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# HYDROGEN ROADMAP FOR THE STATE OF MICHIGAN

## Workshop Report

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University of Michigan  
Ann Arbor

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## Document Description

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The workshop organizing team offers thanks to all of the participants who attended the workshop as well as others who provided input and feedback. The recommendations for deployment of hydrogen technologies in Michigan have been developed by the authors based on our research and discussion and feedback at the workshop and do not imply any commitments on the part of workshop participants or their organizations.

# Abbreviations

AIAA – American Institute of Aeronautics and Astronautics  
ANL – Argonne National Laboratory  
BEV – battery electric vehicle  
BOF – basic oxygen furnace  
CAES – compressed air energy storage  
CCUS – carbon capture, utilization, and storage  
CHP – combined heat and power  
CH<sub>4</sub> – methane  
CO – carbon monoxide  
CO<sub>2</sub> – carbon dioxide  
DHW – domestic hot water  
DOE – U.S. Department of Energy  
DRI – direct reduced iron  
EAF – electric arc furnace  
EGLE – Michigan Department of Environment, Great Lakes, and Energy  
EIA – U.S. Energy Information Administration  
EPA – U.S. Environmental Protection Agency  
FCEV – fuel cell electric vehicle  
gge – gallon gasoline equivalent  
GHG – greenhouse gases  
GWe – gigawatts electric  
GWh – gigawatt-hour  
HDV – heavy-duty vehicle  
H<sub>2</sub> – hydrogen gas  
ICEV – internal combustion engine vehicle  
IEA – International Energy Agency  
INL – Idaho National Laboratory  
IPCC – Intergovernmental Panel on Climate Change  
IRA – Inflation Reduction Act  
ITC – investment tax credit  
kWh – kilowatt-hour  
LDV – light-duty vehicle  
LH<sub>2</sub> – liquid hydrogen  
MDOT – Michigan Department of Transportation  
MDV – medium-duty vehicle  
MMT – million metric tons  
NH<sub>3</sub> – ammonia  
NO<sub>x</sub> – nitrogen oxides  
NREL – National Renewable Energy Laboratory  
OEM – original equipment manufacturer  
ORNL – Oak Ridge National Laboratory  
PHEV – plug-in hybrid electric vehicle  
PM<sub>2.5</sub> – particulate matter, 2.5 microns  
PM<sub>10</sub> – particulate matter, 10 microns  
PTC – production tax credit  
RNG – renewable natural gas  
SMR – steam methane reforming  
SNL – Sandia National Laboratory

SO<sub>x</sub> – sulfur oxides  
SUV – sport utility vehicle  
TWh – terawatt-hour  
VOC – volatile organic compound  
VTOL – vertical take-off and landing

# Executive Summary

The Department of Energy (DOE) Office of Clean Energy Demonstrations (OCED) intends to issue a Funding Opportunity Announcement (FOA) entitled “Regional Clean Hydrogen Hubs” (H2Hubs) in collaboration with the Energy Efficiency and Renewable Energy’s (EERE) Hydrogen and Fuel Cell Technologies Office (HFTO) and the DOE Hydrogen Program. The Notice of Intent to release this FOA indicates that the H2Hubs “will form the foundation of a national clean hydrogen network that will contribute substantially to decarbonizing multiple sectors of the economy while also enabling regional and community benefits.” The Bipartisan Infrastructure Law includes \$8 billion of funding for this effort and is expected to result in at least four H2Hubs across the U.S.

In advance of this announcement, and to identify potential near- and long-term hydrogen deployment opportunities and key enabling factors, the Center for Sustainable Systems (CSS) at the University of Michigan convened the Hydrogen Roadmap for the State of Michigan workshop on May 20, 2022 with support from the Michigan Economic Development Corporation (MEDC) and the University of Michigan Office of Research (UMOR). The CSS research team evaluated hydrogen production, delivery and storage, and end-use application technologies, as well as hydrogen roadmaps and strategy documents from around the world, and presented findings at the Workshop for feedback. The 73 participants at the workshop, who represented commercial, governmental, and academic organizations, also provided input on the location and clustering of Michigan and regional assets related to hydrogen production and use (both current and potential).

The information compiled and presented in this Workshop Report is a high-level assessment intended to guide planning and future detailed analysis. A hydrogen ecosystem encompasses production, delivery, storage, and end-use applications, as illustrated in Exhibit ES-1.<sup>1</sup> The design of a hydrogen ecosystem for Michigan begins with quantifying the end-use applications for hydrogen, which then defines the demand for production, delivery, and storage of hydrogen. More detailed analysis of demand than is presented here is necessary in order to make decisions on which end uses and production methods should be pursued in Michigan and across the wider region. After characterizing the opportunities and challenges for each hydrogen end-use, production, delivery, and storage technology, we explore their spatial distribution in Michigan and across the Midwest region. Current Michigan and regional assets and potential hydrogen transition industries were compiled and mapped to identify potential hydrogen demand clusters. A summary map is presented as Figure ES-1. The evaluation and spatial mapping of technologies provides the foundation for the hydrogen technology deployment recommendations for Michigan that are presented below.

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<sup>1</sup> U.S. DOE, Office of Energy Efficiency & Renewable Energy, *H2@Scale*.  
<https://www.energy.gov/eere/fuelcells/h2scale>



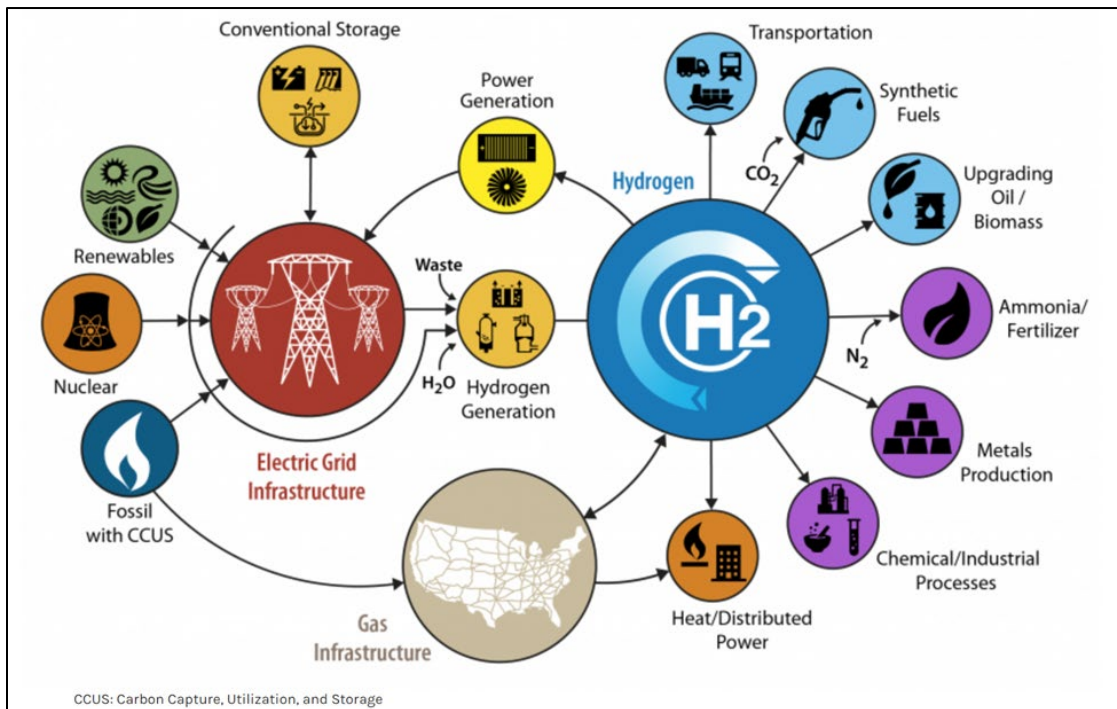
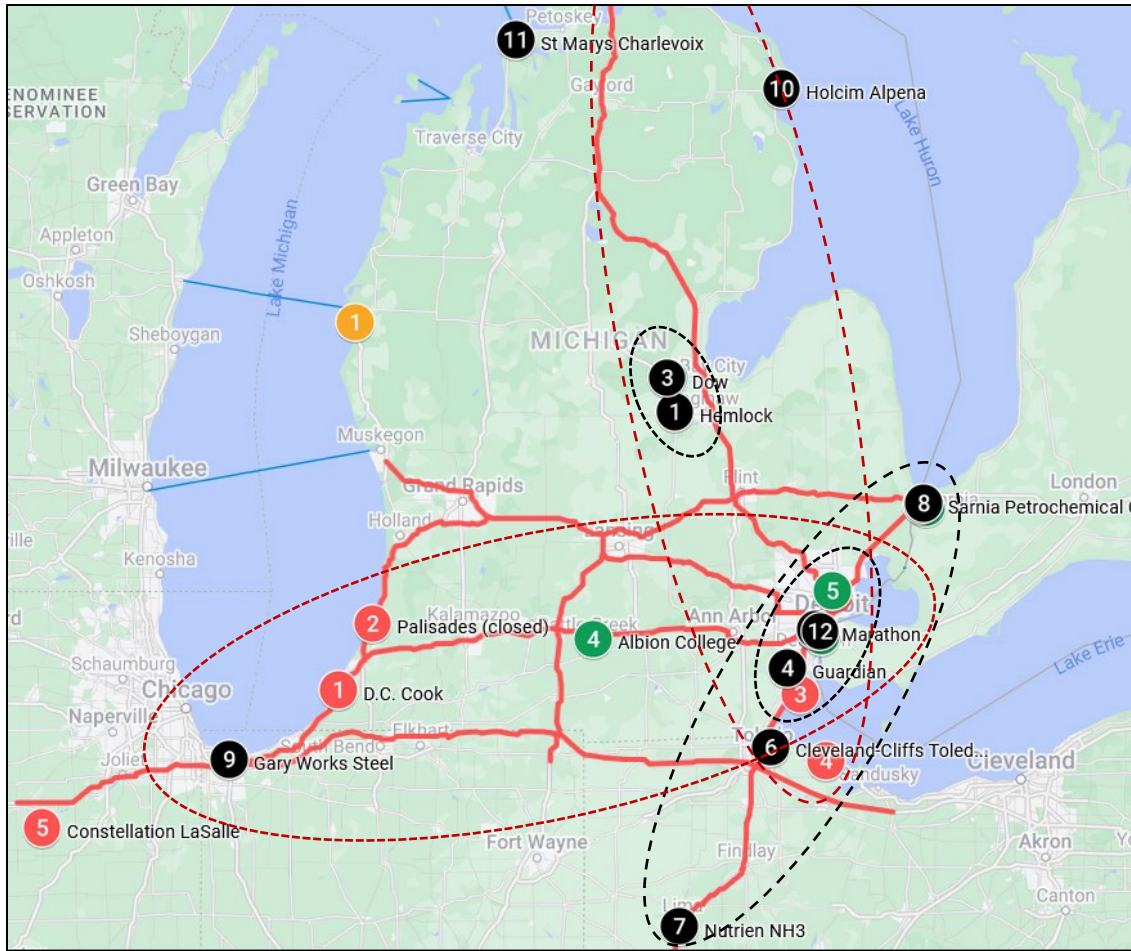


Exhibit ES-1 DOE hydrogen ecosystem diagram (from U.S. DOE, Office of Energy Efficiency & Renewable Energy, H2@Scale. <https://www.energy.gov/eere/fuelcells/h2scale>).



**Nuclear plant**

- 1 D.C. Cook
- 2 Palisades (closed)
- 3 Fermi
- 4 Davis-Besse
- 5 Constellation LaSalle

**H2 production**

- 1 Air Products
- 2 Air Products
- 3 Praxair
- 4 Albion College
- 5 Detroit Arsenal
- 6 Air Products Sarnia
- 7 Praxair Sarnia

**Industry**

- 1 Hemlock Semiconductor
- 2 Marathon Refinery
- 3 Midland chemical complex
- 4 Guardian Glass
- 5 Cleveland Cliffs Rouge Steel
- 6 Cleveland-Cliffs Toledo DR
- 7 Nutrien NH3
- 8 Sarnia petrochemical complex
- 9 Gary Works Steel
- 10 Holcim Cement
- 11 St Marys Cement
- 12 St Marys Cement

Figure ES-1. Potential deployment opportunities in a hydrogen ecosystem (the gold number 1 is Ludington pumped storage). Small black ellipses highlight clusters of hydrogen facilities in Michigan, the larger black ellipse is a potential regional cluster, the maroon ellipses highlight transportation corridors.

## Recommendations

Summary information on all end uses, production, delivery, and storage options is contained in the tables in Section 7. The recommendations from those tables, which are based on the information currently available, are collected here and categorized by what type of action should be taken. We intend these recommendations to be a starting point for further discussion and analysis on the roles where hydrogen can most beneficially be deployed to advance decarbonization.

Several recommendations are more general and pertain to all pathways. Safety is one of these, and should be included as a necessary component of any facility or strategy employing hydrogen. Equity is another integral component of any way forward – reducing emissions, providing equitable access, and protecting public health should all be part of any decarbonization strategy.

Moving medium- and heavy-duty vehicles to low-carbon hydrogen in the region is a key decarbonization strategy that also creates a major opportunity for the Michigan automotive industry. The abundance of high-volume interstate highways in southern Michigan that connect us to Illinois, Indiana, Ohio, and Ontario, as well as the difficulty in electrifying this end use both argue for this path. This path could also coordinate with and connect to southern Ontario's potential hydrogen hub in Sarnia-Lambton. There are other strategies where the case for hydrogen is less compelling. Use in buildings is one of these, as electrification of HVAC and appliances in residential and commercial buildings provides greater GHG emissions reduction. It is also clear that producing hydrogen from low-carbon electricity for later combustion reduces emissions less than using that low-carbon electricity to directly offset higher-carbon sources of grid electricity.

### Near-term action

**Transportation (MDV & HDV):** OEMs should pursue the development of fuel cell MDV and HDVs, and investments should be made in expanding low-carbon hydrogen production and fueling infrastructure.

**Transportation (ships – ferries):** Deploy hydrogen fuel cell ferries on long routes and battery electric ferries on shorter routes.

**Production:** Site hydrogen production near future industrial clusters and fueling hubs.

### Further exploration for action

**Chemicals (ammonia):** Michigan with its large agriculture sector should explore low-carbon ammonia production and partnering with other regional assets (such as Nutrien in Lima, OH).

**Transportation (freighters):** Investigate using hydrogen vessels similar to those being demonstrated in Europe for applications in the Great Lakes.

**Transportation (rail):** Amtrak and freight rail companies should explore electric and hydrogen trains for Chicago to Detroit/Port Huron routes.

**Semiconductor manufacturing:** Explore using low-carbon hydrogen as a feedstock and fuel. Do not recommend using hydrogen as a source for electricity generation.

**Delivery (new 100% H<sub>2</sub> pipelines):** Explore expanding pipeline networks in industrial clusters and delivery to large fueling stations close to production facilities.

**Delivery (ship):** Explore potential for shipping hydrogen on the Great Lakes to demand centers in the region.

**Storage (salt caverns):** Michigan's salt caverns should be studied further for potential as large volume hydrogen storage; proximity to industrial application sites is attractive. Investigate contamination/gas quality concerns.

## No current action

**Buildings:** Hydrogen is not recommended for HVAC or appliances. Hydrogen could play a role in back up power systems to replace NG generators. Propane users should be included in decarbonization and alternative fuel discussions.

**Transportation (aircraft):** No deployment recommended currently. Future hydrogen fueling could be planned for major Michigan airports if this is the direction the industry pursues. Based on plans announced by Airbus this would not be expected before 2035. Sustainable aviation fuels based on hydrogen are also a possibility but high cost is a challenge.

**Power generation:** Hydrogen is not recommended as a combustion fuel or as a major player in energy storage given round trip inefficiencies.

**Storage (NG reservoirs):** Workshop participants rejected the use of NG reservoirs for storage due to contamination and containment concerns, which should be verified for the MI case (geology).

**Delivery (blending with NG):** Not recommended (see building end-use-applications) as other pathways achieve greater carbon reduction.

**Production (fossil w/CCUS):** Renewable and nuclear production pathways are more favorable long term decarbonization strategies. Michigan has capacity to store captured carbon in NG reservoirs but risks and energy penalties need to be addressed.

## Longer-term action (when grid electricity is low- or zero-carbon)

**Transportation (LDV):** Michigan should accelerate transition to light-duty BEVs rather than developing vehicle technology and hydrogen fueling infrastructure for LDVs.

**Chemicals (refineries):** Refineries should transition to low-carbon hydrogen; refinery output will decline with the transition to electrified transportation as processing for chemical feedstocks becomes the primary role of refineries.

**Cement Production:** Michigan's three cement production facilities should transition to clean energy sources including low-carbon hydrogen.

**Glass making:** Guardian Glass plant in Carleton, MI should transition to using low-carbon hydrogen as a melting furnace fuel (depending on the outcome of the HyNet demonstration).

**Steelmaking:** Invest in low-carbon hydrogen for DRI facilities.

**Production (renewables):** Renewable electricity in Michigan can be used for demonstration of hydrogen production but greater decarbonization can currently be achieved by displacing fossil-based electricity. Using excess electricity produced by wind turbines offshore in the Great Lakes should be evaluated for technical and economic feasibility as a hydrogen production route.

**Production (nuclear):** Nuclear energy in Michigan can be used for demonstration of hydrogen production but greater decarbonization can currently be achieved by displacing fossil-based electricity. Small modular reactors could be utilized as new generation sources that could be distributed near hydrogen demand centers.

# 1. Introduction

## 1.1. Context & Motivation

### 1.1.1. Hydrogen Basics

Hydrogen is an important feedstock and fuel currently used in multiple sectors of our economy. The annual U.S. production of hydrogen is approximately 10 million metric tons (MMT), compared to 90 million metric tons produced and used globally.<sup>2</sup> Hydrogen is the most abundant element in the universe, though it is rarely found naturally in its elemental form on Earth. A majority of hydrogen production in the U.S. and abroad is from steam methane reforming (SMR) of natural gas. This process generates CO<sub>2</sub> emissions, which is problematic from a climate change perspective. Electrolysis is a hydrogen production process that uses electricity to split water into hydrogen and oxygen. This production pathway can provide a basis for decarbonizing some sectors of the economy if the electricity is sourced from zero- or low-carbon generators such as renewables and nuclear power. Some basic information about hydrogen is provided in Exhibit 1.

#### Material Properties

- Hydrogen (H<sub>2</sub>) is an odorless, colorless gas
- Does not naturally exist on Earth as a gas in significant concentrations
- Liquefies at -253°C
- Flammable between 4% and 75% (vol) in air, nearly invisible flame
- Is an energy carrier produced from other energy sources (e.g., electricity and natural gas)

#### Energy Properties

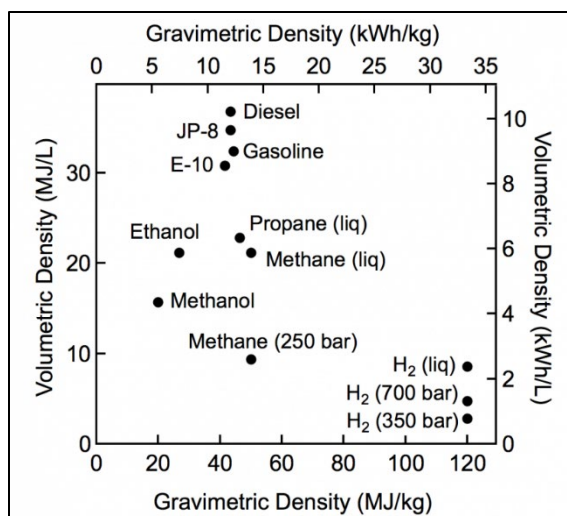
- Energy content of **1kg H<sub>2</sub> ≈ 1 gallon of gasoline**
- Production from electrolysis (approximate): **50 kWh electricity for 1 kg H<sub>2</sub>** (based on a 70% electrolyzer efficiency)
- On a **mass basis**, hydrogen has nearly 3x the energy content of gasoline.  
hydrogen = 120 MJ/kg vs.  
gasoline = 44 MJ/kg
- On a **volume basis**, liquid hydrogen has ¼ the energy density of gasoline.  
hydrogen (liquid) = 8 MJ/liter; compressed gas (700 bar) = 4 MJ/liter vs.  
gasoline = 32 MJ/liter

*Exhibit 1. Hydrogen properties*

A comparison of hydrogen to other fuels and energy carriers on both volume and mass bases is shown in Exhibit 2.<sup>3</sup>

<sup>2</sup> U.S. DOE, February 15, 2022. *DOE Establishes Bipartisan Infrastructure Law's \$9.5 Billion Clean Hydrogen Initiatives.* <https://www.energy.gov/articles/doe-establishes-bipartisan-infrastructure-laws-95-billion-clean-hydrogen-initiatives>

<sup>3</sup> U.S. DOE, Hydrogen and Fuel Cells Technologies Office, *Hydrogen Storage.* <https://www.energy.gov/eere/fuelcells/hydrogen-storage>



*Exhibit 2. Comparison of fuels and energy carriers by mass density and volume density (from U.S. DOE, Hydrogen and Fuel Cells Technologies Office, Hydrogen Storage. <https://www.energy.gov/eere/fuelcells/hydrogen-storage>). For a similar figure that includes ammonia as well as the effect of fuel storage vessels, see Figure 1 in (Dolan et al. 2021).*

### 1.1.2. IPCC carbon reduction targets

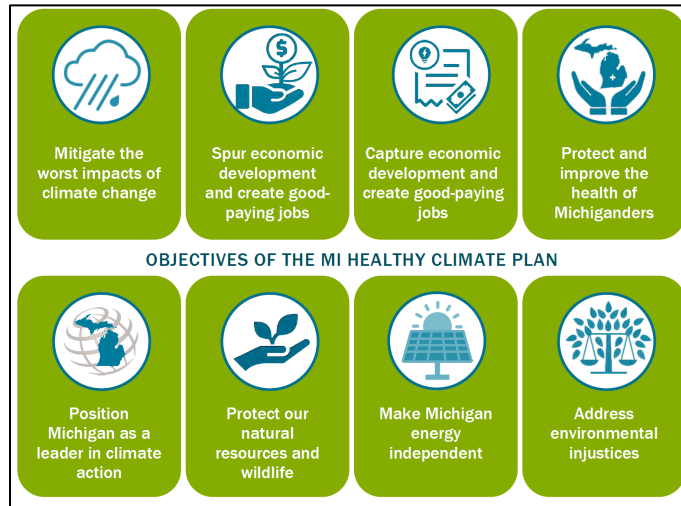
The urgency to decarbonize the economy has been well established and documented by the Intergovernmental Panel on Climate Change (IPCC), including the most recent Assessment Report (AR6), which has been accepted but is subject to final copyediting (IPCC 2022). The goals established by the IPCC have served as the basis for climate mitigation strategies and action plans by government, industry, and community stakeholders around the world. A 2018 IPCC Special Report found that limiting global warming to 1.5°C would require “rapid and far-reaching” transitions in land, energy, industry, buildings, transport, and cities. Global net human-caused emissions of carbon dioxide (CO<sub>2</sub>) would need to fall by about 45% from 2010 levels by 2030, reaching ‘net zero’ around 2050. This means that any remaining emissions would need to be balanced by removing CO<sub>2</sub> from the air. In AR6, the IPCC strengthens their statement, saying that “Modelled mitigation pathways that limit warming to 1.5°C, and 2°C, involve deep, rapid and sustained emissions reductions.” (IPCC 2022, p. SPM-34) Hydrogen production, delivery, storage, and use technologies provide potential solutions for addressing these climate change challenges.

### 1.1.3. Healthy Climate Plan

In 2020 Governor Whitmer charged the Michigan Department of Environment, Great Lakes, and Energy’s (EGLE) Office of Climate and Energy with developing the MI Healthy Climate Plan. The purpose of this plan is “to lay out a broad vision for fulfilling the governor's commitment for Michigan to achieve economy-wide carbon neutrality by 2050 - the global science-based benchmark for reducing greenhouse gas emissions to avoid the most devastating and costly impacts of climate change.” Key objectives of the plan, which was published in April 2022 (EGLE 2022), are indicated in Exhibit 3 and a high-level summary of findings and recommendations are presented in Exhibit 4. These objectives align well with the parameters analyzed in this study (see Scope & Objectives in section 1.2). The MI Healthy Climate Plan proposes a range of strategies for decarbonizing the Michigan economy and “hydrogen” was identified as a potential solution in certain sectors although no specific recommendations were made.

The Plan highlighted a few areas where hydrogen can play a role in accelerating a clean energy transition in Michigan. For example, the “plan recommends the state undertake a pathway analysis to assess options to achieve carbon neutrality from natural gas production, transmission, distribution, compression, storage,

and end uses in a least-cost manner. This analysis should consider a full range of options for decarbonizing natural gas end uses, including energy efficiency, electrification, fuel switching to renewable natural gas and hydrogen, and other potential opportunities.” The Plan also provides an example of one specific application of hydrogen technology, to “create programs to catalyze and accelerate the transition to cleaner technologies like electric and hydrogen fuel-cell farm equipment.”



*Exhibit 3. Michigan Healthy Climate Plan objectives (from EGLE 2022).*

<p><b>Commit to Environmental Justice and Pursue a Just Transition:</b> Ensure that at least 40 percent of state funding for climate-related and water infrastructure initiatives benefit Michigan’s disadvantaged communities (in line with the federal government’s Justice40 guidelines for federal funding); that Justice40 is developed in partnership with leaders in disadvantaged communities; and that Michigan emphasizes a just transition for all workers through proactive engagement, job training, and workforce development.</p>
<p><b>Clean the Electric Grid:</b> Generate 60 percent of the state’s electricity from renewable resources and phase out remaining coal-fired power plants by 2030. Limit energy burden from powering and heating homes to not more than 6 percent of annual income for low-income households.</p>
<p><b>Electrify Vehicles and Increase Public Transit:</b> Build the infrastructure necessary to support 2 million electric vehicles on Michigan roads by 2030. Increase access to clean transportation options – including public transit – by 15 percent each year.</p>
<p><b>Repair and Decarbonize Homes and Businesses:</b> Reduce emissions related to heating Michigan homes and businesses by 17 percent by 2030. Increase investments in repairing and improving buildings to reduce costs for working families and small businesses.</p>
<p><b>Drive Clean Innovation in Industry:</b> Encourage clean innovation hubs where private enterprises strategically co-locate and collaborate to develop and deploy new, cleaner manufacturing technologies and conduct research and development to reduce emissions from hard to decarbonize industries. Triple Michigan’s recycling rate to 45 percent and cut food waste in half by 2030.</p>
<p><b>Protect Michigan’s Land and Water:</b> Protect 30 percent of Michigan’s land and water by 2030 to naturally capture GHG emissions, maintain and improve access to recreational opportunities for all Michiganders, and protect biodiversity. Leverage innovative strategies to support climate-smart agriculture.</p>

*Exhibit 4. High-level recommendations from the Michigan Healthy Climate Plan (from EGLE 2022).*



### 1.1.4. DOE Hydrogen Hub Competition

The Department of Energy (DOE) Office of Clean Energy Demonstrations (OCED) intends to issue a Funding Opportunity Announcement (FOA) entitled “Regional Clean Hydrogen Hubs” (H2Hubs) in collaboration with the Energy Efficiency and Renewable Energy’s (EERE) Hydrogen and Fuel Cell Technologies Office (HFTO) and the DOE Hydrogen Program, which includes multiple offices engaged in hydrogen related technologies across DOE. OCED anticipates issuing the FOA in the September/October 2022 timeframe, and the FOA will be funded by the Infrastructure Investment and Jobs Act, also known as the Bipartisan Infrastructure Law. The mission of the OCED is to deliver clean energy and industrial decarbonization demonstration projects at scale in partnership with the private sector, labor unions, and other stakeholders and communities, and to launch or accelerate market adoption and deployment of technologies as part of an equitable transition to a decarbonized energy system and economy. The Notice of Intent to release this FOA indicates that the H2Hubs “will form the foundation of a national clean hydrogen network that will contribute substantially to decarbonizing multiple sectors of the economy while also enabling regional and community benefits.”<sup>4</sup> The Bipartisan Infrastructure Law includes \$8 billion of funding and the DOE competition is expected to result in at least four Regional Clean H2Hubs across the U.S. The characteristics that will be used to select H2Hubs are:

**Feedstock Diversity:** at least one H2Hub shall demonstrate the production of clean hydrogen from fossil fuels, one H2Hub from renewable energy, and one H2Hub from nuclear energy.

**End-Use Diversity:** at least one H2Hub shall demonstrate the end-use of clean hydrogen in the electric power generation sector, one in the industrial sector, one in the residential and commercial heating sector, and one in the transportation sector.

**Geographic Diversity:** each H2Hub will be located in a different region of the United States and leverage energy resources abundant to that region, including at least two H2Hubs in regions with abundant natural gas resources.

**Employment:** DOE shall give priority to regional clean hydrogen hubs that are likely to create opportunities for skilled training and long-term employment to the greatest number of residents in the region.

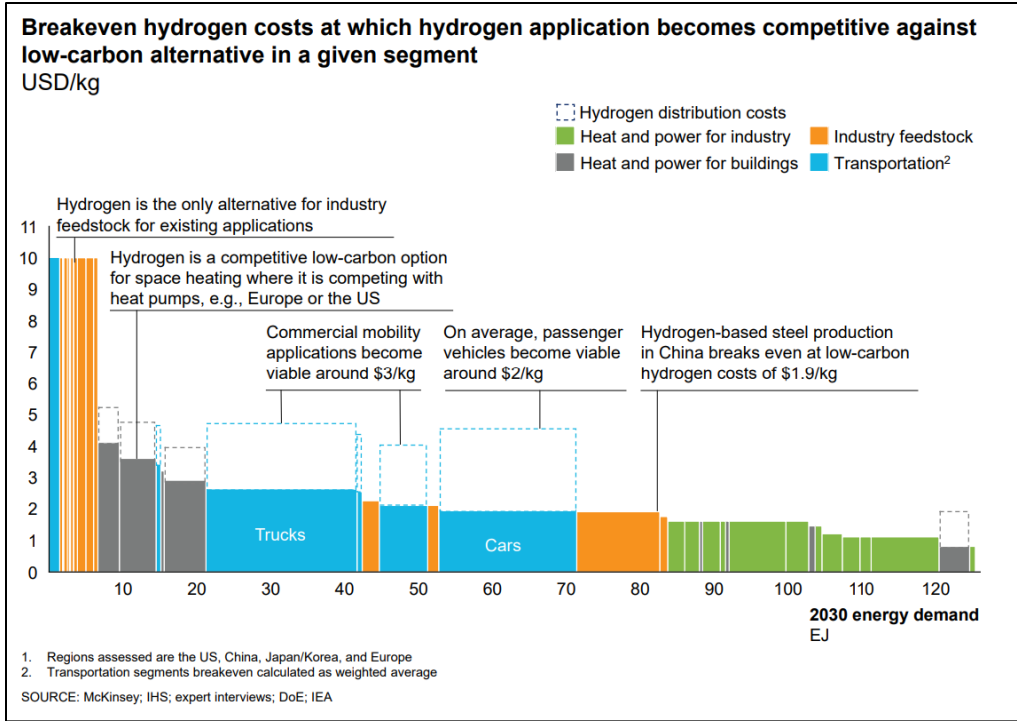
### 1.1.5. Hydrogen technology deployment challenges and opportunities

Low carbon hydrogen has the potential to decarbonize end-use applications where electrification and other alternatives are problematic. The role and deployment rate of hydrogen in the clean energy transition will be highly dependent on the delivered cost of hydrogen. Renewable and low-carbon hydrogen are not currently cost competitive with fossil-based hydrogen (Exhibit 5). DOE’s Hydrogen Shot initiative seeks to reduce the cost of clean hydrogen by 80% to \$1 per 1 kg in 1 decade (“1 1 1”). DOE states that, if successful, Hydrogen Shot will reduce carbon emissions by 16% by 2050 and lead to \$140 billion in revenue and 700,000 new jobs by 2030.<sup>5</sup> The Hydrogen Shot cost target does not include the cost of transporting hydrogen, which is considerable.

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<sup>4</sup> U.S. DOE Office of Clean Energy Demonstrations Funding Opportunity Exchange, DE-FOA-0002768: Notice of Intent to Issue Funding Opportunity Announcement No. DE-FOA-0002779 - Bipartisan Infrastructure Law: Additional Clean Hydrogen Programs (Section 40314): Regional Clean Hydrogen Hubs. <https://oced-exchange.energy.gov/Default.aspx#FoaId4e674498-618c-4f1a-9013-1a1ce56e5bd3>

<sup>5</sup> U.S. DOE, Hydrogen and Fuel Cells Technologies Office, *Hydrogen Shot*. <https://www.energy.gov/eere/fuelcells/hydrogen-shot>



*Exhibit 5. Cost curve for hydrogen production across segments and regions (Hydrogen Council 2020).*

In addition to the production cost challenge, hydrogen must compete with other alternative pathways to decarbonization, including direct electrification of transportation and building systems. The IPCC AR6 report indicates that “As a general rule, and across all sectors, it is more efficient to use electricity directly and avoid the progressively larger conversion losses from producing hydrogen, ammonia, or constructed low GHG hydrocarbons.” (IPCC 2022, p.TS-55) Electrification of end-use applications such as transportation also have the advantage of an existing infrastructure including generation, transmission, and distribution, whereas hydrogen infrastructure faces a chicken and egg problem. For example, fuel cell vehicles won’t be produced at scale until fueling infrastructure is constructed and fuel infrastructure investment won’t occur until there are enough fuel cell vehicles on the road.

A major advantage of hydrogen over electricity as a carrier is its energy storage capacity. Hydrogen (generated via electrolysis) can store electricity generated from variable sources such as wind and solar for conversion back to electricity at a future time and place via fuel cells or combustion in turbines or as an industrial feedstock. Hydrogen can add resiliency to the grid when there is a high penetration of variable renewable sources. Resiliency can come from flexible generation of hydrogen via electrolysis, hydrogen power plants, and long duration hydrogen storage. Round-trip efficiencies from conversion of electricity to hydrogen and back again to electricity are projected to reach up to 50% by 2030. (IPCC 2022, p.TS-55)

## 1.2. Scope & Objectives

To advance hydrogen-based technologies in Michigan and the broader Midwest region, a Hydrogen Roadmap is necessary. This Roadmap can serve as a blueprint to coordinate public and private efforts leading to demonstration and commercialization and support a response to federal funding and private investment opportunities.

The Michigan Economic Development Corporation (MEDC) and the University of Michigan Office of Research (UMOR) funded the Center for Sustainable Systems (CSS) to develop a roadmap for hydrogen infrastructure deployment in MI that evaluates resiliency, economic development, justice and equity, and end use applications across sectors (transportation, power, industry, buildings). The following study parameters were identified to guide the development of this roadmap:

**GHG reduction potential** – contribution to state and national targets, other environmental impacts

**Technology** – readiness, constraints, competition (with other carriers, technologies))

**Scale** – capacity and potential for hydrogen production, delivery, storage, and end use applications

**Spatial mapping and analysis** – of hydrogen supply chain (potential hub(s) and spokes) including: production sites, routing network, industrial sites, fueling stations, etc.

**Regional linkages** – extending beyond Michigan

**Time horizon** – near term (to 2030) and longer term (2030 to 2050)

**Socio-economic impacts** – jobs, justice, and equity issues

CSS organized a one-day Hydrogen Roadmap for Michigan Stakeholder Workshop to identify potential near- and long-term hydrogen deployment opportunities and key enabling factors. The workshop was held in Ann Arbor on May 20, 2022 and provided the framework and foundation for creating this report. A list of the 73 stakeholders from across the state who participated is included (with affiliation and email address) in Appendix A.

The agenda for the Workshop is included in Appendix B. The CSS research team evaluated H<sub>2</sub> production, delivery and storage, and end-use application technologies and presented findings at the Workshop for feedback. The participants also provided input on the location and clustering of Michigan and regional assets for creating a potential Michigan hydrogen ecosystem.

CSS research used existing studies and effectively engaged key stakeholders to construct the roadmap in a short timeframe (between March and August – the originally expected deadline for the DOE H2Hubs competition). The research for the workshop and this report included the following tasks:

- Review relevant literature (government agencies, national labs, industry trade associations, academic journals)
- Conduct interviews with key stakeholder organizations to collect data on technical, economic, and social opportunities and barriers to hydrogen utilization
- Collect feedback on the draft Hydrogen Roadmap from workshop participants, and refine the roadmap prior to release to the public.

### 1.2.1. Expected Outcomes

This report evaluates hydrogen technologies for end-use applications, delivery, storage, and production and creates a preliminary Hydrogen Roadmap for Michigan by characterizing and recommending deployment opportunities. The roadmap also highlights hydrogen hub linkages outside Michigan and the state's role in

the energy transition in the broader Midwest Region, especially the Great Lakes states and Ontario, which has its own hydrogen hub developing in Sarnia-Lambton, across the Detroit River from Port Huron, MI.<sup>6</sup>

The development of a Michigan Hydrogen Roadmap has the following expected outcomes:

- Inform planning, policy and deployment of hydrogen production, delivery and storage infrastructure and end use applications in the State
- Inform Regional H2Hub planning and response to the DOE competition
- Understand the role hydrogen can play in State of Michigan Climate Solutions
- Inform the role Michigan can play as a hydrogen provider and/or consumer in the context of a broader energy transition in the eastern United States
- Highlight where hydrogen can contribute to a just energy system

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<sup>6</sup> Sarnia-Lambton Economic Partnership. *Hydrogen*. Accessed May 3, 2022 from <https://www.sarnialambton.on.ca/key-sectors/hydrogen>

### 1.3. Analysis Framework

This Roadmap draws heavily on existing roadmaps and strategies, as well as CSS energy systems analysis and LCA studies of transportation, renewable energy, hydrogen infrastructure, buildings, materials, and manufacturing systems. This body of knowledge is applied to the State of Michigan and wider Midwest region to develop recommendations for deployment in Michigan using the evaluation criteria presented in the Scope & Objectives section above.

We have compiled and reviewed roadmaps and strategies for hydrogen technology deployment that have been developed by various countries, government agencies, and industry organizations. This list is presented in Appendix C. U.S. DOE was scheduled to release a new Hydrogen Strategic Plan in spring 2022 but this has been delayed.

Ideally, we would develop a detailed energy systems model to evaluate each hydrogen technology against incumbent technologies and alternative competing technologies. Unfortunately, simulating the transition to a hydrogen economy and ecosystem quantitatively using cost and environmental metrics is beyond the allotted time and scope of this work, which is a higher-level assessment intended to guide future, more detailed, work. We have compiled existing indicators and information as a basis to formulate the roadmap findings and recommendations. An example of results from a more comprehensive study to evaluate the timing for deployment of hydrogen technologies and scale of hydrogen demand globally is presented in Exhibit 6 (U.S. DOE FE 2020).

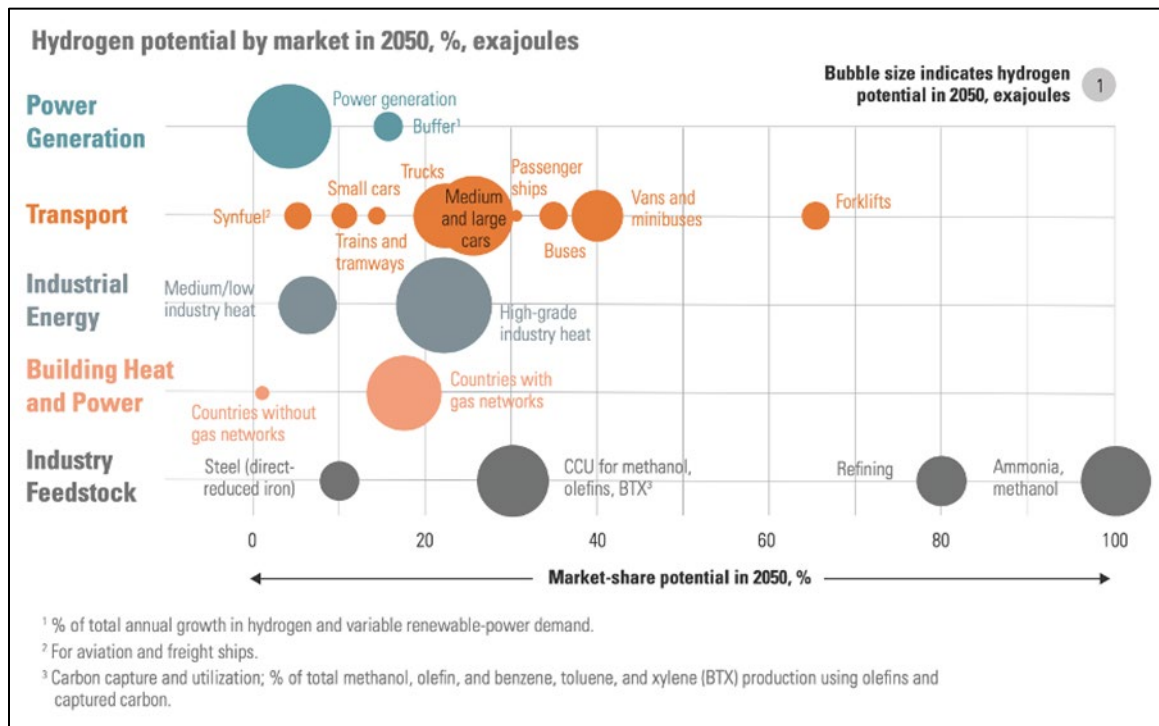


Exhibit 6. U.S. DOE projection of global potential hydrogen future use of hydrogen (from U.S. DOE FE 2020).

Key metrics that are useful in evaluating the performance of hydrogen technologies against incumbents and other alternatives are indicated in Table 2. There are significant gaps in this assessment but the framework is useful for future research, policy and deployment.

A hydrogen ecosystem encompasses production, delivery, storage, and end-use applications as illustrated in Exhibit 7.<sup>7</sup> These activities are evaluated in the next section of this report. The design of a hydrogen ecosystem for Michigan should begin with quantifying the end-use applications for hydrogen, which then defines the demand for production, delivery, and storage of hydrogen.

*Table 1. Potential hydrogen technology evaluation metrics.*

<b>Category</b>	<b>Potential Metrics</b>	<b>Examples</b>
Tech Readiness		
	Technology Readiness Level	Developed, Demonstrated, Commercially available
Cost (short & long term)		
	cost per kg of GHG avoided	\$/ton GHG avoided
	H <sub>2</sub> production cost	\$/ton H <sub>2</sub>
	total cost of ownership	\$ BEV/mile vs \$ FCEV/mile
GHG reduction		
	mass GHG / functional unit produced	kg GHG/kg steel
	mass GHG / mass H <sub>2</sub> produced	kg GHG/kg H <sub>2</sub>
Justice/Equity		
	energy access	Distance to nearest fueling station
	air/water/solid waste pollution/impacts	Reduction in ozone concentration
	health effects	Morbidity/mortality rate

<sup>7</sup> U.S. DOE, Office of Energy Efficiency & Renewable Energy, *H2@Scale*. <https://www.energy.gov/eere/fuelcells/h2scale>



## 2. End-Use Applications

In this section of the roadmap, we collect information on sectors that are potential candidates for transitioning, wholly or partly, to hydrogen. Sectors included are transportation, chemical industry, steel, cement, glass, semiconductors, buildings, and electricity generation. Each sector begins with a brief description that is followed by a listing of GHG reduction potential and other potential strategies, cost / economic impact, technology readiness and demonstrations, Michigan assets, regional assets, equity, and policy issues.

### 2.1. Transportation

In the state of Michigan, vehicles travel approximately 100 million vehicle miles annually, the 10th most of any state. Michigan is the 12<sup>th</sup> leading state in vehicle registrations and is 1<sup>st</sup> in the production of vehicles. There are several freight corridors in the state; two major ones are I-75 (north-south) and I-94 (east-west). The Ambassador Bridge between Detroit and Windsor, Ontario is one of the busiest border crossings in North America, carrying nearly 25% of all commercial trade between the U.S. and Canada. Our state transportation GHG emissions are driven largely by light-duty (passenger) vehicles and freight trucks, as shown in Exhibit 8 (MI healthy climate plan). In terms of existing infrastructure in Michigan for refueling hydrogen vehicles, there are zero public and two private stations, one in Dearborn and one in Grand Blanc.

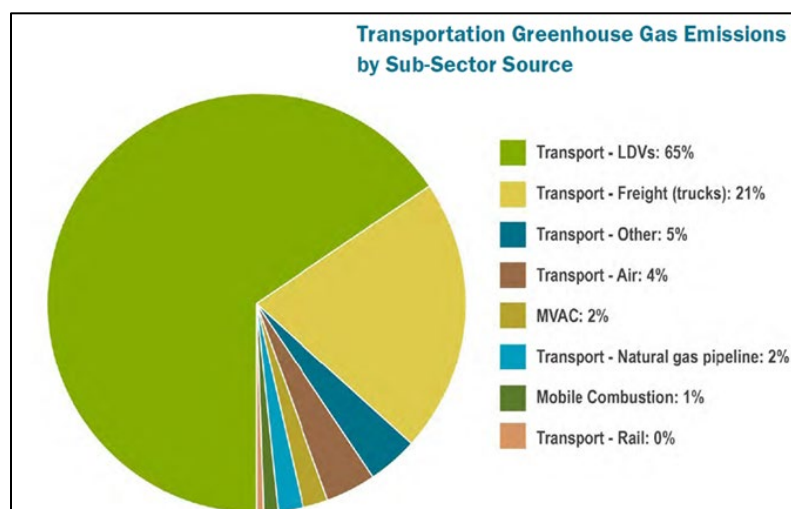


Exhibit 8. Michigan transportation GHG emissions by sub-sector (from EGLE 2022).

As IPCC Working Group III Co-Chair Priyadarshi Shukla states, “Having the right policies, infrastructure and technology in place to enable changes to our lifestyles and behavior can result in a 40-70% reduction in greenhouse gas emissions by 2050. This offers significant untapped potential. The evidence also shows that these lifestyle changes can improve our health and wellbeing.”<sup>8</sup> To keep below 1.5 degrees of warming, transport emissions must fall by 59% by 2050, or 29% for a 2-degree warming scenario relative to modelled 2020 emissions.<sup>9</sup>

<sup>8</sup> Shukla, Priyadarshi. (April 4, 2022). *IPCC Report 2022– Key Takeaways for Travel and Aviation*. <https://oncarbon.app/articles/ipcc-report-2022>

<sup>9</sup> UIC Communications. (April, 2022). *IPCC Working Group Points to a Paradigm Shift for Mobility in Latest Report*. <https://uic.org/com/enews/article/ipcc-working-group-points-to-a-paradigm-shift-for-mobility-in-latest-report>



What is exciting about the potential for strategies to shift transportation modal choice is that they do much more than simply reduce GHG emissions. The IPCC report highlights several co-benefits, including air quality improvements, health benefits, equitable access to transportation services, reduced congestion and reduced material demand. Electrification, combined with low-GHG energy and shifts to public transport, can enhance health and employment and can deliver energy security and equity.

Hydrogen can store and deliver clean energy for transportation. It can serve as a fuel (energy carrier) where it can be used for propulsion via fuel cells or combustion in engines. Key metrics for comparing alternative transportation powertrains are the energy efficiency from well to wheels and the total vehicle life cycle energy and GHG emissions. The advantages of fuel cell vehicles over internal combustion engine vehicles are clear – no vehicle GHG emissions during use. Fuel cells convert a fuel’s chemical energy to electricity and a FCEV can be two to three times more efficient at converting fuel to vehicle motion than an ICEV.<sup>10</sup>

The relative performance of fuel cell vehicles and battery electric vehicles are dependent on the vehicle class (LDV, MDV, HDV), applications, and hydrogen and electricity sources. The IPCC discusses the roles of electrification and hydrogen in transportation systems:

“Electrification is already occurring in several modes of personal and light freight transport, and vehicle-to-grid solutions for flexibility have been extensively explored in the literature and small-scale pilots. The role of hydrogen in transport depends on how far technology develops. Batteries are currently a more attractive option than hydrogen and fuel-cells for light-duty vehicles. Hydrogen and hydrogen-derived synthetic fuels, such as ammonia and methanol, may have a more important role in heavy vehicles, shipping, and aviation. Current transport of fossil fuels may be replaced by future transport of hydrogen and hydrogen carriers such as ammonia and methanol, or energy intensive basic materials processed with hydrogen (e.g., reduced iron) in regions with bountiful renewable resources.” (IPCC 2022, p. TS-56)

As with all fuels, there are safety criteria for the production and use of hydrogen and electricity in transportation applications. Flammability is a potential risk with hydrogen, just as with gasoline and diesel. Refueling, maintenance, and emissions control in hydrogen fueling infrastructure will require adapting procedures and detection techniques from what is currently deployed, and first responders may need additional training to deal with vehicles using hydrogen as fuel. Fuel cell electric vehicles (FCEVs), like battery electric (BEV) and plug-in hybrid (PHEV) vehicles, also present the risk of electric shock. This risk is minor in conventional gasoline and diesel vehicles but is much more significant with these newer powertrains.

### 2.1.1. Light Duty Vehicles

There are two hydrogen fuel cell electric vehicles (FCEVs) currently in production (over 100 BEV and PHEV models are expected to be available by 2023 in selected regions). Current FCEVs have lower emissions than ICEVs and slightly higher emissions than BEVs. In the future, FCEVs using hydrogen produced by electrolysis from renewable electricity may have similar GHG emissions as BEVs charging from a clean grid (see Exhibit D1 in Appendix D). With renewable electricity as the source for hydrogen and electricity, the BEV will have a much higher efficiency (energy to the wheels/renewable energy input = about 70%) compared to the FCEVs (about 20%) (Bossel 2006). This is because for FCEVs, renewable electricity is converted to hydrogen through electrolysis, and

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<sup>10</sup> U.S. DOE, Office of Energy Efficiency & Renewable Energy, February 25, 2022. *Hydrogen's Role in Transportation*. (<https://www.energy.gov/eere/vehicles/articles/hydrogens-role-transportation#:~:text=Hydrogen%20fuel%20allows%20vehicles%20to,of%20miles%20at%20a%20time>)

that hydrogen is converted back to electricity in the fuel cell to power the vehicle. The Michigan-based OEMs are launching a wide range of BEV models with aggressive goals for vehicle sales in the coming decades. While the average time spent fueling an FCEV is under 4 minutes, which is significantly shorter than BEVs, FCEVs are currently limited by higher costs, lack of fueling infrastructure (both of which may change), and lower conversion efficiency than BEVs (which is not likely to change).

### Cost / Economic Impact

FCEVs are projected to be more expensive than conventional alternatives and are more expensive than BEVs (see Fig ES-4 in (Kelly et al., 2022) for an example lifetime cost comparison for a small SUV). The cost for capitalization of the fueling infrastructure for FCEV versus BEVs is also a factor, as hydrogen refueling stations and associated transportation infrastructure is very limited compared to the widespread availability of electricity from the grid.

### Technology Readiness and Demonstrations

The first light duty FCEVs were available in the US in 2014 with models launched by Hyundai and Toyota.<sup>11</sup> The two light duty models currently available are the Toyota Mirai (2014-present) and the Hyundai Nexo (2018-present).

### Michigan Assets

Ford, GM, Stellantis, and Toyota (Toyota Motor North America, Research & Development is located in Ann Arbor) have all developed hydrogen prototypes and/or commercial FC light duty vehicles.

## 2.1.2. Medium and Heavy-Duty Vehicles

Hydrogen can play a role in decarbonizing vehicles that are difficult to convert to BEVs due to battery weight, payload, range, or refueling time constraints. Gaseous and liquid hydrogen vehicles emit fewer GHGs than conventional diesel vehicles for a wide range of medium and heavy-duty vehicles. Hydrogen fuel cell electric vehicles have been used in buses, delivery trucks, and garbage trucks and prototypes have been developed for construction vehicles and semi-trucks. There were over 20,000 hydrogen fuel cell forklifts in use the U.S. as of 2018. These vehicles produce zero tailpipe emissions and can eliminate indoor air pollution and health effects from natural gas, gasoline, and diesel vehicles. Like heavy duty vehicles, farm equipment may have power or capacity constraints that limit the potential for electrification and there is the potential for on-site hydrogen generation with renewables by farmers using biobased feedstocks and wind farm electricity. On selected routes, electrification of MDVs and HDVs could also be accomplished with overhead catenary or in-road charging infrastructure instead of batteries (Moultak, Lutsey, & Hall 2017).

### GHG Reduction Potential & Other Strategies

FCEV and BEV will decarbonize MDV & HDVs depending on electricity and hydrogen source. BEVs have range limitations in transporting heavy loads. See also Exhibit D2 in Appendix D.

The Mission Possible Partnership (2022) has released a transition strategy outlining how the heavy-duty trucking sector can reach zero emissions by 2050. Their strategy includes both electric and hydrogen trucks, and rapid deployment of infrastructure to charge/fuel these vehicles.

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<sup>11</sup> U.S. DOE Office of Energy Efficiency & Renewable Energy, December 10, 2014. *First Commercially Available Fuel Cell Electric Vehicles Hit the Street*. <https://www.energy.gov/eere/articles/first-commercially-available-fuel-cell-electric-vehicles-hit-street>

## Cost / Economic Impact

Medium- and heavy-duty BEVs and FCEVs are both projected to be more expensive than conventional alternatives. BEVs have higher upfront costs; FCEVs have higher operating costs. See also Exhibits D3 and D4 in Appendix D.

## Technology Readiness and Demonstrations

Medium- and heavy-duty FCEVs are in the early commercialization stage. Examples of hydrogen-powered medium- and heavy-duty vehicles include: a UPS delivery truck deployed in Sacramento, CA (2017),<sup>12</sup> a garbage truck in Gothenburg, Sweden (2021),<sup>13</sup> a Stark Area (OH) Regional Transit Authority bus,<sup>14</sup> and prototypes of semi-trucks (Port of Los Angeles, 2021)<sup>15</sup> and construction vehicles (Changsha, China, 2021).<sup>16</sup>

## Michigan Assets

Two hydrogen fuel cell buses were deployed in Flint, MI (2012), with a refueling station in Grand Blanc.

## Regional Assets / Potential

Large fleet of medium- and heavy-duty vehicles on the road in the Midwest region given the concentration of manufacturing and commercial activity.

## Equity

Hydrogen transportation can advance environmental justice by replacing vehicles, especially medium- and heavy-duty trucks that have significant air pollutant emissions, with zero tailpipe-emissions FCEVs. The replacement of diesel trucks with FCEVs can be particularly beneficial for communities near highways, shipping corridors, and other high-traffic locations. It is important to recognize that if hydrogen is produced from non-renewable sources, there is a risk of shifting the air pollution burden from one community (near the vehicles) to another (near the fossil-fueled power plant). With current technology, medium- and heavy-duty FCEVs have lower VOC, CO, NO<sub>x</sub>, PM<sub>10</sub>, and PM<sub>2.5</sub> emissions, but higher SO<sub>x</sub> emissions than diesel alternatives. SO<sub>x</sub> emissions are expected to be reduced as the grid decarbonizes.

### 2.1.3. Ships

There are a wide range of commercial and recreational vessels using the Great Lakes, ranging from large lake freighters and ferries to fishing boats and sailboats. The Great Lakes-St. Lawrence River (GL-SL) waterway is the longest inland deep-draft navigation system in the world, connecting more

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<sup>12</sup> H2-Share. *UPS: fuel cell electric Class 6 delivery truck*. <https://fuelcelltrucks.eu/project/ups-fuel-cell-electric-class-6-delivery-truck/>

<sup>13</sup> Scania, August 12, 2021. *A cleaner type of garbage collection*. <https://www.scania.com/group/en/home/newsroom/news/2021/swedens-first-ever-hydrogen-powered-refuse-collection-truck.html>

<sup>14</sup> SARTA, *A bus that emits only water: You better believe it!* <https://www.sartaonline.com/hydrogen-fuel-cell>, Ohio State University, Transportation and Traffic Management, March 28, 2017. *Hydrogen fuel cell bus makes maiden voyage on campus*. <https://ttm.osu.edu/hydrogen-bus>

<sup>15</sup> The Port of Los Angeles, June 7, 2021. *Port of Los Angeles rolls out hydrogen fuel cell electric freight demonstration*. [https://www.portoflosangeles.org/references/2021-news-releases/news\\_060721\\_zanzeff](https://www.portoflosangeles.org/references/2021-news-releases/news_060721_zanzeff)

<sup>16</sup> SANY, March 26, 2021. *SANY embraces the era of cleaner fuel with hydrogen fuel cell construction vehicles*. [https://www.sanyglobal.com/press\\_releases/682/](https://www.sanyglobal.com/press_releases/682/)

than 110 commercial ports in Canada and the United States, as depicted in Exhibit 9.<sup>17</sup> There have been and continue to be significant shipment of commodities through the Great Lakes, as shown in Exhibit 10.<sup>18</sup>

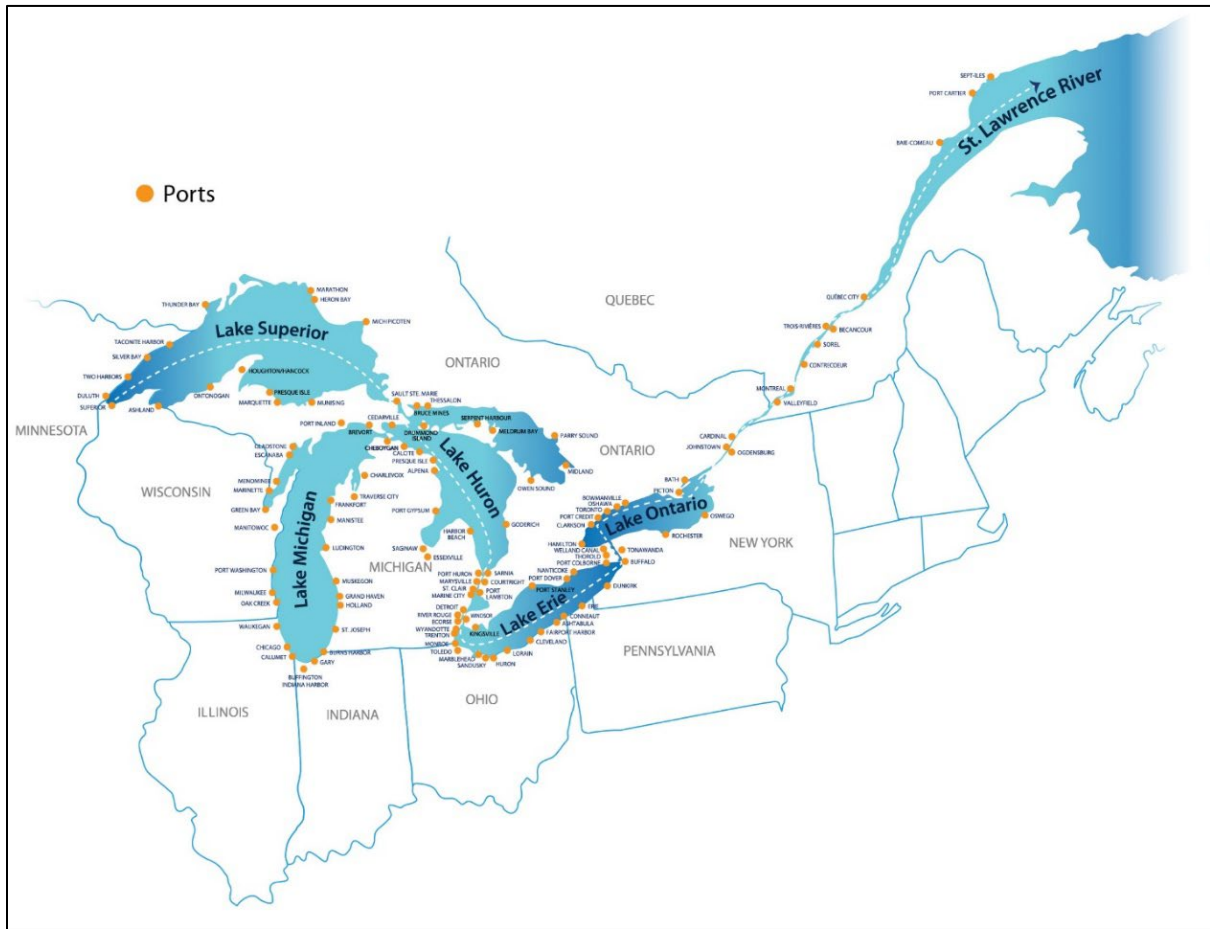


Exhibit 9. Great Lakes – St. Lawrence seaway (from Chamber of Marine Commerce, *Great Lakes-St. Lawrence River Shipping*. <https://www.marinedelivers.com/great-lakes-st-lawrence-shipping>)

<sup>17</sup> Figure from Chamber of Marine Commerce. (Apr. 13, 2022) *Great Lakes-St. Lawrence River Shipping*. <https://www.marinedelivers.com/great-lakes-st-lawrence-shipping/>

<sup>18</sup> Image from <https://project.geo.msu.edu/geogmich/l-m-port.html>, original source unknown.



Exhibit 10. Commodity shipping on the Great Lakes (from <https://project.geo.msu.edu/geogmich/l-m-port.html>, original source unknown).

The International Council on Clean Transportation reported that ships in the GL-SL system consumed more than 500,000 metric tons of fuel in 2019, which led to approximately 1.6 million metric tons of CO<sub>2</sub> emissions, about two-thirds of which were emitted in U.S. Of the fuel consumed, 83% was low-sulfur distillate fuel, 15% was high-sulfur residual fuel used by ships with scrubbers, and 2% was liquefied natural gas. Bulk carriers were responsible for about 62% of the CO<sub>2</sub> emissions in 2019 (Meng & Comer 2022). Replacing fossil fuels with hydrogen is an important decarbonization strategy. For smaller vessels such as ferries, battery electric powertrains are being commercialized. The Lake Michigan ferry based in Ludington is still utilizing coal to generate steam for propulsion. The advantage of hydrogen over electric ferries (as with other transportation vehicles) is shorter refueling time. Generally, ship displacement (i.e., the volume available for powertrain components and fuel storage) and route energy requirements determine whether battery electric or hydrogen fuel cell is the better replacement for fossil-fueled internal combustion propulsion (Minnehan & Pratt 2017). Methanol is also being considered as possible replacement for fossil fuels.<sup>19</sup>

### GHG Reduction Potential & Other Strategies

Electrification and hydrogen represent two strategies for replacing fossil fuels for shipping. Full electrification for freighters may be challenging due to their large energy storage requirements, but ferries are already being electrified. Battery electric ferries will outperform FC ferries in carbon reduction due to the low efficiency (electricity-to-hydrogen-to-electricity) for FC ferries.

The weight of the battery pack has less of an impact on energy consumption for the ferry compared to a ground-based vehicle, which has a higher fuel reduction value (change in fuel consumption/change in mass).

<sup>19</sup> Shippingwatch, August 30, 2022. Major South Korean yard confident in construction boom of methanol-powered ships. <https://shippingwatch.com/carriers/article14354048.ece>.

## Technology Readiness and Demonstrations

As of November 2021, Norway has converted 60 ferries (of approximately 200 in service) to electric or hybrid electric propulsion (Sæther & Moe, 2021). Norway's longest ferry (between Bodø and Moskenes) is scheduled to be converted to hydrogen by 2024 as the distance is too far and the sea conditions too difficult for an electric ferry.<sup>20</sup>

Bastø Electric is the first of three battery-powered ferries operated by the shipping company Bastø Fosen to enter Norwegian waters with more in production in Turkey. Bastø Electric uses batteries with a capacity of 4.3 MWh and a fast-charging system with a capacity of 9 MW.

The MF Hydra is the first liquid hydrogen powered ferry with a capacity of up to 300 passengers and 80 cars, and an operating speed of 9 knots (10 MPH).

## Michigan Assets

Ferries in Michigan are depicted in the map in Figure 1.<sup>21</sup> Note that some of the shorter routes are suitable for electrification with currently available equipment while the longer Lake Michigan and Isle Royale routes may require a different strategy (such as hydrogen) to decarbonize.

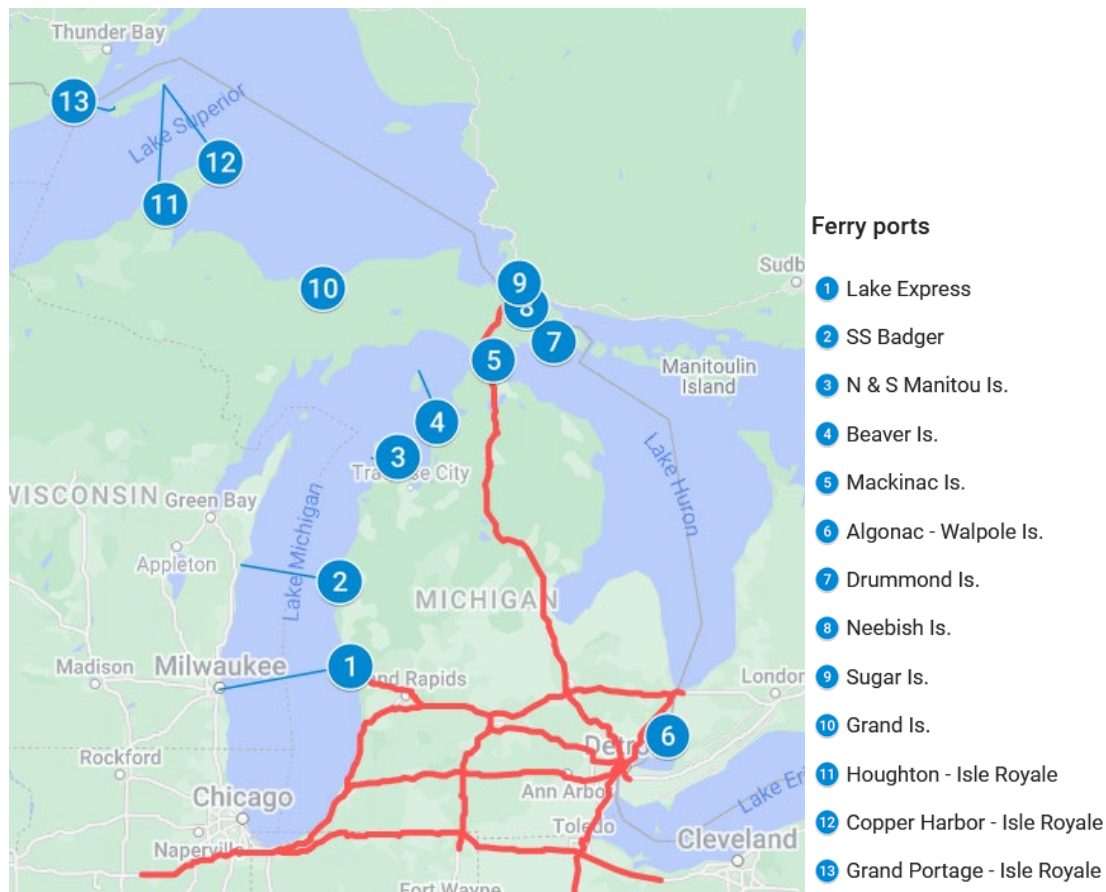


Figure 1. Michigan ferries (ferry routes in blue, highway network in red).

<sup>20</sup> Fuel Cell Works, November 1, 2020. *Norway's Lofoten Islands to have hydrogen ferries by 2024.* <https://fuelcellworks.com/news/norways-lofoten-islands-to-have-hydrogen-ferries-by-2024/>

<sup>21</sup> Map produced from the list at <https://www.michigan.org/ferry-services>

## Policy

The Norwegian government has an action plan with a goal to reduce emissions from domestic shipping and fishing vessels by 50 percent by 2030.

### 2.1.4. Rail

Rail represents one of the most efficient modes for passenger and freight transport. Trains are three to four times more efficient than trucks (AAR 2022) and despite handling a third of all intercity freight volume, rail accounts for only 2% of all transportation-related emissions (U.S. EPA 2109). Most freight rail vehicles in the U.S. are diesel powered. Most of the 27 commuter rail systems in the U.S. use diesel power, but five systems use both diesel and electricity, and another four systems use only electricity. Note this does not include systems classified as hybrid rail, which is a subset of commuter rail operating exclusively on freight railroad right-of-way.<sup>22</sup> Electrified rail is currently used on less than 1% of U.S. railroad tracks while electricity supplies more than one-third of the energy to power trains globally.<sup>23</sup> Electricity can be provided by a fuel cell powered with hydrogen. The first hydrogen train in the U.S. was ordered in 2019 for San Bernardino County, California with service planned to begin in 2024.

## GHG Reduction Potential & Other Strategies

As diesel trains are very efficient, the magnitude of the carbon reduction with hydrogen or electricity will be highly dependent on the electricity fuel mix. Electric trains would be expected to be more energy efficient than hydrogen trains and less carbon intensive if using the same fuel mix used to generate hydrogen. All sources of energy should be evaluated using life cycle (e.g., well-to-wheels) analysis to compare energy efficiency and emissions performance (Hoffrichter et al. 2012).

## Technology Readiness and Demonstrations

Coradia iLint is the first hydrogen fuel cell passenger train and built by Alstom in Salzgitter, Germany. The train was demonstrated on Railway Research Institute's test track in Żmigród, near Wrocław in Poland in 2021.<sup>24</sup> The Coradia iLint hydrogen train is designed for use on non-electrified routes. Almost half (46%) of railway in the European Union is not electrified, which leaves lines that require diesel or alternatives such as hydrogen.

## Michigan Assets

The Michigan Department of Transportation reports that Michigan's rail system (shown in Exhibit 11) has approximately 3,600 miles of rail corridors, operated by 29 railroad companies and carries about 17% of all the state's freight tonnage and 21% of the commodities by value. The rail system also supports three intercity passenger-rail routes.<sup>25</sup>

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<sup>22</sup> U.S. Department of Transportation, National Transit Database Glossary. (Additional resources at [www.transit.dot.gov/ntd](http://www.transit.dot.gov/ntd))

<sup>23</sup> Nunno, R., May 30, 2018. *Electrification of U.S. railways: Pie in the sky, or realistic goal?* Environmental and Energy Study Institute. <https://www.eesi.org/articles/view/electrification-of-u.s.-railways-pie-in-the-sky-or-realistic-goal>

<sup>24</sup> Alstom, June 23, 2021. *Coradia iLint: Alstom presents the world's first hydrogen passenger train in Poland.* <https://www.alstom.com/press-releases-news/2021/6/coradia-ilint-alstom-presents-worlds-first-hydrogen-passenger-train>

<sup>25</sup> <https://www.michigan.gov/mdot/-/media/Project/Websites/MDOT/Travel/Mobility/Rail/Michigan-Railroad-System-Map.pdf?rev=27681eac5dd14479a882318441cf94f9&hash=98B0A25D1C2FBE41E02500B2C1B257121>

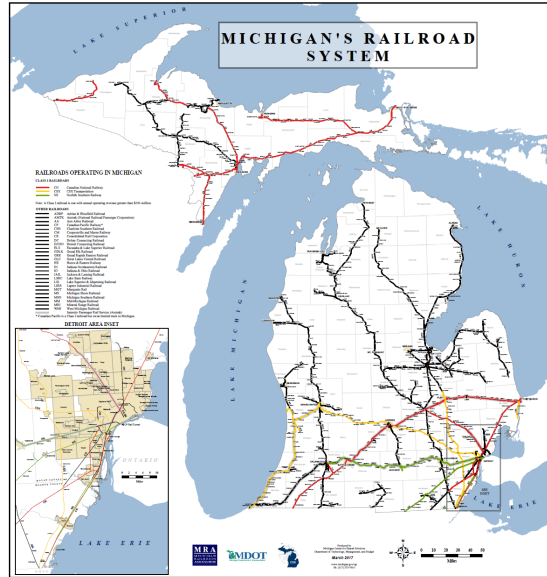


Exhibit 11. Michigan railroads (<https://www.michigan.gov/mdot/-/media/Project/Websites/MDOT/Travel/Mobility/Rail/Michigan-Railroad-System-Map.pdf?rev=27681eac5dd14479a882318441cf94f9&hash=98B0A25D1C2FBE41E02500B2C1B25712>).

## Equity

Eliminating diesel locomotives would reduce noise and air pollution, including particulates, volatile organic compounds, nitrogen oxides, and sulfur oxides, which impact public health.<sup>26</sup> This is especially important for railroads that pass through urban areas. This benefit is expected for both electric and hydrogen-powered trains.

### 2.1.5. Airplanes

The aviation industry has adopted a net-zero by 2050 target,<sup>27</sup> but aviation is particularly difficult to decarbonize. The IPCC states that “Although major investments have been made in engine technology to improve fuel-burning efficiency, there will be no major changes to aircraft configurations until at least 2037.” The IPCC report also notes that aircraft transportation is relatively efficient from a global perspective, and CO<sub>2</sub> emissions reductions from improved aircraft technology or operations are limited and cannot keep pace with projected growth in passenger miles.<sup>28</sup>

The sources cited by the IPCC claim that the only way to reduce emissions is to use lower-carbon biofuels or synthetic aviation fuels. For shorter distances, light aircraft carrying up to 50 passengers could be powered by electricity. A major obstacle to sustainable aviation fuels is their cost, which is

<sup>26</sup> Nunno, R., May 30, 2018. *Electrification of U.S. railways: Pie in the sky, or realistic goal?* Environmental and Energy Study Institute. <https://www.eesi.org/articles/view/electrification-of-u.s.-railways-pie-in-the-sky-or-realistic-goal>

<sup>27</sup> International Civil Aviation Organization (ICAO), October 5, 2021. *ICAO welcomes new net-zero 2050 air industry commitment*. <https://www.icao.int/Newsroom/Pages/ICAO-welcomes-new-netzero-2050-air-industry-commitment.aspx>

<sup>28</sup> Oncarbon, Apr 4, 2022. *11 key takeaways from the IPCC report for travel industry*. <https://oncarbon.app/articles/ipcc-report-2022>



about three times the price of kerosene, though the White House is supportive.<sup>29</sup> Alternatives include electrification of small craft, algal biofuel, and synthetic fuels with CCUS. High-speed trains compete with air travel on some routes. It is estimated that the sweet spot for high-speed trains is in routes that are between 400 km (about 250 miles) and 800 km (about 500 miles); although a proposed route between Chicago and Detroit is not currently planned/under development.

The National Academies has prioritized four approaches to reducing carbon emissions from commercial aircraft: 1) advances in aircraft-propulsion integration; 2) improvements in gas turbine engines; 3) development of turboelectric propulsion systems; and 4) advances in sustainable alternative jet fuels (National Academies 2016).

### GHG Reduction Potential & Other Strategies

Life cycle comparative assessments are needed to differentiate but electric VTOL is limited in passenger capacity and range due to battery weight.

Alternatives include biofuels (algal), synthetic fuels, and electric vertical takeoff and landing (VTOL) aircraft to replace smaller airplanes.

### Technology Readiness and Demonstrations

Airbus hopes to develop a commercial hydrogen propulsion aircraft by 2035. At an Airbus Summit in 2021 the company revealed three different designs for hydrogen powered airplanes: 1) a turbofan design that would be capable of operating trans-continently and would be powered by a modified gas-turbine engine combusting hydrogen, rather than jet fuel; 2) a turboprop design that can carry up to 100 passengers and is powered by hydrogen combustion in modified gas-turbine engines, capable of travelling more than 1,000 nautical miles, making it a potentially feasible option for short-haul trips; and 3) a "blended-wing body" design, where the wings merge with the main body of the aircraft. It would be able to operate trans-continently and could carry up to 200 passengers.<sup>30</sup>

### Michigan Assets

Future hydrogen fueling could be planned for major Michigan airports if this is the direction the industry pursues. Based on plans announced by Airbus, this would not be expected before 2035. Hydrogen aviation fueling infrastructure will need to be implemented at DTW and regional airports in Michigan if the industry selects this option. A list of Michigan general and commercial aviation airports can be found at <https://www.michigan.gov/mdot/travel/mobility/aeronautics/airports>.

No additional information was found regarding hydrogen powered aircraft.

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<sup>29</sup> The White House, September 9, 2021. *Fact Sheet: Biden Administration Advances the Future of Sustainable Fuels in American Aviation*. <https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/>

<sup>30</sup> Business Today India, September 23, 2021. *Airbus aims to make hydrogen-powered zero-emission commercial aircraft by 2035*. <https://www.businesstoday.in/industry/aviation/story/airbus-aims-to-make-hydrogen-powered-zero-emission-commercial-aircraft-by-2035-307382-2021-09-23>

## 2.2. Chemical Industry

The chemical industry is the largest user of hydrogen globally, relying on it as a chemical feedstock in petroleum refining, ammonia production, and methanol production. Natural gas-based steam methane reforming (SMR) is the most common method used by the chemical industry for hydrogen production. “Natural gas is currently the primary source of hydrogen production, accounting for around three quarters of the annual global dedicated hydrogen production of around 70 million metric tons. This accounts for about 6% of global natural gas use.” (IEA 2019)

The IPCC, in describing decarbonization in industry, states:

“Both light and heavy industry are potentially large and flexible users of electricity for both final energy use (e.g., directly and using heat pumps in light industry) and for feedstocks (e.g., hydrogen for steel making and chemicals). For example, industrial process heat demand, ranging from below 100°C to above 1000°C, can be met through a wide range of electrically powered technologies instead of using fuels. Future demand for hydrogen (e.g., for nitrogen fertiliser or as reduction agent in steel production) also offers electricity demand flexibility for electrolysis through hydrogen storage and flexible production cycles. The main use of hydrogen and hydrogen carriers in industry is expected to be as feedstock (e.g., for ammonia and organic chemicals) rather than for energy as industrial electrification increases.” (IPCC 2022, p. TS-56)

### 2.2.1. Refineries & Chemical Plants

Turning crude oil into products such as transport fuels and chemical feedstocks in refineries uses roughly 33% of hydrogen globally (IEA 2019, p.91). In 2017, U.S. hydrogen use for refining was 5.9 million metric tons. Hydrogen is used in refining as a feedstock, reagent, and energy source.

Hydrogen demand at U.S. refineries is depicted in Exhibit 12 (Elgowainy et al., 2020). Michigan is one of 16 states in the Petroleum Administration for Defense District 2 (PADD2), a district with an aggregate annual demand of 1.2 million metric tons of hydrogen. Note the proximity of these facilities in SE Michigan, NE Ohio, and northern Indiana and Illinois. Not illustrated in this U.S. map, but with strongly connected infrastructure, is the refinery complex in Sarnia, Ontario, across the St. Clair River from Port Huron, MI

Capturing CO<sub>2</sub> from combustion or chemical processes is an important activity in decarbonization, but as Elgowainy et al. note “Capturing CO<sub>2</sub> from diluted flue gases is costly and requires a significant amount of energy. However, approximately 100 MMT of U.S. annual CO<sub>2</sub> emissions already occur in concentrated form—from ethanol plants and from SMRs producing hydrogen for petroleum refining or NH<sub>3</sub> production. If all 100 MMT of CO<sub>2</sub> from ethanol, NH<sub>3</sub>, and SMR plants were used to produce synfuels, the potential hydrogen demand could be as high as 14 MMT/year...” (Elgowainy et al., 2020). Synthetic fuels, including methane, methanol, diesel, gasoline, and jet fuel, are produced by combining hydrogen and CO<sub>2</sub>, but would require significant amounts of electricity (1000 TWh to meet 1% of current global oil demand and 700 TWh to meet 1% of global gas demand) (IEA 2019, p. 58). Combusting synfuels for transportation releases CO<sub>2</sub> emissions and consequently would not serve as an effective decarbonization strategy.

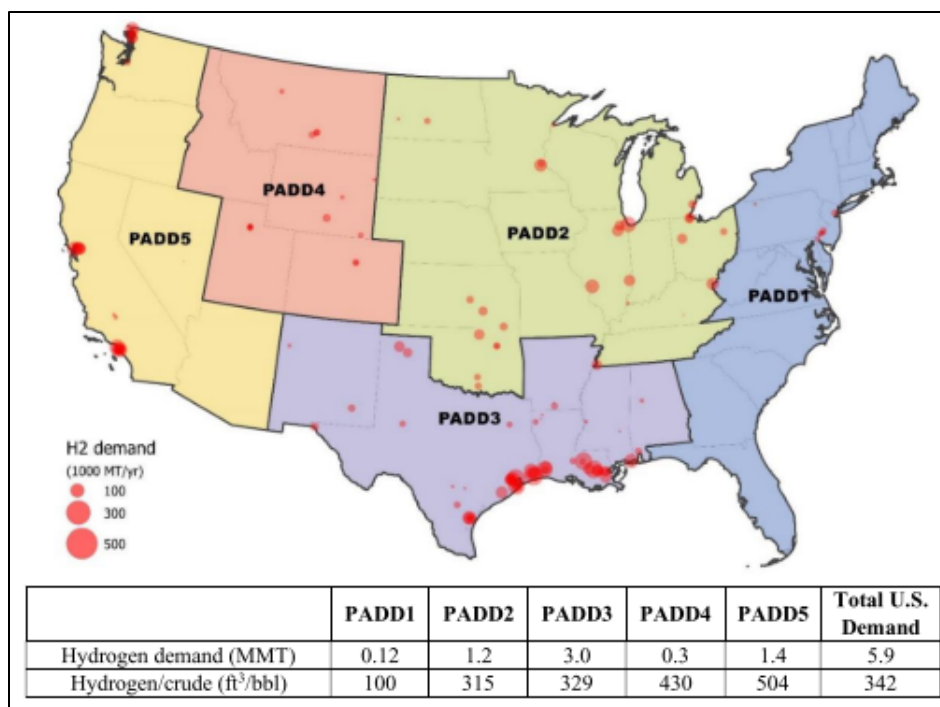


Exhibit 12. Hydrogen demand by U.S. refineries in 2017 (from Elgowainy et al. 2020). Assessment of Potential Future Demands for Hydrogen in the United States).

### Cost / Economic Impact

In regards to the implementation of CCUS at refineries, the IEA notes that “Introducing CCUS would add an incremental cost of some USD 0.25–0.5/barrel, which is higher than today’s carbon price levels (zero to USD 0.1/barrel).” “A carbon price higher than USD 50/tCO<sub>2</sub>, for example, would make natural gas with CCUS economically attractive in most regions and could trigger a wider deployment of CCUS at SMR facilities.” (IEA 2019, p. 96)

Comments from Dow CEO:<sup>31</sup>

Green hydrogen<sup>32</sup> is 10-16 times more expensive than blue hydrogen and blue hydrogen is ready to deploy right now versus more investment and time needed to scale up green hydrogen - time the industry does not have.

The market “desperately needs a market-based voluntary emissions trading system (ETS) in the US to give us a market-based price on carbon and attract investment.”

A global overview on carbon pricing instruments, such as carbon taxes, ETSs, and crediting mechanisms, and how they could accelerate decarbonization can be found in (World Bank 2022).

<sup>31</sup> Chang, J., March 28, 2022. *AFPM '22: Nuclear, circular hydrogen keys to net-zero future for chemicals – Dow CEO*. <https://www.icis.com/explore/cn/resources/news/2022/03/28/10748324/afpm-22-nuclear-circular-hydrogen-keys-to-net-zero-future-for-chemicals-dow-ceo>

<sup>32</sup> Green and blue hydrogen are explained in Exhibit 20, but green is produced using electrolysis and renewable energy while blue is produced from natural gas via SMR with the addition of CCUS.

## Technology Readiness and Demonstration

Comments from Dow CEO:<sup>33</sup>

The land mass needed to supply the alternative energy for green hydrogen is “simply overwhelming” and blue hydrogen is more suited for the constant electricity demand the industry needs.

Dow is in preliminary discussions to access energy from two small modular nuclear reactors. Blue hydrogen is a large component of Dow’s zero carbon cracker, being planned in Fort Saskatchewan, Canada, for start-up in 2027.

H<sub>2</sub> production projects with CCUS are at the pilot scale around the world (one in Texas), and H<sub>2</sub> from electrolysis projects are being considered in Germany and the Netherlands (IEA 2019)

## Michigan Assets

Marathon petroleum refinery in SW Detroit (As of 2012, 137 metric tons H<sub>2</sub>/day, through SMR)<sup>34</sup>

The Andersons Marathon Holdings LLC ethanol biofuel in Albion, MI<sup>35</sup>

Pilot-scale integrated woodchip waste biorefinery in Alpena, MI (DOE 2015)

Midland chemical complex (includes Dow and DuPont operations and Dow spin-off companies SK Saran, Corteva, and Trinseo), hydrogen demand unknown.

## Regional Assets / Potential

Sarnia-Lambton petrochemical and refining complex<sup>36</sup>

### 2.2.2. Ammonia

Ammonia is produced from nitrogen and hydrogen using the Haber-Bosch process. Hydrogen for this process is currently generated by steam methane reforming (SMR). Hydrogen from SMR could be replaced with hydrogen generated via electrolysis using renewable sources or nuclear power. Several ammonia production facilities are demonstrating CCUS technology and hydrogen production via electrolysis.

“Nitrogen (N) fertilizers used in agriculture rely on ammonia (NH<sub>3</sub>) production and the NH<sub>3</sub> synthesis process requires approximately 0.18 kg of hydrogen per kg of NH<sub>3</sub> based on stoichiometry.” (Elgowainy et al. 2020) Hydrogen demand for ammonia in the U.S. is projected to be 3.6 million metric tons in 2050.

Demand for hydrogen in ammonia production in the U.S. is shown in Exhibit 13 (Elgowainy et al. 2020). The Nutrien plant in Lima, OH is a significant regional asset.

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<sup>33</sup> Chang, J., March 28, 2022. *AFPM '22: Nuclear, circular hydrogen keys to net-zero future for chemicals – Dow CEO*. <https://www.icis.com/explore/cn/resources/news/2022/03/28/10748324/afpm-22-nuclear-circular-hydrogen-keys-to-net-zero-future-for-chemicals-dow-ceo>

<sup>34</sup> Hydrocarbons Technology. *Detroit Heavy Oil Upgrade Project*. Retrieved May 3, 2022 from <https://www.hydrocarbons-technology.com/projects/detroit-heavy-oil-upgrade-project/>

<sup>35</sup> Marathon. *Renewable Fuels Portfolio: The Andersons Marathon Holdings LLC*. Retrieved May 3, 2022 from <https://www.marathonpetroleum.com/Operations/Renewable-Fuels/>

<sup>36</sup> Sarnia-Lambton Economic Partnership. *Petrochemical and Refining Complex*. Accessed May 3, 2022 from <https://www.sarnialambton.on.ca/key-sectors/petrochemical-and-refined-petroleum>



Exhibit 13. Estimated hydrogen demand for U.S. NH<sub>3</sub> production in 2017 (from Elgowainy, et al. 2020). Assessment of Potential Future Demands for Hydrogen in the United States).

### GHG Reduction Potential & Other Strategies

Current ammonia production direct emissions are 2.4 metric tons CO<sub>2</sub>/metric ton NH<sub>3</sub> (IEA 2019) and GHG reductions of more than 90% are possible by 2030 when using renewable power in electrolysis (Hydrogen Council 2021a).

### Cost / Economic Impact

“CCUS is currently the cheapest option for reducing emissions in the production of some important chemicals such as ammonia, which is widely used in fertilisers. The estimated costs of CCUS-equipped ammonia and methanol production based on natural gas are around 20-40% higher than their unabated counterparts, while the cost of electrolytic hydrogen routes is estimated to be 50-115% higher.”<sup>37</sup>

See also Exhibit D5 in Appendix D.

### Technology Readiness and Demonstrations

Examples of CCUS at ammonia production facilities include: three facilities in the U.S. as of 2018, two more planned; a larger project in Western Australia planned for 2025 (Hydrogen Council 2021a).

Examples of facilities using hydrogen from electrolysis for ammonia production include the Schmuecker Pinehurst Farm LLC in Iowa,<sup>38</sup> using solar powered electrolysis, and Yara (the world’s largest ammonia producer) collaborating with energy company ENGIE to assess the feasibility of electrolytic hydrogen production in Australia (Hydrogen Council 2021a).

<sup>37</sup> Baylin-Stern, A., and N. Berghout. (Feb. 2021). *Is carbon capture too expensive?* IEA. <https://www.iea.org/commentaries/is-carbon-capture-too-expensive>

<sup>38</sup> Schmuecker Renewable Energy, *The C-Free Tractor*. <https://solarhydrogensystem.com/applications/hydrogen-ammonia-fueled-tractor/>

## Michigan Assets

Agriculture in Michigan contributes approximately \$104.7 billion per year to the state economy.<sup>39</sup>

Total annual fertilizer consumption in Michigan in 2004 was 1.3 million metric tons.<sup>40</sup>

AmmPower research center in Southeast Michigan is exploring green ammonia production.<sup>41</sup>

## Regional Assets / Potential

Nutrien (Lima, OH) has significant H<sub>2</sub> demand for NH<sub>3</sub> production (Elgowainy et al. 2020)

### 2.2.3. Process Heat

Many chemical and industrial processes require heat, which for high temperature processes is currently provided by coal, oil, and natural gas. Use of these fuels results in significant GHG emissions, but there are few viable options to decarbonize industrial processes. “Renewable natural gas” (e.g., methane from landfills) and other biofuels are one option,<sup>42</sup> but even using high RNG resource estimates, supplies are not expected to be sufficient to replace more than 1/3 of the natural gas used across sectors.<sup>43</sup> Biofuels besides RNG are also likely to be in demand for other end uses, such as aviation, that are hard to electrify. Hydrogen is another potential fuel, as is the direct use of electricity through resistance or electromagnetic technology, depending on the application. For applications that are not suitable for electrification, hydrogen is a leading candidate for providing high temperature process heat, though it costs more than the incumbents and biofuels (IEA 2019).

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<sup>39</sup> Michigan Department of Agriculture & Rural Development, 2019. *Michigan Agriculture Facts & Figures*. [https://www.michigan.gov/-/media/Project/Websites/mdard/documents/business-development/mi\\_ag\\_facts\\_figures.pdf?rev=9ca97e867d0d40b392470b02a2694e50](https://www.michigan.gov/-/media/Project/Websites/mdard/documents/business-development/mi_ag_facts_figures.pdf?rev=9ca97e867d0d40b392470b02a2694e50)

<sup>40</sup> Michigan Commission of Agriculture & Rural Development, 2019. *Generally Accepted Agricultural and Management Practices for Nutrient Utilization*. <https://www.michigan.gov/mdard/-/media/Project/Websites/mdard/documents/environment/rtf/2019-GAAMPs/2019-NUTRIENT-UTILIZATION-GAAMP.pdf?rev=64745266e5504f1b857de3d290304bd9&hash=79DC225003C2C6D61306DAAD79B93103>

<sup>41</sup> Ammpower, November 2, 2021. *Ammpower Corp. Announces First Ammonia Production at Its Recently Opened Michigan Manufacturing & Development Facility*. <https://ammpower.com/ammpower-corp-announces-first-ammonia-production-at-its-recently-opened-michigan-manufacturing-development-facility/>;

<sup>42</sup> U.S. EPA, Landfill Methane Outreach Program. Accessed May 3, 2022 at <https://www.epa.gov/lmop/renewable-natural-gas>

<sup>43</sup> American Gas Foundation, 2019. *Renewable Sources of Natural Gas*. [https://gasfoundation.org/wp-content/uploads/2019/12/AGA\\_3894-RNG-2-Pager\\_V-11.pdf](https://gasfoundation.org/wp-content/uploads/2019/12/AGA_3894-RNG-2-Pager_V-11.pdf).

## 2.3. Steelmaking

Steel production accounts for 6-7% of global GHG emissions. Steel is currently produced from iron ore and/or scrap by two basic routes: 1) iron ore is reduced to pig iron in a blast furnace using coke and, with the addition of some scrap steel, is then converted to steel in a basic oxygen furnace (BOF); and 2) scrap steel or direct reduced iron is converted to steel in an electric arc furnace (EAF). The EAF route for steelmaking can use electricity sourced from low-carbon sources as a decarbonization strategy. The EAF can also utilize direct reduced iron (DRI) instead of melting scrap. DRI is a process to chemically reduce iron oxide to iron by using hydrogen electrically heated to about 1600°F, which is then injected into a furnace containing iron pellets to produce an “iron sponge” and water vapor. The iron sponge is melted down with scrap to make steel in the EAF. The DRI-EAF method, which is responsible for 7% of steel production, uses 4 million metric tons of hydrogen per year (IEA 2019).

The BOF route, which accounts for 90% of primary steel production, is more energy- and carbon-intensive as it uses coal to produce coke that is fed into the blast furnace to reduce the iron oxide in the ore to iron. One alternative for reducing CO<sub>2</sub> emissions from the blast furnace is to utilize CCUS, as a coal-fired power plant might, but this requires additional energy and challenges related to carbon storage. The use of green hydrogen in the blast furnace can reduce carbon emissions by up to 20% (Hoffman et al. 2020).

### GHG Reduction Potential & Other Strategies

Production of one metric ton of crude steel produces between 1.4 (IEA 2019) and 1.85 (Hoffman et al. 2020) metric tons of CO<sub>2</sub>. Use of green hydrogen in blast furnaces can reduce CO<sub>2</sub> emissions by up to 20%. The DRI-EAF process with green hydrogen enables nearly carbon-neutral steel production (Hoffman et al. 2020). Iron and steel production account for 2.1% of U.S. emissions (Nimbalkar n.d.).

### Cost / Economic Impact

Without a high price on carbon, switching to low-carbon hydrogen would widen the difference in cost between DRI and BF-BOF routes. “Hydrogen price affects economic feasibility more strongly than the capital and operating costs of the DRI process. It is estimated that a hydrogen price of \$1.7/kg would generate a positive net present value (NPV) for the DRI technology.” (Elgowainy et al. 2020)

### Technology Readiness and Demonstrations

The HYBRIT (Hydrogen Breakthrough Ironmaking Technology) project demonstration is using DRI in Sweden with green hydrogen. This demonstration will produce approximately 1.2 million metric tons of crude steel per year, which corresponds to 25% of Sweden's total production. It has the potential to prevent 14.3 million metric tons of GHG emissions over the first ten years of production.<sup>44</sup>

### Michigan Assets

Dearborn Works plant (Cleveland-Cliffs), SMR hydrogen from Praxair, 3.47 metric tons H<sub>2</sub>/day.<sup>45</sup>

### Regional Assets / Potential

Many other steel production facilities in the Midwest region (e.g., Cleveland-Cliffs DR plant in Toledo, OH).

<sup>44</sup> Hybrit Development AB. *HYBRIT Demonstration*, Accessed May 3, 2020 from <https://www.hybritdevelopment.se/en/hybrit-demonstration/>

<sup>45</sup> Pacific Northwest National Lab. Hydrogen Tools Portal at <https://h2tools.org/>

## 2.4. Cement Production

Cement is produced in a two-step process. First, lime, silica, alumina, iron, and other materials are heated in a rotary kiln to produce clinker. The clinker is then ground and mixed with limestone and gypsum to produce cement. Cement production generates CO<sub>2</sub> emissions both from the combustion of fuels to heat the kiln and from chemical reactions during the calcination process. In 2016, Michigan cement plants produced 3.9 million metric tons of cement that contributed \$9.3 million to state revenue (PCA 2016).

Two basic decarbonization approaches include substituting low-carbon fuels and CCS (Nhuchhen et al. 2022). Rumayor et al. suggest "... a prospective decarbonization scenario for cement manufacturing with complete elimination of CO<sub>2</sub> emissions related to fossil fuel when a mix of 50% hydrogen (H<sub>2</sub>) and 50% biomass is used in the kiln and 83.3% biomass with 16.7% plasma is used in the calciner." (Rumayor et al. 2022)

### Technology Readiness and Demonstrations

No known facilities are using hydrogen as a fuel. An alternative is adding CCUS to existing NG-burning facilities.

### Michigan Assets

Holcim (Alpena, MI)

St. Mary's (Detroit and Charlevoix, MI)

### Regional Assets / Potential

Several other cement production facilities in the Midwest region.



## 2.5. Glass Making

Materials used to produce float glass include sand, soda ash, limestone, dolomite, and cullet (scrap glass). These materials are combined in the desired proportions and are melted in a furnace, with the heat being provided by natural gas. The molten glass is floated on top of a liquid tin bath (to ensure flatness) and then slowly cooled in an annealing lehr, after which it is cut and stored for shipment and further processing. The incumbent process uses some hydrogen (with nitrogen) over the tin bath to prevent oxidation.

### GHG Reduction Potential & Other Strategies

Furszyfer Del Rio et al. state that "...producing 1 kg of glass in a gas-fired furnace generates about 0.6 kg of CO<sub>2</sub> of which, 0.45 kg emerges from fossil fuels combustion and 0.15 kg from the dissociation of carbonate raw." (Furszyfer Del Rio et al. 2022)

If natural gas continues to be used as the fuel for melting, GHG reduction strategies include adding CCUS (max 90% GHG reduction), replacing some fraction of natural gas with electricity for process heat (75-85% GHG reduction), and recovery of waste heat, such as using exhaust heat to preheat incoming cullet/materials (typically 25-30% of the fuel energy input) (max 15% GHG reduction) (Furszyfer Del Rio et al. 2022).

### Technology Readiness and Demonstrations

HyNet fuel switching, Pilkington (St Helens, UK)

### Michigan Assets

Guardian Glass (Carleton, MI)

### Regional Assets / Potential

Owens-Illinois (Toledo, OH),

### Organizations

Functional Glass Manufacturing Innovation Consortium, Glass Futures

## 2.6. Semiconductor Manufacturing

Semiconductors and photovoltaics both start with quartzite (a source of silicon dioxide (SiO<sub>2</sub>)), which is melted in an electric arc furnace with a carbon source (such as coal, coke, or graphite). The reactions in the furnace produce 98% pure (“metallurgical grade”) elemental silicon. This MG silicon can be further purified into polysilicon through the Siemens process (or an alternative fluidized bed process), both of which involve hydrogen. The resulting semiconductor and solar grade silicon can be cast into multicrystalline ingots or used to grow monocrystalline ingots.

Semiconductor manufacturing starts with an ingot of monocrystalline silicon, which is then sliced into wafers and polished. In the deposition step, several layers of conducting, insulating, or semiconducting materials are laid down on the wafer, topped by a photoresist layer. In the lithography step, light is projected onto the wafer through a mask that contains the pattern desired on the wafer. The exposed photoresist layer is then etched to form the desired pattern in the silicon, and the remaining photoresist is removed. The wafer is then sliced into die that are processed into semiconductor chips.

Hydrogen is used in semiconductor processing for epitaxy, deposition, and as a carrier gas (Stockman 2018). Major fabs use approximately 1 metric ton of hydrogen per operating hour (Rochlitz et al. 2019). Taiwan Semiconductor Manufacturing Company, a leading global semiconductor manufacturer, emitted 14 million metric tons CO<sub>2</sub>e in 2020.<sup>46</sup> Emerging technology for extreme ultraviolet (EUV) lithography is 1000x more hydrogen intensive (Stockman 2018).

### GHG Reduction Potential & Other Strategies

Decarbonization will focus on renewable electricity, low-carbon hydrogen, and then finding a substitute for natural gas.

### Cost / Economic Impact

Dominated by materials other than hydrogen

### Technology Readiness and Demonstrations

Infineon & Linde (Villach, Austria) 2 MW PEM electrolyzer to produce up to 0.8 metric tons H<sub>2</sub>/day

### Michigan Assets

Semiconductor industry contributes \$4.6 billion in total gross regional product for MI

Hemlock Semiconductor (polysilicon producer) (Hemlock, MI)

SK Siltron (semiconductor wafer manufacturer headquartered in Auburn, MI) planned \$300 million expansion of operations in Bay County, MI

Infineon Technologies (semiconductor manufacturer in Livonia, MI) recent \$1.5 million investment to expand role in autonomous vehicle industry

KLA semiconductor R&D center (Ann Arbor, MI)

### Organizations

Michigan Chemical Council, World Semiconductor Council

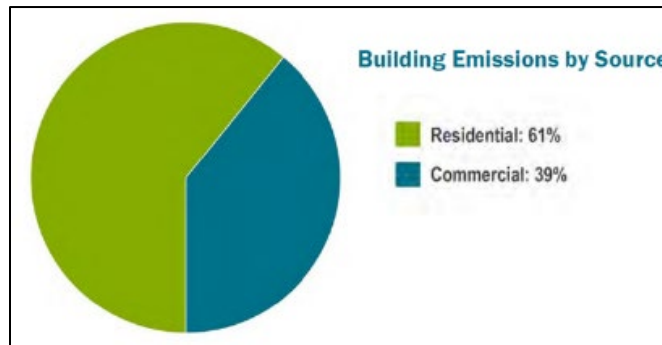
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<sup>46</sup> Bertuzzi, L., 2022. *What the Chips Act doesn't say: The environmental challenge of producing semiconductors.* <https://www.euractiv.com/section/industrial-strategy/news/what-the-chips-act-doesnt-say-the-environmental-challenge-of-producing-semiconductors/>.

## 2.7. Buildings

Our buildings use energy for heating, cooling, and cooking, as well as for lighting and all the other devices that run on electricity. Building-sector emissions come from energy use in both residential and commercial structures (Exhibit 14) (EGLE 2022). In Michigan, more energy is used for heating than for cooling, and this demand is met mostly with natural gas combustion appliances. In terms of mitigating GHG emissions, the IPCC states:

“Electrification is expected to be the dominant strategy in buildings as electricity is increasingly used for heating and for cooking. Electricity will help to integrate renewable energy into buildings and will also lead to more flexible demand for heating, cooling, and electricity.” “The ease of switching to electricity means that hydrogen is not expected to be a dominant pathway for buildings. Using electricity directly for heating, cooling and other building energy demand is more efficient than using hydrogen as a fuel, for example, in boilers or fuel cells. In addition, electricity distribution is already well developed in many regions compared to essentially non-existent hydrogen infrastructure, except for a few chemicals industry pipelines. At the same time, hydrogen could potentially be used for on-site storage should technology advance sufficiently.” (IPCC 2022, p. TS-56).

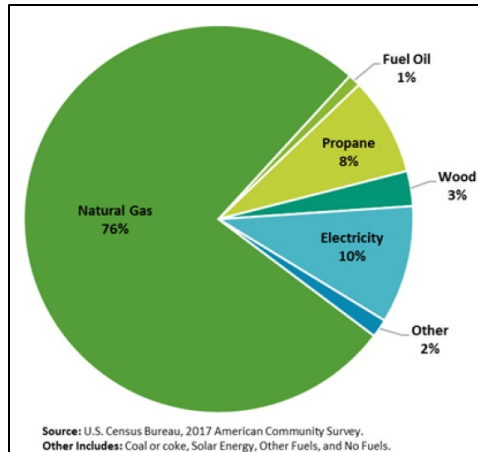


*Exhibit 14. Residential and commercial building GHG emissions in Michigan (EGLE 2022).*

Technologies used for providing building heat (space and DHW) include fossil fuel combustion, renewable natural gas (limited supply), air- or ground-source heat pump, and electrical resistance. Meeting peak demand is a primary challenge – managing demand and supply infrastructure to accommodate large seasonal variation in cold climates – both for heating in the winter and cooling in summer. Electrifying eases the need for seasonal storage of gaseous fuel but increases pressure on grid infrastructure by increasing peak electricity demand.

Heating in Michigan uses mostly natural gas, but also a significant amount of propane, as shown in Exhibit 15,<sup>47</sup> in rural areas not served by natural gas infrastructure. Michigan is the #1 user of propane in the U.S. (320,000 households and 380 million gallons per year). Alternatives to propane are electrification or hydrogen, and the economics of converting from propane to electricity are very good (Deetjen, Walsh & Vaishnav 2021). Financial support is provided in the Inflation Reduction Act to assist with conversion costs. There are no known demos of hydrogen co-firing with or replacing propane, but the pathway is similar to replacing natural gas (retrofit combustion appliances for heating, hot water, and cooking). A new issue in the propane case is dealing with onsite storage – replacing the tank in the yard with local hydrogen storage.

<sup>47</sup> MPSC, 2019. Michigan Statewide Energy Assessment.



*Exhibit 15. Michigan residential heating, 2017 share of households (MPSC 2019).*

Hydrogen can provide heat through direct combustion (in existing/retrofitted NG appliances), gas (combustion) heat pump (either combustion vaporizes refrigerant in an absorption cycle or a combustion engine generates electricity to run a heat pump), catalytic boiler, or in a fuel cell micro-CHP (combined heat and power) system. Fuel cells can run on hydrogen or on some other fuels with the addition of a fuel reformer, but running on other fuels (such as NG) reduce the system’s GHG reduction benefit. Matching building loads with fuel cell outputs can be a challenge, especially if the local electricity provider doesn’t allow resale of excess electricity or pays a low rate for it. Also, the sulfur-based odorants added to natural gas for leak detection poison most fuel cells. Fuel cell – CHP systems are a promising alternative if green hydrogen is used.

#### GHG Reduction Potential & Other Strategies

There are two main pathways to switching to using hydrogen in buildings – an easy one that we can start now with existing appliances but that has small GHG reduction benefits (blending w/NG,  $\approx 6.6\%$  GHG reduction at 20% H<sub>2</sub> vol), and a more costly one that takes more time but has greater GHG emission reduction potential (100% H<sub>2</sub>). The NG blending path provides only a small GHG reduction benefit and will likely extend the time that NG is used, which may not be compatible with decarbonization goals. The 100% hydrogen option is easier and cheaper to accomplish in new neighborhoods but is harder to realize in those that are already built. Switching from natural gas to RNG is another GHG reduction strategy, but the supply is expected not to be greater than 10% of current demand and RNG wouldn’t address leakage issues the gas distribution infrastructure. Electrification of HVAC with heat pumps is a more effective decarbonization strategy than using fuel cells or hydrogen combustion systems, and electrification of appliances is a more effective decarbonization strategy than hydrogen combustion.

#### Cost / Economic Impact

Cost impacts of switching to hydrogen for heating, water heating, and cooking arise from the need to retrofit or replace appliances, and the potential cost of needing to replace the delivery infrastructure to accommodate hydrogen. The cost of fuel is also an impact of switching to hydrogen, especially in the absence of a price on carbon emissions. The Inflation Reduction Act provides financial support for electrification of building energy demands.

## Technology Readiness and Demonstrations

There are several demonstrations of blending hydrogen with natural gas either completed or in process, including:

Frontrunner (Ameland, NL, 2007), up to 20% (vol) standard heating & cooking appliances

GRHYD (France, 2018-21), up to 20% (vol) for 100 dwellings

HyDeploy (UK), testing safety of blending up to 20% (vol)

Phase 1 (2021) Keele University gas network, std appliances

Phase 2 (now) Winlaton – 668 houses, church, school, businesses

SoCalGas (Los Angeles, CA, 2021)

tested up to 20% (vol), std. appliances

H2 House (under construction): test house with PV, battery, electrolyzer, fuel cell, heat pump, conventional appliances

There are a smaller number of demonstrations of 100% hydrogen distribution and use in residential applications, including:

Hy4Heat UK (2018-22): assess technology, economics, safety of NG to H<sub>2</sub> transition in residential and commercial buildings

H100Fife (Scotland, 2022-), 300 houses, new appliances (stove, space heat, DHW)

Hoogeveen & Stad aan 't Haringvliet (Netherlands, 2022-5), up to 600 houses, new appliances

Fuel cells are unfamiliar to most in North America, but have been widely used in Japan, Korea, and Germany. Programs in place include:

ENE-FARM (Japan), residential fuel cell subsidy (350,000 installed as of 3/2021), NG fuel

Korea H2 roadmap targets 2.1GWe by 2040, 15.7 MWe (2021), NG fuel

## Policy

Policies influence the transition from natural gas, and support programs to develop and implement fuel cells in CHP applications for residential and commercial buildings. Policies can take the form of mandates or bans, or technology development support. Mandates/bans include building codes, building performance standards, fossil fuel taxes or hookup prohibition.<sup>48</sup>

Examples of mandates and bans include:

NYC bans NG hookups in new buildings

Washington state energy code mandates heat pumps (gas stoves still allowed)

Netherlands amended Gas Act in 2018 to ban new NG connections

Examples of technology development support include:

ene.field (2012-17) 1,046 NG units across climate & dwelling types, 5.5M operating hours (4.5GWh produced)

PACE (2016-22) 2,800  $\mu$ CHP installations, 740 in Belgium, 710 in Germany

ComSos – 3 commercial mid-size (10-60kW) SOFC

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<sup>48</sup> RMI (Louis-Préscott, L., and R. Golden), August 9, 2022. *How local governments and communities are taking action to get fossil fuels out of buildings*. <https://rmi.org/taking-action-to-get-fossil-fuels-out-of-buildings/>

### Michigan Assets

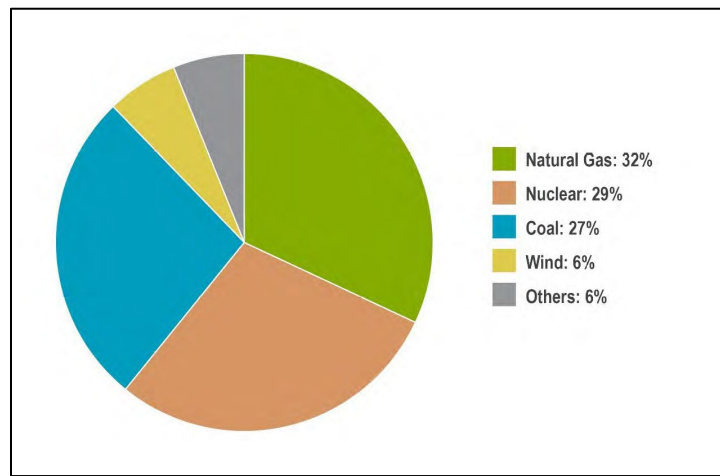
Large inventory of existing residential and commercial buildings needs to be decarbonized, and new construction needs to be planned to be low- or zero-emissions.

### Equity

Propane users must be included in transition planning

## 2.8. Power Generation

Electricity can be produced at utility scale directly from solar radiation with PV cells, by harvesting water and wind energy with turbines, or by using heat from the combustion of fossil fuels, biomass, or municipal waste or from nuclear reactors to make steam that can spin a generator. The electricity system has very little storage built in and production is finely balanced with demand. Currently, batteries are used for small-scale storage (e.g., small amounts of energy over minutes and seconds) and pumped hydro is used in larger scale systems (e.g., larger amounts of energy over days). As more renewable sources are added to the generation mix, storage is a key strategy for dealing with the variability associated with some of these sources. The mix of sources used to generate electricity in Michigan is shown in Exhibit 16 (EGLE 2022).



*Exhibit 16. Mix of fuels used to generate electricity in Michigan (EGLE 2022).*

Hydrogen can be used to displace fossil fuels in combustion processes (e.g., blending with natural gas), but it can also be used to store excess generation from renewables and nuclear sources. Currently, there is low curtailment (excess production) from renewables in Michigan. Blending hydrogen with natural gas could start now, but is limited to 20-30% (vol) by existing infrastructure and combustion equipment and does not provide a high GHG reduction benefit ( $\approx 6.6\%$  reduction at 20% H<sub>2</sub> vol). Blending also extends the use of natural gas and is inconsistent with meeting IPCC goals.

A study on the limitations of blending hydrogen in the European gas system concludes that “Hydrogen blending is not a no regrets option towards 2030. It is suboptimal because it does not specifically target end-uses for which hydrogen is generally agreed to be needed and imposes additional costs for lower greenhouse gas savings compared to using hydrogen directly. Therefore, hydrogen usage should be limited to areas where it is needed and cannot be substituted by electricity.” (Bard et al. 2022).

### GHG Reduction Potential & Other Strategies

Until hydrogen production is decarbonized, it does not seem to have a place as a fuel in utility-scale electricity generation. It could be considered in a storage role, where it would compete with batteries, pumped hydro, compressed air energy storage (CAES), and gravity energy storage. These technologies are evaluated by their round-trip efficiency (from electricity into storage then back into electricity) and GHG emissions. A 2011 DOE Hydrogen and Fuel Cells Program annual review estimated round-trip efficiency of pumped hydro and batteries at 74%, CAES at 71%, and hydrogen at 34% (Elgowainy

2011). Gravity energy storage is still in development <sup>49</sup> but is claimed to have a round-trip efficiency of 80%.

#### Cost / Economic Impact

Hydrogen is not expected to be cost competitive given higher round-trip efficiencies of other storage technologies.

#### Technology Readiness and Demonstrations

There are many utility projects demonstrating the use of hydrogen blended with natural gas up to 30% (vol), nationally and globally. Two projects in New York are:

NYPA Brentwood (Long Island, NY), 2021

Cricket Valley Energy Center (Dover, NY), 2022

100% hydrogen can be used in fuel cells for microgrid & onsite backup (critical infrastructure, data centers), but there are no current combustion examples (under development - within a decade).

#### Michigan Assets

Michigan has a pumped storage facility in Ludington on Lake Michigan. Facilities require specific geography and are thus difficult to site.

There are two utility projects demonstrating cofiring hydrogen with natural gas in Michigan:

Kuester (Marquette), up to 25% hydrogen, 7 reciprocating engines, 126 MW capacity

DTE Blue Water Energy Center (St. Clair) (operational 2024), 2% hydrogen

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<sup>49</sup> Moore, S.K., Jan 5, 2021. *Gravity energy storage will show its potential in 2021*. IEEE Spectrum. <https://spectrum.ieee.org/gravity-energy-storage-will-show-its-potential-in-2021>.



### 3. Delivery

Hydrogen is currently generated close to where it is used (in refineries and chemical plants) to avoid cost and other issues associated with transportation. With the number and geographic dispersion of H<sub>2</sub> uses increasing, transportation and delivery must be addressed. Hydrogen can be transported from where it is generated to where it is used in four ways: pipeline; ship; rail; and road. Pipeline delivery (of both pure hydrogen and blends with natural gas) is in the commercial stage (1,600 miles of hydrogen pipeline in the U.S.), while rail and ship modes are still in R&D. Truck transport over the road in tube trailers is a mature technology, for both gaseous and liquid hydrogen. Liquifying hydrogen requires achieving and maintaining cooling to -253°C, which is energy-intensive and costly.

Hydrogen could be transported as ammonia (NH<sub>3</sub>), reducing impacts due to compression and cryogenic temperatures, though ammonia is a caustic and hazardous material and there is a cost to process H<sub>2</sub> to ammonia and back to H<sub>2</sub>. The energy density of ammonia is 38% higher than liquid hydrogen but the energy loss to crack ammonia back to H<sub>2</sub> is 15-25%.

Hydrogen can also be transported using toluene as a liquid carrier (Papadias & Ahluwalia 2021). This process involves hydrogenation of toluene, transport by ship and/or rail, dehydrogenation, and transport of toluene back to the origin point.

Some of hydrogen's properties make it safer to handle than other common fuels. It is non-toxic and is lighter than air, so it disperses readily in unconfined spaces. Other properties need to be addressed in any system using hydrogen as a fuel. It has a wide range of flammable concentrations in air and a lower ignition energy than natural gas or gasoline, so it is easier to ignite. Also, some metals become brittle when exposed to hydrogen, so material selection is important. There is an American National Standard "Guide to Safety of Hydrogen and Hydrogen Systems" (AIAA 2017) that provides guidance on these issues. The U.S. DOE has indicated that the production and use of hydrogen using the existing gas distribution and storage infrastructure will require identification of and responses to several safety issues (U.S. DOE FE 2020).

Since the primary motivation for switching to hydrogen energy systems is reducing GHG emissions and their adverse climate effects, it is important to consider the atmospheric emissions associated with hydrogen energy systems. This work has begun, with contributions from Frank et al. at Argonne National Lab (Frank et al. 2021) and Ocko and Hamburg from EDF (Ocko & Hamburg 2022). The EDF work examines primarily the direct atmospheric effects of leaked hydrogen but also how the emissions associated with replacing existing fossil fuel systems vary over time and with the hydrogen production method, while the ANL paper takes a life-cycle approach to analyze transportation uses of hydrogen.

#### GHG Reduction Potential & Other Strategies

All forms of transport result in GHG emissions, but pipelines have the lowest GHG since pipelines only need to move the hydrogen, and there is no need to also move a heavy vehicle (e.g., truck, train, or ship).

#### Cost / Economic Impact

The transport distance of hydrogen is a pivotal factor in determining what mode is most cost effective. Tube trailers with gaseous hydrogen are currently most economical at shorter distances (up to 550 km) and liquid hydrogen trucking is more economical at greater distances. Pipelines and rail (liquid) are projected to be cost competitive at commercial scale for longer distances. At least in the short term, delivery costs are estimated to be quite high. In a lifecycle analysis of light-duty vehicle-fuel

pathways, ANL reported the cost for delivery and dispensing of hydrogen to be \$6.14/gge compared to a production cost (via SMR) of \$1.15/gge.<sup>50</sup>

Note that while transporting liquid is lower impact than transporting gas, there is an additional energy and GHG cost to liquify H<sub>2</sub> and keep it cold during transport.

### Technology Readiness and Demonstrations

Fife, Scotland is evaluating a dedicated 100% hydrogen pipeline infrastructure in a residential setting.

The Suiso Frontier is a liquid H<sub>2</sub> carrier ship launched in 2019 to evaluate this mode of transport in trials between Australia and Japan. These trials are of interest in Michigan and other Great Lakes states as this mode is potentially applicable and valuable here.

### Michigan Assets

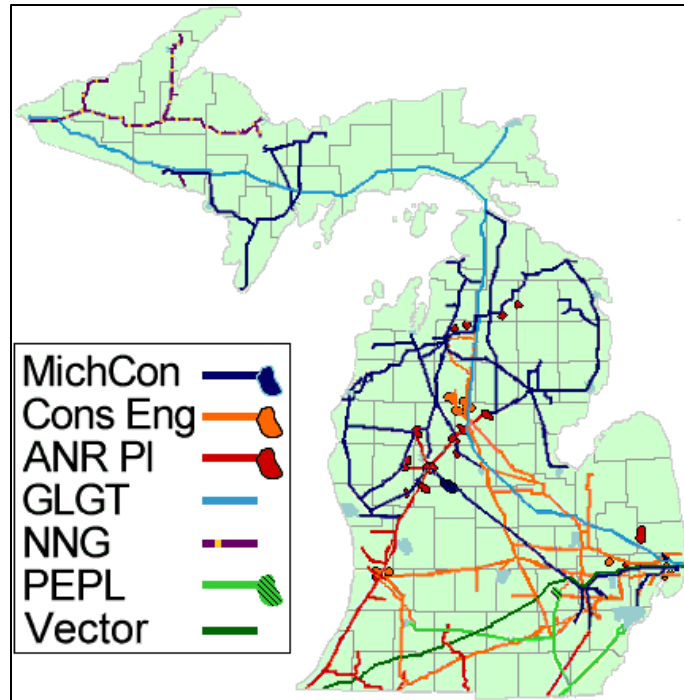
Michigan is located within a major natural gas transportation corridor, which potentially offers an opportunity to deliver hydrogen. A map of major natural gas pipelines and storage facilities in Michigan is shown in Exhibit 17.<sup>51</sup> It's important to note that replacing natural gas with hydrogen in existing natural gas pipelines at volume concentrations higher than 20% cannot always be done since some types of steel pipe can degrade (i.e., embrittle) when they are exposed to hydrogen over long periods, particularly in high concentrations and at high pressures. There is no concern about hydrogen degradation effects for polyethylene (PE) or polyvinylchloride (PVC) pipe materials.

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<sup>50</sup> See Table 22 in Kelly et al. 2022

<sup>51</sup> MPSC. *Natural gas transmission pipeline and storage field map*.

<https://www.michigan.gov/mpsc/consumer/natural-gas/pipeline-maps/natural-gas-transmission-pipeline-and-storage-field-map>



*Exhibit 17. Map of natural gas pipelines and storage sites in Michigan (MPSC, <https://www.michigan.gov/mpsc/consumer/natural-gas/pipeline-maps/natural-gas-transmission-pipeline-and-storage-field-map>).*

There are two private hydrogen fueling stations in Michigan, in Grand Blanc (at the Flint MTA Alternative Fueling Center) and Dearborn (at the Ford Sustainable Mobility Transportation Lab). There are 5.5 miles of dedicated hydrogen pipeline in Michigan and no public fueling stations. A 2005 NREL analysis, which looked to develop a fueling station network taking advantage of local resources and being accessible to the largest number of people, suggested four sites in Michigan for hydrogen refueling stations.

#### Regional Assets / Potential

Strong natural gas pipeline connections between Port Huron, Michigan and Sarnia, Ontario.

#### Organizations

Transportation Security Administration, U.S. Coast Guard, Detroit Wayne County Port Authority

#### Equity:

Concerns include emissions from transport trucks, pipeline leaks, and other impacts related to energy used for transportation and delivery.

## 4. Storage

One of the primary roles envisaged for hydrogen in a low- or zero-GHG electricity system is as an energy carrier, a medium for storing excess electricity that can be used in periods when demand exceeds supply. There are several methods available for hydrogen storage, divided into physical and material-based methods as depicted in Exhibit 18 (U.S. DOE 2020). Physical methods include storing hydrogen as a compressed gas (in tanks or geological reservoirs), or as a liquid. Both methods incur an energy cost, with the cost being higher for liquid storage. Geologic reservoirs include salt caverns, depleted oil and gas reservoirs, aquifers, and mined hard rock caverns (Exhibit 19) (EIA 2008). Existing natural gas reservoirs may not translate to a hydrogen system where substantial engineering obstacles may be encountered since hydrogen is difficult to contain and could combine or react (chemically or biologically) with other materials in the reservoir. Workshop attendees noted that contamination is less of an issue in salt caverns than in natural gas reservoirs. Some industrial uses may be able to tolerate this contaminated hydrogen, but it is an issue for applications requiring high purity hydrogen. Material-based methods include metal hydrides and adsorbents, and chemical carriers such as  $\text{NH}_3$ . Recovering hydrogen from these storage materials requires the addition of heat or a chemical process.

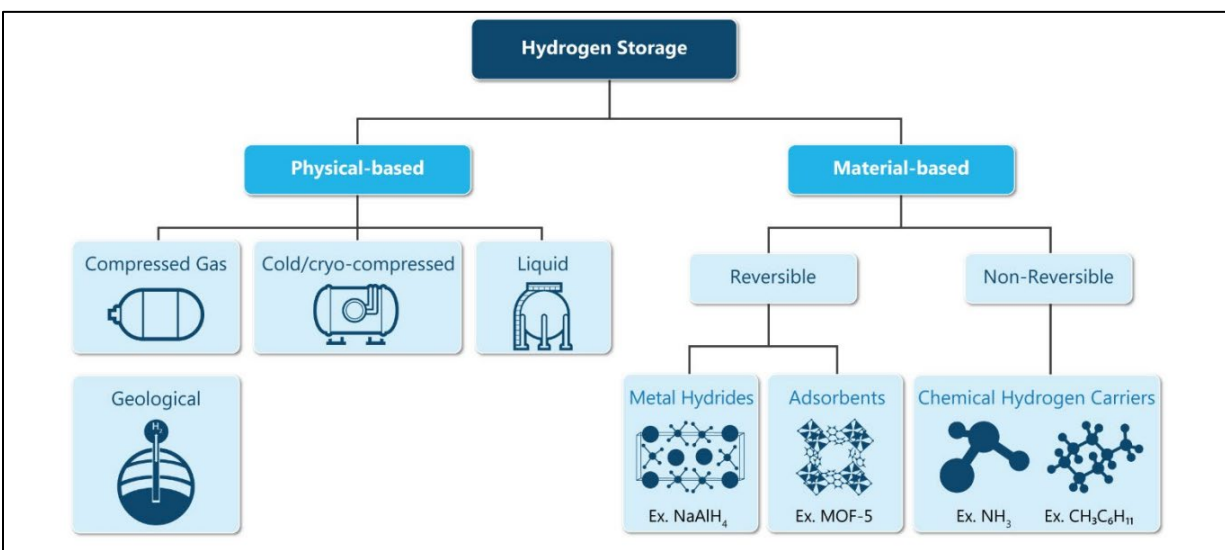


Exhibit 18. Hydrogen storage options (U.S. DOE 2020).

Since the workshop was held in May, there has been pro-hydrogen activity in Congress with the Inflation Reduction Act.<sup>52</sup> The Act expands the scope of the Section 48 energy ITC by adding “energy storage technology” to the categories of energy property eligible for the credit. Qualifying storage technology includes “property (other than property primarily used in the transportation of goods or individuals and not for the production of electricity) which receives, stores, and delivers energy for conversion to electricity (or, in the case of hydrogen, which stores energy), and has a nameplate capacity of not less than 5 kilowatt hours.” This provision places hydrogen storage facilities on equal footing with other energy storage technologies (such as batteries and thermal energy storage facilities) in terms of the availability of tax credits. The ITC for energy storage technology is also subject to the credit multiplier concept. The headline ITC rate is 6% of qualified costs. This credit rate can, however, be increased by up to 500% (up to a credit

<sup>52</sup> King & Spalding, August 11, 2022. *Hydrogen-Related Provisions of the Inflation Reduction Act of 2022*. <https://www.jdsupra.com/legalnews/hydrogen-related-provisions-of-the-2283064/>.

rate of 30%) if certain requirements are satisfied. Bonus credits up to 10% are also available if domestic content and the “energy community” conditions are satisfied. It appears that bonus credits can be stacked.

### GHG Reduction Potential & Other Strategies

Round-trip efficiencies must be considered versus alternative storage methods.

### Cost / Economic Impact

A 1998 NREL study found that underground storage was the cheapest method at all production rates and storage times because of the low capital cost of the cavern. Compressed gas storage (in tanks above ground) competes with liquid hydrogen and metal hydride storage for small quantities of hydrogen and low production rates. Liquid hydrogen storage was found to be not economical at low production rates because of the high capital cost of the liquefier.

### Technology Readiness and Demonstrations

Hypster (Etrez, France), 2023 first EU salt cavern storage and extraction demonstration

Salt dome storage projects operational in Teesside (UK), Spindletop (Beaumont, TX), Moss Bluff, (Houston, TX), Clemens Dome (Brazoria, TX)

There are four hydrogen storage sites in salt caverns in the world that serve as strategic reserves for use in hydrocarbon refineries.<sup>53</sup> Hydrogen in salt caverns is expected to absorb moisture (as is the case for natural gas), and bacteriological and chemical reactions are also possible, thus transforming some of the hydrogen and modifying the overall composition of the gas. Specific treatment to purify and dehydrate hydrogen at the cavern outlet would likely be necessary.

The world’s largest energy storage facility (1,000 MW) is being planned 200 kilometers south of Salt Lake City, partly by storing hydrogen in underground salt caverns. The Advanced Clean Energy Storage project will take excess power generated from hydroelectric, geothermal, solar and wind and electrolyse it into hydrogen for storage in salt caverns, where it can later be used for power, industrial and transport applications. Scheduled for operation by 2025, the first phase will provide 150,000 MWh of storage capacity. The project was invited to apply for up to \$595 million in loans from the U.S. DOE.<sup>54</sup>

### Michigan Assets

Michigan has about 4000 million cubic feet of natural gas underground storage salt caverns capacity.<sup>55</sup>

Michigan has the largest underground working natural gas storage capacity in the U.S.

Spindletop, the largest storage site in the U.S., has a volume that is less than 0.005% of Michigan’s natural gas storage capacity.

### Equity

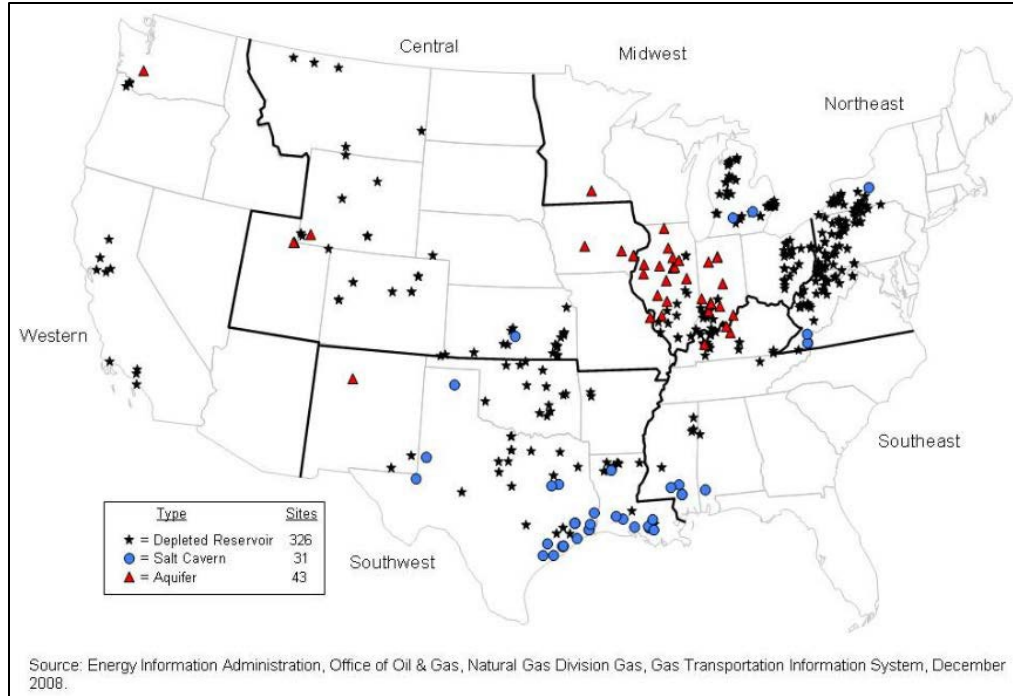
Concerns include effects of leaks from underground storage facilities.

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<sup>53</sup> Engie, July 27, 2021. *H2 in the underground: Are salt caverns the future of hydrogen storage?*  
<https://innovation.engie.com/en/articles/detail/hydrogen-underground-storage-salt-caverns/25906/>

<sup>54</sup> Ibid.

<sup>55</sup> EIA, 2020. *Michigan Natural Gas Underground Storage Salt Caverns Capacity.*  
[https://www.eia.gov/dnav/ng/hist/na1393\\_smi\\_2a.htm](https://www.eia.gov/dnav/ng/hist/na1393_smi_2a.htm)



*Exhibit 19. U.S. underground natural gas storage facilities (as of 2007) (EIA 2008).*

## 5. Production

Hydrogen is produced either chemically via fossil fuels (e.g., coal and natural gas), thermally via nuclear energy, or by using electricity to split water. Electricity can be generated in many ways and the source of the electricity will largely determine the GHG emissions associated with that method. The lowest GHG emissions result from production via electrolysis using renewable electricity. Currently, 96% of hydrogen produced worldwide is produced from natural gas (via steam methane reforming, SMR) or coal (via gasification), resulting in relatively high GHG emissions (10 metric tons CO<sub>2</sub> per metric ton hydrogen produced) (IEA 2019). Globally about 1% of hydrogen production from fossil fuels includes carbon capture and storage (CCS) (Global CCS Institute 2021). There are four ways nuclear energy can be used to generate hydrogen: cold electrolysis; low-temperature steam electrolysis; high temperature steam electrolysis; high temperature thermochemical production. The hydrogen color spectrum, shown in Exhibit 20 (GEI 2021), is a useful way of distinguishing hydrogen production methods, feedstocks employed, and associated GHG emissions.

As of January 2016, Michigan merchant hydrogen producers had an annual capacity of  $\approx 55$ k metric tons (all via SMR),<sup>56</sup> when total U.S. production via all methods was  $\approx 10$ M metric tons.<sup>57</sup>

	Terminology	Technology	Feedstock/ Electricity Source	GHG Footprint
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind   Solar   Hydro Geothermal   Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas   coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

*Exhibit 20. Color terms used to describe hydrogen as a function of production method and energy source, based on original in (GEI 2021).*

The distribution of hydrogen production locations by size and type across the U.S. is shown in Exhibit 21 (Elgowainy et al. 2019)

<sup>56</sup> Calculated using data from <https://h2tools.org/hyarc/hydrogen-data/merchant-hydrogen-plant-capacities-north-america> (data file available at <https://h2tools.org/file/196/download?token=BNg4dM46>).

<sup>57</sup> U.S. DOE Hydrogen and Fuel Cells Technology Office, *Fact of the Month May 2018: 10 Million Metric Tons of Hydrogen Produced Annually in the United States*. <https://www.energy.gov/eere/fuelcells/fact-month-may-2018-10-million-metric-tons-hydrogen-produced-annually-united-states>

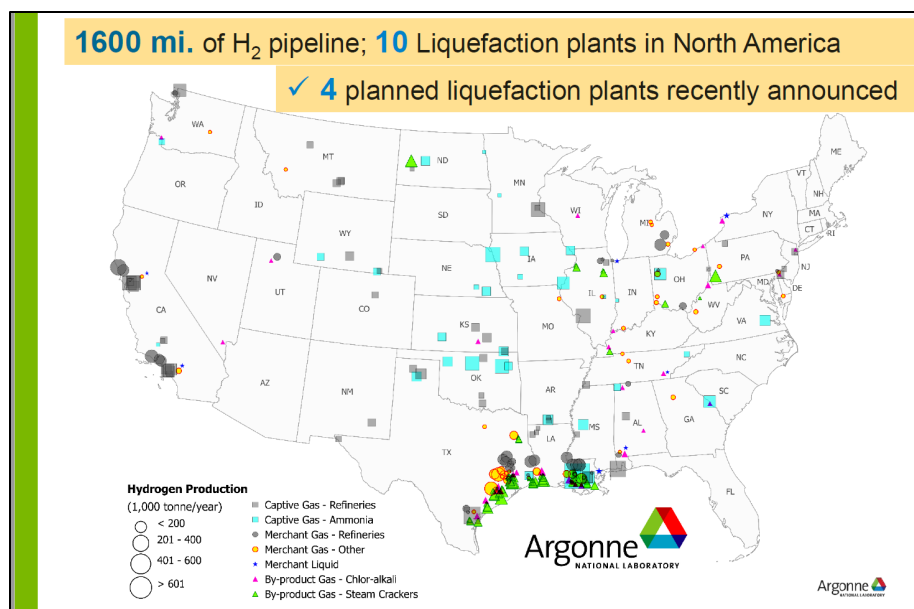


Exhibit 21. U.S. hydrogen production locations and properties (Elgowainy et al. 2019).

Constellation Energy and the University of Toledo presented proposals at the Workshop that included using nuclear power for hydrogen production. Electrolysis at ambient temperature is being undertaken in at least four projects at U.S. nuclear power plants, and is planned for the Kola plant in Russia from 2023 using alkaline and proton exchange membrane (PEM) technology. In August 2021 Nel Hydrogen was contracted to build a 1.25 MW PEM electrolyzer at Exelon’s Nine Mile Point nuclear power plant in Scriba NY to demonstrate integrated production, storage and use at the plant.<sup>58</sup>

Since the workshop in May, Congress has made progress with the Inflation Reduction Act. This Act creates a new Clean Hydrogen Production Tax Credit providing up to \$3 per kg of hydrogen produced at a given facility (as shown in Exhibit 22),<sup>59</sup> based on the carbon intensity of production, or offers a similarly scaled investment tax credit (ITC) up to 30% for new facilities. This benefit is estimated to be worth \$13 billion over the next decade.

Kg of CO <sub>2</sub> per kg of H <sub>2</sub>	Credit Value (\$)
4 - 2.5 kg CO <sub>2</sub>	\$0.60 / kg of H <sub>2</sub>
2.5 - 1.5 kg CO <sub>2</sub>	\$0.75 / kg of H <sub>2</sub>
1.5 - 0.45 kg CO <sub>2</sub>	\$1.00 / kg of H <sub>2</sub>
0.45 - 0 kg CO <sub>2</sub>	\$3.00 / kg of H <sub>2</sub>

Exhibit 22. Inflation Reduction Act clean hydrogen production tax credit, by kg of CO<sub>2</sub> produced per kg of hydrogen (from Fuel Cell and Hydrogen Energy Association, <https://www.fchea.org/transitions/2022/8/5/how-the-inflation-reduction-act-of-2022-will-advance-a-us-hydrogen-economy>).

<sup>58</sup> World Nuclear Association, November 2021. *Hydrogen Production and Uses*. <https://www.world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses.aspx>

<sup>59</sup> Fuel Cell & Hydrogen Energy Association, August 5, 2022. *How the Inflation Reduction Act of 2022 Will Advance a U.S. Hydrogen Economy*. <https://www.fchea.org/transitions/2022/8/5/how-the-inflation-reduction-act-of-2022-will-advance-a-us-hydrogen-economy>



## GHG Reduction Potential & Other Strategies

Various approaches are being pursued to reduce GHG emissions associated with hydrogen production. Carbon capture, use, and storage (CCUS, also referred to as CCS) applies to all of the production methods using fossil fuels. There are significant public acceptance issues with CCUS (Seigo, Dohle, & Siegrist 2014, Fleishman, de Bruin, & Morgan 2010), as well as ongoing concern about long-term permanence of underground storage (Shaffer 2010).

IEA reported in 2019 that “while less than 0.1% of global dedicated hydrogen production today comes from water electrolysis, with declining costs for renewable electricity, in particular from solar PV and wind, there is growing interest in electrolytic hydrogen.” (IEA 2019). A greater emissions benefit may be realized by using renewable and nuclear electricity to displace GHG-emitting generators before it is used to produce hydrogen. A 2020 NREL report evaluated the availability of individual energy resources in the U.S. to produce an additional 10 million metric tons in 2040 (Connelly et al. 2020). The report considers fossil, nuclear, and renewable energy sources and maps their geographic distribution, concluding that there are sufficient domestic resources to meet this hydrogen production goal, though there would be a significant increase in renewable energy consumption.

The Hydrogen Council estimated GHG emissions associated with each hydrogen production pathway in 2030 (reproduced here as Exhibit 23 (Hydrogen Council 2021a)), and they range from 0.3 to 1.0 kg GHG/kg H<sub>2</sub> compared to 11 kg GHG/kg H<sub>2</sub> from NG with SMR.

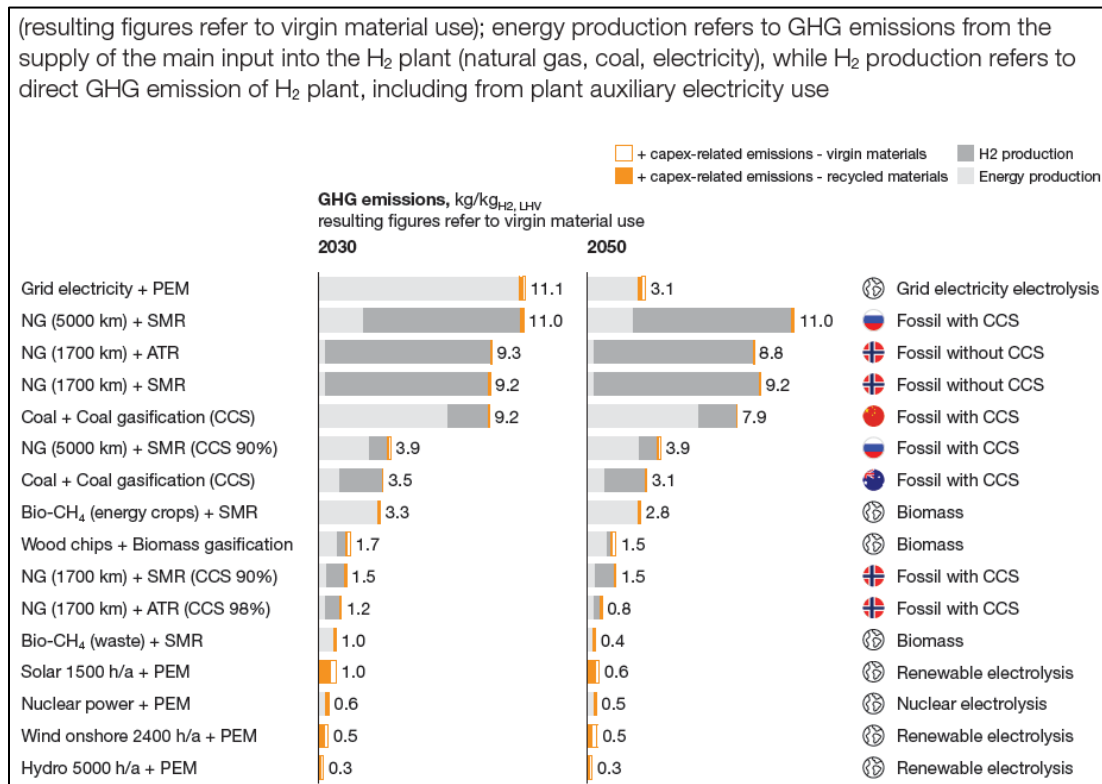


Exhibit 23. GHG emissions for hydrogen production pathways in 2030 and 2050, from (Hydrogen Council. 2021).

Cost / Economic Impact

Currently, producing hydrogen via SMR is significantly less costly than via electrolysis and renewable electricity, though these costs are expected to be equal by 2050. McKinsey has forecast production costs for blue hydrogen to drop from \$4/kg dispensed in 2020 (~35% of total cost) to \$2.2/kg in 2030 (~50% of total cost) (Hydrogen Council 2021b). As electrolytic production ramps up, the value of the oxygen also produced in this process should be an additional consideration (as should the cost of capturing, storing, and transporting this gas). U.S. DOE estimates for current production cost of hydrogen by technology are collected in Exhibit 24 (U.S. DOE FE 2020). Nuclear has the advantage over renewables in electrolysis due to its stable output enabling higher utilization rates of capital-intensive electrolyzers.

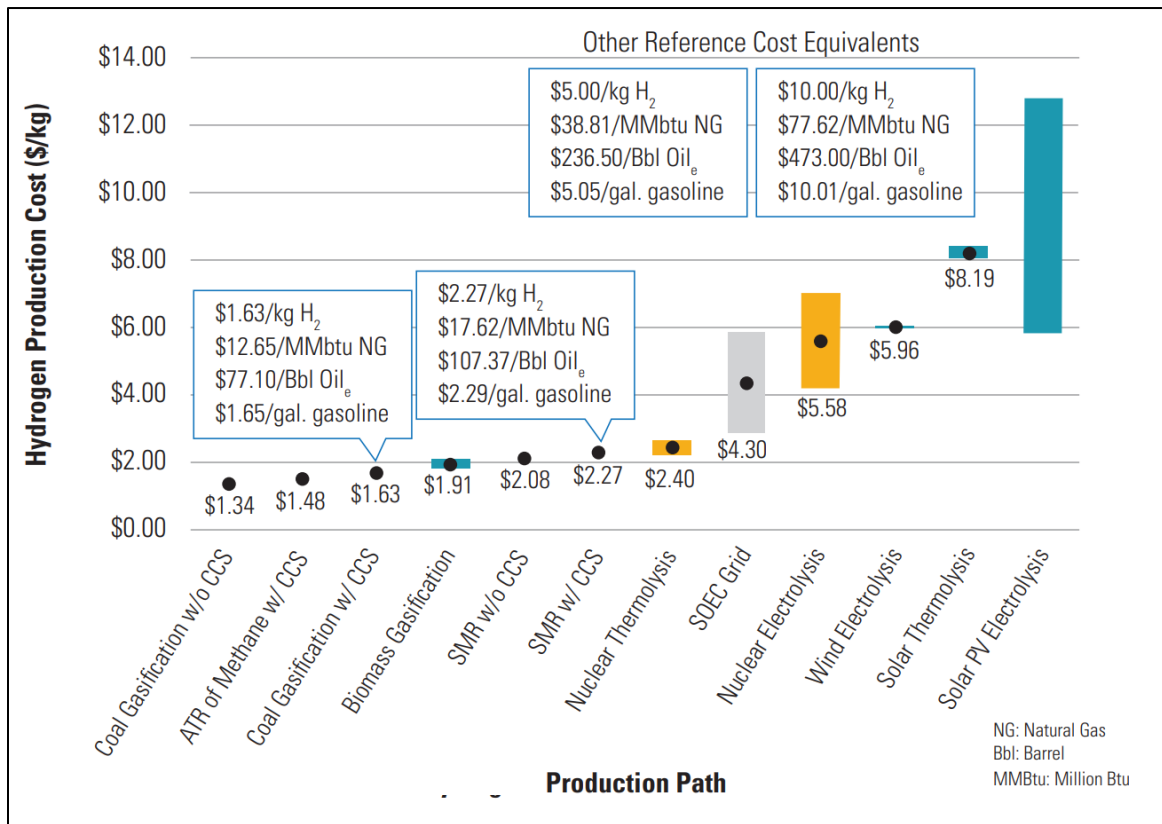


Exhibit 24. Current hydrogen production cost ranges and averages by technology (from U.S DOE FE 2020).

Lazard has conducted an analysis of the levelized cost of hydrogen that finds the primary cost driver of green hydrogen is the cost of electricity, followed by the cost and utilization fraction of the electrolyzer (Lazard 2021). Depending on the type, efficiency, and capacity of the electrolyzer, they estimate production costs between \$3.20/kg and \$6.70/kg.

The IPCC has collected hydrogen production process performance and cost estimates, reproduced here as Exhibit 25 for non-electric processes and Exhibit 26 for electrolysis processes (IPCC 2022, p.6-59).

(1) CSIRO 2021; (2) IEA 2020; (3) IRENA 2019; (4) Hydrogen Council 2020; (5) CCC 2018; (6) BEIS 2021; (7) Ishaq et al. 2021; (8) Al-Mahtani et al. 2021; (9) IEA 2019

Technology	LHV Efficiency (%)		Carbon Intensity (kgCO <sub>2</sub> (kgH <sub>2</sub> ) <sup>-1</sup> )	Cost Estimates* (USD (kgH <sub>2</sub> ) <sup>-1</sup> )	
	Current	Long-term		Current	Long-term
SMR	65 <sup>(5)</sup>	74 <sup>(5,6)</sup>	1.0–3.6 <sup>(5,9)</sup>	1.0–2.7 <sup>(1,2,3,4,5)</sup>	1.5–2.6 <sup>(5)</sup>
Advanced gas reforming	-	81–84 <sup>(5,6)</sup>	0.9–2.9 <sup>(5)</sup>	1.3–2.1 <sup>(5)</sup>	1.2–3.4 <sup>(5,6)</sup>
Hydrogen from coal gasification	54 <sup>(5)</sup>	54 <sup>(5)</sup>	2.1–5.5 <sup>(5,9)</sup>	1.8–3.1 <sup>(1,2,3,4,5)</sup>	2.4–3.3 <sup>(5)</sup>
Hydrogen from biomass gasification	53.6 <sup>(7)</sup>	40–60 <sup>(5)</sup>	Potential to achieve-Negative emission <sup>(5,8)</sup>	4.9 <sup>(5)</sup>	2.9–5.9 <sup>(5,6)</sup>

\*USD per GBP exchange rate: 0.72 (August 2021); LHV: Lower Heating Values; Long-term refers to 2040 and 2050 according to different references

Exhibit 25. Performance and cost characteristics of non-electric hydrogen production processes (IPCC, 2022, p.6-59).

(1) CSIRO 2021; (2) IEA 2020; (3) IRENA 2019; (4) Hydrogen Council 2020; (5) CCC 2018; (6) BEIS 2021; (7) IEA 2019; (8) Christensen 2020

Technology	LHV Efficiency (%)		CAPEX (USD kW <sub>e</sub> <sup>-1</sup> )		Cost Estimates* <sup>+,</sup> (USD (kgH <sub>2</sub> ) <sup>-1</sup> )	
	Current	Long-term (2,5,6,8)	Current <sup>(7)</sup>	Long-term <sup>(7)</sup>	Current	Long-term
Alkaline Electrolysers	58–77 <sup>(1,2,5,6,8)</sup>	70–82	500–1400	200–700	2.3–6.9 <sup>(1,2,3,5)</sup>	0.9–3.9 <sup>(3,5)</sup>
PEM	54–72 <sup>(1,2,5,6,8)</sup>	67–82	1100–1800	200–900	3.5–9.3 <sup>(1,4,5,6)</sup>	2.2–7.2 <sup>(5,6)</sup>
SOEC	74–81 <sup>(2,6,8)</sup>	77–92	2800–5600	500–1000	4.2 <sup>(5)</sup>	2.6–3.6 <sup>(5)</sup>

\*USD per GBP exchange rate: 0.72 (August 2021); + The cost of hydrogen production from electrolysers is highly dependent on the technology, source of electricity, and operating hours, and here some values based on the assumptions made in the references are provided.

Exhibit 26. Performance and cost characteristics of electric hydrogen production processes (IPCC, 2022, p.6-59).

### Technology Readiness and Demonstrations

Idaho National Laboratory tests of a solid oxide electrolyzer demonstrate 88.5% efficiency at an energy demand of 37.7 kWh of electricity per kg of hydrogen produced.<sup>60</sup>

### Michigan Assets

There are currently three commercial hydrogen production facilities in Michigan (two in Detroit and one in Midland), with smaller facilities at the Detroit Arsenal (Warren, MI) and in Albion. These

<sup>60</sup> yahoo!finance, August 9, 2022. Idaho National Lab and Bloom Energy Produce Hydrogen at Record-Setting Efficiencies. <https://finance.yahoo.com/news/idaho-national-lab-bloom-energy-201500925.html>

production facilities serve primarily Rouge Steel, the Marathon Refinery, the Midland chemical complex, and Hemlock Semiconductor.

There are two operating nuclear generating stations in Michigan (Cook (2.2 GWe) in Bridgman and Fermi (1.2 GWe) in Monroe). The Palisades plant in Covert Township (0.8 GWe) was recently closed.

As an illustration, if the entire capacity of existing nuclear plants in Michigan were dedicated to producing hydrogen via electrolysis (at 58.8 kWh/kg H<sub>2</sub>), 643,000 metric tons of hydrogen would be produced (0.64% of the approximately 10 million metric tons produced annually in the U.S.).

Given the huge wind energy resource in the Great Lakes, combining offshore wind turbines with electrolyzers to produce hydrogen that could then be piped or shipped to shore is an option that should also be explored (Ibrahim et al. 2022).<sup>61</sup> This is a possible use for electricity generated in excess of demand.

### Regional Assets / Potential

The Davis-Besse project (Oak Harbor, OH) includes a pressurized water nuclear reactor with a PEM low temperature electrolysis system on the shores of Lake Erie (e.g., access to water). Engineering and site preparations are underway to operate the nuclear hydrogen production system in 2023. In collaboration with Idaho National Laboratory (INL), Xcel Energy, and Arizona Public Service.

### Equity

Depending on energy/fuel source, plant emissions and other potential risks affect surrounding communities.

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<sup>61</sup> Baraniuk, C., February 12, 2021. *The global race to produce hydrogen offshore*. BBC. <https://www.bbc.com/news/business-55763356>

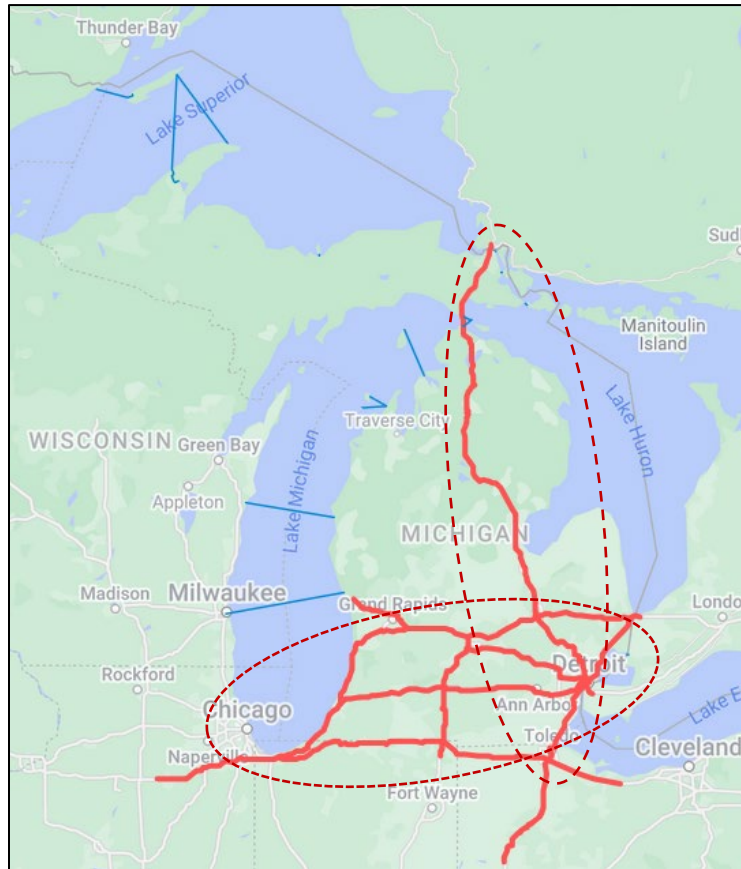
## 6. Michigan Hydrogen Ecosystem

Among the first steps taken when assembling a set of interconnected entities into a functioning ecosystem, mapping allows us to clearly see location and proximity, both of which are important in minimizing GHG emissions and cost from transportation. This section of the roadmap workshop report contains a series of maps that can be used to foster conversation and connection amongst individuals and organizations that are interested in helping to foster the hydrogen economy in Michigan and the surrounding region. Those interested in the DOE H2Hubs competition will hopefully find these maps valuable as well.

The features on these maps are a combination of suggestions from the CSS research team and from workshop attendees, and include hydrogen production facilities, nuclear electricity generating stations, a selection of current and potential end-uses, and ferries and interstate highways. Highway links have been extended beyond Michigan's borders to locations of possible hydrogen ecosystem members, though the highways continue past what is highlighted in the maps. The colors and location numbers are consistent across all maps. We have added dashed ellipses to the maps to highlight nodes and corridors, where proximity or linking infrastructure connect production and use of hydrogen. Note that these ellipses serve only to point out potential groupings and do not determine which facilities are 'in' or 'out' of further discussions.

These maps provide a basis for further evaluation and planning of hydrogen production, delivery, storage, and end-use applications in Michigan and the adjacent region. A Michigan hydrogen ecosystem design must include in-depth consideration of a comprehensive set of evaluation criteria and metrics, a task that can be guided by further spatial analysis and mapping. For example, an EPA environmental justice screening map, presented at the end of this section, can be layered onto transportation corridors to demonstrate and estimate public health co-benefits of a fuel transition from diesel to hydrogen for medium- and heavy-duty vehicles.

The first map, shown in Figure 2, is a base map illustrating the highway network and ferry routes. Note that this network forms a transport corridor linking southern Michigan with northwest Ohio, northern Indiana, and northern Illinois. There are two U.S. – Canada border crossings with significant trade volumes at Detroit-Windsor and Port Huron-Sarnia. The Michigan rail network is shown in Exhibit 11 and the natural gas pipeline network is shown in Exhibit 17.



*Figure 2. Major interstate road corridors (in red) and ferry routes (in blue, see Figure 1 for a map of ferry ports in Michigan). The dotted ellipse highlights primary interconnected transportation corridors through southern Michigan, the dashed ellipse highlights a secondary north-south transportation corridor.*

Figure 3 illustrates the locations of nuclear electricity generating stations in the region. Cook and Fermi in Michigan are currently operating, but Palisades has recently ceased operation. Davis-Besse, in northern Ohio, and Constellation LaSalle southwest of Chicago are proximate to the highway network and could be valuable contributors to the hydrogen ecosystem.

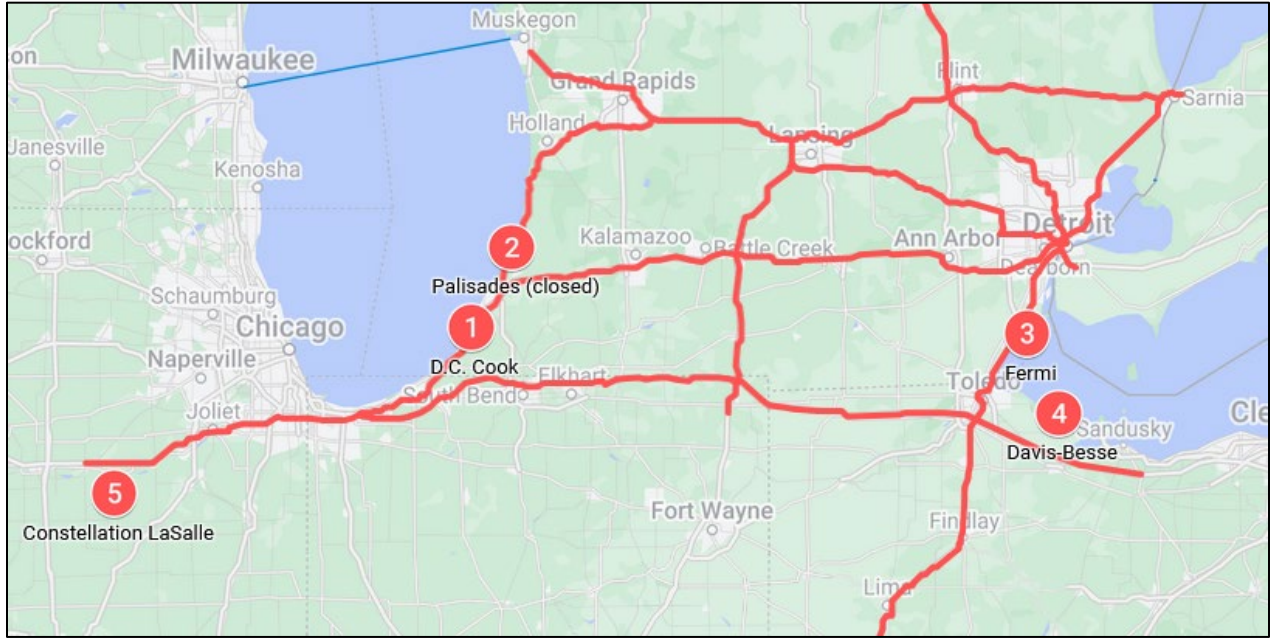


Figure 3. Nuclear electricity generating stations in Michigan and the region for potential low-carbon hydrogen production.

Figure 4 shows the hydrogen producers in southeast Michigan. Most of these producers are adjacent to their refinery and chemical company customers to minimize delivery pipeline length. The Detroit Arsenal produces hydrogen using an electrolyzer as a dump load for its military vehicle test dynamometers, and Albion College plans to produce hydrogen as part of a microgrid research project and is the only low-carbon hydrogen production facility shown.

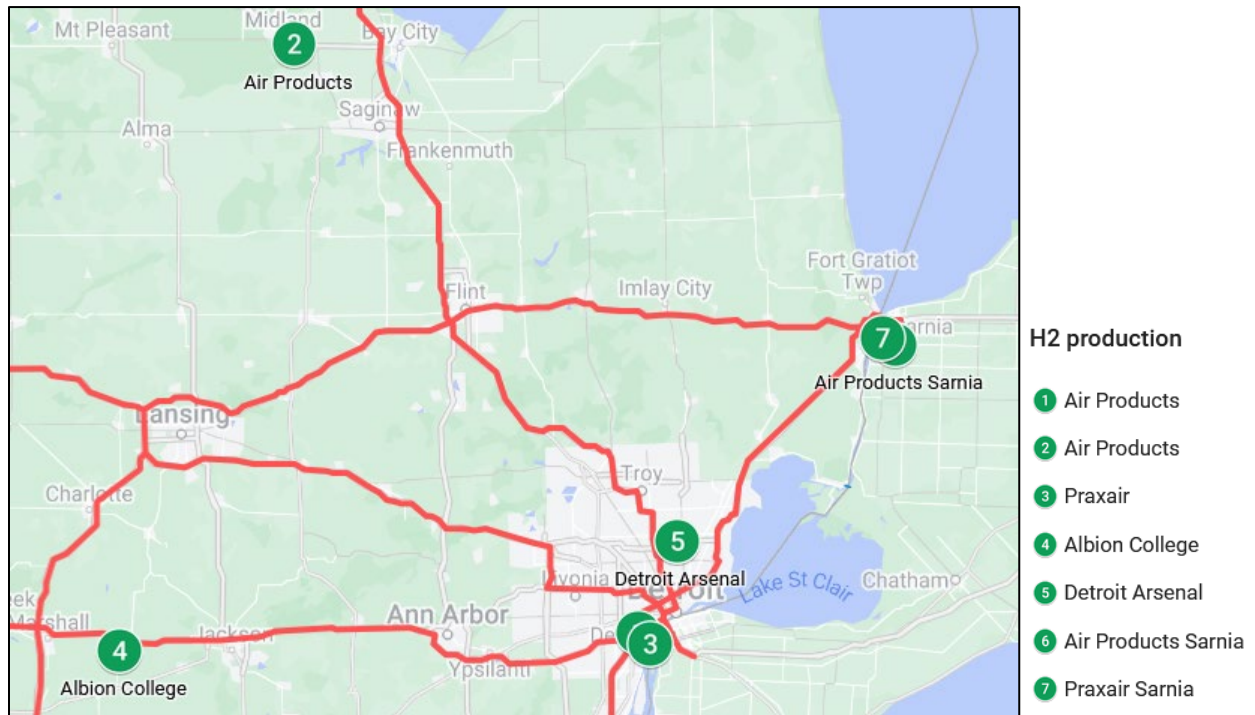
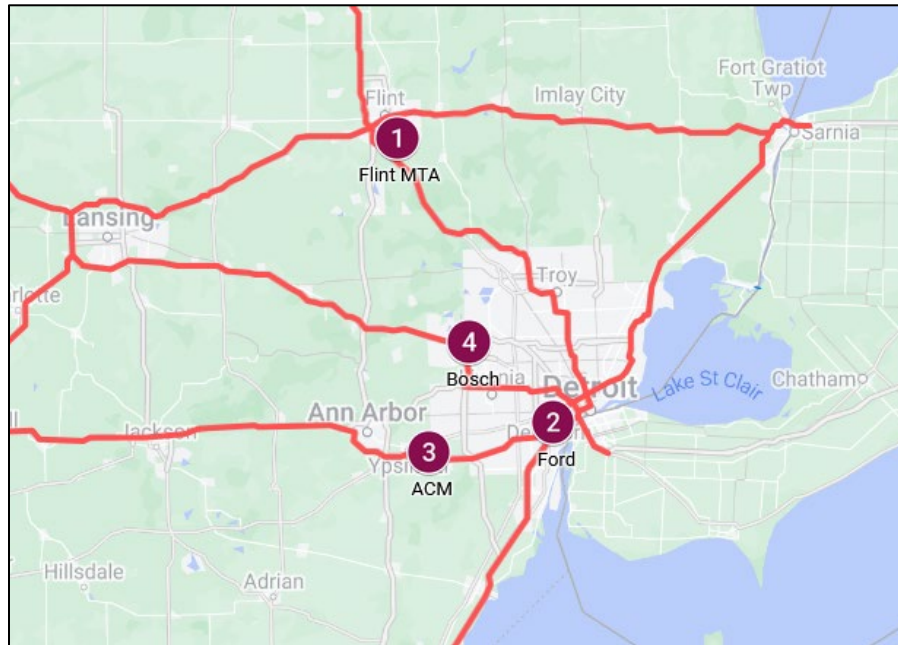


Figure 4. Current hydrogen production facilities in the region (#1 Air Products is partially hidden by #3, and #6 Air Products Sarnia is partially hidden by #7). The Albion College facility is part of a planned microgrid project.



Figure 5 shows several locations in southeast Michigan associated with hydrogen as a transportation fuel. The Flint MTA is a refueling station for a hydrogen bus, and the Ford refueling station is at their Sustainable Mobility Transportation. Lab. ACM is the American Center for Mobility, which is planning a hydrogen refueling station for 2023, and a Bosch hydrogen electrolysis facility is planned for development and testing purposes in Farmington Hills.



*Figure 5. Flint MTA and Ford are active hydrogen fueling stations for transportation, ACM is in the process of setting up a fueling station, and Bosch is planning an electrolysis facility for development and testing.*

Figure 6 shows a variety of current and potential industrial users of hydrogen. Current Michigan users include Hemlock Semiconductor, the Marathon refinery in Detroit, and the Midland chemical complex. Potential users in Michigan include Cleveland Cliffs Rouge steel, Guardian Glass, and the cement plants in Alpena, Charlevoix, and Detroit. In Ohio, current users include the Cleveland Cliffs DR plant in Toledo and the Nutrien ammonia plant in Lima. The Gary Works in Indiana is a potential user and the Sarnia petrochemical complex in Ontario is a current user. Note that all three cement plants are accessible via the Great Lakes.

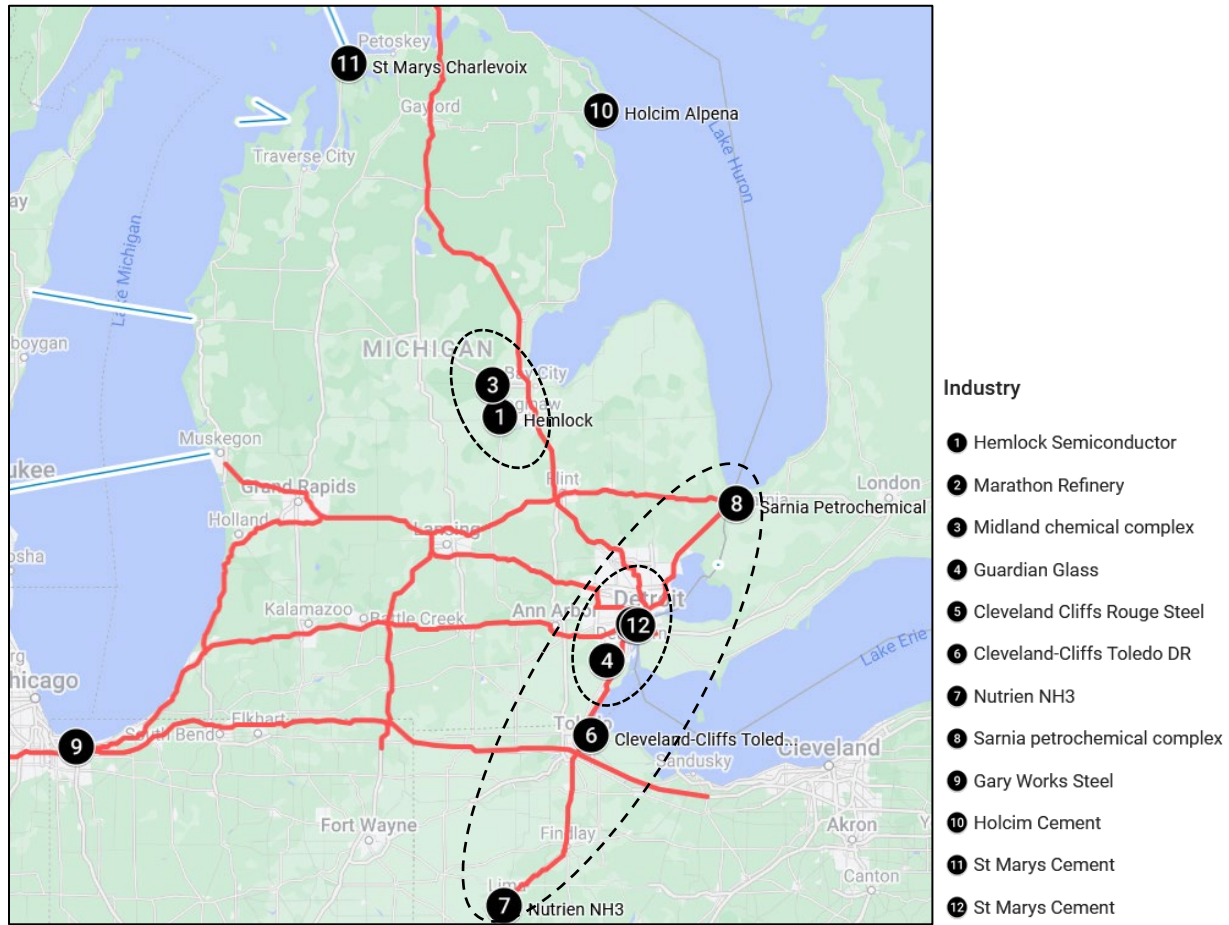


Figure 6. Current and potential industrial end-users of hydrogen in the region (#2 Marathon and #5 Cleveland Cliffs Rouge Steel are under #12 St Marys Detroit). Small black ellipses highlight clusters of facilities in Midland and Detroit, the larger ellipse is a potential regional cluster.

Figure 7 shows the two sites proposed by electricity utility companies for demonstrations of co-firing hydrogen in natural gas turbines.

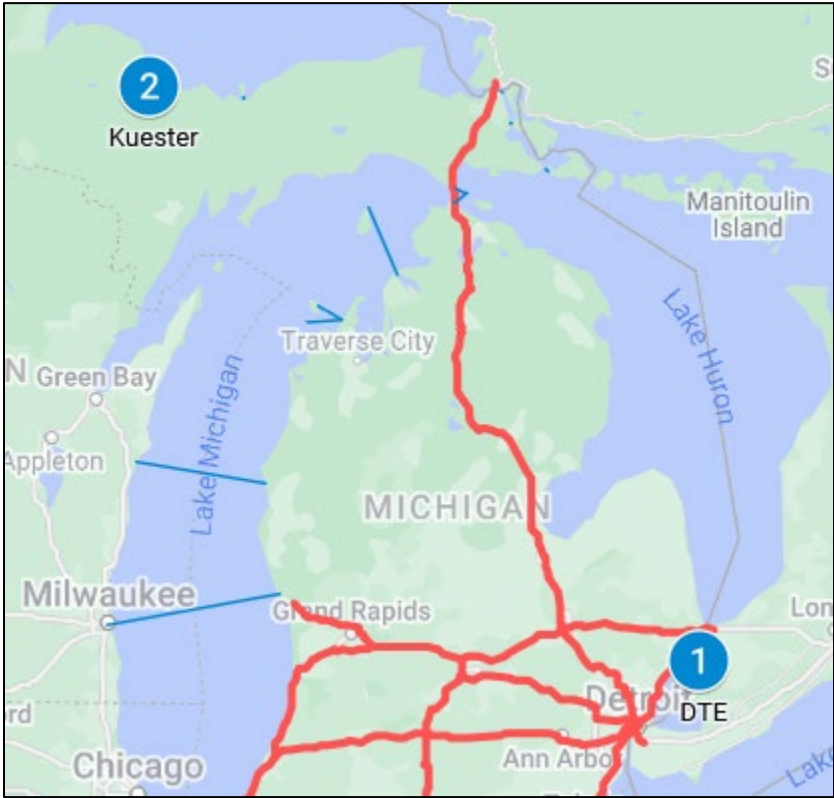
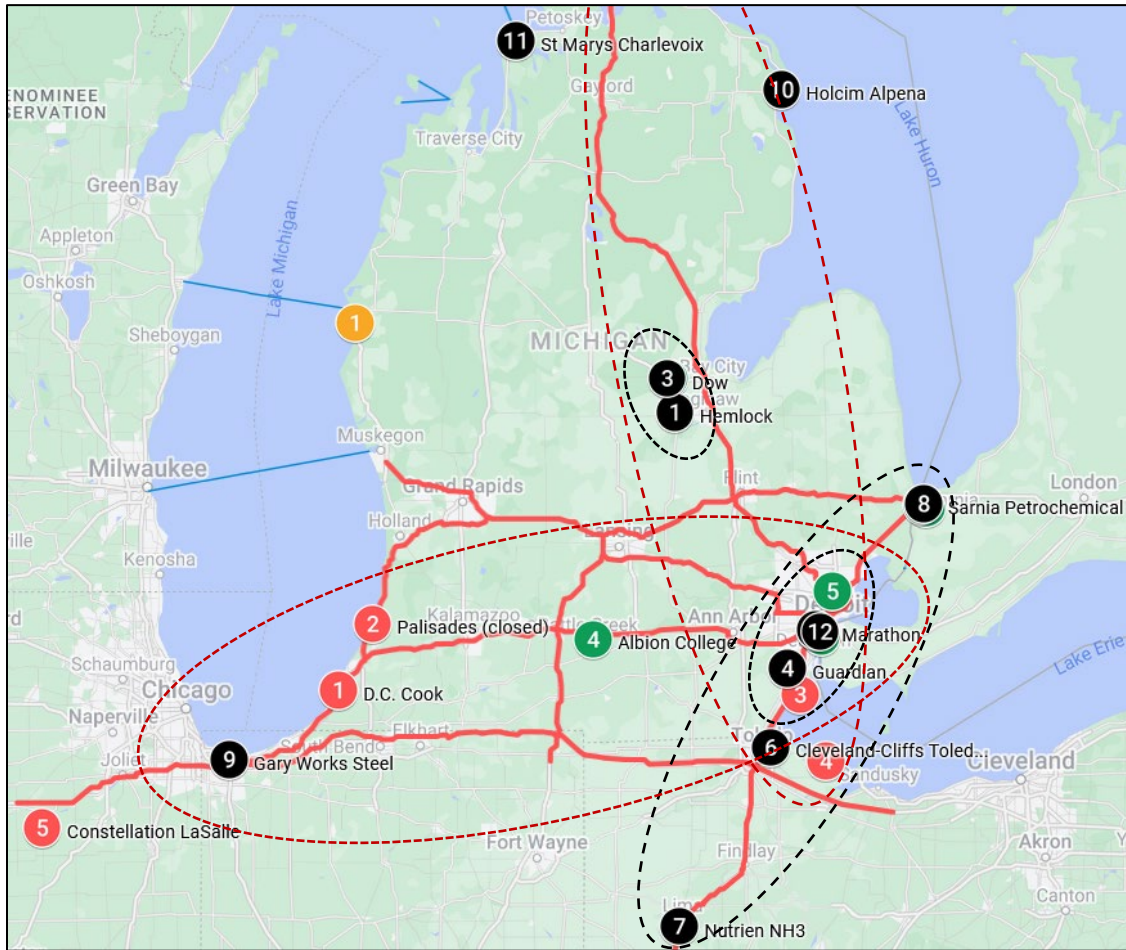


Figure 7. Proposed utility hydrogen blending project sites.

Figure 8 combines all of the previous locations and adds the pumped hydro energy storage facility in Ludington on Lake Michigan. Note that the Palisades nuclear plant (the red number 2) has closed.



**Nuclear plant**

- 1 D.C. Cook
- 2 Palisades (closed)
- 3 Fermi
- 4 Davis-Besse
- 5 Constellation LaSalle

**Industry**

- 1 Hemlock Semiconductor
- 2 Marathon Refinery
- 3 Midland chemical complex
- 4 Guardian Glass
- 5 Cleveland Cliffs Rouge Steel
- 6 Cleveland-Cliffs Toledo DR
- 7 Nutrien NH3
- 8 Sarnia petrochemical complex
- 9 Gary Works Steel
- 10 Holcim Cement
- 11 St Marys Cement
- 12 St Marys Cement

**H2 production**

- 1 Air Products
- 2 Air Products
- 3 Praxair
- 4 Albion College
- 5 Detroit Arsenal
- 6 Air Products Sarnia
- 7 Praxair Sarnia

Figure 8. Potential deployment opportunities in a hydrogen ecosystem (the gold number 1 is Ludington pumped storage). Small black ellipses highlight clusters of hydrogen facilities in Michigan, the larger black ellipse is a potential regional cluster, the maroon ellipses highlight transportation corridors.

Figure 9 is a zoomed-in view of southeast Michigan from the map presented in Figure 8 (use the legend from that map). Several numbers are hidden where facilities are close together enough for the numbers to stack up on top of one another – these are called out in the caption. The proximity of some of these facilities might enable hydrogen infrastructure linkages.

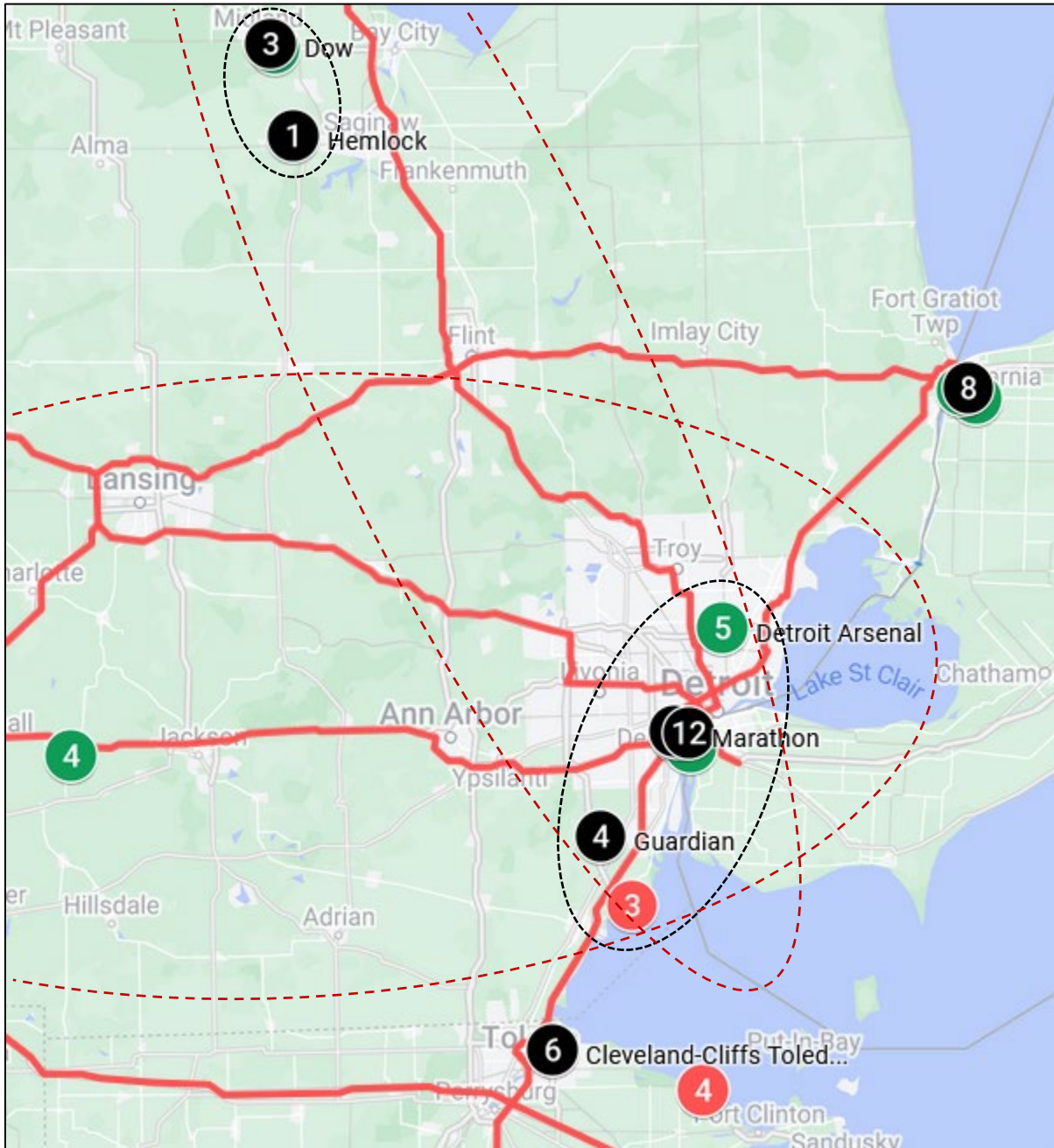


Figure 9. Potential hydrogen ecosystem participants, in southeast Michigan (use the legend from Figure 8). Hidden green producer numbers are #1 and #3 under black #12 in Detroit, #2 under black #3 Midland chemical complex, and #6 and #7 under black #8 Sarnia. Hidden black industry numbers are #2 and #5 under black #12. The black ellipses highlight clusters of hydrogen production and use facilities, the maroon ellipses highlight transportation corridors.

A final map, produced from the U.S. EPA’s EJScreen mapping tool and presented as Exhibit 27, illustrates the distribution of diesel particulate matter (as national percentiles) in southeast Michigan. This map highlights the potential public health benefits of transitioning MDVs, HDVs, and trains away from diesel fuel and to electricity or hydrogen for routes in southeast Michigan.

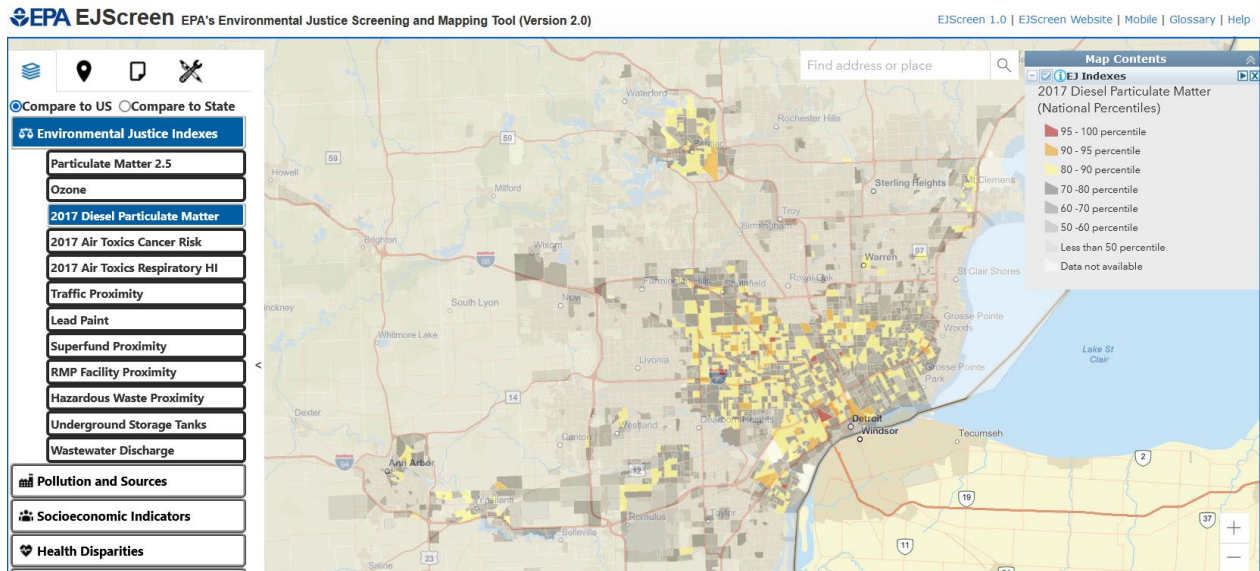


Exhibit 27. U.S. EPA EJScreen map of 2017 diesel particulate matter in southeast Michigan (produced using the EJScreen online mapping tool at <https://ejscreen.epa.gov/mapper/>).

## 7. Recommendations

We have collected and presented a large amount of information in the process of preparing for the workshop and compiling this report. This information has been distilled into a series of tables (included below) on hydrogen production and use facilities. The tables also contain recommendations based on the information we have collected and analyzed, though this information is admittedly incomplete. For example, more detailed analysis of demand is necessary in order to make decisions on which end uses and production methods should be pursued in Michigan and across the wider region. It is clear that current demand is dominated by refineries and chemical facilities, that SMR is the dominant production technology, and that producers are usually situated in close proximity to their customers.

Several recommendations are more general and pertain to all pathways. Safety is one of these, and should be included as a necessary component of any facility or strategy employing hydrogen. Equity is another integral component of any way forward – reducing emissions, providing equitable access, and protecting public health should all be part of any decarbonization strategy. Generally, reducing GHG emissions from fossil fuel combustion will also provide co-benefits by reducing other air pollutant emissions and adverse health effects in neighboring communities.

Discussion during the workshop reinforced ideas that had become apparent during our research, some of which are visible in the maps presented above. We have a major opportunity to move medium- and heavy-duty vehicles to low-carbon hydrogen in the region. The abundance of high-volume interstate highways in southern Michigan that connect us to Illinois, Indiana, Ohio, and Ontario, as well as the difficulty in electrifying this end use both argue for this path. This path could also coordinate with and connect to southern Ontario's potential hydrogen hub. There are other strategies where the case for hydrogen is less compelling. Use in buildings is one of these, as electrification of HVAC and appliances in residential and commercial buildings provides greater GHG emissions reduction. It also seems clear that using low-carbon electricity to directly offset higher-carbon sources of grid electricity reduces emissions more than using that low-carbon electricity to produce hydrogen for later combustion.

These recommendations have been developed by the authors based on our research and discussion and feedback at the workshop and do not imply any commitments on the part of workshop participants or their organizations. We intend these recommendations to be a starting point for further discussion and analysis on the roles where hydrogen can most beneficially be deployed to advance decarbonization.

Table 2. *Transportation (LDV) summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
FCEV	Commercialized, models available	BEV	BEVs with renewable/low-carbon electricity are more energy efficient and can achieve greater decarbonization than FCEVs. FCEVs have a higher total cost of ownership	Accounts for 58% of transportation energy sector emissions Ford, GM, Stellantis, and Toyota have all developed hydrogen prototypes and/or commercial FC light duty vehicles	DOE Alternative Fuel Corridor Program for fueling infrastructure; The Inflation Reduction Act will revive and expand the alternative fuel station credit, which will foster more hydrogen fueling stations. <sup>62</sup>
<p><b>Recommendation:</b> Michigan should accelerate transition to LD BEVs rather than develop hydrogen fueling infrastructure for LDVs</p>					

<sup>62</sup> Fuel Cell & Hydrogen Energy Association, August 5, 2022. *How the Inflation Reduction Act of 2022 Will Advance a U.S. Hydrogen Economy*. <https://www.fccea.org/transitions/2022/8/5/how-the-inflation-reduction-act-of-2022-will-advance-a-us-hydrogen-economy>



Table 3. *Transportation (MDV & HDV) summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
FCEV	Early commercialization stage, examples listed in Sec. 2.1.2	BEV	FCEV and BEV will decarbonize MDV & HDVs depending on electricity and hydrogen source. BEVs have range limitations in transporting heavy loads	Accounts for 20-25% of transportation energy sector GHG emissions Two FC buses deployed in Flint, 2012.	DOE Alternative Fuel Corridor Program.  The Inflation Reduction Act will revive and expand the alternative fuel station credit which will foster more hydrogen fueling stations. <sup>63</sup>
<p><b>Recommendation:</b> OEMs should pursue the development of Fuel Cell MDV and HDVs, and investments should be made in expanding low-carbon hydrogen production and fueling infrastructure.</p>					

<sup>63</sup> Fuel Cell & Hydrogen Energy Association, August 5, 2022. *How the Inflation Reduction Act of 2022 Will Advance a U.S. Hydrogen Economy*. <https://www.fcchea.org/transitions/2022/8/5/how-the-inflation-reduction-act-of-2022-will-advance-a-us-hydrogen-economy>

Table 4. *Transportation (Ships - Ferries) summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
Fuel Cell	Early commercialization stage. Norway is the leading example (60 of 200 ferries electric or hybrid), FC ferry scheduled for 2024.	Battery Electric	BE ferries will outperform FC ferries in carbon reduction due to the low efficiency (electricity-to-hydrogen-to-electricity) for FC ferries	Michigan has a large fleet of ferries operating on the Great Lakes	Electric and Low Emitting Ferry Pilot Program <sup>64</sup>
<p><b>Recommendation:</b> Deploy FC ferries on long routes and BE ferries on shorter routes</p>					

<sup>64</sup> Federal Transit Administration, *Electric or Low-Emitting Ferry Pilot Program - IIJA§71102*. <https://www.transit.dot.gov/grants/grant-programs/electric-or-low-emitting-ferry-pilot-program-iija-ss-71102>

Table 5. *Transportation (Freighters) summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
LH <sub>2</sub>	In development stage <sup>65</sup>	Synthetic and bio-based fuels	Hydrogen powered systems can replace diesel combustion engines and diesel generators provide propulsion and electricity and many burn heavy bunker fuel, which is carbon intensive	The Great Lakes-St. Lawrence waterway is the longest inland deep-draft navigation system in the world, connecting more than 110 commercial ports in the U.S. and Canada. Maritime transport accounts for 3% of CO <sub>2</sub> emissions annually on a global scale.	
<p><b>Recommendation:</b> The industry should investigate using current hydrogen vessels being demonstrated in Europe for applications in the Great Lakes.</p>					

<sup>65</sup> Offshore Energy, July 20, 2021. *Air Liquide steps up its support to world 1<sup>st</sup> hydrogen ship*. <https://www.offshore-energy.biz/air-liquide-steps-up-its-support-to-world-1st-hydrogen-ship/>.

Table 6. *Transportation (Rail) summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
Fuel cells	Hydrogen trains are being demonstrated in Germany and China. Both diesel passenger and freight trains will also need to be replaced beginning with routes where hydrogen fuel is available at terminal stations	Electric trains (require overhead catenary infrastructure)	As diesel trains are very efficient, the magnitude of the carbon reduction with hydrogen or electricity will be highly dependent on the electricity fuel mix.  Electric trains would be expected to be more energy efficient than hydrogen trains and less carbon intensive if using the same fuel mix used to generate hydrogen.	MDOT reports that Michigan’s rail system has ≈3,600 miles of rail corridors, operated by 29 railroad companies and carries about 17% of all the state’s freight tonnage and 21% of the commodities by value. The rail system also supports three intercity passenger-rail routes.	
<p><b>Recommendation:</b> Amtrak and freight rail companies should explore electric and hydrogen trains for Chicago to Detroit/Port Huron routes.</p>					

Table 7. *Transportation (Aircraft) summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
<p>Gas turbine engines combusting hydrogen;</p> <p>Hydrogen can also be used for producing low-carbon aviation fuels.</p>	<p>Development stage, Airbus demo by 2035.</p>	<p>Biofuels (algal), synthetic fuels, electric vertical takeoff and landing (VTOL) aircraft to replace smaller airplanes.</p> <p>Cost is currently a major barrier for producing low-carbon aviation fuels.</p>	<p>Life cycle comparative assessments are needed to differentiate but electric VTOL is limited in passenger capacity and range due to battery weight.</p>	<p>Would expect deployment at DTW and then larger regional airports</p>	
<p><b>Recommendation:</b> No deployment recommended currently. Future hydrogen fueling could be planned for major Michigan airports if this is the direction the industry pursues. Based on plans announced by Airbus this would not be expected before 2035. Sustainable aviation fuels based on hydrogen are also a possibility but high cost is a challenge.</p>					

Table 8. **Chemicals (Refineries)** summary and recommendations

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
SMR	H <sub>2</sub> production projects with CCUS are at the pilot scale around the world (one in TX), and H <sub>2</sub> from electrolysis projects are being considered in Germany and the Netherlands	Low-carbon hydrogen production is necessary to decarbonize		Marathon refinery in Detroit has the largest hydrogen demand.  Midland complex.  Industrial clustering should consider Sarnia Lambton petrochemical and refining complex.	The Inflation Reduction Act authorizes DOE to provide more than \$5.8 billion in grants, rebates, direct loans and cooperative agreements on a competitive basis for up to 50% of project costs to install advanced industrial technology designed to accelerate the reduction of greenhouse gas emissions to net zero (these would be available through September 30, 2026). <sup>66</sup>  DOE Industrial Efficiency and Decarbonization grants <sup>67</sup>
<p><b>Recommendation:</b> Refineries should transition to low-carbon hydrogen; refinery output will decline with the transition to electrified transportation; Refining for chemical feedstocks will become the primary products.</p>					

<sup>66</sup> King & Spalding, August 11, 2022. *Hydrogen-Related Provisions of the Inflation Reduction Act of 2022*. <https://www.jdsupra.com/legalnews/hydrogen-related-provisions-of-the-2283064/>.

<sup>67</sup> U.S. DOE, Office of Energy Efficiency & Renewable Energy, July 1, 2022. *U.S. Department of Energy will fund applied research and development to accelerate decarbonization of American Industry*. <https://www.energy.gov/eere/amo/articles/us-department-energy-will-fund-applied-research-and-development-accelerate>

Table 9. *Chemicals (Ammonia) summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
NH <sub>3</sub> is produced from nitrogen and hydrogen using the Haber-Bosch process.	Solar-based electrolysis and ammonia production has been demonstrated	Several ammonia production facilities are demonstrating CCUS technology.	Use low-carbon hydrogen to replace SMR hydrogen. Major GHG reductions of more than 90% are possible by 2030 when using renewable power in electrolysis	AmmPower research center in Southeast MI exploring green ammonia production  Nutrien NH <sub>3</sub> plant (Lima, OH)	The Inflation Reduction Act authorizes DOE to provide more than \$5.8 billion in grants, rebates, direct loans and cooperative agreements on a competitive basis for up to 50% of project costs to install advanced industrial technology designed to accelerate the reduction of greenhouse gas emissions to net zero (these would be available through September 30, 2026). <sup>68</sup>  DOE Industrial Efficiency and Decarbonization grants <sup>69</sup>
<p><b>Recommendation:</b> With a large agricultural economy, Michigan should explore low-carbon ammonia production and partnering with other regional assets (such as Nutrien in Lima, OH).</p>					

<sup>68</sup> King & Spalding, August 11, 2022. *Hydrogen-Related Provisions of the Inflation Reduction Act of 2022*. <https://www.jdsupra.com/legalnews/hydrogen-related-provisions-of-the-2283064/>.

<sup>69</sup> U.S. DOE, Office of Energy Efficiency & Renewable Energy, July 1, 2022. *U.S. Department of Energy will fund applied research and development to accelerate decarbonization of American Industry*. <https://www.energy.gov/eere/amo/articles/us-department-energy-will-fund-applied-research-and-development-accelerate>

Table 10. *Steelmaking* summary and recommendations

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
DRI using hydrogen with BOF and EAF	Pilot scale hydrogen-based steelmaking using DRI in Sweden. Aggressive RD&D and pilot and demonstration is needed for transformative technologies such as H <sub>2</sub> -based steel production, electrolysis of iron ore, and CCUS to realize near zero GHG emissions goal by 2050. (Nimbalkar n.d.)	Producing iron by electrolysis of iron ore, (slide 14 in (Nimbalkar n.d.)) CCUS also possible	Green hydrogen in blast furnaces can reduce CO <sub>2</sub> emissions by up to 20% DRI-EAF with green hydrogen enables nearly carbon-neutral steel production; note iron and steel account for 2.1% of U.S. emissions. (Nimbalkar n.d.)	Cleveland Cliffs Dearborn Works plant should transition to hydrogen based direct reduction processes.	The Inflation Reduction Act authorizes DOE to provide more than \$5.8 billion in grants, rebates, direct loans and cooperative agreements on a competitive basis for up to 50% of project costs to install advanced industrial technology designed to accelerate the reduction of greenhouse gas emissions to net zero (these would be available through September 30, 2026). <sup>70</sup>  DOE Industrial Efficiency and Decarbonization grants <sup>71</sup>
<b>Recommendation:</b> Cleveland Cliffs Dearborn facility already uses some hydrogen; explore DRI with low-carbon hydrogen.					

<sup>70</sup> King & Spalding, August 11, 2022. *Hydrogen-Related Provisions of the Inflation Reduction Act of 2022*. <https://www.jdsupra.com/legalnews/hydrogen-related-provisions-of-the-2283064/>.

<sup>71</sup> U.S. DOE, Office of Energy Efficiency & Renewable Energy, July 1, 2022. *U.S. Department of Energy will fund applied research and development to accelerate decarbonization of American Industry*. <https://www.energy.gov/eere/amo/articles/us-department-energy-will-fund-applied-research-and-development-accelerate>



Table 11. *Cement production summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
Using hydrogen as a fuel	No known cement production using hydrogen as a fuel	Using fossil-based fuels with CCS	Cement production generates both process CO <sub>2</sub> and fossil fuel related emissions from the calcination process. Use of hydrogen fuel does not address process CO <sub>2</sub> emissions.	Holcim (Alpena), St. Marys (Detroit & Charlevoix)	<p>The Inflation Reduction Act authorizes DOE to provide more than \$5.8 billion in grants, rebates, direct loans and cooperative agreements on a competitive basis for up to 50% of project costs to install advanced industrial technology designed to accelerate the reduction of greenhouse gas emissions to net zero (these would be available through September 30, 2026).<sup>72</sup></p> <p>DOE Industrial Efficiency and Decarbonization grants<sup>73</sup></p>
<p><b>Recommendation:</b> Michigan’s three cement production facilities should transition to clean energy sources including low-carbon hydrogen</p>					

<sup>72</sup> King & Spalding, August 11, 2022. *Hydrogen-Related Provisions of the Inflation Reduction Act of 2022*. <https://www.jdsupra.com/legalnews/hydrogen-related-provisions-of-the-2283064/>.

<sup>73</sup> U.S. DOE, Office of Energy Efficiency & Renewable Energy, July 1, 2022. *U.S. Department of Energy will fund applied research and development to accelerate decarbonization of American Industry*. <https://www.energy.gov/eere/amo/articles/us-department-energy-will-fund-applied-research-and-development-accelerate>.

Table 12. *Glass making summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
Hydrogen fuel used in melting furnace	Technology demonstration: HyNet fuel switching, Pilkington (St Helens, UK)	NG as a fuel with CCUS, replacement of NG with electricity, waste heat recovery	Carbon reduction with depend on source of hydrogen. Process energy efficiency unclear from this Glass International statement: “However, in glass manufacturing it will only be used as a very inefficient (45% of energy at the most ends up in the glass) heat source, representing a huge waste of energy” <sup>74</sup>	Guardian Glass (Carleton, MI), Owens-Illinois (Toledo, OH)	The Inflation Reduction Act authorizes DOE to provide more than \$5.8 billion in grants, rebates, direct loans and cooperative agreements on a competitive basis for up to 50% of project costs to install advanced industrial technology designed to accelerate the reduction of greenhouse gas emissions to net zero (these would be available through September 30, 2026). <sup>75</sup>  DOE Industrial Efficiency and Decarbonization grants <sup>76</sup>
<p><b>Recommendation:</b> Guardian Glass in Carleton, MI should transition to low-carbon hydrogen as a melting furnace fuel when it is technically feasible (and depending on the outcome of the HyNet demonstration).</p>					

<sup>74</sup> Glass International, August 10, 2022. *Will hydrogen be the new energy carrier for glassmaking?* <https://www.glass-international.com/features/will-hydrogen-be-the-new-energy-carrier-for-glassmaking#:~:text=Be%20aware%3A%20hydrogen%20is%20an,a%20huge%20waste%20of%20energy>.

<sup>75</sup> King & Spalding, August 11, 2022. *Hydrogen-Related Provisions of the Inflation Reduction Act of 2022*. <https://www.jdsupra.com/legalnews/hydrogen-related-provisions-of-the-2283064/>.

<sup>76</sup> U.S. DOE, Office of Energy Efficiency & Renewable Energy, July 1, 2022. *U.S. Department of Energy will fund applied research and development to accelerate decarbonization of American Industry*. <https://www.energy.gov/eere/amo/articles/us-department-energy-will-fund-applied-research-and-development-accelerate>.

Table 13. *Semiconductor manufacturing summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
Electricity, natural gas, H <sub>2</sub> used in semiconductor manufacturing. Low-carbon hydrogen can be used as chemical feedstock and fuel	Infineon’s Villach site in Austria is partnering with Linde to produce hydrogen; demonstration plant expected to open this year		Decarbonization will focus on renewable electricity, low-carbon hydrogen and then finding a substitute for natural gas. Note: Semiconductor costs dominated by materials other than H <sub>2</sub> . H <sub>2</sub> -related emissions incorporated in “Bulk gas” which account for around 5% of the total carbon emissions.	Hemlock Semiconductor (Hemlock, MI) SK Siltron (Bay County, MI). Infineon Technology (Livonia, MI) KLA R&D (Ann Arbor, MI) Semiconductor industry contributes \$4.6 billion in total gross regional product for MI	The Inflation Reduction Act authorizes DOE to provide more than \$5.8 billion in grants, rebates, direct loans and cooperative agreements on a competitive basis for up to 50% of project costs to install advanced industrial technology designed to accelerate the reduction of greenhouse gas emissions to net zero (these would be available through September 30, 2026). <sup>77</sup>
<p><b>Recommendation:</b> Explore using low-carbon hydrogen as a feedstock and fuel. Do not recommend using hydrogen as a source for electricity generation.</p>					

<sup>77</sup> King & Spalding, August 11, 2022. *Hydrogen-Related Provisions of the Inflation Reduction Act of 2022*. <https://www.jdsupra.com/legalnews/hydrogen-related-provisions-of-the-2283064/>.

Table 14. **Buildings** summary and recommendations

	Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
HVAC	Hydrogen combustion (blending with NG or 100% H <sub>2</sub> )	Fuel cells already used in buildings, HVAC using blended hydrogen and 100% H <sub>2</sub> have been demonstrated	Electric heat pumps (ground and air source), RNG	Electrification of HVAC with heat pumps is a more effective decarbonization strategy than using fuel cells or hydrogen combustion systems		The Inflation Reduction Act contains rebates for low-and moderate-income households to electrify HVAC and appliances, and extends existing tax credits <sup>78</sup>
Appliances	Hydrogen combustion (blending with NG or 100% H <sub>2</sub> )	NG appliances using blended hydrogen and 100% H <sub>2</sub> have been demonstrated	RNG or electric appliances	Electrification of appliances is a more effective decarbonization strategy than hydrogen combustion		
Other	FC for backup power	Commercialized <sup>79</sup>	Batteries	Batteries have a higher round trip efficiency compared to a FC system		
<p><b>Recommendation:</b> Hydrogen is not recommended for HVAC or appliances. Hydrogen could play a role in back up power systems to replace NG generators. Propane users should be included in decarbonization and alternative fuel discussions.</p>						

<sup>78</sup> BPA Connections, August 8, 2022. *How the Inflation Reduction Act (IRA) Affects Our Industry*. <https://bpa.connectedcommunity.org/blogs/macie-melendez1/2022/08/12/how-the-inflation-reduction-act-ira-affects-our-in>.

<sup>79</sup> e.g., GenSure green hydrogen fuel cells – <https://www.plugpower.com/fuel-cell-power/gensure-backup-power/>

Table 15. **Power generation** summary and recommendations

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
Use stored hydrogen in a FC or combust in a turbine to produce electricity	Hydrogen production from renewables with storage and use for power generation has been demonstrated. <sup>80</sup>	Other storage technologies including batteries, pumped hydropower, compressed air storage,	Round-trip efficiencies of other technologies are generally much higher.	Ludington pumped storage. Kuester (Marquette), up to 25% H <sub>2</sub> , 7 reciprocating engines, 126 MW capacity DTE Blue Water Energy Center (St. Clair) (operational 2024), 2% H <sub>2</sub>	
<p><b>Recommendation:</b> Hydrogen is not recommended as a combustion fuel or as a major player in energy storage given round trip inefficiencies.</p>					

<sup>80</sup> Power, June 4, 2020. *World's First Integrated Hydrogen Power-to-Power Demonstration Launched*. <https://www.powermag.com/worlds-first-integrated-hydrogen-power-to-power-demonstration-launched/>

Table 16. *Delivery (Blending with NG) summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
Blend up to 20% with NG in pipelines	Has been demonstrated	RNG could be used as a decarbonization strategy but supply is limited (estimated 10% of NG demand) and leakage from NG infrastructure is still problematic	Blending has small GHG reduction benefits (blending w/NG, $\approx$ 6.6% GHG reduction at 20% H <sub>2</sub> vol).	Michigan has an extensive NG transmission and distribution network	
<p><b>Recommendation:</b> Not recommended (see building end-use-applications) as other pathways achieve greater carbon reduction.</p>					

Table 17. *Delivery (new 100% H<sub>2</sub> pipelines) summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
Delivery of 100% hydrogen	1600 miles of hydrogen pipeline in the U.S.	Truck, rail or transport as ammonia, toluene, or other chemicals	The 100% H <sub>2</sub> option has greater GHG reduction potential than blending, is easier to accomplish in new neighborhoods but is harder in those that are already built. All forms of transport result in GHG emissions, but pipelines have the lowest GHG since pipelines need to move only the H <sub>2</sub> , and there is no need to also move a heavy vehicle (e.g., truck, train, or ship).	5.5 miles of hydrogen pipeline in MI. Optimize location of production and end use to minimize pipeline transport distance. Use appropriate pipe materials.	
<p><b>Recommendation:</b> Explore expanding pipeline networks in industrial clusters and delivery to large fueling stations close to production facilities.</p>					

Table 18. **Delivery (ship)** summary and recommendations

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
Compressed or liquified	Demonstrations of LH <sub>2</sub> shipping Australia-Japan	Pipeline or truck	Expected to be less carbon intensive than delivery by land vehicles	Great Lakes waterways give access to port cities along the coasts and St. Lawrence	
<p><b>Recommendation:</b> Explore potential for hydrogen transport on the Great Lakes to demand centers in the region.</p>					



Table 19. Storage (salt caverns) summary and recommendations

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
<p>Large volume storage capacity; Depending on their depth, salt caverns may be operated at pressures up to 200 bar, allowing for large-volume hydrogen storage (from 9 to 6,000 tons)</p>	<p>Globally, four salt caverns are storing H<sub>2</sub> as reserves for refineries. World’s largest storage facility (1,000 MW) planned in Utah, stores H<sub>2</sub> in underground salt caverns.</p>	<p>High pressure tanks for storage as a gas; storage of hydrogen as a liquid requires cryogenic temperatures; and for smaller volumes can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption) Conversion to and from ammonia, toluene, etc.</p>	<p>Large volume storage can contribute to decarbonization by storing renewable electricity which is variable. Round trip efficiency must be considered vs. alternatives.</p>	<p>Michigan has about 4000 million cubic feet of natural gas underground storage salt caverns capacity</p>	<p>The Inflation Reduction Act makes “energy storage technologies” eligible for the Investment Tax Credit with a definition specifically including hydrogen.<sup>81</sup></p> <p>DOE Energy Storage Demonstration Pilot Grant Program<sup>82</sup></p> <p>DOE Long-Duration Energy Storage Demonstration Initiative and Joint Program<sup>83</sup></p>
<p><b>Recommendation:</b> Michigan’s salt caverns should be studied further as potential large volume hydrogen storage; proximity to industrial application sites is attractive. Investigate contamination/gas quality concerns.</p>					

<sup>81</sup> King & Spalding, August 11, 2022. *Hydrogen-Related Provisions of the Inflation Reduction Act of 2022*. <https://www.jdsupra.com/legalnews/hydrogen-related-provisions-of-the-2283064/>.

<sup>82</sup> U.S. DOE. *Energy Storage Demonstration and Pilot Grant Program*. <https://www.energy.gov/bil/energy-storage-demonstration-and-pilot-grant-program>

<sup>83</sup> U.S. DOE. *Long-Duration Energy Storage Demonstration Initiative and Joint Program*. <https://www.energy.gov/long-duration-energy-storage-demonstration-initiative-and-joint-program>

Table 20. *Storage (NG reservoirs) summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
Storage in depleted NG reservoirs		Salt caverns			
<p><b>Recommendation:</b> Workshop participants rejected the use of NG reservoirs (other than salt caverns) for storage due to contamination and containment concerns, which should be verified for the MI case (geology).</p>					

Table 21. **Production** summary and recommendations

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
Details in Tables 23-25					Inflation Reduction Act creates a new Clean Hydrogen Production Tax Credit providing up to \$3 per kg of hydrogen produced at a given facility, based on the carbon intensity of production, or offers a similarly scaled investment tax credit (ITC) up to 30% for new facilities. <sup>84</sup>
<b>Recommendation:</b> Site near future industrial clusters and fueling hubs including demand centers in the region (e.g., Marathon Refinery, Sarnia-Lambton Petrochemical and Refining Complex)					

<sup>84</sup> Fuel Cell & Hydrogen Energy Association, August 5, 2022. *How the Inflation Reduction Act of 2022 Will Advance a U.S. Hydrogen Economy*. <https://www.fchea.org/transitions/2022/8/5/how-the-inflation-reduction-act-of-2022-will-advance-a-us-hydrogen-economy>

Table 22. *Production (renewables) summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
Solar, Wind, Hydropower, Biomass	Nuclear energy is another low-carbon electricity source.	Nuclear	Carbon emissions from renewable pathways were estimated to range in 2030 from 0.3 to 1.0 kg GHG/kg H <sub>2</sub> compared to 11 kg GHG/kg H <sub>2</sub> from NG with SMR (Hydrogen Council 2021a)	Solar, Wind, Hydropower, Biomass assets throughout Michigan	Inflation Reduction Act creates a new Clean Hydrogen Production Tax Credit provides up to \$3 per kg of hydrogen produced <sup>85</sup>
<p><b>Recommendation:</b> Renewable electricity in Michigan can be used for demonstration of hydrogen production but greater decarbonization can currently be achieved by displacing fossil-based electricity. Excess electricity produced by wind turbines offshore in the Great Lakes should be evaluated for technical and economic feasibility as a hydrogen production route.</p>					

<sup>85</sup> Fuel Cell & Hydrogen Energy Association, August 5, 2022. *How the Inflation Reduction Act of 2022 Will Advance a U.S. Hydrogen Economy.* <https://www.fchea.org/transitions/2022/8/5/how-the-inflation-reduction-act-of-2022-will-advance-a-us-hydrogen-economy>

Table 23. **Production (nuclear) summary and recommendations**

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
<p>Cold electrolysis of water, using off-peak capacity (needs 50-55 kWh/kg).</p> <p>Low-temperature steam electrolysis, using heat and electricity from nuclear reactors.</p> <p>High-temperature steam electrolysis, using heat and electricity from nuclear reactors.</p> <p>High-temperature thermochemical production using heat from nuclear reactors.</p>	<p>Hydrogen production from nuclear power has been demonstrated and new projects are being planned.<sup>86</sup></p>	<p>Nuclear has an advantage over variable renewable sources by enabling higher utilization rates of capital-intensive electrolyzers.</p>	<p>Carbon emissions from renewable pathways were estimated to range in 2030 from 0.3 to 1.0 kg GHG/kg H<sub>2</sub> compared to 11 kg GHG/kg H<sub>2</sub> from NG with SMR (Hydrogen Council 2021a)</p>	<p>Michigan has two operating nuclear power plants (Cook (2.2 GWe) in Bridgman and Fermi (1.2 GWe) in Monroe). Davis-Besse project (Oak Harbor, OH). Constellation Energy and the University of Toledo presented proposals at the Workshop on using nuclear power for hydrogen production</p>	<p>Inflation Reduction Act will create a new Clean Hydrogen Production Tax Credit provides up to \$3.00 per kilogram of hydrogen produced<sup>87</sup></p>
<p><b>Recommendation:</b> Nuclear energy in Michigan can be used for demonstration of hydrogen production but greater decarbonization can currently be achieved by displacing fossil-based electricity. Small modular reactors could be utilized as new generation sources that could be distributed near hydrogen demand centers.</p>					

<sup>86</sup> World Nuclear Association, November 2021. *Hydrogen Production and Uses*. <https://www.world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses.aspx>

<sup>87</sup> Fuel Cell & Hydrogen Energy Association, August 5, 2022. *How the Inflation Reduction Act of 2022 Will Advance a U.S. Hydrogen Economy*. <https://www.fchea.org/transitions/2022/8/5/how-the-inflation-reduction-act-of-2022-will-advance-a-us-hydrogen-economy>

Table 24. *Production (fossil w/CCUS) summary and recommendations*

Hydrogen Technology	Tech readiness	Alternatives	GHG reduction potential and other criteria	Scale: MI Assets, Regional linkages	Govt Funding
A wide range of pathways for hydrogen production from fossil fuels with CCUS	Renewable and nuclear energy pathways	Greater decarbonization can be achieved through renewable and nuclear pathways.	Globally about 1% of hydrogen production from fossil fuels includes CCUS (Global CCS Institute 2021)	Michigan utilities are phasing out fossil-based power plants.	Inflation Reduction Act will create a new Clean Hydrogen Production Tax Credit depending on the carbon intensity of the production process. See table in production section of report <sup>88</sup>
<p><b>Recommendation:</b> Renewable and nuclear production pathways are more favorable long term decarbonization strategies. Michigan has capacity to store captured carbon in NG reservoirs.</p>					

<sup>88</sup> Fuel Cell & Hydrogen Energy Association, August 5, 2022. *How the Inflation Reduction Act of 2022 Will Advance a U.S. Hydrogen Economy.* <https://www.fchea.org/transitions/2022/8/5/how-the-inflation-reduction-act-of-2022-will-advance-a-us-hydrogen-economy>

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# Appendices

A – Workshop participants

B – Workshop agenda

C – Supplemental data & figures presented at the Workshop

Appendix A – Workshop Participants

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Appendix B – Workshop agenda

# Hydrogen Roadmap for Michigan Workshop Agenda

May 20, 2022, 9am – 3pm with lunch

*Location:* University of Michigan Ann Arbor Campus  
Michigan League Ballroom (9am – 1pm) and Michigan Room (1-3pm)  
911 N University Ave, Ann Arbor, 48109

## *Workshop Goals:*

**Goal 1:** seek stakeholder input to identify and begin to **characterize potential** (tech readiness and scale, economics, competition, efficiency/carbon reduction, justice issues/opportunities) **for H2 production, delivery, storage and end-use across time and space** and connections to hubs and spokes in the Region

**Goal 2:** Discuss **options for DOE Regional Hub proposal(s)**, i.e., source for generation, marketplace, delivery routes, partnerships and **outline next steps** for developing proposal

## *Timeline:*

**9:00 am – 9:20 am:** WELCOME and INTRODUCTIONS

### **Part A: Morning Session– Hydrogen Roadmap**

**9:20 am – 9:35 am:** Roadmap Overview

**9:35 am – 11:15 am:** End-Use Applications

*9:35 am – 10:00 am:* Transportation

*10 am – 10:30 am:* Industry

-----**10:30 – 10:45: BREAK**-----

*10:45 am – 11:00 am:* Power Generation

*11:00 am – 11:15 am:* Heating and Buildings

**11:15 am – 11:30 am:** Production

**11:30 am – 11:45 am:** Delivery

**11:45 am – 12:00 pm:** Storage

-----**12:00 pm – 12:45pm: LUNCH**-----

### **Part B: Afternoon Session – DoE Clean Hydrogen Hub Opportunity**

**12:45 pm – 1:15 pm:** Midwest Initiatives

*University of Toledo,*

*Constellation Energy*

**1:15 pm – 2:00 pm** Identify Hydrogen Clusters

*1:15 pm – 1:45 pm:* End-Use Applications

*1:45 pm – 2:00 pm:* Production

**2:00 pm – 2:30 pm:** Regional Linkages (Including Delivery and Storage)

**2:30 pm – 2:50 pm:** Partnerships

**2:50 pm – 3:00 pm:** NEXT STEPS - Models for Grant Application

## **Event Sponsors:**



MICHIGAN ECONOMIC  
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Appendix C. Sample of publicly available hydrogen roadmaps and strategy reports, most recent at the top.

<b>Author</b>	<b>Title</b>	<b>Web link</b>	<b>Date</b>
US Committee on Science Space & Tech	H2 Success Hearing Charter	<a href="https://science.house.gov/imo/media/doc/hearing_charter-_h2success_-_2-17-22.pdf">https://science.house.gov/imo/media/doc/hearing_charter-_h2success_-_2-17-22.pdf</a>	2022
NITI Aayog & RMI	Harnessing Green Hydrogen	<a href="https://rmi.org/insight/harnessing-green-hydrogen/">https://rmi.org/insight/harnessing-green-hydrogen/</a>	2022
British Columbia Ministry of Energy, Mines, and Low Carbon Innovation	B.C. Hydrogen Strategy	<a href="https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/electricity/bc-hydro-review/bc_hydrogen_strategy_final.pdf">https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/electricity/bc-hydro-review/bc_hydrogen_strategy_final.pdf</a>	2021
Black & Veatch	Hydrogen 2021: A Roadmap to Net Zero	<a href="https://www.bv.com/resources/hydrogen-2021-roadmap-net-zero">https://www.bv.com/resources/hydrogen-2021-roadmap-net-zero</a>	2021
Canada MOE	Alberta Hydrogen Roadmap	<a href="https://open.alberta.ca/dataset/d7749512-25dc-43a5-86f1-e8b5aaec7db4/resource/538a7827-9d13-4b06-9d1d-d52b851c8a2a/download/energy-alberta-hydrogen-roadmap-2021.pdf">https://open.alberta.ca/dataset/d7749512-25dc-43a5-86f1-e8b5aaec7db4/resource/538a7827-9d13-4b06-9d1d-d52b851c8a2a/download/energy-alberta-hydrogen-roadmap-2021.pdf</a>	2021
Colorado Energy Office	Opportunities for low-carbon hydrogen in Colorado	<a href="https://www.ethree.com/wp-content/uploads/2021/12/Colorado-Low-Carbon-Hydrogen-Roadmap.pdf">https://www.ethree.com/wp-content/uploads/2021/12/Colorado-Low-Carbon-Hydrogen-Roadmap.pdf</a>	2021
IEA	Net Zero by 2050: A Roadmap for the Global Energy Sector	<a href="https://read.oecd.org/10.1787/c8328405-en?format=pdf">https://read.oecd.org/10.1787/c8328405-en?format=pdf</a>	2021
OK Hydrogen Production, Infrastructure, & Infrastructure Task Force	Report and Roadmap	<a href="https://oklahoma.gov/content/dam/ok/en/governor/documents/Hydrogen%20Production%20Task%20Force%20Report.pdf">https://oklahoma.gov/content/dam/ok/en/governor/documents/Hydrogen%20Production%20Task%20Force%20Report.pdf</a>	2021
UK Secretary of State	UK Hydrogen Strategy	<a href="https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf">https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf</a>	2021
EU Commission	A Hydrogen Strategy for Climate-Neutral Europe	<a href="https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf">https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf</a>	2020
FTI Consulting	India's Energy Transition Towards a Green Hydrogen Economy	<a href="https://www.fticonsulting.com/-/media/files/apac-files/insights/reports/2021/india-energy-transition-green-hydrogen-economy.pdf?rev=80b5bfa4d2c04d8f95c9778edebb3ab4&amp;hash=2C69F277FB259319C3ECAAC84B2E0A66">https://www.fticonsulting.com/-/media/files/apac-files/insights/reports/2021/india-energy-transition-green-hydrogen-economy.pdf?rev=80b5bfa4d2c04d8f95c9778edebb3ab4&amp;hash=2C69F277FB259319C3ECAAC84B2E0A66</a>	2020
Fuel Cell & Hydrogen Energy Association	Road Map to a US Hydrogen Economy	<a href="https://www.fchea.org/s/Road-Map-to-a-US-Hydrogen-Economy-Full-Report.pdf">https://www.fchea.org/s/Road-Map-to-a-US-Hydrogen-Economy-Full-Report.pdf</a>	2020
NRCAN	Hydrogen Strategy for Canada	<a href="https://www.nrcan.gc.ca/sites/nrcan/files/environment/hydrogen/NRCAN_Hydrogen%20Strategy%20for%20Canada%20Dec%2015%202200%20clean_low_accessible.pdf">https://www.nrcan.gc.ca/sites/nrcan/files/environment/hydrogen/NRCAN_Hydrogen%20Strategy%20for%20Canada%20Dec%2015%202200%20clean_low_accessible.pdf</a>	2020
US DOE	Hydrogen Strategy: Enabling A Low Carbon Economy	<a href="https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf">https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf</a>	2020
Columbia SIPA	Low-Carbon Heat Solutions for Heavy Industry	<a href="https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/LowCarbonHeat-CGEP_Report_100219-2020.pdf">https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/LowCarbonHeat-CGEP_Report_100219-2020.pdf</a>	2019

Fuel Cells & Hydrogen	Hydrogen Roadmap Europe	<a href="https://fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe%20Report.pdf">https://fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe Report.pdf</a>	2019
CSIRO Australia	National Hydrogen Roadmap	<a href="https://www.csiro.au/-/media/Do-Business/Files/Futures/18-00314_EN_NationalHydrogenRoadmap_WEB_180823.pdf">https://www.csiro.au/-/media/Do-Business/Files/Futures/18-00314_EN_NationalHydrogenRoadmap_WEB_180823.pdf</a>	2018
Calstart Inc	Hydrogen Roadmap for the U.S. Midwest Region	<a href="http://www.midwesthydrogen.org/site/assets/files/1252/hydrogen_roadmap_for_the_midwest_09152017.pdf">http://www.midwesthydrogen.org/site/assets/files/1252/hydrogen_roadmap_for_the_midwest_09152017.pdf</a>	2017
MN Dept. of Commerce	MN Renewable Hydrogen Roadmap	<a href="https://www.cleanenergyresourceteams.org/sites/default/files/publication_files/MNRenewableHydrogenRoadmap.pdf">https://www.cleanenergyresourceteams.org/sites/default/files/publication_files/MNRenewableHydrogenRoadmap.pdf</a>	2010
CTC	South Carolina Hydrogen Economy	<a href="https://energy.sc.gov/files/SCH2_ROADMAP.pdf">https://energy.sc.gov/files/SCH2_ROADMAP.pdf</a>	2005
US DOE	National Hydrogen Energy Roadmap	<a href="https://www.energy.gov/sites/default/files/2014/03/f8/national_h2_roadmap.pdf">https://www.energy.gov/sites/default/files/2014/03/f8/national_h2_roadmap.pdf</a>	2002

Appendix D – Supplemental data & figures presented at the Workshop

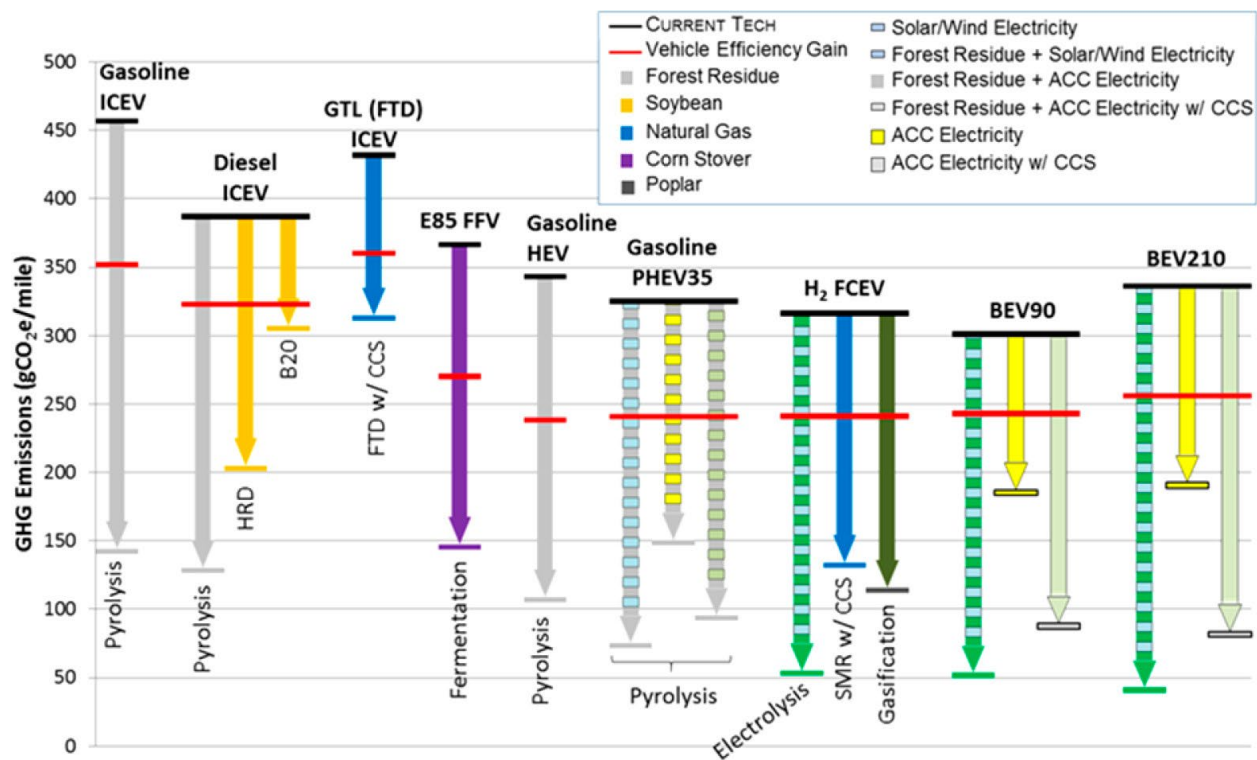


Exhibit D1, from Elgowainy, Amgad, Jeongwoo Han, Jacob Ward, Fred Joseck, David Gohlke† Alicia Lindauer, Todd Ramsden, Mary Bidy, Mark Alexander, Steven Barnhart, Ian Sutherland, Laura Verduzco, and Timothy J. Wallington. Current and Future United States Light-Duty Vehicle Pathways: Cradle-to-Grave Lifecycle Greenhouse Gas Emissions and Economic Assessment. *Environ. Sci. Technol.* 2018, 52(4): 2392–2399 <https://doi.org/10.1021/acs.est.7b060>

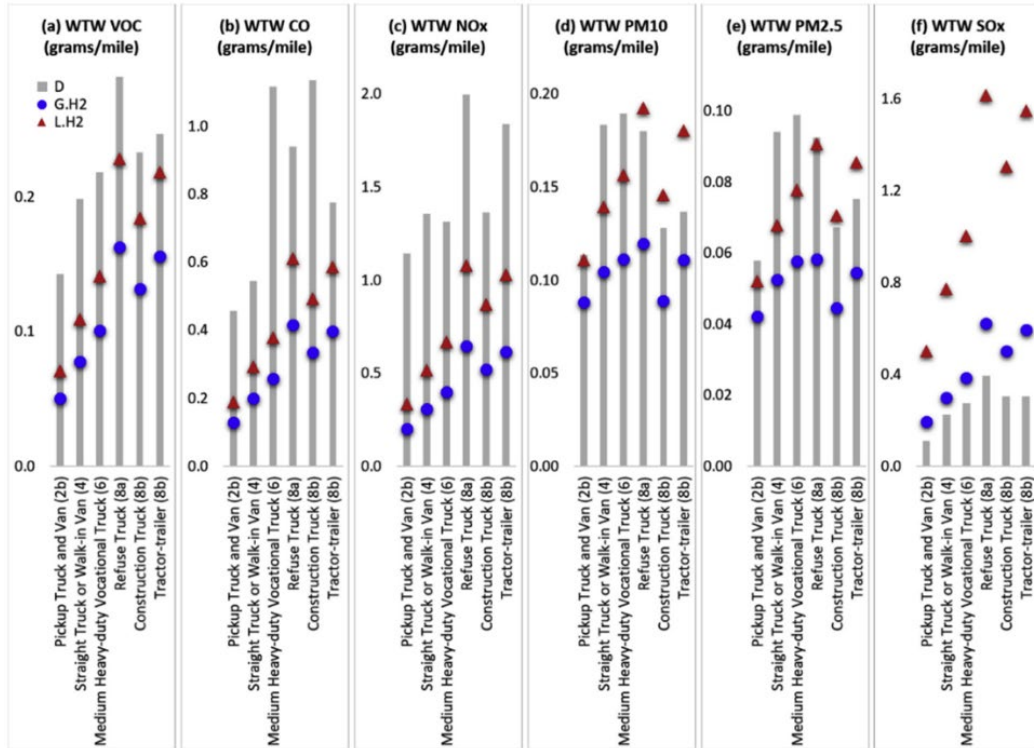


Exhibit D2, from Dong-Yeon Lee, Amgad Elgowainy, Andrew Kotz, Ram Vijayagopal, Jason Marcinkoski. Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks. 2018. *Journal of Power Sources* 393(217-229) <https://doi.org/10.1016/j.jpowsour.2018.05.012>.

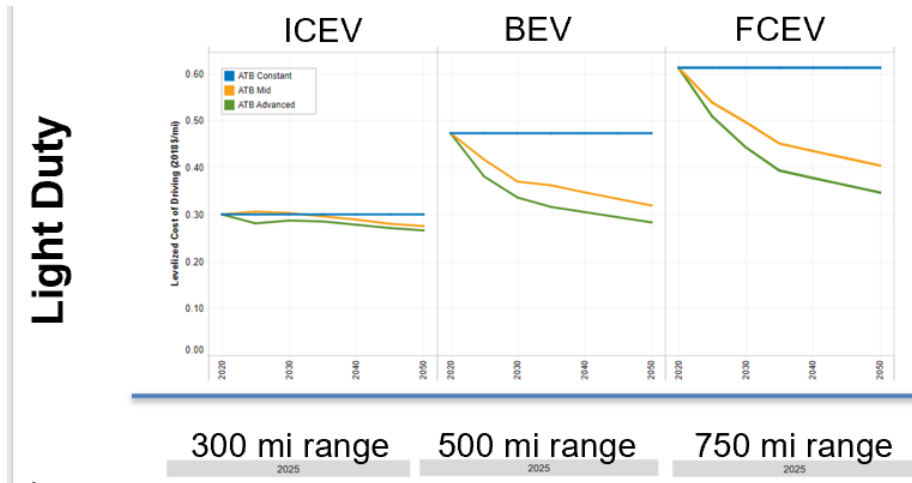


Exhibit D3, from Hunter, Chad, Michael Penev, Evan Reznicek, Jason Lustbader, Alicia Birky, and Chen Zhang. 2021. Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-71796. <https://www.nrel.gov/docs/fy21osti/71796.pdf>.

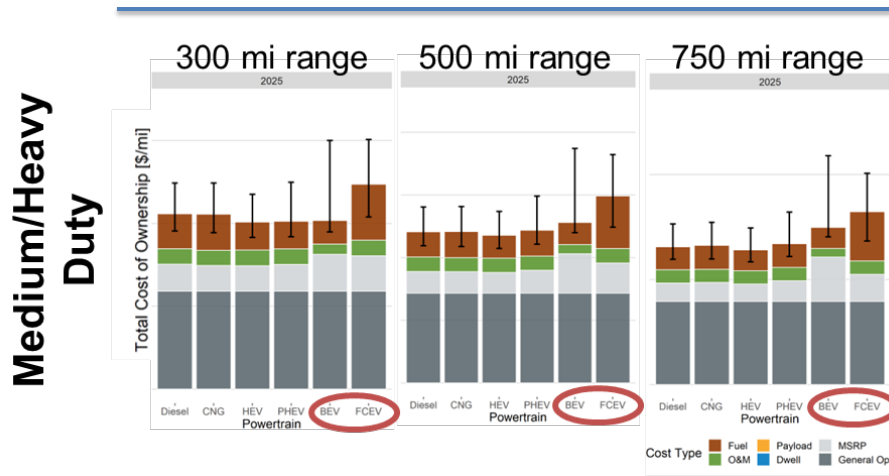
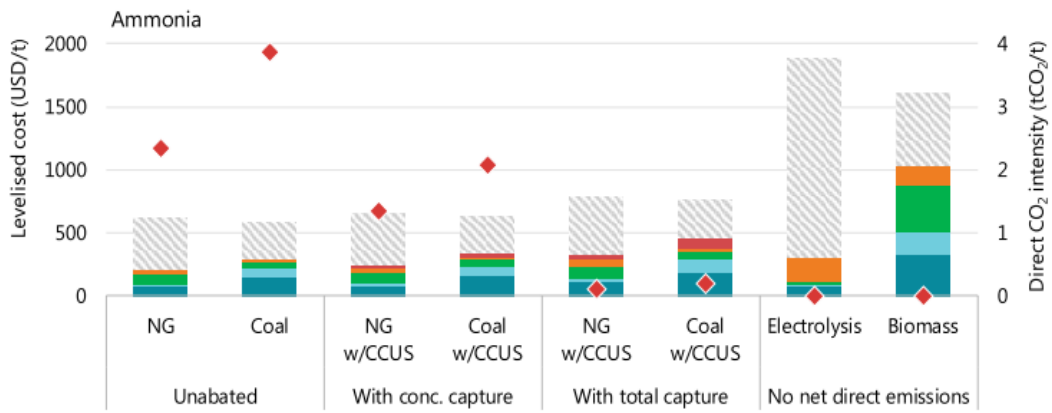


Exhibit D4, from Hunter, Chad, Michael Penev, Evan Reznicek, Jason Lustbader, Alicia Birky, and Chen Zhang. 2021. Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-71796. <https://www.nrel.gov/docs/fy21osti/71796.pdf>.

**Figure 41. Costs and CO<sub>2</sub> intensities for greenfield ammonia and methanol production in 2018**



*Exhibit D5, from IEA. (2019). The Future of Hydrogen: Seizing today's opportunities.*



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