EXECUTIVE SUMMARY

Hydrogen technology was created in the 1830s and is considered a versatile and mature technology, but it has not scaled to achieve the commercial hydrogen economy many supporters of the industry envisioned. Recently, hydrogen technology garnered billions of dollars in financial investment from the federal government and private industry to catalyze its commercialization. The current Biden Administration announced ambitious goals to decarbonize the United States economy and made investments in clean hydrogen to partake in accomplishing these goals. The United States Congress also made major investments in the development of clean hydrogen via provisions passed and pending passage seen in P.L. 117-58 - Infrastructure Investment and Jobs Act (IIJA) and H.R. 5376 - Build Back Better Act (BBBA). These federal investments are reviewed and further examined in this paper.

Although hydrogen has the potential to become a consequential clean energy resource and important decarbonization tool, it is currently primarily produced from fossil fuels. This raises legitimate concerns over its true potential to meaningfully serve as a low-carbon alternative and address the climate crisis. Therefore, due to hydrogen’s maturity as a technology and carbon intensive production portfolio, this paper identifies the barriers to deployment for scaling clean hydrogen while highlighting the potential climate impacts. Current and anticipated federal resources, as well as policy recommendations to overcome the enumerated barriers will be made.

Emerging technologies do not exist in a vacuum and are influenced by political climates, societal events, and economic activity, which is a key theme of the curriculum for the Masters of Science Energy Policy and Climate program at Johns Hopkins University. This paper is informed by the scientific, technical, and policy knowledge and research skills gained from this masters program as well as from my Bachelors of Science Chemistry from Chapman University. Additionally, my professional experience in government affairs, climate advocacy, and clean energy policy development was utilized to guide the robust resource selection and analysis for this paper. This paper’s findings are meant to be continually built upon and add to the body of knowledge policy-makers can utilize regarding the commercialization of hydrogen energy.
ACKNOWLEDGEMENTS

The author would like to acknowledge and give special thanks to capstone advisor Patrick Currier, J.D. The Catholic University of America, Columbus School of Law; capstone professor Michael Schwebel, Ph.D. Temple University; Rachael Nealer, Ph.D. Carnegie Mellon University; Shane Skelton, J.D. Southwestern University School of Law; Ben Brenner, MPA Princeton University; Kelly Fleming, Ph.D. University of Washington; Aaron Goodman, Ph.D. Candidate Princeton University; and Nikita Pavlenko, Senior Researcher at the International Council on Clean Transportation.
# Table of Contents

**EXECUTIVE SUMMARY** .............................................................................................................. i

**ACKNOWLEDGEMENTS** ............................................................................................................... iii

**LIST OF TABLES** ........................................................................................................................ iv

**LIST OF FIGURES** ....................................................................................................................... vi

**INTRODUCTION** ................................................................................................................................ 1
   Why the Hydrogen Hype? ................................................................................................................... 1
   Different Types of Hydrogen Production .......................................................................................... 4

**METHODS** ....................................................................................................................................... 11
   Analysis Background ....................................................................................................................... 11
   Analysis ............................................................................................................................................ 13
   Why Not Go all Green? .................................................................................................................... 13
   Current and Future Costs of Electrolyzers ..................................................................................... 17
   Hydrogen Use - Cases .................................................................................................................... 20
   Hydrogen Transportation in the United States ............................................................................... 21
   The Hydrogen Hub .......................................................................................................................... 26
   Example s of Upcoming Use - Cases ............................................................................................. 29

**DISCUSSION** ................................................................................................................................... 33
   Potential Benefits of Scaling Hydrogen Accounting for Current Politics ..................................... 33
   Hydrogen’s Main Barriers to Deployment ....................................................................................... 36
   Repository of Supportive Hydrogen Policies ............................................................................... 40
   Current Laws, Incentives, and Programs for Hydrogen ................................................................. 41
   P.L.117-58 - Infrastructure Investment and Jobs Act (IIJA) ......................................................... 42
   H.R. 5376 - Build Back Better Act (BBBA) ................................................................................. 43

**FURTHER POLICY RECOMMENDATIONS** .................................................................................... 43
   Current Political Environment ......................................................................................................... 44

**CONCLUSION** ................................................................................................................................ 53

**REFERENCES** ................................................................................................................................. 55
LIST OF TABLES

Table 1: Hydrogen Costs for PEM Electrolysis................................................................. 15
Table 2: Current Federal Hydrogen Laws and Incentives............................................... 41
Table 3: Clean Hydrogen Provisions in P.L.117-58 - Infrastructure Investment and Jobs Act (IIJA)...... 42
Table 4: H.R. 5376 - Build Back Better Act (BBBA)......................................................... 43
LIST OF FIGURES

Figure 1: IEA’s Hydrogen Company Fundraising by Stage of Funding………………………………….. 2
Figure 2: Hydrogen’s Informal Color Classifications ........................................................................... 5
Figure 3: Carbon-equivalent Emissions by Hydrogen Production Pathways, 2030 and 2050 … 7
Figure 4: Polymer Electrolyte Membrane (PEM) Electrolyzer.............................................................. 9
Figure 5: Fuel Cell & Hydrogen Basics from the (FCHEA) .................................................................. 11
Figure 6: Hydrogen Production Costs by Production Source ............................................................... 13
Figure 7: Forecast Global Range of Levelized Cost of Hydrogen Production From Large Projects ........ 16
Figure 8: Global Hydrogen Demand By Production Technology in the Net Zero Scenario, 2020-2030... 17
Figure 9: Existing and Emerging Demands for Hydrogen................................................................. 20
Figure 10: DOE EERE’s AFCD’s ‘Alternative Fueling Station Locator’................................................. 22
Figure 11: Hydrogen Potential by Market in 2050, %, exajoules ......................................................... 28
INTRODUCTION
Why the Hydrogen Hype?

Hydrogen has recently garnered significant global attention as an energy source. Several nations, including EU member states (European Commision, 2020), Japan, South Korea (McPherson et al., 2020), and of particular geo-political interest to the United States, China (Hydrogen Council, 2021), have made ambitious commitments to hydrogen investment and deployments (McPherson et al., 2020). Additionally, the United States’ private sector and federal government have also recently made announcements of sizable investments for clean hydrogen, indicating a serious appetite for scaling the technology in the United States.

*International Energy Agency’s (IEA) Global Hydrogen Review 2021* found hydrogen investments rose with unprecedented private fundraising despite economic slowing caused by the COVID-19 pandemic. The review found companies specializing in production, distribution, and utilization of hydrogen raised almost $11 billion USD in equity between January 2019 and mid-2021, a considerable increase from prior years and can be seen in the following Figure 1 below (IEA, 2021b)
Furthermore, contracts funded by government recovery packages are expected to further augment project investments. The most notable federal investments in the United States was made recently by its 117th Congress which appropriated $9.5 billion to further develop its domestic clean hydrogen energy industry. This was made law this past November 2021 with the passage and presidential signature of P.L.117-58: Infrastructure Investment and Jobs Act (U.S. Department of Energy (DOE), 2021b).

In addition to financial commitments, the United States alongside other economically

---

1 Note. PE = private equity. M&A = mergers and acquisitions. VC = venture capital. PostIPO includes private investment in public equity (PIPE) transactions and other new share sales. Early-stage VC includes seed, Series A and Series B. Only deals with disclosed values are included, which notably excludes certain M&A deals with undisclosed values. Sources: Calculations based on Cleantech Group (2021) and Prequin (2021)

developed nations, have made commitments to decarbonize their economies, which contributed to the choices of energy centered in these major investments. With that said, hydrogen is of particular interest because of its perceived and unique ability to replace fossil fuels in sectors considered difficult to decarbonize. Although there is not a general consensus if hydrogen can completely replace fossil fuels, there are particular characteristics of hydrogen that contribute to its versatile application, including:

- **Its potential to be used as a low-emissions fuel**. Hydrogen fuel can be used to produce electricity while not emitting carbon emissions (DOE, HFCTO).

- **Its ability to be used as an energy carrier**. Hydrogen can be transported or stored for later use (DOE, *Hydrogen Storage Fact Sheet*). Its storage capability is considered viable on a large-scale (Andersson et. al, 2019), but comes with technical barriers regarding its portable application that other fuels sources do not have (DOE, Hydrogen Storage). Hydrogen's energy content by volume is low and makes storing it a challenge by requiring high pressures, low temperatures, or chemical processes to be stored compactly (Alternative Fuels Data Center, *Hydrogen Benefits and Considerations*). These barriers will need to be addressed if hydrogen’s ability to be stored can be a fully realized valuable benefit.

- **Its capacity to provide the high-temperature conditions necessary for industrial processes and commodities**. These conditions are required for industrial processes that are integral to the United States economy such as cement, steel, and chemical manufacturing which fossil fuels are traditionally needed to execute (DOE, *Fuel Cells*). The high-temperature conditions provide excess heat waste that can be recycled for
additional applications and provide opportunities for increasing overall efficiency of a project (European Commission, 2020).

These applications make hydrogen an attractive clean energy alternative for applications in the transportation, industrial, and agricultural sectors. However, along with the excitement surrounding hydrogen, skepticism regarding its climate integrity has been raised, as well as differing opinions and political tensions about the role to which policy and the federal government should play in its commercialization. This paper aims to present research of a high-level overview of hydrogen’s current and potential applications while identifying its climate impacts and barriers to deployment. An analysis of the current and potential federal resources as well as additional policy recommendations to scale clean hydrogen will be provided.

Different Types of Hydrogen Fuel Production:

There are several ways to produce hydrogen which led to the establishment of an informal color-coding system. However, this informal system is considered by those entrenched in the clean energy industry as an oversimplification that contributes to hindering hydrogen’s attempts of being technology neutral and further scaled (Hiltbrand et al., 2021). This oversimplification is considered to dilute the public’s and, more importantly, policy-makers’ understanding of the need for an elaborate ecosystem of clean energy choices, including hydrogen, to decarbonize our economy. The following Figure 2 depicts the colors used to classify the various forms of hydrogen generation that vary in feedstock, carbon intensity, and therefore climate implications.
Figure 2: Hydrogen’s Informal Color Classifications. \(^3\) Source: Taylor Krause.

\(^3\) Note: Not included in Figure 2 are the colors turquoise and white as they were considered outside the scope of this analysis. Turquoise is the most recent addition. Turquoise is also considered to have major potential to generate low-emission hydrogen as it can produce hydrogen and solid carbon via methane pyrolysis. White refers to hydrogen naturally found in geological formations which currently does not have well-known methods of exploiting (Giovannini, 2020).
Hydrogen can be extracted from fossil fuels and biomass, from water, or from a mix of both indicating that although hydrogen may generate electricity cleanly, the overall production process of hydrogen can vary in upstream carbon emissions (IEA, 2021c). The two primary pathways of hydrogen production are 1) thermochemical processing and 2) water electrolysis. The main goal of both methods is to separate hydrogen from a more complex molecule. In the case of thermochemical processes, hydrogen is separated from hydrocarbons by applying large amounts of heat and, in most practices, certain chemical catalysts (Basile et al., 2017). Various fossil fuels are used to provide these hydrocarbons, causing a significantly more carbon intensive process. As a result, hydrogen production by the electrolysis of water has near-zero emissions is most attractive to climate advocates. The following Figure 3 showcases how these different production pathways compare in greenhouse gas emissions. For example the SMR of natural gas (NG) results in over ten times greater greenhouse gas emissions than the production of hydrogen via electrolysis (PEM) powered by solar energy.
Figure 3: Carbon-equivalent Emissions by Hydrogen Production Pathways, 2030 and 2050.\

Source: The Hydrogen Council, LBST.

Water electrolysis is a process that can be powered purely by renewable energy and appropriately named green hydrogen. Green hydrogen production has a minimal net carbon impact when compared to alternative methods that utilize fossil fuels (DOE, Hydrogen Fuel Basics). However, in an IEA report, “The Future of Hydrogen” it identified that water electrolysis accounts for less than 0.1% of hydrogen production globally; therefore the primary

---

4 Note: NG stands for natural gas and the terms PEM, SMR, and ATR are elaborated on later in this paper. (Resulting figures refer to virgin material use); energy production refers to GHG emissions from the supply of the main input into the H2 plant (natural gas, coal, electricity), while H2 production refers to direct GHG emission of H2 plant, including from plant auxiliary electricity use.

production pathways of hydrogen are entirely via the thermochemical processing of fossil fuels. The report further detailed that hydrogen production uses six percent of global natural gas and two percent of global coal which causes 830 million tonnes of carbon dioxide emissions per year and is equal to the emissions of the United Kingdom and Indonesia combined (IEA, 2019d).

**Steam Methane Reforming**

Natural gas is currently the primary feedstock for hydrogen production but coal can also be used (Basil et al., 2017). When using natural gas feedstock, hydrogen is separated from the methane (CH₄) molecules in natural gas by applying high-temperature steam (700°C - 1,000°C) in the presence of a catalyst, a process called “Steam Methane Reforming (SMR)”. This reaction results in hydrogen gas (H₂), carbon monoxide (CO), and a relatively small amount of carbon dioxide (CO₂) and is outlined in the following chemical reactions (DOE, *Hydrogen Production*).

**Steam Methane Reforming Reaction:**

\[
\text{CH}_4 + \text{H}_2\text{O} (+ \text{heat}) \rightarrow \text{CO} + 3\text{H}_2
\]

**Water-gas Shift Reaction**

\[
\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 (+ \text{small amount of heat})
\]

Supplying hydrogen to industrial users is currently a major business around the world. As SMR continues to be the main hydrogen production pathway and continues to grow its industrial scale it will remain responsible for significant global carbon emissions (IEA, 2019d).
**Electrolysis Explained**

Water electrolysis is the process of splitting water into hydrogen and oxygen by applying electricity. The medium that this reaction takes place in is fittingly called an electrolyzer. Electrolyzers consist of an anode and a cathode separated by an electrolyte to facilitate a reduction and oxidation process to produce hydrogen which can be seen in Figure 4.

**Different Kinds of Electrolyzers**

- **Size** - Electrolyzers can vary in size depending on their intended application. They can range from small, appliance-size equipment that is well-suited for small-scale distributed hydrogen production to large-scale, central production facilities.

---

- **Material** - The process of electrolysis consists of an anode and a cathode separated by an electrolyte. However the electrolyte materials used for these fundamental functions can differ, changing the ionic species it conducts, chemistry of the reaction, and leads to various types of electrolyzers.

- **Common Types of Electrolyzers** - Polymer electrolyte membrane (PEM) electrolyzers, Alkaline electrolyzers, and Solid oxide electrolyzers (DOE, 2021d).

**Importance of Electrolyzer Research**

From a technical standpoint, increasing the understanding of electrolyzer cell and stack degradation processes can lead to the development of mitigation strategies that increase the operational life of electrolyzers, which can lead to better performance and cost. From an economic standpoint, electrolyzer costs remain a main deployment barrier for green hydrogen production. As a result, research and development to reduce the capital cost of the electrolyzer unit is needed. In order to drive the commercialization of green hydrogen production and its utilization in different regions of the country, the energy efficiency of electrolysis over a wide range of operating conditions needs to be better understood and improved (DOE, 2021d).

**Fuel Cells Explained**

Fuel cells are an important hydrogen technology as they can use hydrogen fuel to produce electricity and heat. Like an electrolyzer, the fuel cell has an anode and cathode that converts hydrogen gas and oxygen into electricity, shown in Figure 5 (Dolan, 2019). The easiest way to conceptualize the process of a fuel cell is an electrolyzer that runs in reverse.

Having a basic understanding of how fuel cell technology works will better facilitate formulating effective policies to scale innovative hydrogen fuel cells and other complementary technologies. Additionally, fuel cell technology is of particular interest for its potential
contribution to scaling net zero electrical production and has a DOE office dedicated to its research, Hydrogen and Fuel Cell Technologies Office (HFCTO). The office highlights

Fuel cells can be used in a wide range of applications, providing power for applications across multiple sectors, including transportation, industrial/commercial/residential buildings, and long-term energy storage for the grid in reversible systems. Fuel cells have several benefits over conventional combustion-based technologies currently used in many power plants and vehicles. Fuel cells can operate at higher efficiencies than combustion engines and can convert the chemical energy in the fuel directly to electrical energy with efficiencies capable of exceeding 60%. Fuel cells have lower or zero emissions compared to combustion engines. (DOE, Fuel Cells).

Figure 5: Fuel Cell & Hydrogen Basics from the Fuel Cell & Hydrogen Energy Association (FCHEA). Source: FCHEA

---

METHODS

Analysis Background

The study conducted an integrative literature review that utilized a variety of qualitative and quantitative resources to compile data and conduct analysis for the formulation of this capstone. Keywords like ‘hydrogen’, ‘hydrogen production’, ‘green hydrogen’, ‘clean hydrogen’, and ‘electrolysis’ were used for all database searches. The basis of the hydrogen specific data for the Introduction, Analysis, Discussion, and Policy Recommendations were gathered from published federal and industry resources as well as reports and scientific papers. The federal resources were mainly garnered from records and reports from the United States. government agencies such as the Department of Energy and Energy Information Agency and intergovernmental agencies such as the International Energy Agency. Additional federal resources such as announcements, blogs, or background information from specific agency offices’ government issued websites were also utilized. Industry resources were not systematically chosen and were chosen at the study team’s discretion with the lens of selectively utilizing resources from organizations that are considered trustworthy and commonly referred to in the clean energy policy space and utilize recent industry data (published after 2018). Examples of such organizations are the Hydrogen Council, BloombergNEF, the Rhodium Group, and the Green Hydrogen Coalition.

For the Discussion portion of this paper, the specific case-studies were selected from personal industry knowledge and industry specific news sources to represent case-studies considered viable and salient for the commercialization of clean hydrogen in the United States. The novel analysis to create the Repository of Supportive Hydrogen Policies was conducted
on legislative text and fact sheets on legislation provided by the White House. The novel analysis incorporated searching for all instances of the word, ‘hydrogen’ and categorizing them into their statutory application and ability to contribute to the funding or financial incentive of scaling clean hydrogen.

**Analysis**

*Why Not Go All Green?*

Although the generation of grey hydrogen is a carbon intensive process, it is the most widespread form of hydrogen production. Currently, green hydrogen production is roughly three to five times more expensive than blue or grey hydrogen production (Hiltbrand et al., 2021). The variance in cost of hydrogen depending on its production source can be seen below in International Energy Agency (IEA) Figure 6 as of March 2020.
Figure 6: Hydrogen Production Costs by Production Source.  

Therefore, practical implementation of hydrogen energy in a carbon effective manner requires reduced cost and improved scaling of clean hydrogen generation technologies. Factors that make grey hydrogen less expensive than green hydrogen include:

- Grey hydrogen production has existed for nearly a century and has allowed it to reach economies of scale.
- Grey hydrogen mainly uses natural gas as a feedstock and has historically been cheaper than renewable sources of energy.
- Green hydrogen has the higher capital costs of electrolyzers.

Current and Future Costs of Electrolyzers

Renewable energy prices for wind and solar have continued to fall and become cost-competitive with natural gas, therefore the cost for electrolyzers is considered a major cost barrier to a competitive levelized cost of green hydrogen production. Currently, electrolyzers cost about $1000 per kW of capacity. There is also a cost barrier in sourcing renewable electricity – there is an energy loss when converting it into hydrogen; considered to be about 10-30%. IEA’s Future of Hydrogen Report found the hydrogen conversion efficiency loss rate is 20-40% with current technological capabilities. The actual percentage will depend on the type of electrolyzer being used, and IEA anticipates a 10-25% loss rate with future improvement (IEA, 2019d).

---

8 Note: Figure 6 is included in a report that was published in 2018 but Figure 6’s data was last updated on March 6, 2020.
10 Note: The $/kW estimates for electrolyzer are a measure of price per capacity and do not take into account the cost of electricity. The electricity cost (in KWh) is additional. For example, a 1 MW electrolyzer would cost $800k to construct at a mid-range price of 800/kW".
The DOE Hydrogen and Fuel Cell Technologies Office (HFTO) conducted an analysis in September 2020 that provided the Program Record, “Cost of Electrolytic Hydrogen Production with Existing Technology,” which found hydrogen can be produced from “...(PEM) electrolyzers at a cost of ~$5 to $6/kg -H2...” This record also provides a modeled example of PEM electrolysis costs assuming:

- An electrolyzer capital cost of $1,000/kW
- Coupled to utility scale photovoltaic (PV) solar and utility scale onshore wind

Under these assumptions, the cost of hydrogen is estimated to range from ~$4 to $6/kg and can be seen in the following Table 1 (Vickers et al., 2020).

<table>
<thead>
<tr>
<th></th>
<th>Electricity Cost ($/kWh)</th>
<th>Capacity Factor</th>
<th>System CapEx ($/kW)</th>
<th>H₂ Cost ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Low</td>
<td>5.0</td>
<td>90.0%</td>
<td>1,500</td>
<td>5.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,000</td>
<td>4.37</td>
</tr>
<tr>
<td>Grid High</td>
<td>7.0</td>
<td>90.0%</td>
<td>1,500</td>
<td>6.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,000</td>
<td>5.50</td>
</tr>
<tr>
<td>Solar PV Utility</td>
<td>3.2</td>
<td>31.8%</td>
<td>1,000</td>
<td>6.09</td>
</tr>
<tr>
<td>Los Angeles, CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar PV Utility</td>
<td>2.9</td>
<td>35.1%</td>
<td>1,000</td>
<td>5.54</td>
</tr>
<tr>
<td>Daggett, CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind Onshore</td>
<td>3.8</td>
<td>38.0%</td>
<td>1,000</td>
<td>5.76</td>
</tr>
<tr>
<td>Utility, Class 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind Onshore</td>
<td>2.8</td>
<td>52.1%</td>
<td>1,000</td>
<td>4.22</td>
</tr>
<tr>
<td>Utility, Class 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 1:** Hydrogen Costs for PEM Electrolysis.\(^{11}\) *Source: DOE Hydrogen and Fuel Cells Program Record #20004.\(^{12}\)*

\(^{11}\) Note: Costs are in 2020 $ amounts. Assuming existing technology, low volume electrolyzer capital costs as high as $1,500/kW, and grid electricity prices of $0.05/kWh to $0.07/kWh. Results were derived from using Hydrogen Production Analysis (H2A) model and today’s technology assumptions with associated inputs of electricity cost, capacity factor, and uninstalled system capital cost.

Looking ahead, BloombergNEF Hydrogen Economy Outlook found that while electrolyzers, “...are still expensive in Western markets, there are encouraging signs. The cost of alkaline electrolyzers made in North America and Europe fell 40% between 2014 and 2019, and Chinese made systems are already up to 80% cheaper than those made in the West. If electrolyzer manufacturing can scale up, and costs continue to fall, then our calculations suggest renewable hydrogen could be produced for $0.7 to $1.6/kg in most parts of the world before 2050. This is equivalent to gas priced at $6-12/MMBtu, making it competitive with current natural gas prices in Brazil, China, India, Germany and Scandinavia on an energy-equivalent basis, and cheaper than producing hydrogen from natural gas or coal with carbon capture and storage.” These cost projections are represented in the following Figure 7 show and show renewable hydrogen (green hydrogen) starts to get competitive in 2030 (Bloomberg Finance, 2020).

**Figure 7:** Forecast Global Range of Levelized Cost of Hydrogen Production From Large
IEA projects in the Net Zero Scenario, 2020-2030 the global demand for hydrogen production by water electrolysis is projected to be greater than other production pathways that utilize fossil, even those that use Carbon Capture and Storage (CCS). This can be seen in the following Figure 8.

---

13 Note: Renewable hydrogen costs based on large projects with optimistic projections for capex. Natural gas prices range from $1.1 - 10.3/MMBtu, coal from $30 - 116/t.”
The United States’ current capacity of commercial electrolysers is increasing. According to DOE Program Record #20009, as of June 2021 PEM electrolyzer capacity installations in the United States that are currently installed, being constructed, or firmly announced totaled an approximate 172 MW capacity. This total approximate capacity represents an approximate capacity of commercial electrolysers as it only accounted for projects 120 kW or greater per site and does not include smaller units such as those used for laboratory research. Current installations account for approximately 13.4 MW and therefore less than ten percent of the total 172 MW indicating the majority of new commercial electrolyzer capacity is underway, approximately 159 MW. It is not clear if this increase in capacity will be sufficient enough to work out technological and economic concerns that currently hinder green hydrogen production writ-large. It does, however, indicate the capacity of commercial electrolysers is anticipated to increase ten-fold and could provide additional opportunities to assess the barriers to deployment for water electrolysis and green hydrogen more broadly, as well as their potential technological, financial, and policy solutions to overcome them.

Intermediate Needs and Production Scale

The federal government has announced goals of reaching gigawatt (GW) level facility sizes for green hydrogen announced in a DOE’s Request for Information (RFI) issued in June 2021. A key milestone is the announcement of a Request for Information (RFI) by the Department of Energy (DOE) in June 2021. The RFI invited proposals for large-scale electrolysis facilities, with targets of gigawatt (GW) level capacity. This marks an important step in the development and deployment of green hydrogen technology in the United States. The RFI was part of a broader initiative to stimulate innovation and investment in hydrogen technologies, with the ultimate goal of transitioning to a low-carbon energy future. The announcement reflects the growing recognition of hydrogen’s potential as a key component of green energy systems.

---

2021 (Vickers et. al, 2020). However, an average blue hydrogen facility under current economic conditions can produce about 100 times more kilograms of hydrogen per year than a green hydrogen plant (Hiltbrand et al., 2021). This indicates the disparity that still exists between cheaper, more developed, and more carbon intensive processes and green hydrogen production.

While these lower-carbon forms of hydrogen production are developing there have been intermediate pathways proposed which may trade carbon intensitivity for cost. The thermochemical treatment of fossil fuels has provided a larger scale of production, but with a larger carbon-footprint. These forms of production have, and can be, more widely coupled with carbon capture and sequestration (CCS) techniques to decrease overall carbon intensity, but not in a manner that makes it a near-zero emissions process, as the average capture rate of hydrogen production from natural gas via SMR is about 55% (Zhou et. al, 2021). This has been presented as a potential intermediary pathway to scale demand for hydrogen while developing more cost-effective utility scale green hydrogen. However, this has been deemed a contentious pathway by climate advocates due to the current low capture rate. It has also been deemed to perpetuate the long-term use of fossil fuels, especially natural gas which during its production and distribution even when coupled with CCS experience methane leakage which is a potent greenhouse gas (Antonini et. al, 2020).

On the horizon there are also other hydrogen production methods being adopted like autothermal reforming (ATR) and hydrogen from biomass. ATR is similar to SMR in that it also thermochemically processes natural gas to produce hydrogen and can also be coupled with CCS. ATR has been considered to have a carbon capture rate higher than that of SMR and be done at a lower cost. However, taking into account the previously mentioned low capture rate
of CCS technology in hydrogen production, this consideration may be overly optimistic and would need to be thoroughly demonstrated (IEA, 2021e). Regarding biomass production, it has been found to provide a net-negative carbon process but is in nascent stages and needs to be further developed (DOE, 2020c).

These multifaceted processes have led to competing visions to achieve the same energy needs and climate goals that either pit production pathways of hydrogen against each other or advocate for these various pathways to complement each other. The stages of development and realities of each pathway should be taken into account when allocating federal resources and formulating complementary policies for the overall benefit of the hydrogen industry and its desired long term environmental benefits.

**Hydrogen Use -Cases**

There are existing and emerging demands for hydrogen which can be seen in the following **Figure 9** from “DOE’s Hydrogen Program Plan” published in November 2020 (Rodrique, 2021). Hydrogen already plays a crucial role in our economy as an industrial
feedstock and has cross-sector demands. More commercialization opportunities for clean hydrogen could be presented if the infrastructure to support it is created which the following use-cases aim to pioneer.

**Hydrogen Transportation in the United States**

Although in its nascent stages, it is useful to have a high-level understanding of the current hydrogen transportation landscape especially when considering what infrastructure would be most effective to support the cross-sector demands for hydrogen technology this paper champions to leverage.

**Why certain hydrogen FCEVs are not competitive**

Hydrogen technology exists in modes of transportation, primarily as hydrogen fuel cell electric vehicles (FCEVs) in light-duty vehicles, heavy-duty trucks, and buses. Globally there are about 30,000 hydrogen FCEVs on the road (DOE, 2020a) and as of June 1, 2020 there were only 8,363 FCEVs sold or leased in the United States, meaning that FCEVs make up a miniscule percent of the American automobile fleet (DOE, AFDCa). Commercial auto manufacturers like Toyota, Honda, and Hyundai provide light-duty hydrogen FCEVs but they

---

are limited and only offered in California auto markets (DOE, Arjona). The auto manufacturers that offer FCEVs have a starting Manufacturer’s Suggested Retail Price (MSRP) ranging from about $35,000 for a 2021 Honda Clarity (CFCP, 2021), to $49,500 for a 2022 Toyota Mirai (DOE, Hydrogen Basics), to $58,935 for a 2021 Hyundai Nexo and are more expensive than typical internal combustion engine (ICE) cars, and competing electric vehicles (EVs).

The other component of any transportation mode is the infrastructure that supports the mode’s use. FCEVs have a travel range that is a minimum of 300 miles before needing to be refueled is considered a convenient refueling process as it can rapidly happen in minutes (DOE, 2016). However, hydrogen fueling stations are not widely available and the current infrastructure to support hydrogen’s use in transportation remains the largest deployment barrier. There are 43 retail hydrogen fueling stations across the United States and the majority are in California and can be seen below in Figure 10 (DOE, AFDC).

![Figure 10: DOE EERE’s AFCD’s ‘Alternative Fueling Station Locator’. Source: DOE EERE’s](image-url)
There are efforts underway to expand hydrogen fueling locations in Hawaii, across the East Coast, and to other regions where consumer demand is increasing (DOE, *Hydrogen Fueling Stations*), but it is unclear if the development of these stations will create the comprehensive fueling network needed to catalyze the commercial adoption of FCEVs in these regions. As it pertains to hydrogen’s application in transportation, it is useful to examine its deployment barriers separately.

**Barriers to Deployments for Hydrogen Transportation:**

- **Lack of fueling infrastructure** - Lack of hydrogen infrastructure limits the regions where FCEVs can be more widely adopted as customer concerns of range anxiety cannot be ameliorated and decreases consumer investment in FCEVs. The U.S. currently does not have a comprehensive network of hydrogen fueling stations with the largest concentration of stations being in Southern California and clearly seen in Figure 10. Currently, the infrastructure is insufficient to support wide-scale adoption and can be further explored on the interactive map provided by DOE EERE’s Alternative Fuel Data Center’s ‘Alternative Fueling Station Locator’ (DOE, *AFDCd*). Additionally, hydrogen stations must be near a source of hydrogen and customers, which further narrows the deployment of hydrogen stations.

- **Competition with EVs** - FCEVs are heavily competing with EVs in the light-duty vehicle arena. EVs are not only more widely adopted but also have a more robust

---

infrastructure, with convenient consumer options like direct-current fast chargers (DCFC) to support its fleet.

- **EV Infrastructure Cost** - DOE's Alternative Fuels Data Center states “DCFC units range in cost from $10,000-$40,000, depending on the power level and additional features. Installation costs can range from $4,000-$51,000, depending on how close the DCFC is to the electrical service and if there is sufficient electrical capacity for the DCFC's high power needs.” (DOE, 2015). Therefore, DCFCs have a more favorable building price tag compared to hydrogen fueling stations that can cost over a million dollars to build (Koleva et al., 2020).

- **EV Efficiency** - Hydrogen powered fuel cells are more than twice as energy efficient for cars and about twice as efficient for trucks when compared to conventional internal combustion engine vehicles (CARB, 2016). In practice, this means fuel cells used in vehicles are twice as efficient at generating power than that of an internal combustion engine and need about half the amount of hydrogen to go twice as far (DOE, 2016). However, electric motors are even more efficient than hydrogen fuel cells. Electricity used to power cars is 3.4 times 1.5 more efficient for cars and about five times more efficient for trucks (CARB, 2020). There have been proposals for coupling station designs to lower the total system cost to promote better load balancing and equipment cost sharing, but this seems to be an unlikely solution given the competitive nature between hydrogen FCEVs and EVs in light-duty vehicles (NREL, 2020a).

- **Cost of Hydrogen Fuel** - Currently, it costs approximately $8-$11/kg of hydrogen
(depending on the volume delivered) to deliver hydrogen to fueling stations. Additional costs like the amortization of capital costs for equipment, production of hydrogen, maintenance costs, land lease agreements, and other operational costs need to be factored into the final price at the pump and reason for the difference in the price found in Table 1. For a relative price estimate according to California’s Fuel Cells Partnership, the price at the pump at a True Zero station in Sunnyvale, CA as of November 2021 was $13.08/kg (Malone, 2021). This price highlights hydrogen fuel as significantly more expensive compared to other gasoline powered vehicles and increasingly, electric vehicles (DOE, 2016). The price of hydrogen fuel is ultimately one of the most significant barriers to its wide-scale commercialization in light-duty vehicles.

- **Storage/weight limitations** - Compared to gasoline, hydrogen fuel has a lower volumetric density which requires it to be stored at a higher pressure than petroleum-based fuels. This creates the need for a larger tank in order to store hydrogen on a vehicle therefore causing weight limitations. Although medium and heavy-duty vehicles have more space for larger tanks, they could face weight limitations and reduce the total load potential to stay within vehicle restrictions dictated by the Department of Transportation (DOE, *Hydrogen Fueling Stations*).

**Future Opportunities for Hydrogen in Transportation**

After reviewing the current landscape and identifying the barriers to deployment for hydrogen in transportation, hydrogen's application in FCEVs for light-duty vehicles may not be the avenue with the most potential to commercially deploy hydrogen technology. However, there are some transportation niches where hydrogen is a better alternative to electric counterparts.
• **Other modes of transportation** - There are other forms of transportation that FCEV adoption may be more commercially viable.

  ○ **Application in Medium to Heavy-duty Vehicles** - Currently there are limited ways to decarbonize medium to heavy-duty vehicles forms of transportation like forklifts and heavy-duty trucks (DOE, *Hydrogen Basics*). Due to their large duty cycle and long-haul applications it is difficult to electrify these transport modes with current battery technology. However, these hard-to-abate forms of transportation can utilize hydrogen fuel-cells (Hiltbrand et al., 2021) which are more reliable for commercial trucking needs and reduce their emissions. Hydrogen fueling stations may be expensive and regionally sparse but they are considered compatible with heavy-duty trucks. These trucks typically utilize the same routes and could consistently utilize the same hydrogen stations along the way and avoid the lack of stations. Hydrogen stations could additionally ensure quick fueling turnover needed for a heavy-duty fleet that need a long-haul range and to get back out to work quickly.

  ○ **Future Forms of Shipping and Aviation** - Looking ahead, there are forms of shipping and aviation (ICCT, 2020) being researched and developed from companies like ZeroAvia (British Airways, 2020) and Airbus (Airbus, 2020), but are far from commercial scale or even public use (Ziady, 2020). Hydrogen’s use in maritime fuels shows particular potential for enabling hydrogen as a favorable alternative in shipping modes. Especially if used in maritime shipping, hydrogen would have the potential to scale even more quickly by leveraging the importance of maritime shipping in global trade (Rodrigue, 2021).
Adoption of Low Carbon Fuel Standards (LCFS) Policies

- The implementations of state-level LCFS policies have made low-carbon fuels like hydrogen more competitive in states like California, Oregon, and Washington. Pioneering policies that prove success are policies that can more easily be adopted by decision-makers. As these LCFS state initiatives mature, lower emissions, and provide more tangible benefits, they could serve as an exemplary policy to be duplicated to achieve their state’s emission targets and contribute to additional commercial opportunities for hydrogen fuel.

The Hydrogen Hub

The concept of “Hydrogen Hubs” has been proposed by developers as the favored project design to scale clean hydrogen development. The terminology was even adopted by Congress and enacted into law as part of the Infrastructure Investment and Jobs Act of 2021 (P.L. 117-58); which included $8 billion for what it termed “Regional Clean Hydrogen Hubs,” along with significant other funding for other types of hydrogen-related research and applications. This indicates the initial adoption of commercial scale hydrogen technology will not be sector-specific but rather location-specific where hydrogen technology would be used across multiple sectors. This is important context to keep in mind given decarbonization goals and plans are usually presented as sector-specific and should be accounted for when formulating complementary policies to help spur clean hydrogen’s commercialization.

DOE’s “Office of Fossil Energy and Carbon Management” released a report in July 2020 that highlights the future potential in scaling hydrogen’s global market share across multiple sectors in Figure 11 (Rodrigue, 2021).
While there are several potential models for such hubs, their common, overarching goals are to leverage hydrogen’s unique cross-sector capability by making the effort to lower upfront capital costs. This initial cost lowering is done by developing multiple hydrogen facilities with co-located infrastructure that can share the initial costs. This cost-sharing model is of particular relevance to maritime transportation given port infrastructure can integrate hydrogen technology and is among the most capital intensive to build and expensive to maintain and operate. Maritime transportation specifically has a deeper linkage to heavy industry processes, such as steel and petrochemical manufacturing, than any other mode of

---

transportation. This presents the opportunity for hydrogen integration at ports, recalling that hydrogen can be used in these heavy industry processes. Moreover, their industrial facilities are typically adjacent to port sites. Because hydrogen has been proven to serve as an alternative fuel in such processes, this presents an opportunity to create hydrogen hubs while decarbonizing multiple sectors (Rodrigue, 2021).

**Examples of Upcoming Use Cases**

The following use-cases were chosen to showcase clean hydrogen projects that are utility-scale, demonstrate cross-sector applications, and show commercial viability in the United States. There is a long-term goal of green hydrogen being primarily used as an electricity storage and balancing resource at a commercial scale, however, in the interim as green hydrogen is being scaled and decision makers are formulating pathways to achieve net-zero emissions by mid-century, creative thinking and complex trade-offs will have to occur. Innovative use-cases such as the ones outlined in this paper will lay the groundwork for additional key-lessons and takeaways that can contribute to the body of knowledge needed to commercialize clean hydrogen. (Williams et. al, 2021)

**HyDeal LA Use Case**

There is a shared dichotomy amongst driving down cost for developing energy technologies, “which needs to come first: the demand or the innovation to create demand?”. The prime real world example of the aforementioned hydrogen hub is that of, “HyDeal Los Angeles” (HyDeal LA). The initiative aims to position Los Angeles as the first green hydrogen city in North America and deliver green hydrogen at under $2/kg by 2030. At this price point green hydrogen would be economically competitive with natural gas. In efforts to be cost-effective and create a large source demand for green hydrogen, the project plans to repurpose
existing fossil-power generation infrastructure to generate green hydrogen while deploying new green hydrogen production equipment over time (Williams et. Al, 2021).

The Los Angeles region has the following attributes that make it an ideal testing ground for the multi-sectoral use of green hydrogen:

- Friendly regulatory environment: California has a low carbon fuel standard (LCFS) and LA set a sustainability goal to become 100% renewable by 2035.
- Being in a state like California that has large agricultural and maritime sectors.
- California is a state with a major refinery industry that could utilize green hydrogen production and help generate LCFS credits.
- Proximity to the Asia-Pacific region that has large offtakers of hydrogen products.
- The Port of LA and Long Beach combined is the largest port in North America and could pilot hydrogen applications in industrial and shipping practices.
- International LAX airport for opportunities with hydrogen aviation efforts.

HyDeal LA plans to convert four gas-fired power plants in the LA region in partnership with the Los Angeles Department of Water and Power California (LADWP).

The duo’s first conversion will be converting a 1,800 MW coal-fired Intermountain Power Plant in Utah into an 840 MW combined-cycle gas turbine facility that will provide power to the LADWP service territory. The converted facility is operated by LADWP and would also provide the dual benefit of providing offtake assurances. This initial conversion will result in a facility with an approximate 30% hydrogen mix and future targets of operating entirely on clean hydrogen (Green Hydrogen Coalition, n.d.). In addition to this partnership, the project participants committed to allocating portions of their existing renewable power to run electrolyzers with the goal of eventually running them on excess renewable power.
To accomplish future green hydrogen targets, HyDeal LA developers will need to scale up electrolyzer technology while keeping costs low. Electrolyzers’ expensive manufacturing costs remain a large commercialization barrier to the technology. In efforts to offset this, developers plan to partner with experts and have operators run the electrolyzers as much as possible to recoup their capital costs. The selected expert partners are 174 Power Global Corp and Mitsubishi Power. 174 Power Global Corp is planning to develop a utility-scale solar plant to power electrolyzers while Mitsubishi Power is providing the turbines for the project to demonstrate that turbines can run for years on green hydrogen while other commercialization developments take place. Additionally, this green hydrogen will also need to be transported and the idea of utilizing existing pipeline networks in the territory is considered a cost-effective solution. There have been demonstration pitches to do this from other gas utilities like Southern California Gas Co.

In order to achieve its 100% renewable energy goals, LADWP determined it would need thousands of megawatts of in-basin storage. This is a distant goal and will require significant capital and temporal investments as well as creativity to accomplish HyDeal LA’s vision. The next innovation HyDeal planned is continuing its model of re-developing more gas-fired plants starting with LADWP’s Scattergood, Haynes and Harbor combined cycle gas-fired power plants (DiChristopher, 2021).

More broadly, HyDeal serves as a template for other cities looking to scale their green hydrogen production by providing key takeaways like:

1. New and mid-term progress can happen sooner by utilizing existing electric and natural gas infrastructure.

2. Displacing competitive natural gas with green hydrogen assets will increase demand
and drive down delivery costs.

3. Synergy between private sector investment and utility cooperation create optimal opportunities for creating the comprehensive system of supply, offtake, and storage needed to support utility scale green hydrogen.

4. Improve regulatory certainty while better clarifying access to benefits on a federal, state, and municipal level to further attract private investment (Green Hydrogen Coalition, n.d.).

*Nuclear Use - Case*

A DOE program record titled, “Hydrogen Production Potential from Nuclear Power” stated, “A nuclear power plant providing 1 GW of power for hydrogen production year-round could produce between approximately 150,000 and 160,000 metric tons (tonnes) of hydrogen per year using polymer electrolyte membrane (PEM) electrolyzers. Ten such plants could provide over 1.5 million tonnes of H2 or roughly 15% of the hydrogen produced today in the U.S. Between 180,000 and 210,000 metric tons of hydrogen per year could be produced if the 1 GW nuclear plant utilized solid oxide electrolysis cell (SOEC) technology.” (DOE, Hydrogen Program Record 20003).

Coupling nuclear power with hydrogen generation is in its nascent stages but is another prospective avenue for private-public partnerships and investment in existing infrastructure to accelerate clean hydrogen production. Excitingly and recently, there have been private-public-partnership announced to start this avenue at the Davis-Besse Nuclear Power Plant in Ottawa, Ohio (Carson, 2021) and the Palo Verde Generating Station in Tonopah, Arizona (ANS, 2021), which are both in part funded by the DOE.
DISCUSSION

Potential Benefits of Scaling Hydrogen Accounting for Current Politics

In the wake of the COVID-19 pandemic, policy-makers prioritized passing policies that enable economic recovery and create jobs. The additional layer of addressing climate change was added to these general policy priorities when Democrats won control of both the legislative and executive branches in the 2020 election cycle. Adding to this momentum, Wall Street, private equity, and corporate America are making bold investments by the billions in clean energy while setting short, medium, and long-term clean energy and carbon reduction goals. Addressing climate change is not a new priority to the Democratic party, they simply now have the authority to boldly legislate on their climate priorities. This flex of legislative power is rendered into the form of passing and building momentum for the legislative vehicles, *P.L.117-58 - Infrastructure Investment and Jobs Act (IIJA)* and *H.R. 5376 - Build Back Better Act (BBBA)*.

These interdisciplinary policy priorities were utilized to identify the following potential benefits of scaling clean hydrogen energy projects and increase the likelihood of their adoption by policy-makers.

*Potential Benefits of Scaling Clean Hydrogen Energy Projects:*

- **Job Creation** - An analysis from the Rhodium Group found retrofitting a typical grey hydrogen facility with carbon capture would take about 4-6 years and create on average:
  - 543 jobs, where 306 jobs were to install and operate the retrofit technology and 237 jobs from the required supply chain.
50,000 jobs if all SMR facilities in the United States were retrofitted with carbon capture (Hiltbrand et al., 2021).

Since these retrofits would occur on already existing facilities they would only provide job opportunities to certain regions of the country. Accounting for this regional specificity is important when discussing the potential benefits of retrofitting existing facilities with policy-makers as they will prioritize the benefits for the district or state they represent. The areas identified with the most opportunity for carbon capture retrofitting would be in the Gulf Coast, the Midwest, and California.

The same Rhodium analysis projected job creation associated with the construction of a green hydrogen plant. The construction period for a 50 MW green hydrogen facility would likely be a bit shorter than a typical blue hydrogen retrofit as the green hydrogen facility in the Rhodium study would be a first-of-its-kind plant. Rhodium’s research did not have a concrete time frame, but expected the construction to take around three to four years. Because it would not be dependent on retrofitting a pre-existing facility it would not be limited to particular regions and could provide benefits to a wider array of regions. The analysis projected the construction of this assumed 50 MW green hydrogen would average in creating:

- 388 jobs, where 223 jobs stem from the supply chain required to build and operate the facility and the remaining 363 jobs are associated with the plant investment, including the construction, engineering, materials, and equipment required to build the facility.

- An additional 26 ongoing jobs for projected operations and maintenance (Hiltbrand et al., 2021).
The amount of jobs created and sustained from either project will vary in significance depending on the region’s population, employment levels, and other socio-economic factors.

- **Environmental and Public Health** - Hydrogen combustion only emits water vapor, which has environmental benefits when compared to the conventional combustion of fossil fuels used for energy production that typically result in greenhouse gasses that contribute to climate change and a myriad of adverse effects on communities globally. Displacing fossil fuels with hydrogen fuel across the transportation, industrial, and power sectors could lower point-source pollution, leading to immense public health benefits locally. The Environmental Protection Agency (EPA) outlined the communities that disproportionately benefit less from the use of fossil fuels which are typically minority, low-income, and indigenous populations that suffer from criteria air pollutants. It is well documented these communities have also historically suffered the most from air pollution caused by fossil fuels as they are the communities that fossil fuel power plants are usually in a closer proximity to and causes the members of these communities to frequently experience adverse health outcomes, such as developing heart or lung diseases (EPA, n.d.). The Port of Los Angeles in its “Port of Los Angeles Inventory of Air Emissions - 2019” estimated if it were to convert all its heavy-duty vehicles within the ports of Los Angeles and Long Beach that solely handle cargo equipment from diesel combustion vehicle to fuel cell electric vehicles, it would eliminate 555,280 tonnes of CO2e per year which would be equivalent to planting 9.2 million trees. This would have immense public health benefits as it would reduce the population-weighted cancer risk associated with maritime industry-related diesel
particulate matter (DPM) emissions in the communities and throughout the residential areas in the Port region (Port of Los Angeles, 2020).

- **Storage Capabilities** - Hydrogen can be stored as a gas or liquid and has capabilities of being used in stationary, remote, and portable power applications. This storage capability presents an opportunity to synergize with renewables to help avoid and/or address issues of intermittency other renewable technologies logistically face. Meaning that during periods of excess energy production from renewables, green hydrogen could be produced. This green hydrogen could be stored for future use to meet the demands of the grid when renewables are unable to meet instantaneous electricity demands. In this way, hydrogen and other renewables can work synergistically to achieve more ambitious goals of carbon reduction (NREL, 2020b). An exciting example are potential use cases proposed to couple hydrogen storage with offshore wind, but this is still an expensive process and further discussed in the **Hydrogen's Main Barriers to Deployment** section of this paper (DOE, Wind).

**Hydrogen’s Barriers to Deployment**

It should be noted hydrogen technology is not novel and is considered a mature technology. Fuel cell technology that utilizes hydrogen as a fuel source was created in the 1830’s, making the technical feasibility of hydrogen as a fuel source well understood (APS News, 2019). The following section identifies the prominent barriers of deployment to hydrogen’s commercialization and potential technical solutions where appropriate. Associated policy recommendations to overcome these will be discussed in the ‘**Policy Recommendations** ’ portion of this paper.

1. **Climate Integrity and Environmental Justice** - Although when used in a fuel cell,
hydrogen does not directly combust into CO\(_2\), the various ways of producing hydrogen can create upstream carbon emissions. Depending on how the hydrogen was produced, its net climate impact may be comparable to the fuels it is intended to replace. This caused political tensions regarding hydrogen fuel and put into question hydrogen’s climate integrity, creating another barrier to deployment. It is also noteworthy these concerns are credible given hydrogen energy’s production portfolio is currently over 99% coming from fossil fuels (IEA, 2021a), meaning grey, brown, black, and blue hydrogen classified in Figure 2: Hydrogen’s Informal Color Classifications. Given the majority of current hydrogen production is carbon intensive it does give credible concern to its climate integrity.

Additionally, there are environmental justice concerns if hydrogen fuel were to contribute to the continuation of industrial processes that cause local pollution. A byproduct of industrial applications are nitrogen oxide pollutants (NOx) that research shows have adverse impacts on local communities, which historically are disadvantaged communities and communities of color (EPA, n.d.). Since hydrogen can be used to provide the high temperature environment needed to facilitate industrial processes which can produce NOx, there is concern that although hydrogen energy doesn’t have harmful emissions when generating electricity, it can contribute to other processes that do (Hiltbrand, 2021). However, NOx pollution is specifically shown to be able to mitigate these impacts when coupled with policy support and existing technological processes that can control the amount of NOx produced (Menzies et. al, 2019).

2. **Cost of Electrolyzers** - In terms of hydrogen produced by water electrolysis, the cost
for electrolyzers has the greatest effect on the levelized cost of green hydrogen. Currently electrolyzers’ capital costs are priced in terms of $ per kW to consider the costs of the actual electrolyzer and the purchase of electricity. The capital cost of an electrolyzer can vary depending on the (average) electricity purchase price during the time of operation, capacity factors, and other electricity market scenario factors. Currently the average cost of an actual electrolyzer is about $1000/kW and a maximum capital cost for an electrolyzer is considered $1,500/kW (IEA, 2019d).

Additional research and development to lower the actual cost of the electrolyzer and utilize cost-effective electricity from renewable energy would be the optimal solution to this cost barrier. However, using existing technology, in order to minimize green hydrogen’s final cost ($/kg), electrolyzer utilization has to be balanced with electricity prices. In theory, utilizing an electrolyzer longer would produce more hydrogen and reduce the specific share of electrolyzer capital costs in hydrogen production costs. However, the real-world trade off is that in utilizing an electrolyzer to produce more hydrogen means utilizing more electricity longer (to possibly occur during hours of expensive electricity) and increase electricity costs (Ball et. al, 2016).

Additionally there is also a cost barrier in sourcing renewable electricity that should be considered; there is an energy loss that occurs when utilizing renewable energy to create electricity for hydrogen production and there is a loss rate of about 10-30%. Looking ahead as renewable energy prices for wind and solar continue to fall and become cost-competitive with natural gas, the cost for electrolyzers is considered a major cost barrier to a competitive levelized cost of green hydrogen.

3. **Lack of Distribution Infrastructure** - Currently hydrogen fuel regardless of production
source is typically transported by truck and contributes to its overall price. There is not
a comprehensive pipeline network dedicated to the transportation of hydrogen, but
formulating such a network could help address this barrier.

Hydrogen fuel is blended with natural gas (<20% hydrogen concentration) and
successfully tested to be utilized in existing natural gas pipeline infrastructure. Although
this presents an opportunity for more efficient transportation of hydrogen fuel it also
raises the challenge of the continued use of natural gas (Nationalgrid, 2020). Although
successfully tested at lower concentrations, if pipeline networks are going to be purely
dedicated to hydrogen transportation there is still a need for robust research,
standardization, and regulation of pipeline safety (DOE, 2020). Technical barriers such
as these currently have federal resources being used to solve them (NREL, 2020c).
Additionally, hydrogen pipelines must anticipate the imminent obstacles of “upgrade
costs, loss of energy density, the long-term cost discrepancies compared to electrifying
natural-gas-fired heat and appliances in buildings” (St. John, 2020).

4. **Storage Limitations and Cost** - Compared to gasoline, hydrogen fuel has a lower
volumetric density which requires it to be stored at a higher pressure than petroleum-
based fuels and makes it considerably more difficult to store than petroleum-based
fuels. (Alternative Fuel Data Center, n.d.) BloombergNEF’s Hydrogen Economy Outlook
estimated “If hydrogen were to replace natural gas in the global economy today, three
to four times more storage infrastructure would need to be built, at a cost of $637 billion
by 2050 to provide the same level of energy security. Storing hydrogen in large
quantities will be one of the most significant challenges for a future hydrogen economy.
Low cost, large-scale options like salt caverns are geographically limited, and the cost
of using alternative liquid storage technologies is often greater than the cost of producing hydrogen in the first place.” BloombergNEF (2020).

Hydrogen is also highly combustible and requires additional safety precautions. All of these factors ultimately add to the cost of storage and contribute to the overall operating expenses utilizing hydrogen as fuel. As a result, there is a need for additional research and development of solutions to more cost-effectively store hydrogen and additional investments in infrastructure are needed to overcome this deployment barrier.

Repository of Supportive Hydrogen Policies

Current Laws, Incentives, and Programs for Hydrogen

- State laws and incentives can be looked up by state with the interactive resources provided by DOE’s EERE Alternative Fuels Data Center (DOE, AFDCc). Of particular interest is the LCFS in California, Oregon, and Washington that contributed to making hydrogen fuel more cost-effective and furthered commercialization in these states (CARB, 2020).
- Federal laws, incentives, and programs enacted to help build and maintain a market for hydrogen fuel and vehicles and their associated details are also listed on the DOE’s EERE Alternative Fuels Data Center, but are summarized in the Table 2 below (DOE, Hydrogen Laws and Incentives).
Table 2: Current Federal Hydrogen Laws and Incentives. Source: Formatting by Taylor Krause and data provided by DOE’s EERE Alternative Fuels Data Center 19

Table 3 provides a summary of my novel analysis of the provisions included in P.L.117-58 - Infrastructure Investment and Jobs Act (IIJA) aimed to support the commercialization of Hydrogen. 19

Clean hydrogen.

<table>
<thead>
<tr>
<th>Hydrogen Provision</th>
<th>Provision Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional Clean Hydrogen Hubs</td>
<td>$8,000,000,000 will be authorized and appropriated for the period of fiscal years 2022 through 2026 for DOE to establish a program to support the development of at least 4 regional clean hydrogen hubs. The selection of these hubs will be at the discretion of the Secretary with the criteria in mind of feedstock diversity, end use diversity, geographic diversity, and hubs in natural gas producing regions.</td>
</tr>
<tr>
<td>Clean Hydrogen Electrolysis Program</td>
<td>$1,000,000,000 authorized (to be appropriated to the Secretary to carry out the program for the period of fiscal years 2022 through 2026 to remain available until expended) for DOE to establish a program for purposes of commercialization of hydrogen for the purpose of improving efficiency, improving durability, and reducing the cost of producing clean hydrogen using electrolysers. The goals of the program are to reduce the cost of hydrogen produced using electrolysers to less than $2 per kilogram of hydrogen by 2026.</td>
</tr>
<tr>
<td>Domestic Manufacturing Conversion Grants</td>
<td>Appropriates $3.5 billion to DOE for domestic manufacturing conversion grants relating to hydrogen fuel cell electric vehicles, domestic production of plug-in electric hybrid, and plug-in electric drive including its components.</td>
</tr>
<tr>
<td>Grants for Charging and Fueling Infrastructure</td>
<td>Establishes a grant program for Alternative Fuel Corridors and a set-asides for Community grants, designed to deploy publicly accessible infrastructure including Hydrogen fueling.</td>
</tr>
<tr>
<td>Grants for Clean Hydrogen Manufacturing and Recycling</td>
<td>$500,000,000 will be authorized (to be appropriated to the Secretary to carry out) for the period of fiscal years 2022 through 2026 to grant funding for clean hydrogen equipment manufacturing projects with the following criteria: utilize existing energy infrastructure, increase cost efficiency, support domestic supply chains, identify and incorporate non-hazardous alternative materials, operate in partnership with tribal energy development organizations, and are located in economically distressed areas in the major US natural gas-producing regions. Minimize environmental impact from recovery and disposal process of the recovery of raw materials from clean hydrogen technology, address any barriers to recycling clean hydrogen devices, and develop strategies to increase consumer acceptance of, and participation in, the recycling of fuel cells.</td>
</tr>
<tr>
<td>Carbon Intensity Standard</td>
<td>Directs the Secretary, in consultation with the EPA Administrator and outside stakeholders, to develop an initial standard for the carbon intensity of clean hydrogen production from renewable, fossil fuel with CCUS, nuclear, and other fuel sources, beginning at 2 kgs of CO2 per kg hydrogen. After five years it will be adjusted to account for technological and economic feasibility.</td>
</tr>
</tbody>
</table>

Table 3: Clean Hydrogen Provisions in P.L.117-58 - Infrastructure Investment and Jobs Act
H.R. 5376 - Build Back Better Act (BBBA)

Table 4 provides a current summary of the provisions included in, H.R. 5376 - Build Back Better Act (BBBA) aimed to support the commercialization of clean hydrogen. It should be noted that as of December 17, 2021 this legislative text is not law, is still seeking passage in the Senate with presidential approval, and is therefore subject to change.

<table>
<thead>
<tr>
<th>Hydrogen Provision</th>
<th>Provisions Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>State Energy Programs Assistance</td>
<td>Appropriates $200 million to DOE to give financial assistance through State Energy Programs for hydrogen fueling equipment with a target for the buildout of infrastructure in rural, underserved, and disadvantaged areas.</td>
</tr>
<tr>
<td>Creates a New Hydrogen PTC</td>
<td>Qualifying facilities:</td>
</tr>
<tr>
<td></td>
<td>- Must begin construction in 2022 through 2029.</td>
</tr>
<tr>
<td></td>
<td>The credit rates:</td>
</tr>
<tr>
<td></td>
<td>- Base Rate: up to $0.60/kg</td>
</tr>
<tr>
<td></td>
<td>- Bonus Rate: up to $3/kg</td>
</tr>
<tr>
<td></td>
<td>The amount of credit is determined by the greenhouse gas (GHG) emissions rate:</td>
</tr>
<tr>
<td></td>
<td>- 8.4% of the credit for 4 -6 kg CO2e per kg of hydrogen</td>
</tr>
<tr>
<td></td>
<td>- 20% of the credit for 2.25 -4 kg CO2e per kg of hydrogen</td>
</tr>
<tr>
<td></td>
<td>- 33.4% of the credit for 1.5 -2.5 kg CO2e per kg of hydrogen</td>
</tr>
<tr>
<td></td>
<td>- 50% of the credit for 0.45 -1.5 kg CO2e per kg of hydrogen</td>
</tr>
<tr>
<td></td>
<td>- 100% of the credit for less than 0.45 kg CO2e per kg of hydrogen</td>
</tr>
<tr>
<td></td>
<td>Additional options:</td>
</tr>
<tr>
<td></td>
<td>- Commercial taxpayers can opt to make these credits refundable.</td>
</tr>
<tr>
<td></td>
<td>- Taxpayers can elect a 30% ITC in lieu of the PTC, if labor requirements are met</td>
</tr>
</tbody>
</table>

Table 4: H.R. 5376 - Build Back Better Act (BBBA). Source: Formatting and analysis by Taylor Krause

FURTHER POLICY RECOMMENDATIONS

20 It should be noted that IIJA (P.L.117 -58) was enacted into law, however its recent passage and future enactment dates warranted separate analysis.
In efforts to scale clean hydrogen, policy recommendations should focus on bridging the gaps between production, storage, distribution, and end use to enable the most cost-effective application scenario. The following policy recommendations are meant to address the identified deployment barriers while accounting for political feasibility.

**Current Political Environment**

Energy policies are privy to the current political environment and this environment must be accounted for to improve the chances of adoption. The following political factors shape the current legislative landscape energy policies need to navigate:

- **Democratic Majority** - The Democratic party gained control of both chambers of Congress and the White House in the 2020 election cycle, which provided opportunities for partisan legislating like budget reconciliation.

- **Sense of Urgency** - The upcoming 2022 midterm election predicts the Republican party will take back the majority in one if not both chambers of Congress. Democrats who currently hold majority power likely have a sense of urgency to accomplish their legislative priorities.

- **Narrow Majority** - House Democrats have a majority of 222-212 but an even more narrow majority in the Senate with a 51-49, which accounts for the two Independent Party Senators as Democrats. Although Democrats have the majority, it is a narrow one and lends to each Democrat in Congress having a vote that holds more weight. Their vote can be leveraged to stall the legislative process to negotiate their priorities. The primary example of this is Senator Joe Manchin from West Virginia who is considered a moderate Democrat. He is also of particular relevance to energy policies because he chairs the Senate
Committee on Energy and Natural Resources and is supportive of fossil-fuel interests given West Virginia’s heavy fossil-based energy portfolio.

- **Global Pressure** - The 26th United Nations Climate Change conference (COP26) was held recently and world leaders assembled to accelerate action toward the goals of the Paris Agreement and the UN Framework Convention on Climate Change. U.S. leaders expressed a need to showcase U.S. climate progress and particularly wanted to expedite the passage of the bipartisan infrastructure deal.

**Policy Recommendations**

1. **Ensure Climate Integrity and Environmental Justice:**

   - Governments provide incentives for the scaling of clean hydrogen at the local, state, and federal level. The production of green hydrogen doesn’t involve any fossil fuels so projects that produce green hydrogen should be prioritized to receive benefits like grants, loan guarantees, credit subsidies, tax credits, etc. Hydrogen projects that generate upstream greenhouse gas emissions in their lifecycle (i.e. blue, grey, brown, black hydrogen) can still qualify for incentives based on their net carbon intensity, meaning they would need to be coupled with significant CCS and appropriately monitored. The impact of CCS should be clearly defined in a standardized carbon intensity metric. Additionally, given hydrogen’s versatility (i.e. hydrogen fuel can be used as a feedstock for other on-demand chemical production), the carbon intensity metric should account for the lifecycle emissions associated with the end-use of the product or service, particularly the combustion of chemicals. The carbon intensity metric should
include qualifications that account for the entire lifecycle of the hydrogen fuel.

- Additional hydrogen specific policies should be made in line with the Biden Administration’s Justic40 Initiative that aims to prevent climate impacts on local communities (The White House, 2021). Specifically, policies that consider what applications of hydrogen energy should be incentivized or more stringently regulated i.e. hydrogen’s application in industrial processes. Qualifying carbon intensive hydrogen practices as well as their CCS efforts should be required to couple with programs that conduct local monitoring programs that are designed to consistently collect emissions data, have rigid emissions’ limits, and significant penalties for lack of compliance.

- **Continue to Fund or Increase the Resources for the DOE Programs Leading Hydrogen Research, Development and Demonstration (R&D) Efforts like:**

  - DOE’s Hydrogen Earth Shot Initiative, which was recently launched on June 7, 2021. The initiative seeks to “reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram in 1 decade with an interim target of $2 per kilogram by 2025” (DOE, Hydrogen Shot). DOE anticipates achieving this $1 figure would be conducive with unlocking new markets for hydrogen, particularly in steel manufacturing, clean ammonia, energy storage, and heavy-duty trucks and increase the overall commercialization of clean hydrogen. Following this announcement on July 7, 2021, DOE announced a $52.5 million commitment to fund 31 projects that support the Hydrogen Shot program and advance next-generation clean hydrogen technologies (DOE, 2021a).
○ DOE’s Hydrogen Shot Fellowship, which invests in the future work force needed to support a clean hydrogen industry. This fellowship plans to recruit diverse talent to be trained alongside current DOE Hydrogen Program managers and foster future hydrogen professionals (DOE, 2021c).

○ DOE H2@Scale, which enables integral cross-sector collaboration for the hydrogen industry at-large. It is a DOE initiative that brings together stakeholders to advance affordable hydrogen production, transport, storage, and utilization in efforts to enable decarbonization and revenue opportunities across multiple sectors (DOE, H2@Scale).

○ DOE EERE’s Hydrogen Fuel Cell Technologies Office (HFCTO). This office is leading the charge on scaling the production of hydrogen in an array of applications. A prime example includes HFCTO’s efforts in the personal transportation like setting and accomplishing technical targets for light -duty vehicles to ultimately contribute to the commercialization of FCEVs (DOE, DOE Technical Targets).

• Foster Cross-Department/Agency Collaboration

○ DOE is a very large agency with several offices and associated resources that were developed over decades to respond to individual technological needs and specific sectors. As previously highlighted, hydrogen’s application is versatile and can span multiple sectors which can lead to bureaucratic confusion as to which office will facilitate certain research development and demonstration (RD&D) efforts of hydrogen. In particular, hydrogen-specific research and development programs within the DOE have been created or augmented.
significantly in recent years. Increasing collaborations across different offices enables a sharing of knowledge and tools to better overcome immense obstacles like deployment barriers. An example of such collaborations is the “2021 Laboratory CRADA Call” which created a joint partnership between National Renewable Energy Laboratory’s (NREL’s) Advanced Research on Integrated Energy Systems (ARIES) and qualified partners like H2@Scale to seek proposals that would better enable the integration of hydrogen technologies in future energy systems (DOE, 2020b).

○ Efforts to create this kind of collaboration have been made in the structure of the funding of federal programs that share common interests but differ in their sources of funding via crosscutting efforts21 which have varying degrees of success and collaboration between different DOE programs. For example, if a new program draws funding from several other existing federal programs this would limit resources and not foster collaboration to achieve common goals. A form of more effective funding would be specifically dedicating funding for the crosscutting efforts of clean hydrogen innovation. This would avoid the siphoning of funding from other programs, more adequately resource the RD&D of clean hydrogen at a commercial scale, and incentivize bureaucratic collaboration on shared technology goals.

○ This paper has highlighted hydrogen’s various applications across multiple sectors which other federal agencies have jurisdiction over and is outside the

---

21 Definition of crosscutting effort: linking traditionally separate or independent interests between agency offices (or potentially other federal agencies) to collaborate on multi-program efforts with shared goals. Each affiliated office also contributes to the funding and resources of the effort.
scope of DOE’s influence. There should be a system created to track all initiatives and developments regarding hydrogen across all federal agencies. The system should be one that is promptly updated and sufficiently shared to optimize opportunities for collaboration. This could foster new cross-agency collaborations to more efficiently develop and further integrate hydrogen technologies at scale. Examples of other agencies and their role in hydrogen development are:

i. The Federal Energy Regulatory Commission (FERC): transmission jurisdiction
ii. Environmental Protection Agency (EPA): climate integrity monitoring and chemical standards for processing applications
iii. Department of Transportation (DOT): sector-specific funding and incentives
v. Department of Defense (DoD): all hydrogen applications

- **Incentivize private industry to invest in hydrogen technology and infrastructure:**
  - **Increase in public-private partnerships:** Hydrogen is currently used more commonly as an alternative fuel in transportation than for power generation (DOE, 2017a), but in order to scale the technology there needs to be more development across all sectors. As a result, there needs to be an increase in public-private partnerships to further drive investment and development of hydrogen infrastructure across all sectors.

- **Increase financial investment certainty within the hydrogen industry:**
The EPA and Congress could expand the definition of “renewable” fuels in the federal renewable fuel standard to allow for renewable electricity to count as a renewable fuel. This would create the opportunity for green hydrogen producers to receive credits in the existing EPA renewable fuel standard and could incentivize further investment in green hydrogen’s production.

Broadening federal investment in hydrogen could help develop business models that are more financeable and scalable. This ripple effect would inject more capital into all aspects of the clean hydrogen industry and help unlock the hydrogen market holistically. In particular, the federal government can help finance hydrogen projects that may be considered too risky for private investors by providing federally backed financial instruments like credit subsidies, small business and innovation research grants (SBIR), improved technology transfer, direct investment, and loan guarantees. Prime examples of existing pathways to accomplish this are DOE’s Loan Program Office (LPO) (Reed, 2021) and its Advanced Technology Vehicle Manufacturing (ATVM) program (DOE, ATVM Loan Program) which historically played a significant role in the commercialization of renewable energy technologies.

DOE’s LPO and ATVM programs play a significant role in the commercialization of renewable energy technologies and recently received significant funding to deploy financial instruments to foster clean hydrogen projects. The DOE is authorized to issue loan guarantees pursuant to Title XVII of the Energy Policy Act of 2005 which means Title XVII outlines what projects can qualify for these loan guarantees. Currently, Title XVII statutorily requires qualifying projects to be
“innovative” which may limit the program's pool of applicants. For example, at face value, electrolysis is no longer “innovative” and limits the support LPO could lend to finance large-scale electrolysis projects because of outdated semantics. More broadly, this change could shift LPO’s ability to not only develop innovative clean technologies, but foster their deployment across the country.

- **Create a production tax credit for clean hydrogen fuel**: A hydrogen production tax credit was seen in the legislative text passed in the House of Representatives' budget reconciliation legislation known as the Build Back Better Act and is currently seeking passage in the Senate (House-Budget, 2021). The credit is tiered to reward hydrogen production technologies with the lowest lifecycle greenhouse gas emissions. It also advantages green hydrogen by prohibiting a claimant from taking advantage of the carbon oxide sequestration credit (26 USC 45Q) and the hydrogen production credit for the same facility, but should be more explicit in its intent as it could be read so as to prohibit any facility that includes carbon capture equipment.

- **Increase the tax credits hydrogen powered vehicles can qualify for**: As it stands, hydrogen fuel cell vehicles qualify for alternative fuel vehicle tax credits and are currently considered an alternative fuel under the Energy Policy Act of 1992 (DOE, Key Federal Legislation) and under the recent IRC 30D (IRS, 2021) tax credit which passed in the Infrastructure Investment and Jobs Act. Looking ahead, it is recommended to ensure a new hydrogen incentive known as 36C is included in the Build Back Better Act, as well as the legislative vehicle as a
whole, is passed.

- **Develop stronger fuel economy standards:** Continue EPA and NHTSA coordination efforts to reduce GHG emissions by developing stricter fuel efficiency standards for medium and heavy duty vehicles. Ultimately this could pinch conventional trucks as it would cause their price tag to bear its emissions price and potentially drive investment into FCEVs and their infrastructure (Transport Policy, n.d.).

- **Provide funding for states to create or continue fostering regional hydrogen programs:**
  - Given the location-specific hub design and considering the key takeaways from Hydeal LA, it is clear there should be local and state policies created to drive the adoption and development of the infrastructure needed to use hydrogen at a commercial scale (Green Hydrogen Coalition, n.d.).
  - This recommendation dovetails with incentivizing private investment in hydrogen transportation as auto manufacturers will likely provide FCEV models in sync with what developing infrastructure can support. The Low Carbon Fuel Standard (LCFS) in California (CA) is proven to reduce carbon intensity of fuels (CARB, 2021) and scale hydrogen fueling opportunities in the state. Therefore, similar state policies should be adopted by additional non-western states or the federal government should adopt a national LCFS more broadly to foster the development of additional regional hydrogen programs.

- **Continue analysis of government interventions’ effect on the hydrogen industry:**
  - Continue to monitor use-cases and their key-takeaways to add to the body of
knowledge for developing successful LCFS state programs. Additionally sharing these successes and lessons with other state decision makers could expand the regions where hydrogen is more competitive. Washington state recently enacted a “Clean Fuel Standard” structured the same as California’s LCFS and made hydrogen fuel more cost-competitive in the state. This could be dually used as another use-case by states like Oregon and Colorado which have been considering implementing similar standards.

- **Upgrade the current federal resources for hydrogen:**
  - Example being DOE’s EERE’s Alternative Fuels Data Center lists all of the laws and incentives related to hydrogen (DOE, *Hydrogen Laws and Incentives*). However, this database could be more user-friendly as well as better solicited amongst hydrogen fuel producers and developers to potentially better inform their business decisions.

**CONCLUSION**

Increasing the diversity of alternative low-carbon energy solutions increases competition, consumer choice, and investment, drives down cost, and ultimately contributes to the commercialization of clean energy writ large. In order to scale the commercial adoption of clean hydrogen in the United States, this paper argued the need for creative collaboration and innovative input from the largest variety of both public and private stakeholders. If clean hydrogen is to play a major role in radically decarbonizing the power, industrial, and transportation sectors with climate integrity it is clear the following needs remain:

- Water electrolysis be the preferred and cost-effective method of hydrogen production.
● Cost-effective business models invest in the research and development of infrastructure for the safe storage, transportation, and distribution of hydrogen need to be continued.

● Carbon capture technology be used for carbon-intensive forms of hydrogen production and distribution, to significantly increase its carbon capture rate.

● Design creative policies to better leverage the government's resources and authority to scale hydrogen technology and minimize its impact on the environment and public health.

Government tools like tax incentives and RD&D historically help incentivize private investment in certain energy technologies. Directing government investment in developing clean hydrogen technology would not only garner resources to bring the cost down of hydrogen but also create market signals to the private sector to further invest in hydrogen technologies. Although there is private investment in clean hydrogen development, the investments and policies from the Biden Administration and Congress contributed to creating a more friendly regulatory environment for hydrogen and enabled its market penetration. However, this political environment is subject to change and it is not clear that if hydrogen were to become commercially available if it would remain viable from market forces alone. There is an arduous need to bolster sustainable market trends for clean hydrogen that could outlast an unfriendly political environment and eventually realize the clean hydrogen economy many have envisioned.
REFERENCES


California Air Resources Board (CARB). (2026, December 10). Hydrogen in the LCFS-


U.S. Department of Energy (DOE). DOE Announces $52.5 Million to Accelerate Progress in


