Are there regional opportunities in the near-term to exploit underutilized renewable resources for hydrogen production/storage/transport/utilization in industrial or grid applications? • What partnerships (e.g. within industry) could support production and utilization of renewable hydrogen as means for utilizing stranded renewable resources?

TABLE A15: TRANSPORTATION SERVICES
There are nearly 35 retail hydrogen fueling stations in the U.S., with an additional 28 in development, and at least 40 more planned.[66,67] Stations are concentrated primarily in California, and have recently begun emerging along the East Coast. These stations serve the nearly 4,500 fuel cell vehicles currently on the road. Additionally, 25 fuel cell bus prototypes are currently in use in the U.S, with 32 in

development and four fuel cell shuttles in development as well.[68] Recently, hydrogen fuel cells have been deployed in other prototype medium and heavy-duty vehicles, such as drayage trucks.

There are three primary challenges for hydrogen stations: cost (both capital and operating), footprint, and reliability. The footprint of large-capacity liquid stations is limited by setback distances from exposures like building air intakes and property lines that make deployment in dense, urban areas—the areas most likely to need a high-capacity station—a challenge. This leaves some stations to rely on multiple, daily tube trailer deliveries, which present logistical challenges.

In California, hydrogen retails for $13-$16/kg.[69] Station capital costs range from approximately $800k to $3.25M, depending on factors such as station capacity, location and technology deployed.[70] Maintenance costs have decreased in recent years, but can still account for over $10,000 per station per quarter[71]—an unsustainable level.

New Hydrogen Opportunities: Fuel cell powered transportation is still in its nascence, and has substantial potential for growth, particularly in states with zero emission vehicle (ZEV) goals. Growth of hydrogen use in medium and heavy duty vehicles in particular is of significant interest. Please see relevant case studies Included in Appendix E

Example Techno-economic Considerations:

- What are the main barriers to using hydrogen as transportation fuel? How significant are production vs. transport costs for hydrogen at the needed scales? What R&D would help address these barriers?

TABLE A16: Niche Small-Scale Demands for Hydrogen
Hydrogen is commonly used at small scales for diverse industrial applications, including annealing, generation of high-temperature flames (via torches) for soldering or welding, as a reductant, and as a chemical input. [72,73] Such industries include laboratories, power plant cooling, float glass manufacturing, electronics production, metals annealing, food processing, welding, and jewelry manufacturing. Hydrogen demand in these facilities can range from tens to hundreds of thousands of kilograms per day, and may be met through a combination of sources; these sources include on-site electrolysis or hydrogen delivery via liquid tankers or tube trailers. On-site electrolyzers are often chosen because the quantity of hydrogen required is too small to warrant on-site steam methane reforming or hydrogen deliveries, the requirement for high-purity hydrogen incentivizes electrolysis, or locations of hydrogen demand are distant from natural gas infrastructure. Within the U.S., identifying regions with many small-scale consumers of hydrogen can help define the value proposition for growth in regionally distributed hydrogen production technologies. Use of large-scale electrolysis may have a value proposition in such cases, particularly when the purity

requirements of consumers are substantial. Moreover, in recent years, the capacities of commercially available electrolyzers have substantially increased. Megawatt-scale electrolyzers are commercially available, and can produce hundreds of kilograms of hydrogen per day.[74] Hydrogen produced by such large-scale electrolyzers can ultimately be supplied to multiple regional industries. For example, in Mainz, Germany, six megawatts of electrolysis have been integrated with the electricity grid, and the hydrogen produced is both filled into tube trailers and blended into district natural gas pipelines; the tube trailers supply both industrial applications and hydrogen fueling stations. This manner of coupling multiple sectors that produce and utilize electricity and hydrogen is gaining interest worldwide. One example of a developing proof-of-concept is the GrInHy project in Europe. GrInHy comprises the development of a reversible solid oxide fuel cell (RSOFC), which will be co-located with a steelmaking plant. The RSOFC will be able to produce hydrogen that will be used for annealing, and combined with natural gas for power production (via the RSOFC).

Example Technoeconomic Considerations:

- What are common price points for hydrogen in industries that consume at small scales?
- How do small-scale consumers typically receive hydrogen today, and what are barriers to changing their supply mode (e.g., existing long-term contracts)?
- What are the purity requirements for hydrogen in small-scale industries, and how influential are they in the choice of supply method?

APPENDIX B: Recent Hydrogen Cost Trends

Cost-competitiveness of diverse options for large-scale hydrogen production is key to H2@Scale. Figure B1 shows the current and historic range of hydrogen production costs for several commercial and near-commercial technologies.[75,76] The projected costs, reported in $/kg (based on techno-economic case studies assuming high-volume production and widespread commercialization) do not include taxes or dispensing; and the cost spreads shown include major feedstock and capital cost variability. As shown, commercial production technologies based on reforming fossil resources (natural gas and coal) are well developed, producing the lowest cost hydrogen at <$2/kg. The figure also indicates how R&D has been bringing down hydrogen production costs in the technologies based on alternative, more sustainable domestic resources including biomass reforming and water splitting. These have dropped from a 2005 baseline of ~$2.50–$8.00/kg to ~$2.00–$6.50/kg by 2015. Biomass gasification is a relatively mature technology, with the potential for producing low-cost hydrogen, but the production cost is highly sensitive to the biomass feedstock pricing. Water electrolysis technologies (both low and high-temperature) have seen significant improvements since 2005, but the hydrogen production costs currently remain above $2/kg for electricity pricing above $0.01/kWh. Electricity pricing as a key cost driver in these technologies; and the falling costs of 'renewable' electricity can be a key enabler to H2@Scale.

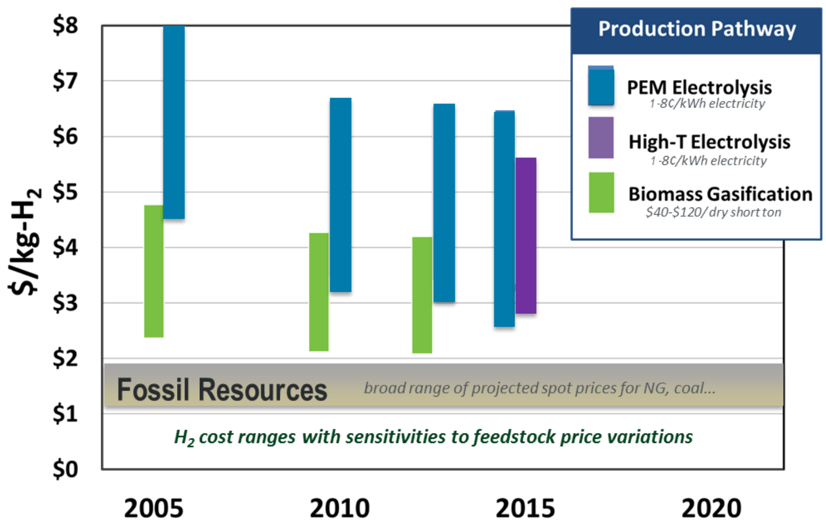

Figure B1: Cost trends in hydrogen production (undispensed/untaxed, reported in $/kg with feedstock and capital cost variability, assuming high-volume production and widespread commercialization)

The cost of hydrogen infrastructure also contributes significantly to the ultimate price of hydrogen for a consumer. Hydrogen is typically delivered throughout the U.S. via tube trailers, liquid tankers, and pipelines. Tube trailers are commonly used when the distance of delivery is short (100-200 miles), and have payloads of less than 1,000 kg. Liquid tankers can travel several hundred miles, and have payloads of up to 3,000 kg of hydrogen. Pipelines transport hundreds of thousands of kilograms of hydrogen per day, and are typically installed to serve large-scale consumers (e.g. petroleum refineries, ammonia plants) with demand that is expected to remain stable for at least 30 years. Pipelines are the most efficient approach to large-scale hydrogen delivery, but their deployment is constrained by their capital intensity; pipelines cost about $1 million per mile to build. The U.S. currently has about 1,600 miles of hydrogen pipelines, located primarily along the Gulf Coast, along with 9 liquefaction plants and three underground geologic caverns that store thousands of tonnes to buffer seasonal differences in supply and demand.[77,78,79,80]

When hydrogen is being supplied to fuel cell vehicles, the infrastructure at the fueling station is also capital intensive. Hydrogen fueling stations currently cost approximately $1.5 million - $4 million for stations that range in capacity from 100 kg/day- 400 kg/day.[81] Over 30 hydrogen fueling stations are currently open in the U.S., primarily in California.[82] Multiple stations have also been built in the Northeast, and a total of 12-25 are currently planned. Interest in hydrogen fueling stations for medium- and heavy-duty applications is also growing. At least seven locations in the U.S. operate fuel cell bus fleets, and at least 14 fueling stations are currently planned for upcoming deployments of fuel cell trucks.[83,84]

APPENDIX C: Water Electrolysis

The emergence of commercially-viable electrolyzer technologies for hydrogen production represents one of the key recent enablers for H2@Scale. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer. Electrolyzers can range in size from small, appliance-size equipment that is well-suited for small-scale distributed hydrogen production to large-scale, central production facilities (MW scale and above) that could be tied directly to renewable or other forms of electricity production.[85] Electricity feedstock cost is the dominant cost component (up to 75%) of the H_2 production cost via the electrolysis H_2 production pathway. Based on the sensitivity studies from the techno-economic analysis described below, this pathway starts to become cost competitive with natural gas steam methane reforming for H_2 production when the electricity cost drops below ~$0.01-$0.03₵/kWh. Similar to fuel cells, electrolyzers consist of an anode and a cathode separated by an electrolyte. Different electrolyzers function in slightly different ways, mainly due to the different type of electrolyte material involved.

Polymer Electrolyte Membrane Electrolyzers

In a (PEM) electrolyzer, the electrolyte is a solid specialty plastic material.

- Water reacts at the anode to form oxygen and positively charged hydrogen ions (protons): $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
- The electrons flow through an external circuit and the hydrogen ions selectively move across the PEM to the cathode.
- At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas: $4H^+ + 4e^- \rightarrow 2H_2$

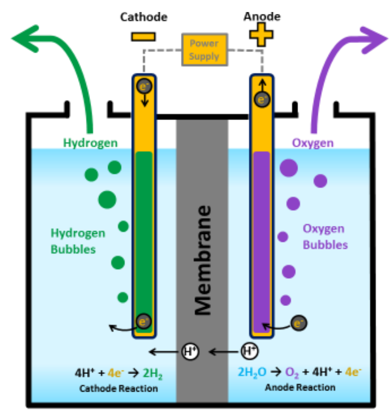

Figure C1: Electrolysis Schematic

PEM electrolyzers are an emerging commercial technology. They have been used for years at smaller scales (e.g., laboratory gas generators). With increasing demand for electrolyzers at the MW-scale and up, the industry is currently significantly scaling up its manufacturing capacity. Commercial products in this range have recently been introduced to the market by several suppliers.

Alkaline Electrolyzers

Alkaline electrolyzers operate via transport of hydroxide ions (OH^-) through the electrolyte from the cathode to the anode with hydrogen being generated on the cathode side. Electrolyzers using a liquid alkaline solution of sodium or potassium hydroxide as the electrolyte have been commercially available for many years. Newer approaches using solid alkaline exchange membranes as the electrolyte are showing promise on the lab scale.

Solid Oxide Electrolyzers (High Temperature)

Solid oxide electrolyzers (SOEC) typically use a solid ceramic material as the electrolyte that selectively conducts negatively charged oxygen ions (O^{2-}) at elevated temperatures. Water at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions; and the oxygen ions pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit. SOEC operates at temperatures high enough for the solid oxide membranes to function properly (~700°–800°C, compared to 70°–90°C for PEM).With the ability to effectively use heat available at these elevated temperatures (from various sources, including nuclear energy), SOEC electrolyzers can maintain high H_2 production rates with high electrical efficiencies, and with low/non-PGM catalysts. This technology is still primarily at the R&D stage, though commercial products are being planned for the near future.

Electrolysis Cost Status

Baseline cost projections from H2A analyses for H_2 production via PEM and SOEC electrolysis are shown in Table C1, including stakeholder-vetted results based on current electrolyzer technologies as well as future advanced electrolyzers. The untaxed cost projections, which assume economies of scale, include an average electricity pricing of ~$0.065/kWh derived from the Energy Information Administration's (EIA) Annual Energy Outlook (AEO).

Table C1: *Techno-economic Baseline Cost Projections of Centralized PEM[86] and SOEC[87] Electrolysis*

Costs based on average electricity pricing of ~6.5₵/kWh	PEM Baseline ($/kg H_2)	SOEC Baseline ($/kg H_2)
Current Technology Projections	$5.12	$4.95
Future Technology Projections	$4.20	$3.83

Cost sensitivities for the baseline cases represented in Table C1 are shown in the tornado plots in Figures C2 and C3 for PEM electrolysis and high-temperature SOEC, respectively. As electrolyzer technologies continue to mature and start to achieve economies-of-scale through widespread market adoption, the cost of hydrogen produced by electrolysis starts to become cost-competitive with incumbent SMR production (<$2/kg H2) at electricity pricing <$0.01/kWh.

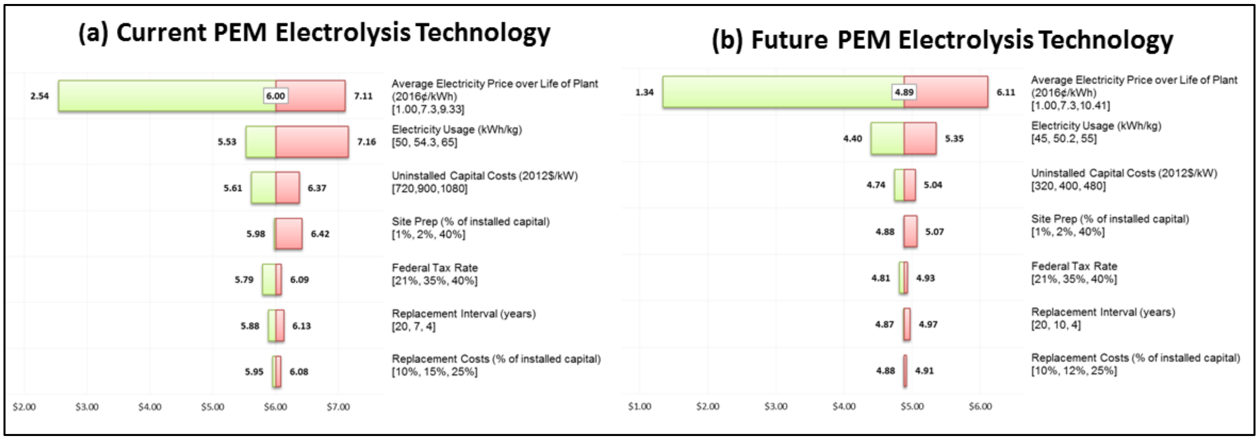

Figure C2: Tornado charts showing parameter sensitivities projected hydrogen costs from a centralized PEM electrolysis facility based on (a) current PEM technology; and (b) future optimized PEM technology

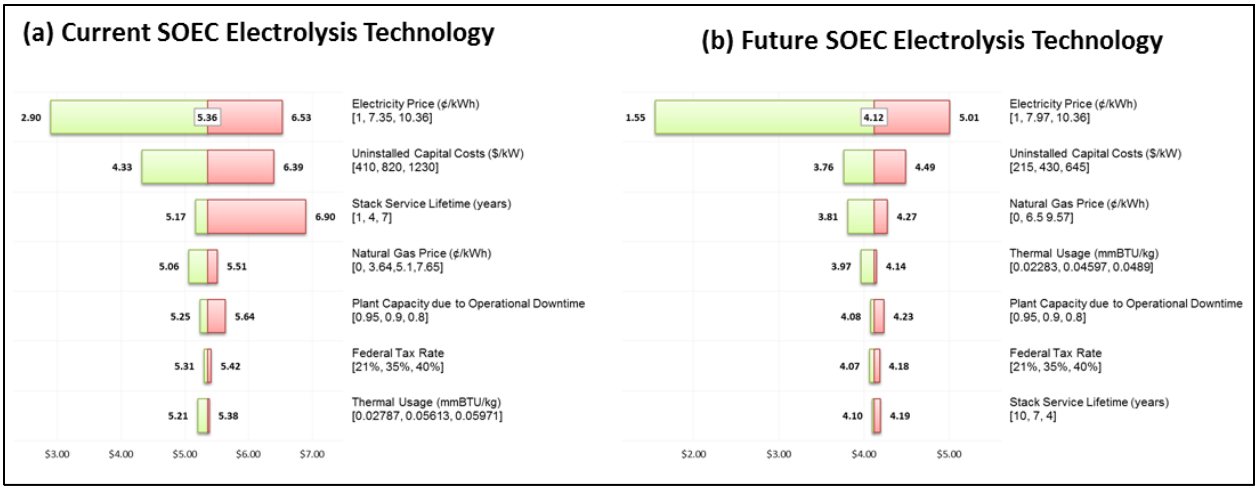

Figure C3: Tornado charts showing parameter sensitivities projected hydrogen costs from a centralized SOEC electrolysis facility based on (a) current SOEC technology; and (b) future optimized technology

Additional Value Propositions

Electrolytic hydrogen production may be particularly useful for load-leveling of the electricity generated from wind turbines, reducing fluctuations in capacity or augmenting capacity during periods of peak electricity demand. It may be feasible to negotiate favorable electricity rates by operating the electrolyzers during off-peak periods. Electrolyzers potentially have a secondary use for grid stabilization (e.g., by mitigating frequency disturbances). In Europe, electrolysis is being pursued as a means of grid stabilization through hydrogen storage, where, for example, excess wind energy, which would otherwise not be utilized, produces H_2 via electrolysis which is then injected into the natural gas grid as a means of storage and renewable gas production.[88,89]

Ongoing Research Needs

Important ongoing research in electrolysis focuses on stack and system-level improvements in efficiency (to reduce electricity usage), reductions in capital costs, and exploration of alternative chemistries and operating regimes offering potential for cost reductions. For example, the platinum group metal (PGM) catalysts needed in PEM electrolysis remain a cost challenge. New catalysts and membranes (such as the alkaline exchange membranes which significantly reduce the need for PGM catalysts) are being developed to address this challenge. The high temperature operations of SOEC electrolyzers increase the stack electrical efficiency, but continued R&D is needed to enhance durability under these conditions (e.g., in the development of corrosion-resistant materials, improved seals, etc.) High pressure electrolysis (as high as 10,000 pounds per square inch gauge (psig), compared with typical electrolyzers currently generating H_2 up to 300 psig) is also being explored, particularly in support of the fuel cell electric vehicle sector where the requirement of hydrogen compression for 10,000 psig operations is a significant cost component.

Additional balance-of-plant and system integration R&D is also needed to improve the economics of water electrolysis. For example, water electrolyzers operate on DC power, and similar to batteries, are comprised of stacked cells, each requiring ~1-5-2 volt (V) power input. Depending on the stack configuration, electrolyzers can efficiently utilize up to ~1000V DC. With conventional power electronics, grid AC power can be converted to appropriate DC levels; alternatively, advanced DC-DC power electronics (based, for example on new wide bandgap semiconductor devices currently under development) offer the potential for higher efficiency through direct DC coupling between renewables and electrolyzers.

APPENDIX D: Monetizing Stranded/Underutilized Resources through Hydrogen

The economic and environmental benefits of hydrogen to domestic industries can be enhanced by diversifying the feedstock used in its production,[90] which currently relies almost exclusively on natural gas and coal. The U.S. currently produces ~10 MMT of hydrogen per year, mainly for petroleum refining and ammonia production.[91] For economic reasons, the hydrogen demand is currently being met primarily through SMR of low-cost natural gas. Figures D1 and D2 show the domestic reserves of natural gas along with existing SMR facilities and related infrastructure for hydrogen production and distribution. A comparison of these figures illustrates the current geographical correlation between resource availability and production capacity, including large concentrations of relevant infrastructure in the Gulf region. In contrast, the national demand centers for hydrogen, shown in Figure D3, are more regionally spread out, with high concentrations in the Midwest, among other regions, driven in part by critical industries such as large-scale ammonia production. Distribution infrastructure and associated costs of hydrogen transport between supply and demand centers already challenge such industries.

Moreover, the growing hydrogen needs in petroleum refining and ammonia production along with emerging markets, such as hydrogen-powered FCEVs or reduction of iron using hydrogen[92], are creating expanded demand levels across the nation that are expected to further strain current supply and distribution infrastructure. The technical potential of hydrogen demand in the U.S., with aggressive growth of hydrogen use in fuel cell vehicles, heating, power generation, ironmaking, and biofuels production, is estimated at 60 MMT/year.[93] As demand grows, supplementing the current supply with a sustainable portfolio of production options becomes increasingly important. As shown in Figure D4, the technical potential of hydrogen supply from solar, wind, and biomass resources is significant and widespread throughout the U.S.; these results are currently being updated with a study underway at the DOE national laboratories. In comparing Figures D3 and D4, it is evident that many U.S. regions with high hydrogen demand are also rich in renewable energy resources, which are often unharnessed, underutilized, and/or curtailed. Large-scale hydrogen production offers new options to leverage and monetize the abundant domestic energy resources in these regions; and opportunities to co-locate large-scale hydrogen supply and demand can offer additional market benefits through reduced hydrogen transport and distribution costs.

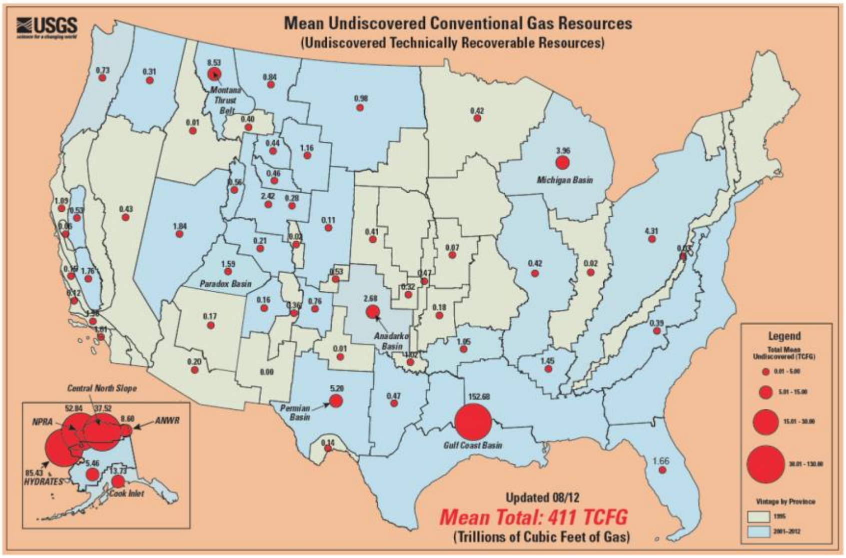

Figure D1: U.S. map indicating the geographical reserves for natural gas, which represent the current main source for near-term large-scale hydrogen production in the U.S.[94] In the continental U.S., the largest reserves remain in the Gulf region.

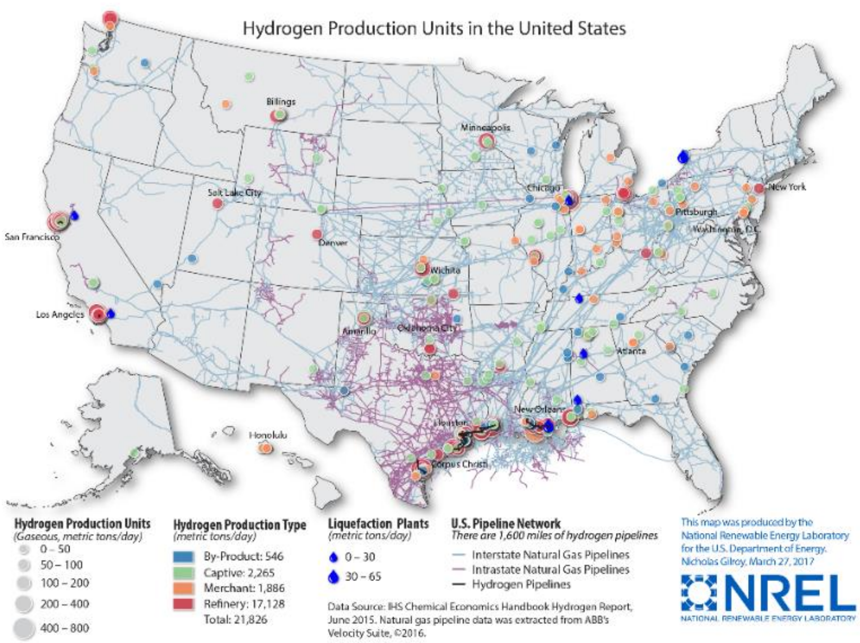

Figure D2: U.S. map indicating the locations of hydrogen production plants, liquefiers, and pipelines, along with locations of natural gas pipelines (preliminary NREL analysis). The dark blue dots represent hydrogen liquefaction plants, while the other dots represent hydrogen production by source (light blue = by-product; green = captive; orange = merchant; red = refinery). The pink and blue lines represent natural gas pipelines and the sparse black lines represent hydrogen pipelines.

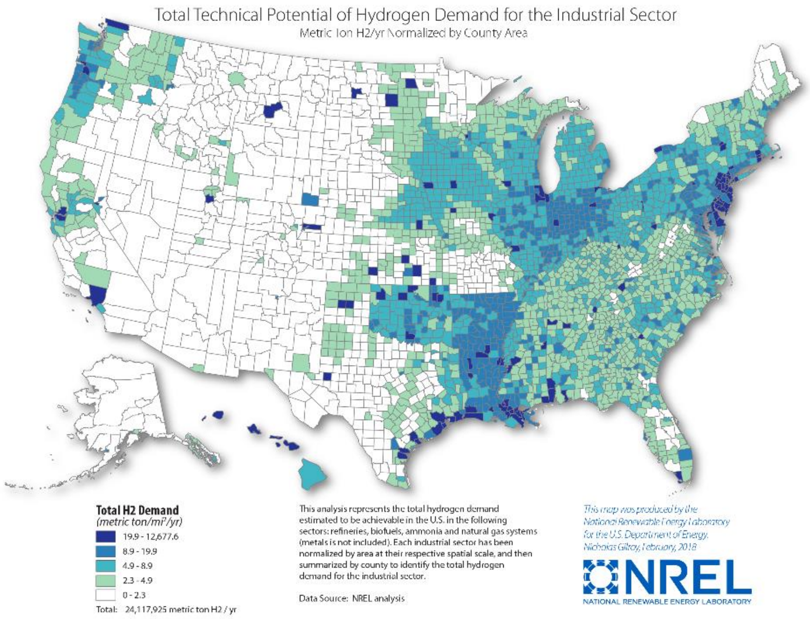

Figure D3: U.S. map indicating major sites of industrial demand for hydrogen, including refineries, biofuels, ammonia, and natural gas systems (based on preliminary NREL analysis). Darker blue areas represent regions of higher industrial demand.

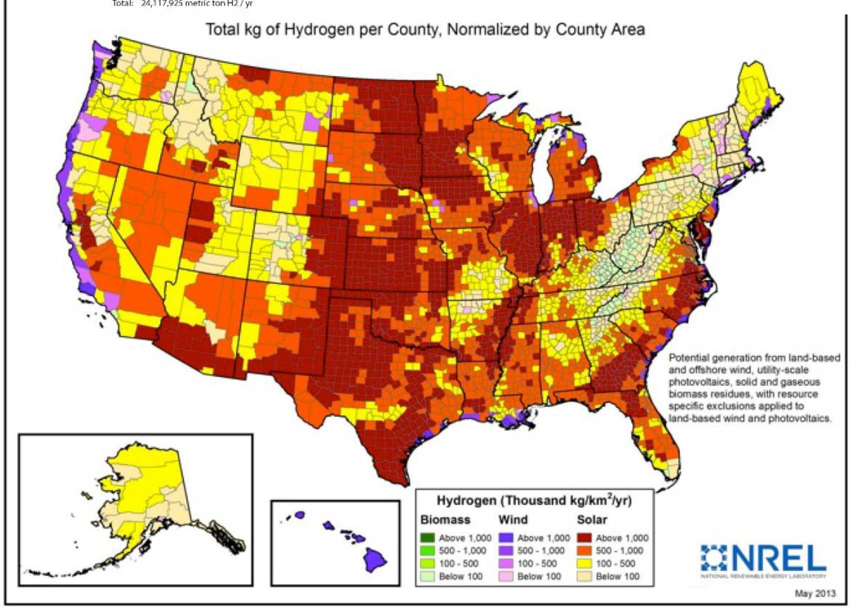

Figure D4: U.S. Map indicating potential renewable resources for large scale hydrogen production including land and offshore wind, PV, and biomass (based on NREL analysis compiling information from multiple DOE EERE Offices).[94]

In regions with a high penetration of renewables in the electricity grid, hydrogen can be produced using grid-tied electrolysis, taking advantage of the renewable electricity that might otherwise be curtailed during off-peak demand. The hydrogen could also be produced using renewable energy through off-grid options (such as integrated wind/electrolysis and solar/electrolysis facilities, as well as emerging technologies such as direct solar thermochemical or photoelectrochemical hydrogen production). Today, utilization of renewable energy can be deterred by the cost of connecting with the electricity grid, and energy transmission through the grid. Consequently, in some cases, use of renewable energy to produce chemical feedstocks and energy carriers, such as hydrogen, offers a potentially stronger value proposition compared with grid electricity options. The results of a recent modeling study demonstrate that the cost of long-distance electrical transmission normalized per delivered MWh is about eight times higher than for hydrogen, about eleven times higher than for natural gas, and twenty to fifty times higher than for liquid fuels. While the capital costs of construction of electrical transmission lines and the pipelines are about the same (between about $2 million and $4 million per mile, and may vary depending on the particular project size, location, topography, financing options, etc.) the energy carrying capacity of the electric wires is much lower than for gaseous and liquid pipelines. Multiple electrical transmission lines would have to be built in order to transport the equivalent amount of energy as a single high-capacity pipeline. Furthermore, operating energy losses are much greater in electrical transmission lines than in chemical fuel transportation. These two factors make electrical transmission the most expensive transmission method among the studied energy carriers.

The co-location of hydrogen production with industrial processes that can directly use the hydrogen to produce high-value products offers another approach for better monetizing resources in H2@Scale energy scenarios. Such co-location would effectively mitigate the need and costs of infrastructure to transport hydrogen long distances. In light of increasing market demands along with policies and customer preferences that could incentivize increased leveraging of renewables, the use of hydrogen to monetize diverse renewable energy resources and feedstocks that are currently stranded or underutilized is becoming more attractive. The ongoing development and widespread adoption of cost-effective technologies to capture and utilize these stranded/underutilized resources for large-scale hydrogen production is expected to be a critical enabler for H2@Scale. Some illustrative examples of monetizing regional renewable resources through large-scale hydrogen production are shown below. These include: 1) Cost-effective harnessing of wind and tidal power through hydrogen production, 2) Ammonia synthesis using co-located renewable hydrogen production, 3) Synthetic liquid fuel production leveraging regional resources for renewable hydrogen production; and 4) Biofuels production and the importance of low-cost renewable hydrogen.

Case Study: Use of Hydrogen to Capture Wind and Tidal Power

An example of the use of hydrogen to capture stranded energy at the megawatt-hour scale is in the Orkney Islands of Scotland. Orkney's power generation is comprised of a higher proportion of renewables than any county in the UK. In recent years, the islands' installations of wind power have increased dramatically, from 5,000 kW in 2000 to 45,000 kW in 2014. In 2010, the islands also closed the world's first leasing round for commercial wave and tidal projects, awarding leases for 1.2 GW of installations. Orkney is connected to the Scottish mainland via subsea cables, and became a net exporter of electricity in 2013.[95,96] However, a challenge facing existing and new installations of renewable power is connection with the electricity grid. Wind turbines in Orkney currently curtail over 30% of their output on average.[97] Curtailment is driven in part due to a moratorium on connections of new renewables to the region's distribution grid, instated in 2012 when the grid reached its capacity.[98]

Many solutions are being considered to mitigate curtailment of Orkney's power generation. Examples include dynamic grid management, use of 2 MW of battery energy storage, as well as the Building Innovative Green Hydrogen Systems in Isolated Territory (Big HIT) and Surf'n'Turf projects to produce hydrogen from otherwise curtailed electricity.[99] These projects will utilize otherwise curtailed wind and tidal power to produce hydrogen via 1.5 MW of electrolysis. About 50 tonnes of hydrogen are expected to be produced per year, which will be transported by ferry to the Orkney islands for use in stationary heat and power (for ferries and buildings), as well as transportation (in fuel cell range extenders for light duty vehicles).[100,101]

Case Study: Renewable Hydrogen Conversion into Chemicals and Fertilizers.

Hydrogen may serve as an intermediate in converting renewable energy into chemicals and fertilizers if hydrogen generated from renewable sources is substituted for hydrogen produced from natural gas in the synthesis process.

One example of such development is the University of Minnesota's Wind-to-Ammonia project at the West Central Research and Outreach Center. About $400 million worth of anhydrous ammonia fertilizer is used annually in Minnesota. Minnesota has no fossil energy resources though, so all ammonia (which is commercially produced from natural gas in industrial scale Haber-Bosch plants) is brought to the state from other locations in the U.S. and overseas. On the other hand Minnesota, located on the edge of the Great Plains, has an abundant wind resource in the western portion of the state. A lack of transmission means the resource is only partially developed. Developing the wind resource to include hydrogen production would mean better use of the wind resource, added jobs and stability in the local rural economy, and an opportunity for ammonia production that could be used by local farmers to replace imported fertilizers. The map in Figure D5 shows how wind resource is co-located with ammonia demand.

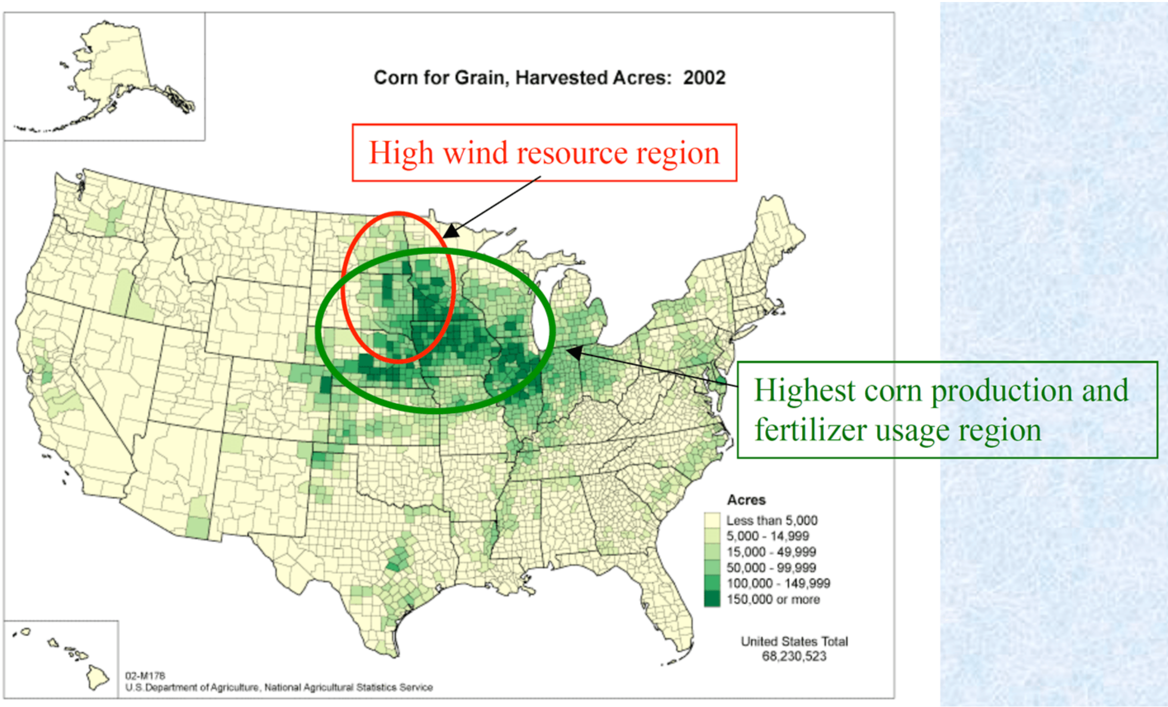

Figure D5: High supply of wind and high demand for ammonia (courtesy of University of Minnesota College of Food, Agriculture, and Natural Resource Sciences)

The University of Minnesota project utilizes a 1.65 MW wind turbine installed at the research facility. Electricity from the wind turbine is used to power a low-temperature electrolyzer to produce renewable hydrogen. A prototype scaled down Haber-Bosch system is then used to combine 1.28 pounds (lb)/hour (h) H_2 with 5.74 lb/h nitrogen (N_2) to produce 7.35 lb/h liquid ammonia at 250 psi.

The pilot plant started operation in early 2013. The economics, though, are not competitive with a large scale NG based ammonia synthesis. More recently, a team at the University of Minnesota started a project to investigate modifications to the Haber-Bosch process to incorporate ammonia separation with the synthesis reactor. This would allow operation of the process at lower pressure, significantly reducing cost.

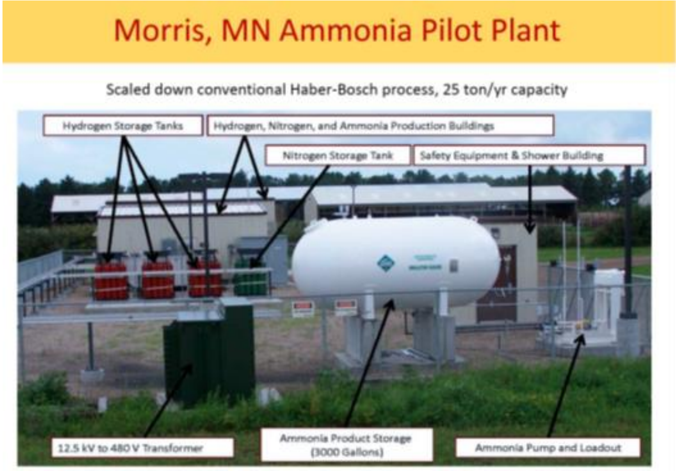

Figure D6: Wind-to-Ammonia project showing NH_3 production facility and wind turbine[102]

Case Study: Renewable Synthetic Liquid Fuels Production

Hydrogen can also be an intermediate in converting renewable wind and solar energy into synthetic liquid fuels that can be readily stored and transported. For renewable synthetic fuels production, hydrogen produced through water splitting using renewable wind and solar energy should be combined with CO_2 captured from point sources, like power plants or industrial furnaces, or eventually with CO_2 captured directly from air, to produce hydrocarbon liquids, like methanol, dimethyl ether (DME), or even gasoline and diesel-type fuels.

An example of renewable energy conversion into liquid fuels is the George Olah plant in Svartsengi, Iceland, where geothermal energy and hydropower are used to produce methanol. The plant uses grid electricity (comprised largely of geothermal and hydro power) to produce 800 tonne (t)/year (yr) of hydrogen using low-temperature alkaline electrolysis. This hydrogen is combined with 5,600 t/yr CO_2 released in geothermal steam, and then combined with hydrogen to produce 4,000 t/yr of methanol. The plant was first commissioned in 2012 and expanded in 2015. Geothermal power is available worldwide, and production capacity has grown at a rate of about 3% per year since 2005; 27% of the world's geothermal power production capacity is in the U.S.[103]

Figure D7: George Olah geothermal-to-methanol plant utilizing hydrogen from water electrolysis[104]

Case Study: Hydrogen Demand in Biomass Conversion to Biofuel

One approach to production of biofuels is through upgrading of biomass using hydrogen. The 2015 NREL report[105] on conversion of lignocellulosic biomass to hydrocarbons describes a potential biomass conversion process to hydrocarbon products by way of catalytic conversion of lignocellulosic-derived hydrolysate. The described techno-economic model leverages expertise established over time in biomass deconstruction and process integration as well sugar purification and catalysis. The overarching process design converts biomass to diesel and naphtha-range fuels using dilute-acid pretreatment, enzymatic saccharification, purifications, and catalytic conversion focused on deoxygenating and oligomerizing biomass hydrolysates. The hydrogenation step is an important part of the process. The report estimates hydrogen demand at ~0.54 kg H_2 per GGE of produced biofuel.[106]

Feasibility-level analysis has been performed for a plausible catalytic conversion process to meet an intermediate DOE cost goal of $5/gallon/GGE in a timeframe prior to 2022. It was found that biorefinery processes of 2,205 dry tons biomass/day could achieve a fuel selling price of ~$4.0/GGE with a total fuel yield of 78.3 GGE/dry ton assuming low-cost hydrogen is purchased from off-site production (e.g., through SMR of natural gas). However, if hydrogen is instead produced in situ by diverting a fraction (41%) of hydrolysate carbon towards reforming reactions, fuel yield drops to 45.3 GGE/dry ton and selling price increases to $5.48/GGE as shown in Figure D8. If instead hydrogen is produced by diverting a fraction of biomass to a gasification process to produce and subsequently refine syngas to hydrogen, such a scenario would require 36% of the available biomass and would translate to a fuel yield of 50.1 GGE/dry ton and selling price of $4.95/GGE, also shown in the Figure. (Note that alternative biofuel pathways may require significantly lower hydrogen input [i.e. biological conversion of sugars to hydrocarbons require only 0.05 kg H_2 per gge biofuel], but the cost of production is higher, resulting in minimum fuel selling price MFSP of $5.10 /GGE[107]).

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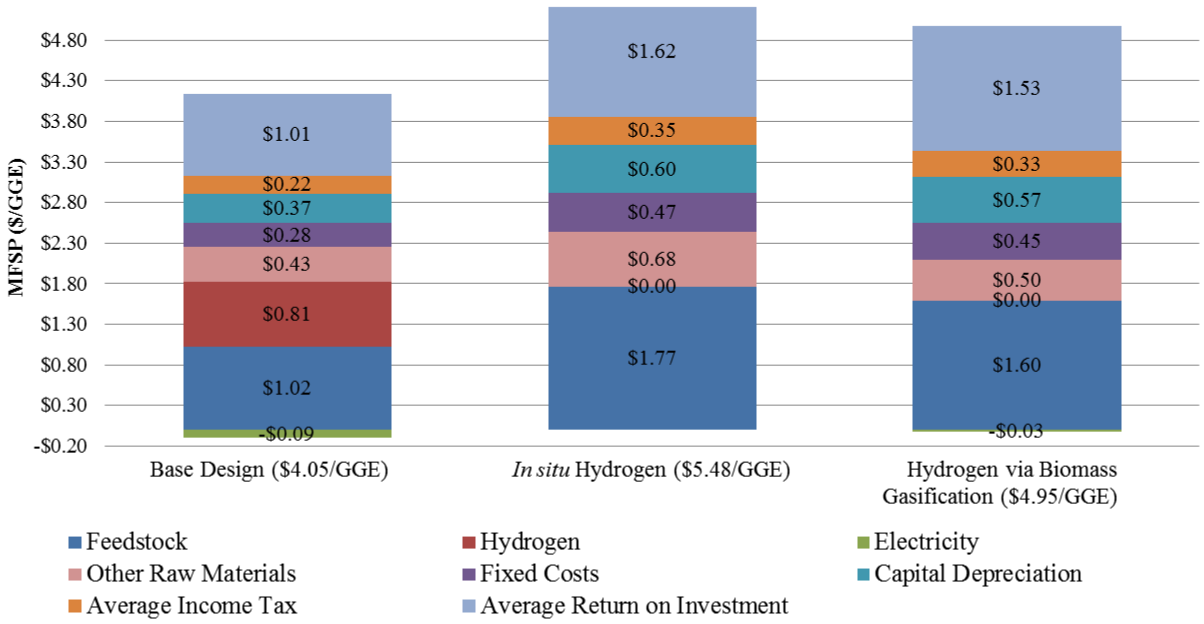

Figure D8: Minimum fuel selling price results for external (purchased) hydrogen base design versus internal hydrogen production via in situ reforming of hydrolysate and biomass gasification

The analysis emphasizes the critical role of hydrogen and the associated hydrogen price, given the large amount of hydrogen import required in the base case. While the single-point sensitivity to hydrogen price is intended to capture a reasonable range of expected costs in the context of U.S. natural gas price fluctuations over recent years (i.e., $2–$7.4/million BTU (MMBTU), hydrogen price variances are further expanded over a larger range of values, as shown in Figure D9 below, to consider potential implications for higher natural gas prices based on the H2A model for current SMR technology.[108] The analysis in the report suggests that availability of low-cost sources of hydrogen in the regions of the country with high biomass producing potential can significantly reduce the cost of biofuel production, thus stimulating growth of biorefineries and production clean domestic fuels.

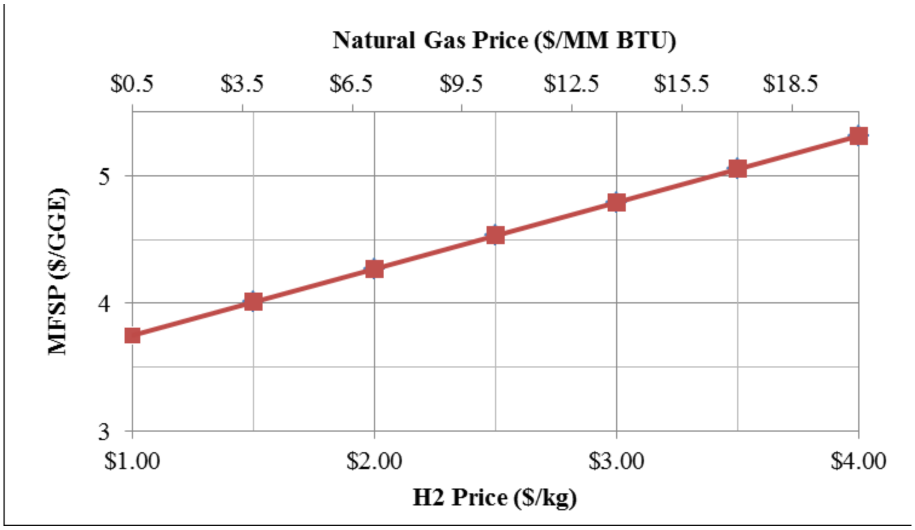

Figure D9: MFSP sensitivity scan as a function of hydrogen price and correlated SMR natural gas prices

Case Study: Nikola Motors FCEV Semi-truck and 700 MPa H_2 Refueling Infrastructure

An example of a hydrogen and fuel cell technology application in the large scale cargo trucking industry is Nikola Motor Company's Nikola Two semi-truck.[109] The hydrogen-powered truck performance is expected to match or exceed that of a regular diesel truck having horsepower up to 1000 HP, torque up to 2000 ft-lbs and operating range up to 750 miles using up to 80 kg of hydrogen at 70MPa (10,000 Psi). Because of higher torque and lower weight the acceleration from 0-60 mph under load should be about 30 seconds compared 60 seconds for a regular diesel tractor trailer.

Figure D10: Nikola One hydrogen fuel cell semi-truck[110]

To allow for refueling of the truck fleet Nikola Motor Company is cooperating with Nel ASA – a world leader in hydrogen production through water electrolysis - to develop the largest hydrogen refueling station network spanning across the US initially with 16 commercial stations thereafter following by a roll out of 400+ stations. Nikola has already started the work on two stations for research and development purposes to develop the 70MPa fast fueling. Nikola's objective is to produce hydrogen through renewable energy sources whenever possible by using wind, solar and hydro-electricity. Nikola Motor is also helping coordinate standardization with SAE and ISO of this new hydrogen infrastructure and vehicle.

Some specific details include:

- Hydrogen commercial stations will initially produce four-eight tons daily. Nikola intends to sell hydrogen mostly to heavy duty H70 HF (High Flow) FC vehicles but each station will have light H70 J2601 duty fueling. The stations are planned to be able to be expanded to produce up to 32 tons per day, for truck depot applications
- Each station will have around 1,000 kg+ of backup storage for redundancy
- Each Nikola station is anticipated to produce for both light and heavy-duty hydrogen at 70MPa (10,000 psi)
- Each Nikola truck is anticipated to consume between 50-75 kg per day, depending on application

APPENDIX E: Leveraging Industries and Infrastructure for H2@Scale

Case Study: Repurposing Natural Gas Pipelines for Hydrogen Service[111]

Currently, up to 20% of the existing oil and natural gas pipeline infrastructure in the U.S. is being idled for a number of reasons, including the fact that their sources and destinations no longer match where profitable markets exist.

Idled pipelines could offer a significant opportunity for large-scale energy storage. The rough estimate in Table E1 below indicates that over 500-GWh of storage is possible if only 2% of the installed U.S. pipeline infrastructure was idled and available to store hydrogen. The goal would not be to use the idled pipelines primarily to move energy from place to place, but rather to repurpose parts of the existing pipeline infrastructure to store large volumes of hydrogen. Idled pipeline storage may enable opportunities to put energy in at one point and withdraw it from storage at another point.

Table E1: *U.S. Hydrogen Energy Storage Potential in Repurposed U.S. Pipeline Infrastructure*

	Crude Trunk Lines	Refined Oil Lines	Natural Gas Gathering Lines	Natural Gas Transmission Lines
Approx. Total Pipeline length (km)	80,467	152,888	32,187	447,398
Idled Pipeline length, 2% of total (km)	1,609	3,058	644	8,948
Nominal Diameter (cm)	46	61	41	61
Nominal Pressure (MPa)	4.1	4.1	5.8	5.8
H_2 density at Pressure, 25°C, (kg/m^3)	3.2	3.2	4.5	4.5
Volume (m^3)	300,000	900,000	100,000	2,600,000
Approx. H_2 Energy Storage potential based on H_2 LHV of 120MJ/kg (GWh)	32	96	15	390

Approx. H_2 Energy Storage Potential (GWh)	**500**

Case Study: Hydrogen as a By-Product of Industrial Processes

Over the past decade, evolutions in the domestic energy system have created new and emerging sources of hydrogen supply. For example, hydrogen is a by-product of the production of chlorine and ethylene. U.S. production capacity for ethylene is expected to grow by 50% by 2020 as a result of growth (shown in Figure E1) in domestic supply of natural gas liquids (NGLs) such as ethane, propane, and butane that are present in natural gas streams in certain regions of the country. NGLs are feedstock in the production of high-value chemicals, such as ethylene, and are driving billions of dollars of investments in domestic chemicals production as well as export markets.[112,113,114] By 2020, the hydrogen by-product from chlorine and ethylene production is expected to reach nearly 3 million tonnes per year (sufficient to fuel about 16 million FC vehicles).

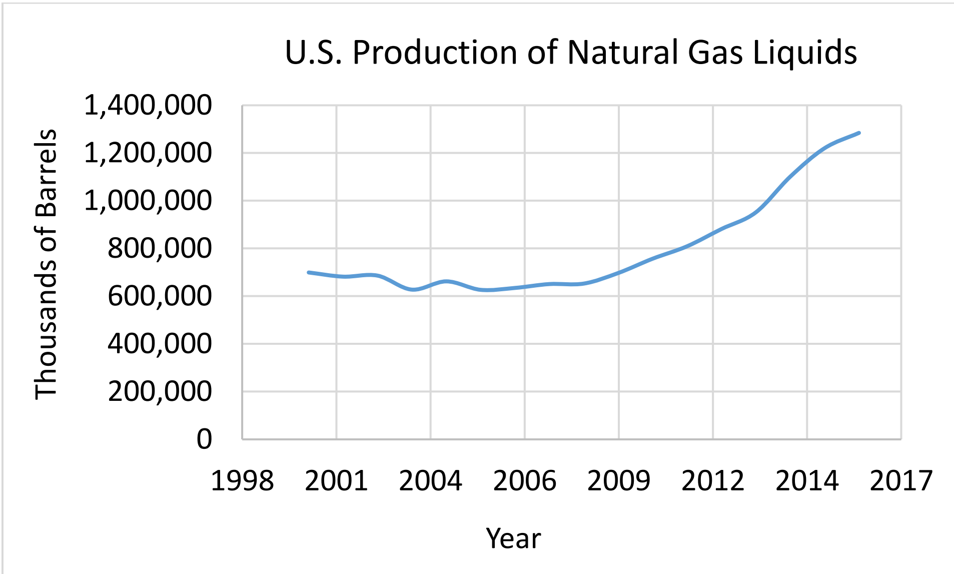

Figure E1: Growth in U.S. Production of Natural Gas Liquids (U.S. Energy Information Administration[115])

Today, the by-product hydrogen is typically burned at the facilities where it is produced to provide heat to the process. Hydrogen can, however, be substituted by cheap natural gas as fuel and recovered from these facilities to be used to supply higher value markets, such as fuel cell vehicles. The cost of recovering hydrogen from by-product streams is estimated to be \$0.50-\$0.60/kg. This includes the cost of replacing the hydrogen with natural gas as the process heating fuel, and purifying the hydrogen via pressure swing adsorption. For comparison, the cost of producing hydrogen from a new SMR plant (the incumbent technology) is <\$2.00/kg.

As an example, a joint venture between Yara and BASF recently announced the opening of the newest ammonia plant in Freeport, Texas that will produce 750,000 metric tons of ammonia per year using by-product hydrogen.[116] The industrial gas company Praxair will capture and purify by-product hydrogen from Dow's new ethylene cracker plant, also in Freeport and which started up in September 2017, and deliver it to Yara's plant through Praxair's hydrogen pipeline grid. The hydrogen contract is structured in such a way that using the primary supply of by-product hydrogen, rather than hydrogen produced from fossil fuels, results in ammonia which has a significantly reduced carbon footprint.

However, widespread recovery of by-product hydrogen from chlor-alkali and ethylene cracking plants in other parts of the country is restricted by the substantial costs of infrastructure required to connect demand with supply. Figure E2 shows a map of cracking and chlorine plants. California and the Northeast are experiencing a growing hydrogen demand for FCEVs. By-product hydrogen supply, however, is concentrated around the Gulf Coast. Emerging satellite industries requiring low-cost hydrogen (such as value chemical, food, metallurgy, etc.) could be attracted by the opportunity to better leverage the by-product hydrogen in these regions.

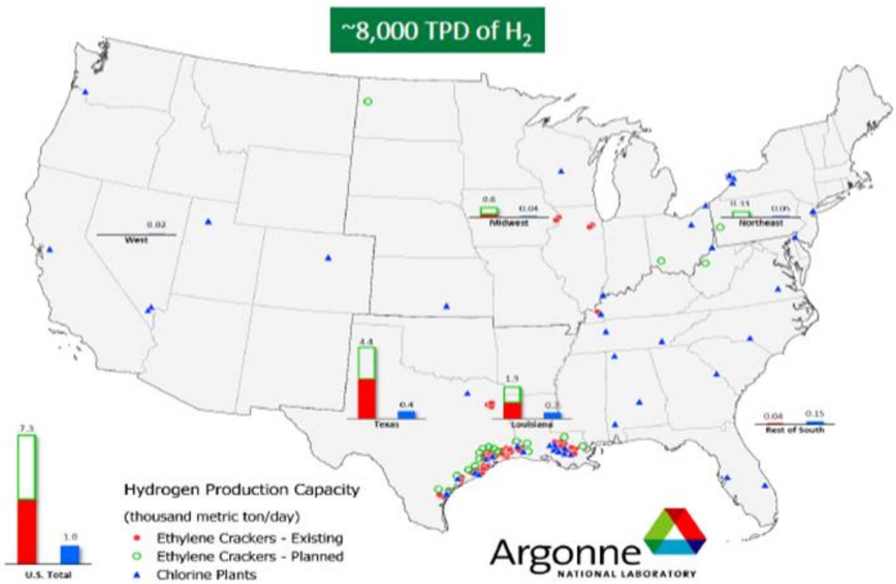

Figure E2: Locations of U.S. Cracking and Chlorine Plants[117]

Case Study: Natural Gas Conversion into Hydrogen and Solid Carbon

Non-oxidative thermal decomposition of natural gas to carbon and hydrogen, can be an attractive alternative to SMR and produce CO_2-free hydrogen. Key attributes for methane decomposition are that the gaseous product stream contains a very high concentration of hydrogen, the relatively low heat of reaction, and production of a solid carbon that can be sequestered or sold as a commodity by-product. The produced carbon can be sold as a co-product, thus providing economic credit that reduces the delivered net cost of hydrogen. Suitable technologies optimized to produce both hydrogen and valuable carbon byproducts must be developed, as no known commercial process produces both carbon and hydrogen as commercial products. Commercial processes for producing carbon black typically burn the hydrogen to generate process heat, with a portion of the heat used for the reaction process and the remainder used at the plant or sold to nearby facilities. Commercial processes also exist for producing fuel cell-quality hydrogen, but carbon is not recovered. Instead, carbon is burned to regenerate the catalyst and to provide process heat.

Techno-economic analysis performed in a recent report by Argonne National Laboratory (ANL) and the Pacific Northwest National Laboratory (PNNL)[118] demonstrates the potential for significant reduction in hydrogen cost in emerging methane pyrolysis technologies with the sale of valuable carbon byproducts— yet the carbon selling price is a critical factor and needs to be high in order for such technologies to compete with the incumbent SMR technology. Further development of natural gas pyrolysis methods that yield high-value forms of carbon, such as carbon fiber or carbon nanotube is critical for successful commercial implementation. Examples of existing high-value carbon markets include:

- Graphite is a high-value product used in lithium-ion batteries.
- Carbon fiber is a premium product used in carbon-reinforced composite materials.
- Nanotube carbons are high-value products used in polymers, plastics, and batteries.
- Needle coke is used in graphite electrodes for electric arc steel furnaces.

Carbon product pricing can vary tremendously and depends on product characteristics and purity. It should be noted that solid carbon as a by-product can reduce the cost of the methane decomposition reaction only if sufficiently large markets for the carbon products are found. Some of the niche carbon markets, with the possible exception of carbon black and needle coke, would be saturated before a fraction of the overall hydrogen market demand is met.

Carbon black is the oldest and most mature market for carbon. Currently, carbon black for use in tires, plastics and electrical equipment is largely produced by pyrolysis of heavy oil fractions from processing crude oil, not of natural gas. The high reaction temperature (>1000°C) required for methane conversion contributes greatly to process inefficiencies, limits the choice of materials of construction, adversely impacts catalyst life, and exacerbates heat losses. Catalytic thermal decomposition has been extensively researched at the laboratory scale with the primary purpose of decreasing the temperature required for conversion. Non-thermal plasma processes for producing carbon and hydrogen have been reported as alternatives, but they require a significant amount of electric power. Molten-metal technology has been reported to have a major benefit from the relative ease of solid carbon separation from the molten metal due to density differences; however, a high conversion temperature is still required. Solar thermochemical processes leverage the use of inexpensive solar heat, but non-catalytic processes require high temperature (e.g., 1600°C), and the high conversion temperature requires the use of expensive construction materials. Figure E3. Shows the U.S. carbon black market projected through 2022.

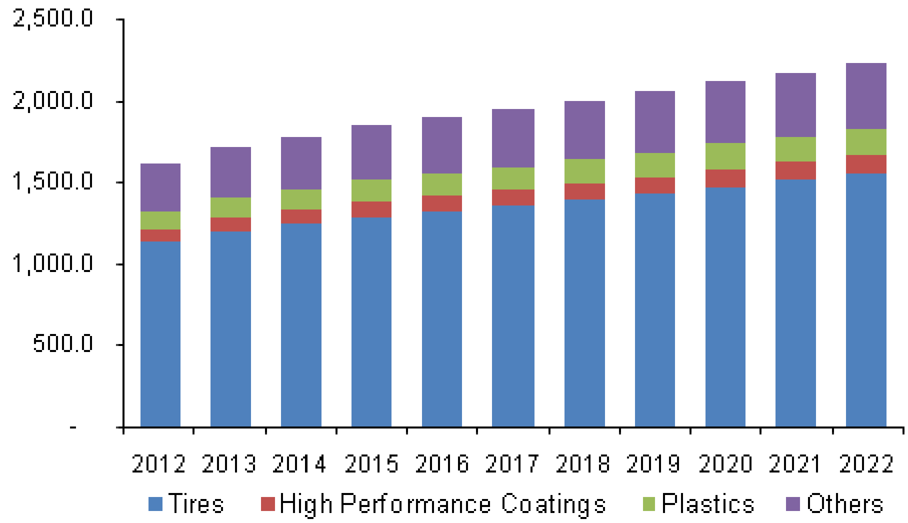

Figure E3: U.S. Carbon Black Market Volume (in kilotons) by Application from 2012 Projected through 2022 [119]

With favorable market factors provided by low-cost natural gas prices in the U.S., new companies such as Monolith from Redwood City, California are entering the market. Monolith's pilot plant in Redwood City, shown in Figure E4, is the first carbon black manufacturing facility built and licensed in the United States in the last 30 years. In October 2016, Monolith broke ground on construction of a larger commercial carbon black plant in Hallam, Nebraska. Hydrogen from that process will be utilized to provide carbon free electricity in the nearby power plant.

Figure E4: Monolith's Seaport demonstration plant located in Redwood City, California [120]

Case Study: Nuclear-Renewable Hybrid Energy System for Hydrogen Production

An area of interest for alignment of hydrogen production with nuclear power is in the development of "hybrid energy systems" based on high-temperature electrolysis that integrate heat from nuclear plants, integrate electricity from renewable generation, and water splitting technologies that produce hydrogen. Such hybrid systems have the potential to offer nuclear generators a new revenue stream (in addition to electricity generation), preventing them from idling at times when baseload electricity production is unprofitable. A recent report by NREL[121] analyzed the financial performances of two nuclear-renewable hybrid energy systems (N-R HESs) scenarios. Each N-R HES has the potential to generate electricity for the grid and produce hydrogen. The High-Temperature Electrolysis (HTE) scenario includes an HTE subsystem that utilizes heat from the nuclear reactor and electricity from the thermal power cycle, the wind power plant, and/or the grid. Two Low-Temperature Electrolysis (LTE) scenarios include an LTE subsystem that utilizes only electricity. One involves projected electrolyzer costs and performance and the second involves lower cost electrolyzers that have a reduced efficiency. Electricity for electrolysis could be from thermal power cycle, the wind power plant, and /or the grid.

APPENDIX F: Successful H-Prize Competition: H2 ReFuel

In recent years, the DOE has used prizes that were mandated by Congress to drive American innovation in addressing pressing energy challenges. For example, in 2014, the DOE launched the H-Prize, a competition that was mandated by the Energy Independence & Security Act of 2007[122], and solicited the development of a small-scale hydrogen fueling device. In 2017, the DOE awarded the $1-million H2-Refuel H-Prize to SimpleFuel for its successful demonstration of a 5 kg/day home hydrogen refueler (shown in Figure F1). As a result of this prize, SimpleFuel now offers a commercially available, cost-effective, 700 bar hydrogen fueling appliance for automotive applications such as state/municipal fleets (supporting 10-20 FCEVs per refueler), and workplace fueling. The modular, drop-in installation design is intended to simplify permitting and provide a stand-alone fueling option for areas outside of existing hydrogen infrastructure. The system can be integrated with renewable power, and its drop-in installation allows it to be easily redeployed, acting as a seed for growing hydrogen infrastructure.

The H-Prize competition comprised multiple contestants who were progressively down-selected by an independent panel of expert judges on the ability of their proposed technologies to meet stringent cost, performance, and safety criteria set by DOE.

After the judge's panel selected SimpleFuel as the finalist, the DOE hydrogen safety panel reviewed the device's safety features. Once the device was operational, NREL validated the operation of the SimpleFuel device over a number of months, using remote telemetry to measure performance data in real time. NREL compared the device's performance against the prize criteria and presented the results to the judge's panel who recommended that DOE make the $1-million award to SimpleFuel.

Figure F1: The SimpleFuel H_2 dispensing appliance, illustrating the ease of refueling[123]

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