The Center for Houston’s Future, an independent twenty-year-old non-profit affiliated with the Greater Houston Partnership (the Houston region’s major economic development organization) is pleased to submit these comments in response to the Department’s Request for Information on Clean Hydrogen Manufacturing, Recycling, and Electrolysis.

The Center focuses on understanding future global trends and their impact on the Houston region, and then, works with community, business, and government partners to spur actions to improve Houston’s presence as a major global city.

Against the backdrop of climate change and Houston’s position as the world’s energy capital, the Center has been heading a community effort focused on recognizing that Houston can and should become the “low-carbon” energy capital. The Center, over the past several years, has undertaken research, conferences, webcasts, projects, work with partners and other activities to catalyze this vision.

The Center has led an intensive process of convening energy companies, academic institutions, local and state government agencies, and nonprofits to work collaboratively on developing a common vision and roadmap for creating a clean hydrogen ecosystem in the Houston region. Currently, over 120 stakeholders are participating in this roadmap development process, assisted by global consulting firm McKinsey & Company. We expect to publicly release the roadmap in the next month.

As a result of this work, we believe that the Texas Gulf Coast, home to the nation’s largest concentration of hydrogen production assets, dedicated hydrogen pipeline infrastructure and large number of sophisticated industrial hydrogen customers, can leverage these unique assets to become a global clean hydrogen leader.
As we described in our Hydrogen Hub RFI submission, our research shows that the Texas Gulf Coast anchors one of the world’s leading hydrogen systems, producing one third of U.S. total hydrogen gas per year from 48 production plants and over 900 miles of hydrogen pipelines (representing over half the US hydrogen pipelines capacity and a third of the global capacity). Three of the world’s six hydrogen salt storage caverns are located near Houston. Our assets will also allow us to lead in “blue” hydrogen and “green” hydrogen. ERCOT is the largest wind power state and second largest utility scale solar state, and our research shows that Texas will be able to produce green hydrogen at globally competitive prices.

**Opportunity for leveraging Houston’s role as home to a major energy manufacturing sector**

As discussed in our comments below, the Houston region also has the assets, talent, and workforce necessary to assist DOE with the goal of achieving electrolysis costs of $2/kg by 2026 and the “earthshot” goal of further reducing the cost to $1/kg by 2030.

We believe the Houston energy sector is well positioned to provide many of the solutions required to achieve these DOE goals. Houston’s energy manufacturing sector, already important suppliers to the energy industry, can play a significant role in producing electrolyzers and their components, and can assist in achieving DOE’s objective of creating a domestic, low-cost clean hydrogen supply chain.

We briefly describe the characteristics of the sector to provide some context for our perspectives below. In our comments below, we then show how DOE can leverage the strengths of the existing energy manufacturing sector in reaching its 2026 and 2030 targets by building on this deep base of companies, workforce, and knowhow in Houston’s energy manufacturing sector to reach these goals.

The Houston energy sector comprises the largest concentration of petrochemical manufacturing in the world, including for synthetic rubber, insecticides, and fertilizers. It is the world's leading center for oilfield equipment construction. Houston is home to more than 3,000 energy-related businesses, including many of the top oil and gas exploration and production firms and petroleum pipeline operators.¹

Houston is also home to the top nine companies in oil and gas manufacturers in the US market as shown the chart below.²

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² [https://www.industryselect.com/blog/top-9-us-oil-and-gas-machinery-manufacturers](https://www.industryselect.com/blog/top-9-us-oil-and-gas-machinery-manufacturers)
Top Nine U.S. Oil and Gas Machinery Manufacturers

<table>
<thead>
<tr>
<th>COMPANY</th>
<th>EMPLOYEES ON SITE</th>
<th>CITY</th>
<th>STATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halliburton Co.</td>
<td>3,000</td>
<td>Houston</td>
<td>TX</td>
</tr>
<tr>
<td>Schlumberger Technology Corp.</td>
<td>2,100</td>
<td>Sugar Land</td>
<td>TX</td>
</tr>
<tr>
<td>Schlumberger Technology Corp. - DT&amp;R Div.</td>
<td>2,000</td>
<td>Houston</td>
<td>TX</td>
</tr>
<tr>
<td>Baker Hughes Co.</td>
<td>1,500</td>
<td>Houston</td>
<td>TX</td>
</tr>
<tr>
<td>Halliburton Energy Services, Inc.</td>
<td>1,500</td>
<td>Houston</td>
<td>TX</td>
</tr>
<tr>
<td>Western Geco, LLC</td>
<td>1,500</td>
<td>Houston</td>
<td>TX</td>
</tr>
<tr>
<td>Weir Pumps, Inc.</td>
<td>1,000</td>
<td>Fort Worth</td>
<td>TX</td>
</tr>
<tr>
<td>National Oilwell Varco, Inc.</td>
<td>975</td>
<td>Orange</td>
<td>CA</td>
</tr>
<tr>
<td>Baker Hughes Oilfield Operations, LLC</td>
<td>900</td>
<td>Houston</td>
<td>TX</td>
</tr>
</tbody>
</table>

As we did in our Hydrogen Hub RFI response, we first provide some overarching principles that DOE should consider in implementing the provisions of the BIL relating to clean hydrogen RD&D and manufacturing. We then apply these principles to respond to specific questions in the RFI.

We start by suggesting that DOE adopt a more expansive-focus in implementing these sectors by taking a broad definition of the electrolysis supply chain. By adopting such a broad definition, existing energy manufacturers can contribute in a significant way to achieving the DOE’s clean hydrogen goals.
Key Principles in Implementing DOE’s Goals for Clean Hydrogen RD&D and Manufacturing

DOE Should Adopt a Broad Definition of the Electrolysis Supply Chain

DOE’s recent supply chain report, Water Electrolyzers and Fuel Cell Supply Chain Deep Dive Assessment, defined the supply chain for electrolysis and fuel cells as follows:\(^3\):

![Diagram of electrolysis supply chain](image)

The focus on early stages of the development of electrolysis equipment reflects the extensive research effort that DOE has undertaken over many years in developing the underlying raw materials and components required to lower the cost of electrolysis.

While the DOE’s efforts are commendable and the results of the research consortia created by the DOE have significantly lowered the cost of electrolysis, we believe that now is the time for the Department to widen its lens and focus on the creation of a domestic electrolysis industry by incorporating the entire supply chain in its efforts.

This broader focus will require that the Department look beyond raw and processed materials and subcomponents required to build electrolyzers as discussed in the recent DOE supply chain report.

As an example, the Department can adopt a framework similar to that of a recent study of electrolysis supply chain by the Dutch manufacturing industry. This study recognized that the supply chain consists of the total package of products and services required to build an electrolyzer. \(^4\) While materials, parts and components are a significant part of the supply chain,
it also demonstrated that the supply chain requires substantial investments in subsystem development, systems integration and engineering and construction resources, as shown below:

Segmentation of supply chain:
3. Top-down decomposition

![Diagram of PEM electrolysis system (example)]

DOE has recognized that a secure, resilient energy supply chain will be critical for capturing the economic opportunity inherent in the energy transition.\(^5\)

We believe that the Department, if it is to achieve the goal of creating viable supply chains for electrolysis to support the broader goals of the energy transition, would be well-served by broadening its focus beyond materials, parts, and components to encompass the entire supply chain required to create an electrolysis industry.

Reframing the Department’s priorities to encompass the entire value chain will have significant impacts on how the Department approaches the development and implementation of both the Clean Hydrogen Electrolysis RD&D Program and the Clean Hydrogen Manufacturing RD&D program.

Below we discuss some of these implications.

**DOE should leverage existing components and materials rather than focus solely on “novel” and “unexplored” areas**

As an example of how the DOE should reframe its work, we need to look no further than the focus of this RFI. The RFI has requested information on the “novel” (see Q1 of the Clean Hydrogen Electrolysis RD&D Program).

\(^5\) https://www.energy.gov/policy/securing-americas-clean-energy-supply-chain
Electrolysis RD&D RFI) or “unexplored” (see Q2 of the Clean Electrolysis RD&D RFI) components, parts, and materials.

Yet, we believe that DOE should also recognize that many parts of existing energy supply chains could be leveraged to reduce the cost of electrolysis. For example, as shown below, the Dutch Manufacturing study demonstrates that many component and subsystem parts can be leveraged from existing energy supply chains.  

![Detailed built-up for PEM electrolyser system](image)

As a result, DOE’s focus for both electrolysis and for manufacturing should include identifying not only novel or undefined materials, parts, and components, but should also look for those existing elements of the energy manufacturing value chain that can be leveraged to accelerate the cost reduction of electrolysis.

**DOE should include the entire electrolysis value chain in its RFPs**

Studies consistently demonstrate that for both PEM and Alkaline electrolysers, the cost of the electrolyzer stack represents around 50% of overall system costs. While the PEM and Alkaline technologies have different stack cost characteristics (with electrode and mechanical components accounting for a larger share in Alkaline than in PEM systems), in each technology

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the balance of plant, power electronics and water and gas treatment elements represent approximately 50% of the system costs.\(^7\)

Looking at both stack and system costs will be important to achieve the Department’s aggressive cost targets. To illustrate this point, a study by NREL has projected the greatest potential cost reduction in total system costs for electrolyzers will be in the non-stack aspects of the value chain.\(^8\) While stating that the largest cost reduction potential is in the stack, the study also found that “balance-of-plant (BOP) cost for a 1-MW electrolyzer contributes to about two-thirds of the system cost, with power electronics contributing half the BOP cost, while the water circulation and hydrogen processing subsystems each share about one-fifth of the BOP cost.”

Thus, more than innovation to stack materials components and architectures is required. Effective scale up to industrial size hydrogen plants will require innovation across the supply chain including balance of plant components, as well as innovation in systems integration and in creating a virtuous cycle of learning from opportunities for demonstration and early market development. As shown on the chart below, the supply chain for electrolysis should incorporate manufacturers who understand balance of plant and system integration and customers who will have an important role to play in identifying and developing the needs of the industry.\(^9\)

Thus, in implementing this program, DOE should include the innovation challenges related to the materials, architecture, and components of the stack as well as low-cost manufacturing

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\(^8\) NREL, Manufacturing Cost Analysis for PEM Water Electrolyzers, [https://www.nrel.gov/docs/fy19osti/72740.pdf](https://www.nrel.gov/docs/fy19osti/72740.pdf)

\(^9\) Electrolyzers: Opportunities for the Dutch manufacturing industry, op. cit.
processes and opportunities for early demonstration and market development that will factor into plans for effective scale up of industrial hydrogen plants.

**DOE should focus on leveraging technology from existing energy supply chains**

In addition to working broadly at the entire supply chain, DOE should be seeking to leverage those energy manufacturing companies with a strong position or competitive advantage in related markets, such as the oil and natural gas market. These industry segments already possess relevant knowledge and technology that can be leveraged to address manufacturing challenges related to hydrogen’s unique characteristics as indicated in the chart below:

<table>
<thead>
<tr>
<th>Hydrogen Characteristics</th>
<th>Existing technology</th>
</tr>
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<tbody>
<tr>
<td>Not detectable</td>
<td>Gas sensors</td>
</tr>
<tr>
<td>Small molecule</td>
<td>High quality materials, such as alloys, liners, coatings, and sealants</td>
</tr>
<tr>
<td>Low density</td>
<td>High pressure and cryogenic materials and know-how</td>
</tr>
<tr>
<td>High purity</td>
<td>Filtering and separation technologies</td>
</tr>
</tbody>
</table>

Thus, DOE should investigate existing energy supply chains to determine where they can provide the technologies required to meet its cost targets.

**DOE should focus on achieving “early wins” in Manufacturing**

Adopting a broader supply chain approach means that DOE should look for opportunities to cost reduce the manufacturing process. These types of cost reductions are likely to produce more immediate results while the payoffs from DOE’s more fundamental research mature.

As shown on the chart below, research by the Dutch manufacturing industry shows that “early cost reduction wins” can come from reducing the cost of electrolysis through manufacturing (which occurs at higher TRL levels) in addition to investment in innovation in components and materials (which occur at lower TRL levels and have longer term impacts).  

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10 Electrolyzers: Opportunities for the Dutch manufacturing industry, op. cit.
Thus, DOE should identify “early wins” in high TLR areas to build scale at the same time as it focuses on new RD&D. By broadening the scope of its work to include manufacturing and design, as well as materials and components, DOE could accelerate cost declines by focusing initially on manufacturing cost reductions while investing in new innovations that could create a pathway to further cost reductions over the long run.

**Testing of Novel Components Should Leverage Existing Energy Skills and Know-how**

Bringing down the cost and shortening the time to market will require testing of novel components to understand their underlying characteristics. Understanding the underlying characteristics of materials is important, but testing should also focus on understanding customer needs of customers. Testing driven by potential users of the technology is critical since the ultimate goal of testing is to understand both the potential of and barriers to scaling up clean hydrogen technologies.
Incorporating the twin goals of materials testing with user needs implies that testing facilities should be physically located close to customers and to demand centers.

As a result, DOE should seek to link its innovation programs to hydrogen pilots and demonstrations.

We now answer selected DOE RFI questions using the Key Principles stated as a guide.

**Applying the Key Principles to Specific RFI Questions**

**Clean Hydrogen Equipment Manufacturing Questions**

A. Increasing efficiency and cost effectiveness of the manufacturing process or in the use of resources:

5. What existing energy infrastructure can be leveraged to reduce equipment manufacturing costs? What steps should be taken to reduce environmental impacts from repurposing existing energy infrastructure, especially in disadvantaged communities?

As discussed in the Key Principles section above, existing energy infrastructure can be leveraged to reduce equipment manufacturing costs across the clean hydrogen manufacturing value chain. NREL studies, cited above, found that “balance-of-plant cost for a 1-MW electrolyzer contribute to about two-thirds of the system cost, with power electronics contributing half the BOP cost, while the water circulation and hydrogen processing subsystems each share about one-fifth of the BOP cost.”

The principles above indicate that DOE should seek to:

- Expand the scope of its definition of the manufacturing supply chain.
- Seek to leverage existing components and materials rather than focus solely on “novel” and “unexplored” areas.
• Examine industry segments that already possess relevant knowledge and technology and determine how they can be leveraged to address challenges of hydrogen’s unique characteristics.

8. Would a consortium for advanced manufacturing for process validation and demonstration benefit the Hydrogen Equipment Manufacturing community? Which type of equipment specifically would benefit?

As discussed in the Key Principles, a consortium that seeks to bring down the cost of and shorten the time to market for novel components would benefit the industry. We recommend the consortium include the hydrogen equipment manufacturing community and customers as the ultimate goal of testing is to understand how end users will implement clean hydrogen technologies.

11. What specific areas should DOE prioritize under EPACT section 815 funding of $500M over 5 years, given the funding available in EPACT section 816 ($1B over 5 years) focused primarily on electrolysis?

As discussed in the Key Principles, DOE should consider an integrated approach to research and development and manufacturing of clean hydrogen equipment. DOE should seek “early wins” by reducing the cost of electrolysis manufacturing (which occurs at higher TRL levels) as well as investing in innovation in components and materials (which occur at lower TRL levels and have longer term impacts).

E. Clean hydrogen technology manufacturing opportunities in economically distressed areas of major natural gas producing regions and equity, environmental and energy justice strategies, including significant and meaningful community engagement plans

2. Please identify relevant manufacturing activities that exist in “regions of the United States with the greatest natural gas resources,” or that could leverage existing manufacturing facilities for new manufacturing of clean hydrogen technologies.

The Department should adopt a broad definition of “regions of the United States with the greatest natural gas resources” in order to incorporate the significant energy equipment manufacturing facilities that could assist in reaching the DOE’s clean hydrogen production goals. In the overview, we discussed how the Houston energy sector comprises the largest concentration of petrochemical manufacturing in the world and is also home to the top nine companies in oil and gas manufacturers in the US market. DOE should seek to incorporate the entire energy manufacturing value chain and should seek to identify those existing elements of the energy manufacturing value chain that can be leveraged to accelerate the cost reduction of electrolysis.
Approaches to Increase the Reuse and Recycling of Clean Hydrogen Technologies

F. Increasing efficiency/cost effectiveness of recovery of raw materials from clean hydrogen components and systems, including electrolyzers and fuel cells

4. Please comment on the value of forming a clean hydrogen manufacturing and recycling center that includes industry, national labs, labor unions, environmental justice organizations, community-based organizations, and academia.

As discussed in the Key Principles and in the Response to A.8, a consortium that seeks to bring down the cost of and shorten the time to market for novel components would benefit the industry. We recommend that the consortium include both the hydrogen equipment manufacturing community and customers, as the ultimate goal of testing is to understand how end users will implement clean hydrogen technologies.

Part II: Clean Hydrogen Electrolysis Program Questions

1. Electrolyzers including, low-temperature electrolyzers (i.e., liquid alkaline or membrane-based); high-temperature electrolyzers that combine electricity and heat to improve the efficiency of clean hydrogen production; advanced reversible fuel cells that combine the functionality of an electrolyzer and a fuel cell; and other advanced electrolyzers, capable of converting intermittent sources of electric power to clean hydrogen with enhanced efficiency and durability. Please state the specific electrolyzer technology your response relates to.

d. What demonstration projects could enable and/or validate progress towards the $2/kg goal?

As discussed in the Key Principles, we believe the Department would be well-served by broadening its focus beyond materials, parts, and components to encompass the entire supply chain required to create an electrolysis industry. Given that system and balance of plant represent over 50 percent of the cost of electrolyzers, demonstration projects should look across the entire manufacturing value chain. Indeed, it appears that focusing on scaling up manufacturing could create early wins.

5. Technologies that integrate hydrogen production with clean hydrogen compression and drying technologies, clean hydrogen storage, transportation or stationary systems, and renewable power or nuclear power generation technologies. Please note the technology or technologies discussed in the response.

b. How can demonstrations be best used to accelerate commercialization of electrolyzer produced hydrogen?
i. Who should be the target audience for electrolyzer demonstrations (e.g., utilities, end users, disadvantaged communities, investors, other)?

ii. How should demonstration projects be formulated to maximize their impact in accelerating acceptance and use of electrolyzer-produced hydrogen and what funding is required and at what scale?

iii. How can demonstrations for the integration of hydrogen production with existing manufacturing processes and infrastructure accelerate commercialization/acceptance? Please provide specific examples and funding required.

As discussed in the Key Principles, demonstrations for the integration of hydrogen production with existing manufacturing processes and infrastructure can accelerate commercialization/acceptance. The target audience for these demonstrations should be end users who are responsible for developing electrolysis projects.

8) National testing facilities

a. How would the establishment of national stack-level and system-level testing facilities provide value and/or accelerate the deployment of MW-and GW-scale electrolyzer systems?

b. If you have used electrolyzer test facilities before, what capabilities have you found beneficial and what were the limitations of those test facilities?

c. What scale, or range of scales, are needed in testing facilities?

d. What capabilities would the ideal testing facility possess?

e. What is the value of having multiple, diverse testing facilities (e.g., different geographical locations, capabilities, etc.)?

As discussed in the Key Principles, DOE should establish system level testing facilities close to hydrogen clusters to drive the development of scale and networking effects across the entire hydrogen value chain.

10) Program structure

a. Given the H2NEW, HydroGEN, and ElectroCat Consortia established by HFTO, what additional gaps need to be addressed in establishing the Clean Hydrogen Electrolysis Program? Is this best done by expanding or modifying these existing consortia or establishing new consortia? Provide any suggestions as appropriate and benefits of the proposed approach.

As discussed in the Key Principles, DOE should broaden its approach. This would require establishing new consortia and seeking to bring in new partners. Preliminary work by the Center for Houston’s Future shows that there are significant academic resources as well as industry players which could assist with the implementation of DOE’s goals. We would
be pleased to work with the Department and the HFTO to explore how we might leverage these skills and capabilities.