Midwest Regional Hydrogen Economy White Paper

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AEG Chicago 21Q4 Hydrogen Hub Task Force

Milestone 1

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AEG CHICAGO

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Section 1: Introduction

Background

In recent years, decarbonization of the global economy has converged at multiple levels. Globally, the United Nations concluded the 26th Climate Change "Conference of the Parties" (COP26) during November, 2021. Nationally, the Biden administration also signed the $1 trillion bipartisan Infrastructure Investment and Jobs Act into law during November, 2021, with portions of the bill dedicated to funding a variety of decarbonization projects and initiatives. Illinois passed the Climate and Equitable Jobs Act (CEJA) during September, 2021, setting the state on a path toward 100% decarbonized energy by 2050. Finally, at the local level, Chicago is currently investing $173M into local climate and environmental projects and is in the midst of revising its existing Climate Action Plan. Building on this momentum, the Advanced Energy Group (AEG) Chicago chapter convened a 1-year regional clean hydrogen economy task force. This white paper is the first planned deliverable for this task force.

Purpose of White Paper

Decarbonization discussions often center around increasing renewable power generation (i.e. - solar and wind) capacity, as well as broad electrification ("electrify everything") of the economy. In recent years, there has been a growing awareness of the potential role that "clean hydrogen" can play in decarbonizing the economy. The most technically appropriate and economically viable approach to decarbonization will vary depending on the particular end-use application and geography. In many sectors of the economy, there is an argument to be made for hydrogen-based solutions.

The purpose of this Advanced Energy Group (AEG) white paper is to collect the key facts required to understand a Midwestern regional clean hydrogen economy. A coordinated local network of clean hydrogen production, delivery, and consumption has the potential to complement existing electrification efforts, meet regional decarbonization targets, and create jobs. By organizing this information in a short, readable document, organizations within the public, private and nonprofit sectors can quickly understand the big picture. In particular, the reader can understand the locations of existing assets, projects currently under development, and policy discussions underway. Interested organizations can therefore more easily develop strategy and partnerships required to connect their specific goals to the developing roadmap of a regional hydrogen economy.

Overview of Advanced Energy Group

Founded in 2016, Advanced Energy Group (AEG) works with leaders in Boston, Chicago, DC, New York, and the Caribbean to deliver systemic change on energy, equity and resilience. AEG works with multiple city governments, utilities, regulators, two national energy labs and over 50 organizations to overcome critical obstacles preventing systemic change on energy and equity impacting over 75 million people.

Working on a quarterly meeting schedule, AEG provides guided collaboration for leaders and organizations to make progress toward local decarbonization and resiliency goals. The outcome of each quarter is a volunteer task force dedicated to achieving quarterly milestones on the path toward the 1-year goal. This hydrogen economy task force was formed during the December 2021 Stakeholder Dinner to leverage the AEG network and standardized task force approach. AEG's framework has proven to be a successful way to address problems that are broader than any single stakeholder.

Geographic Focus of White Paper

This white paper will focus on a hydrogen economy centered within Chicago but extending throughout the broader Midwest. As one of the world's major global cities, largest economic regions, and a critical global logistics hub, it is appropriate to consider Chicago's role in the emerging global hydrogen economy. However, a clean hydrogen economy does not recognize borders. This complex market - organizations producing, delivering, storing, and consuming clean hydrogen - will exist and operate in different cities of the broader Midwest. An approximately 350 mile radius centered around Chicago will encompass the wide variety of stakeholders who may participate in a regional Midwestern Hydrogen economy. Centered within greater Chicagoland and heavily industrial Northwest Indiana, this paper will also review various considerations throughout the rest of Illinois as well as portions of Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin.

Before proceeding, we will note one unique geographic consideration - electricity supply and delivery. Electricity pricing and dispatch are set within regional transmission organizations (RTO's) or Independent System Operators (ISO's), electricity markets that coordinate and balance electric power generation, transmission, distribution, and consumption. Two RTO's dominate the geographic region covered by this paper. The Midcontinent ISO (MISO) encompasses the electricity market in Iowa, Minnesota, Missouri, Wisconsin, Indiana, Michigan, and the majority of Illinois.

The Chicagoland area participates in the PJM market, which connects to Ohio through Northern Indiana. However, PJM also extends into the Mid-Atlantic states, impacting electricity pricing in Chicago. Likewise, the majority of Illinois participates in MISO, which also extends as far south as Louisiana. Although we mention these considerations, we will consider this paper as a Midwestern regional effort, focused on the eight states listed above. See Figure 1 for a map of these United States ISO's and RTO's.

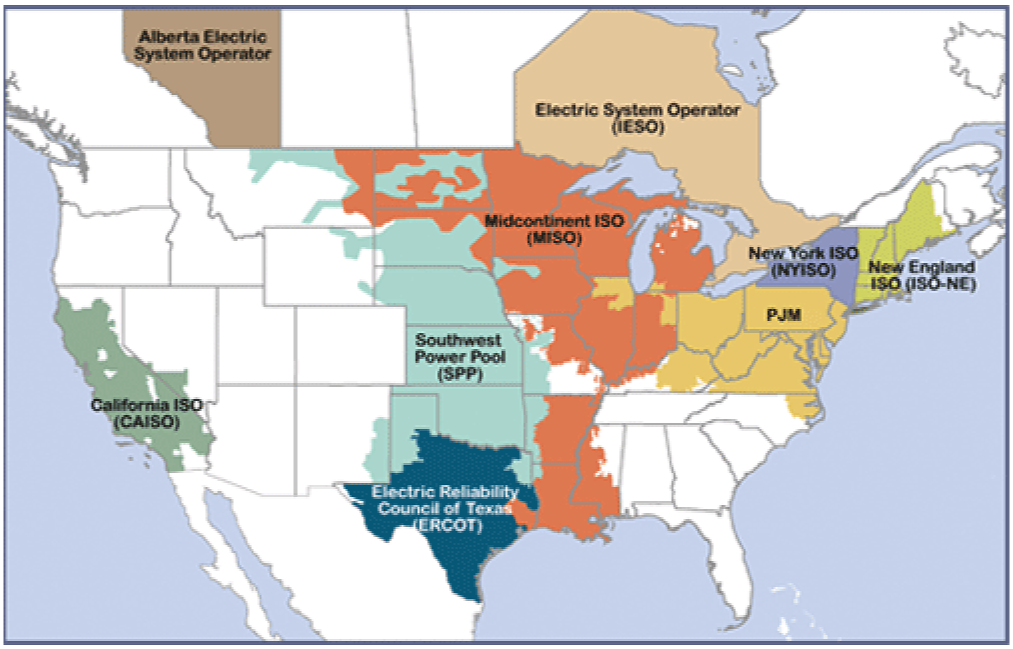

Figure 1 - US ISO's and RTO's that oversee the US power markets

Section 2: Background

Hydrogen vs. electricity as an energy carrier

Most energy used in the Midwest to operate homes, schools, hospitals, and businesses is delivered by wire from the electric grid or by natural gas pipeline. Fuel used for power is primarily nuclear, coal, and natural gas supplemented with intermittent renewable wind and solar generation. Our current electric grid carries the energy in these primary fuel sources and transmits it as electricity. These fuels are used at time-of-use to meet the "real-time" continuously balanced demand for electricity.

Both generation capacity and industrial energy are supported by a robust fuel transportation, processing, and storage network of coal and natural gas that has built up in the region over the last 100 years to meet our infrastructure needs. Traditionally, the only energy storage available in this model is the fossil and nuclear fuel used to produce electricity, which is held in tanks, solid fuel stockpiles, pipeline volume, and reserve storage. More recently, modern battery storage paired with renewables is a growing alternative. Clean hydrogen is emerging as an important part of the energy landscape. In many applications, hydrogen provides an alternative means of carrying energy long distances to its point of use. Hydrogen has the advantage of being a clean-burning fuel whose only emission at the point-of-use is water vapor. Hydrogen can also be utilized to store renewable electricity for long durations, delivering the energy and storing it for months at a time similar to current fossil-based liquid fuels such as diesel. By adapting existing infrastructure and creating new capacity for generating, storing, and transporting hydrogen, the region can therefore diversify our fuel mix and provide a storage option for unused electrical production, including solar and wind capacity.

To scale regional infrastructure and implement hydrogen as a bulk energy carrier will require significant investments to be made across the region's stakeholders. The region would start with existing hydrogen infrastructure focused on production and distribution for industrial uses in fertilizer, and petroleum refining process using well-established technologies and demand centers. The goal is to build an Illinois H_2 infrastructure to complement the existing energy infrastructure, creating an Illinois Clean Hydrogen Hub at the center of the Midwest and supporting expansion of the emerging clean Hydrogen Economy.

Definitions

"Hydrogen economy"

The "Hydrogen Economy" is defined as an industrial market where clean hydrogen is a primary energy carrier as well as an industrial feedstock to chemical industries such as ammonia manufacturing and sustainable aviation fuel (SAF) production. The feedstock and energy input to create usable H_2 fuel is available in our region. Utilizing our technical expertise to develop and incentivize expansion can create an Illinois Clean Hydrogen Hub at the center of the Midwest and support expansion of a broad Midwestern hydrogen economy.

"Hydrogen hub"

"Regional Clean Hydrogen Hub" is defined in the recent Nov 2021 Infrastructure Investment and Jobs Act as "a network of clean hydrogen producers, potential clean hydrogen consumers, and the connective infrastructure located in close proximity."

Through the Infrastructure Bill, DOE is launching a $8 Billion program to support at least 4 regional clean hydrogen hubs in different regions of the US. The hubs must utilize local energy and infrastructure resources to demonstrate the viability of a regional Hydrogen economy including storage, production, transport, and industrial usage. These Clean Hydrogen Hubs are envisioned as the starting point of a national clean hydrogen network to facilitate a clean hydrogen economy. Current understanding is that this 2-phase process will begin with a draft Funding Opportunity Announcement (FOA) in mid-May, 2022, with the FOA expected to be released in the June/July timeframe.

According to the DOE, diverse feedstocks are intended to be used for hydrogen production in these hubs, including production from nuclear, renewables, or fossil with carbon capture utilization and sequestration (CCUS). Likewise, the goal is to expand H_2 usage across electric power generation, multiple industrial sectors, residential/commercial buildings, and transportation.

<u>“Clean hydrogen”, per new DOE definition</u>
The current Department of Energy (DOE) definition of clean hydrogen is for hydrogen produced with less than 2 kg of CO_2 equivalent for each kg of H_2 produced at the site of production.

This includes H_2 produced using
- Fossil fuels with CCUS;
- Hydrogen-carrier fuels (including ethanol and methanol);
- Renewable energy resources, including biomass;
- Nuclear energy; and
- other methods as determined by DOE

This standard for clean hydrogen is intended to be reviewed on a 5 year basis, presumably to tighten requirements as technology and infrastructure allows.

Section 3: Regional Clean Hydrogen Production

With the availability of renewables and nuclear as well as the potential for carbon sequestration and usage, the Midwestern region has several options for the production of clean hydrogen. The following sections provide a survey of clean hydrogen production options.

Baseline production - Steam Methane Reforming (SMR)

Before discussing various methods for "clean hydrogen" production, we provide an overview of Steam Methane Reforming (SMR). SMR is currently the main process for producing hydrogen in the world today. The typical production process uses fossil fuels such as coal gasification or natural gas, but renewable fuels such as biomethane can be substituted. Currently, over 95% of hydrogen production in the world relies on fossil fuel steam methane reforming without carbon capture, often called "Grey Hydrogen."

In SMR, methane reacts with steam under 3-25 bar pressure (1 bar= 14.5 psi) in the presence of a catalyst to produce hydrogen and carbon monoxide. In a "water-gas shift reaction," the carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen. In a final process step called "pressure-swing adsorption," carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen. The process will produce approximately 10 kg of CO_2 for each 1 kg of H_2 produced. Addition of carbon capture onto the back end of SMR has typically been denoted "blue hydrogen" and is a key strategy for scaleup of clean hydrogen.
Production of hydrogen using SMR without carbon capture provides the baseline cost for comparison with all other methods. Any end-user application considering hydrogen will look to the comparison with the least expensive available grey hydrogen on the market, typically from either onsite production or delivery from a major industrial gas supplier such as Linde, Air Liquide, or Air Products.

Pricing of approximately $1/kg is often listed as a baseline number, with strong dependence on the price of natural gas. Figure 2 below provides a typical range found in market analyses. Pricing throughout 2021 and 2022 has increased due to rising natural gas prices. Price estimates for blue and green hydrogen are also listed below.

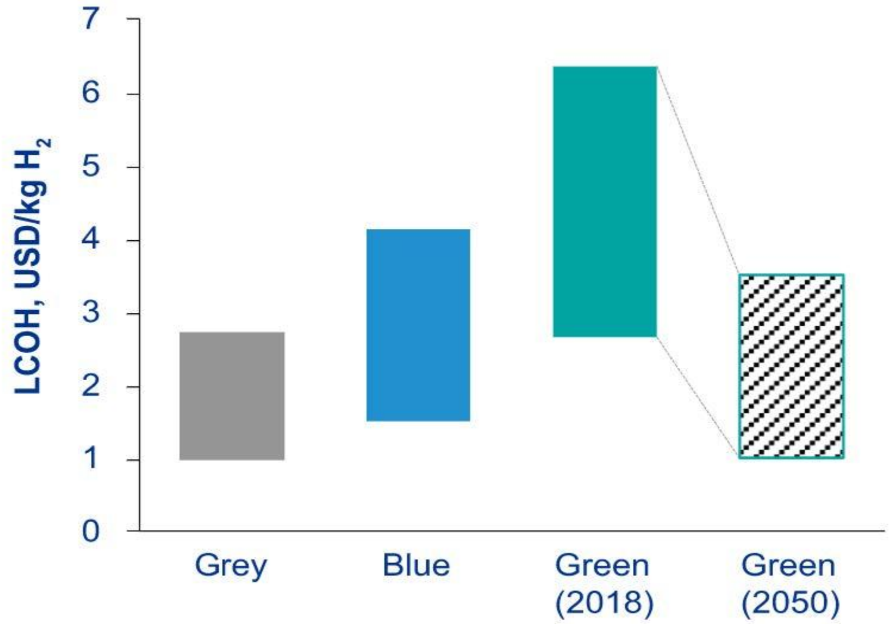

Figure 2 - Typical Grey, Blue, and Green Levelized Cost of Hydrogen[1]

Similar relative order-of-magnitude pricing conclusions have been reached by other analysts. Additionally, Platts launched its hydrogen price assessments product in late 2021 to track grey, blue, and green hydrogen pricing at various locations around the world. This is helpful for tracking and understanding falling costs and the competitive position of the Midwest, especially when additional shipping and delivery costs are considered.

The first challenge of green and blue hydrogen must therefore be to reach cost parity with unabated grey hydrogen. A second challenge, as discussed in later sections, is for a clean hydrogen-based technology to reach cost parity with other fossil-based competitor technologies in a particular application (i.e. - diesel fuel for trucking). A final challenge is for clean hydrogen to reach cost parity with an alternative clean competitive technology (i.e. - battery electric vehicles charged using a wind power purchase agreement).

H_2 production via electrolyzers

Technical Overview of Process

Electrolysis is an electrochemical process which uses electrical energy to decompose water into its elemental constituents, hydrogen and oxygen. The process occurs in a piece of

[1] "The Hydrogen Trajectory" - https://home.kpmg/xx/en/home/insights/2020/11/the-hydrogen-trajectory.html

equipment called an electrolyzer. When the electricity source powering the electrolyzer is a renewable, carbon-free source such as wind or solar, this process is typically referred to as "green hydrogen." Likewise, when produced from carbon-free nuclear electricity to an electrolyzer, it is often referred to as "pink hydrogen."

The DOE is moving away from these colors and generally refers to "clean hydrogen" meeting a certain carbon intensity. Nevertheless, the color terms persist throughout the global literature and the various technical and financial analyses that one may encounter. The Infrastructure Investment and Jobs Act also provides an additional $1B for "Clean Hydrogen Electrolysis" for improving electrolysis technology to achieve the DOE Earth Shot target of $1/kg of H2 target by 2030. One of the key drivers of hydrogen pricing is the falling price of electrolyzers, which is expected to accelerate in the coming years, similar to the decline in both solar panel and wind turbine pricing over the past ten years.

Electrolyzers range in size. Small units at the kilowatt-scale provide hydrogen for applications that require little hydrogen, such as chemical analytical equipment, while large units at the megawatt scale provide hydrogen for manufacturing applications and centralized hydrogen production. Commercial electrolyzers use one of three different electrolysis technologies: alkaline water electrolysis (AWE), polymer electrolyte membrane water electrolysis (PEMWE - typically referred to as PEM electrolyzers within the industry), and solid oxide electrolysis (SOEC).

Alkaline water electrolysis

Hydrogen produced by alkaline water electrolysis is a well-established technology, with electrolyzers at the megawatt scale commercially available. An alkaline water electrolyzer consists of two electrodes operating in a liquid alkaline electrolyte solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH). These electrodes are separated by a diaphragm, separating the product gases, and transporting the hydroxide ions (OH^-) from one electrode to the other electrode. Key advantages of alkaline electrolyzers are the use of cheaper catalysts than PEM electrolyzers, high proven durability, and the ability to provide high purity hydrogen.

Polymer electrolyte membrane water electrolysis (PEMWE)

PEMWE was developed to overcome the drawbacks of the AWE such as partial load, low current density, and low pressure operation. PEMWE technology is very similar to PEM fuel cell technology using the same solid polysulfonated membranes as the proton conductor. PEMWE offers several advantages including high current densities, high efficiencies, fast response, compact design enabling a small footprint, and production of ultrahigh purity hydrogen. The fast response of PEMWE makes them ideal for industrial applications as well as rapid response to fluctuating electric power input provided by renewables. PEMWE uses precious metal catalysts which provide for higher activity than AWE but at a higher cost.

Solid oxide electrolysis (SOEC)

SOEC technology is a high-temperature process operating at temperatures ranging from 500-1000°C and using ceramic membranes as the proton conductor. SOEC technology is very similar to solid oxide fuel cell technology. Unlike the low temperature electrolysis processes, AWE and PEMWE, which use liquid water, SOEC's use steam. A major advantage of the higher operating temperature is that the electric energy demand decreases with increasing thermal energy as the temperature increases. As such, SOEC operates at very high efficiencies. However, the high operating temperatures introduces material durability and stability challenges which have limited its commercialization until recently.

Production cost of hydrogen using electrolysis

Hydrogen produced using water electrolysis currently encompasses a broad pricing band that is expected to fall over time. The break-even cost of hydrogen is the sum of fixed cost and variable cost. The former covers return on invested capital plus labor etc. while the latter primarily reflects the delivered cost of power. As shown in Figure 3 developed by Chicago-based Energy and Water Development LLC ("EnWaDev"), the production price of electrolyzer-based green (renewable power) or pink (nuclear power) hydrogen is significantly impacted by select factors:

- Price of electricity ($/kw-hr)
- System capacity factor (CF), reflecting annual utilization of the equipment
- Economies of scale through increased production volume

OUTPUT	UNIT	VALUE
Capacity Factor (CF)	%	60%
Weighted Avg. Cost of Capital (WACC)	%	10%
Overall Efficiency 70%	KWh/Kg H2	56

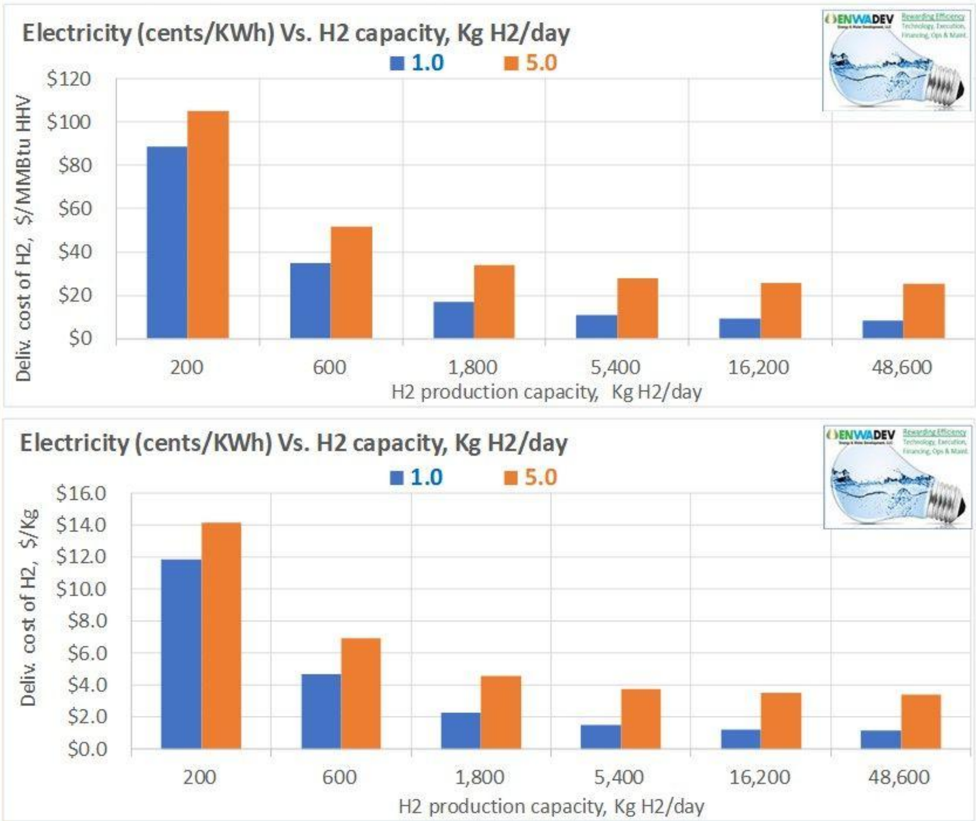

Figure 3 - Delivered cost of hydrogen vs. production capacity and electricity cost

Generally, the pricing of hydrogen on a $/kg basis falls as capacity increases. This is a key driver for the argument behind hydrogen hubs and local hydrogen economies - aggregating the demand of multiple end users within a single region allows for increased production capacity and short distribution distances, leading to falling local production costs for the region and the potential to provide a globally competitive clean hydrogen product for export. Decreasing cost of electricity also corresponds to a lower delivered cost of hydrogen.

Electrolyzer Power Requirements

The amount of energy required to produce one kilogram of hydrogen from water is 33.33 kW-hr assuming no efficiency losses. Current AWE and PEMWE electrolyzers have efficiencies ranging from 62-82% and 67-82%, respectively, with most commercial units exhibiting efficiencies around 67-70%. Accounting for inefficiencies, about 50 kW-hr of energy is required to produce 1 kg of hydrogen or approximately 50 MW-hr per metric ton

(1000 kg) of hydrogen. SOEC's operating at high temperatures have efficiencies ranging from 82-86% thus requiring about 35% less electrical energy than the low temperature AWE and PEMWE but do require process heat.

Available Midwestern Renewables Capacity for Green Hydrogen

Despite pandemic-related delays and supply chain constraints, the Great Lakes region, defined as Illinois, Wisconsin, Indiana, Minnesota, Iowa, Missouri, Michigan and Ohio, witnessed strong growth in 2020 and 2021 as developers in the wind belt faced a ramp-down in the production tax credits. For the year ending 2021, the region increased wind and solar generation capacity to 37 GW.

While renewables growth has historically been driven by new wind projects, upcoming projects in the Midwest will be predominantly solar and solar + storage, and the pace of origination has been growing exponentially as witnessed by the number of new applications in both MISO and PJM. In 2021, the Midwest Independent System Operator (MISO) announced a record of 500 new interconnection queue applications, representing 77 GW of new projects, of which 56 GW were new solar and storage projects. As of September 2021, 980 projects are active in the interconnection process, 63% of which are solar projects. Five states comprise the bulk of all MISO applications: Illinois, Indiana, Wisconsin, Michigan, and Iowa.

For PJM, a record 1,223 new queue positions were filed in 2021, 100 times greater than the 123 applications filed in the 2017/2018 AD queue cycle. Like MISO, the bulk of these queue applications are solar and solar + storage. Of the applications filed, 18.2 GW of projects are in Illinois, Indiana, and Ohio.

While the volume of Midwest projects being contemplated point to the tremendous potential for onsite green hydrogen, the extensive MISO and PJM footprint mean that electrolyzers have the ability to source renewable generation more broadly to meet target capacity factors. Increases in capacity also should lead to review of available transmission capacity. If developers note bottlenecks in the ability to receive power deliveries, this may lead to consideration of co-locating hydrogen production onsite at a wind farm or solar field, increasing the importance of physical gas pipeline discussions for the region. This strategy is not without regulatory challenges because a wholesale renewables project cannot sell directly to a retail end user such as a hydrogen production project, and a retail provider is typically regulated by state public utility commissions. Another option would be for the hydrogen production facility to buy renewable energy certificates (REC's).

While the private sector continues its efforts, ambitious policy at the state level ensures that the Midwest has the right environment for directed renewable investment. In Illinois, for example, the Climate and Equitable Jobs Act passed in 2021 commits the state to one of the highest clean energy and decarbonization targets in the country, with a 100% renewable energy target by 2050. Similar activity is taking place in Michigan and in Minnesota, where the major utilities have announced plans for massive renewable investments over the next decade.

Nuclear Power for Hydrogen Production

Local Nuclear Capacity

Illinois has more nuclear generating capacity than any other state, a dispatchable carbon-free electricity source that is a major competitive advantage of the state and the broader Midwest. There are eleven nuclear reactors operating at six sites - Dresden, Clinton, LaSalle, Quad Cities, Braidwood, and Byron, all owned by Constellation (formerly Exelon), with a combined nameplate generating capacity of 11,500 MW. In 2020, Illinois nuclear power plants generated more than 100.2 TW-hr of electricity, 12.6% of the U.S. total nuclear electricity generated, which accounted for 58% of Illinois's in-state electricity generation.

Nuclear hydrogen is the name applied to hydrogen produced by processes that utilizes the electrical power and/or process heat generated by a nuclear power plant. Hydrogen produced using nuclear energy has a carbon footprint similar to hydrogen produced from wind, solar, or other renewables. In the hydrogen color spectrum, nuclear hydrogen has typically been referred to as either "pink" or occasionally "purple" hydrogen.

Among the various process technology for producing hydrogen using nuclear energy are:

- Low-temperature electrolysis requiring only electrical power from a nuclear plant,
- Thermochemical cycles which require only process heat
- Hybrid processes such as high temperature steam electrolysis and hybrid thermochemical cycles which require both electrical power and process heat.

The selection of the hydrogen production technologies for producing hydrogen greatly depends on the nuclear power plant.

Low-temperature electrolysis

Low-temperature electrolysis processes use electrical energy to break water down into hydrogen and oxygen at temperatures below 100°C. Two types of low temperature electrolyzer technologies are the polymer electrolyte membrane (PEM) electrolyzer and the alkaline water electrolyzer (AWE). Illinois nuclear power plants are best suited for low-temperature electrolysis.

Thermochemical cycles

Splitting water into hydrogen and oxygen using thermal energy is an alternative to electrochemically splitting water. However, splitting water in a one-step process requires temperatures above 2500°C to obtain reasonable yields, which is not industrially feasible. However, multi-step processes involving a series of chemical reactions that proceed at different temperatures using compounds that are regenerated and recycled in the process can split water into hydrogen and oxygen at moderate temperatures. The only input to these processes is water and process heat. These multi-step processes are referred to as thermochemical cycles.

One of the most studied thermochemical processes is the sulfur-iodine (S—I) process developed by General Atomics. In the S—I process, hydrogen is generated by a reaction involving iodine compounds at 400°C while oxygen is generated by a reaction involving sulfur at 900°C. The energy efficiency of the S—I process is estimated to be between 40-50%. While numerous thermochemical cycles have been proposed, all have design challenges, and none have been implemented on the commercial scale.

High temperature steam electrolysis

Unlike low temperature electrolysis which requires only electrical energy from the nuclear power plant, high temperature steam electrolysis (HTSE) requires both electrical energy and process heat. The benefit of HTSE compared to low temperature water electrolysis is that the electrical energy required decreases as the temperature rises. HTSE uses solid oxide electrolyzers (SOECs), which are the reverse of a solid oxide fuel cell (SOFC), operating at temperatures ranging from 800-1000°C. Operating in this temperature range, SOECs require about 35% less electrical energy compared to low temperature electrolyzers.

Hybrid thermochemical cycles

A hybrid thermochemical cycle is a multi-step process for splitting water into hydrogen and water that uses both a thermochemical reaction and an electrochemical reaction in the process. In these processes, the low temperature reaction has a low thermodynamic yield and is forced to high yield electrochemically. An example of a hybrid thermochemical cycle is the hybrid—sulfur (HyS) process, initially developed by Los Alamos National Laboratory and then further developed by Westinghouse. The HyS process is a variation of the S—I process but only requires sulfur compounds.

Nuclear pilot-scale hydrogen projects

Since 2019, four demonstration projects have been funded by the Department of Energy to produce hydrogen using nuclear energy. None of these projects are located within Illinois, but two are located within the broader Midwest - Xcel's Prairie Island outside of Minneapolis, MN and Energy Harbor's Davis-Besse near Toledo, OH.

Energy Harbor was awarded $9.2M funding in 2019 to demonstrate a 1- to 3-MWe low-temperature electrolyzer at its Davis-Besse Nuclear Power Station near Toledo, Ohio. The project will produce hydrogen for first movers of clean hydrogen including fuel cell buses, heavy-duty trucks, forklifts, and industrial users. Partners include Xcel Energy, Arizona Public Service, and Idaho National Laboratory.

Xcel Energy was awarded $10 million in 2020 to explore hydrogen production using high-temperature steam electrolysis, likely at its Prairie Island Nuclear Generating Station located in Red Wing, Minnesota. The project will carry out the planning, design, installation, testing, demonstration, and evaluation of non-electric, hybrid energy technologies connected to a light-water reactor power plant. Project deliverables are a fully-functional hydrogen plant capable of operating as a hybrid system to test diverse electrolysis technologies coupled with a Light Water Reactor, and the design development for a hybrid reversible system. Both project deliverables are to be integrated into the normal operating routine of a nuclear power plant. Idaho National Laboratory (INL) is a partner on this project.

Exelon was awarded $3.6 million in 2019 to install a 1 MW polymer electrolyte membrane (PEM) electrolyzer at its Nine Mile Point nuclear power plant in Scriba, New York. The electrolyzer provides hydrogen for in-house use at the plant. It is also simulating operation of a larger electrolyzer participating in power markets. Partners on this project are Nel Hydrogen, Argonne National Laboratory, Idaho National Laboratory, and the National Renewable Energy Laboratory.

PNW Hydrogen is leading a $20 million project to produce and store six metric tons of hydrogen at the Palo Verde Generating Station in Tonopah, Arizona. The hydrogen will be produced using a low-temperature electrolysis system and the hydrogen will be used to fuel a natural gas–fired power plant owned by Arizona Public Service. Partners on the project include the Electric Power Research Institute, Arizona State University, the University of California Irvine, Idaho National Laboratory, the National Energy Technology Laboratory, and the National Renewable Energy Laboratory.

Representative nuclear hydrogen pricing

Idaho National Laboratory (INL) has published technical and economic analyses of the Minnesota nuclear units at Xcel's Prairie Island and Monticello nuclear plants. As a representative nuclear hydrogen case study, INL reviewed various cost and technical sensitivities for onsite hydrogen production.

Figure 4 below, listed as Figure E-2 within INL's 2020 analysis, shows the production costs of hydrogen using high temperature steam electrolysis (HTSE) with base and advanced technology design. INL compared the levelized cost of hydrogen (LCOH) with the hydrogen production cost using SMR directly at the end user's site. A natural gas price was assumed for SMR, and a hydrogen delivery cost from the nuclear plant to that end user was assumed.

In particular, IINL demonstrated the sensitivity to wholesale power prices. Carbon pricing or a carbon tax on SMR would be required to raise the cost of SMR "grey hydrogen" and make nuclear hydrogen competitive for typical wholesale power prices (i.e. - $30/MWhr). Alternatively, another means of lowering hydrogen costs such as a production tax credit could make nuclear hydrogen competitive with SMR when no carbon price is included on SMR.

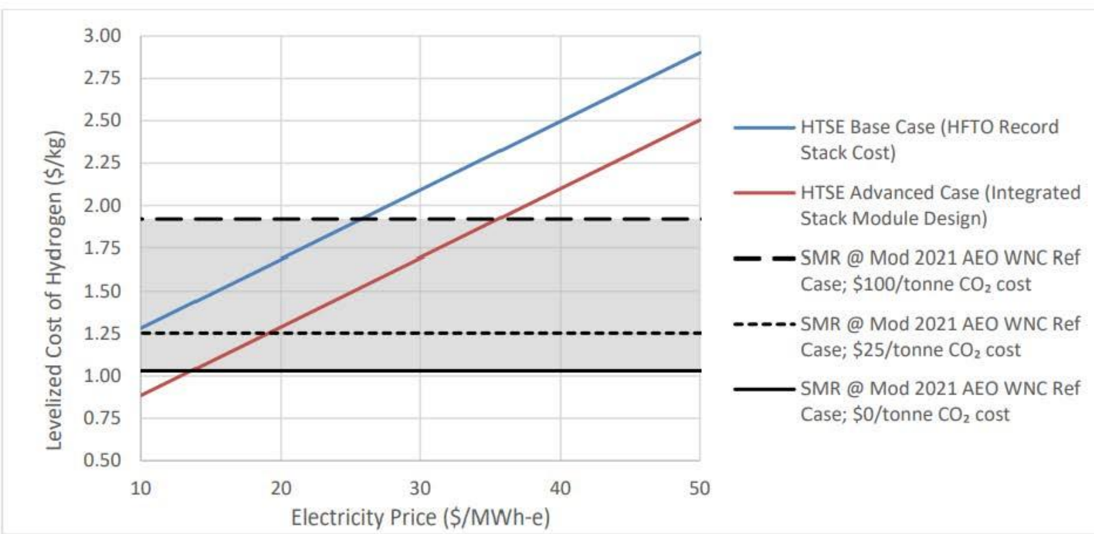

Figure E-2. LCOH of 347 tonne/day HTSE base and advanced cases versus 342 tonne/day SMR with $0, $25/tonne, and $100/tonne CO_2 cost. The HTSE LCOH includes a $0.16/kg adder for the cost of transporting hydrogen product to an off-site customer. SMR natural gas feedstock pricing based on Modified 2021 AEO West North Central (WNC) Region Reference Case.

Figure 4 - INL analysis Figure E-2 modeling the production[2]

[2] "Technoeconomic Analysis," INL - https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_55988.pdf

Water Consumption Considerations

Water demand for hydrogen

Water contains 11.1% hydrogen by weight. Thus to produce one metric ton of hydrogen would require nine metric tons of water, equivalent to 2377 gallons per metric ton (1000 kg) of hydrogen produced, or 2.38 gallons of water per kg of H_2. The U.S. Department of Energy estimates that currently there is approximately 10 million metric tonnes (MMT) of hydrogen production annually and an additional 10 MMT would add less than 1% increase to the United States' freshwater withdrawals. However, regional water capacity issues are likely to be more pronounced particularly as climate change continues to shift precipitation patterns. Figure 5 below illustrates water stress throughout the United States, indicating regions that may be more or less favorable for hydrogen production.

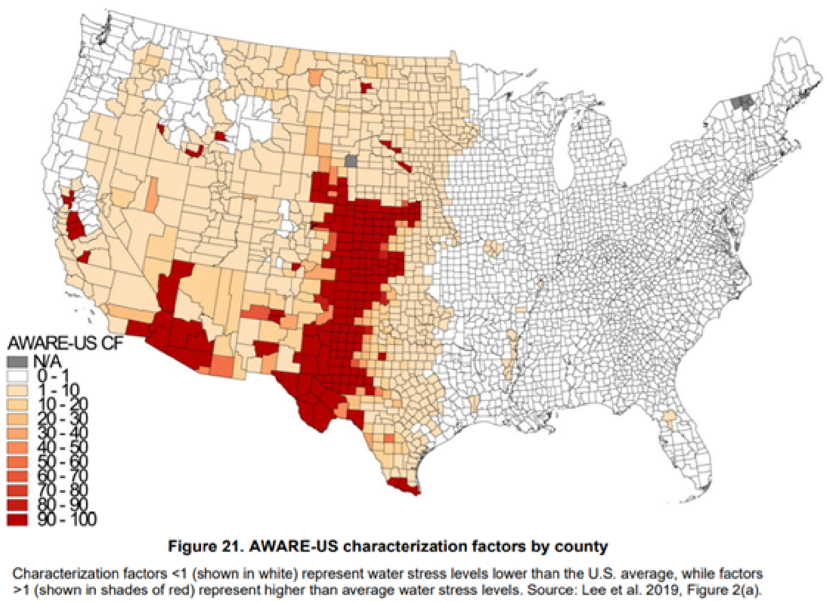

Figure 5 - Water stress levels throughout the United States[3]

Regional water issues

The Midwest is fortunate to have low levels of water stress issues compared to other regions of the US, especially the desert Southwest. Additionally, the Great Lakes region is fortunate to be home to one of the world's largest surface freshwater ecosystems. However, while the Great Lakes are large, less than 1% of Great Lakes water is renewed annually through precipitation, surface water runoff, and inflow. Lake levels are also potentially threatened by climate change and in recent decades have alternated between higher highs and lower lows more rapidly than previously recorded.

[3] "Quantifying Water Stress Impacts" - https://www.sciencedirect.com/science/article/pii/S0048969718332145

In order to protect this vital resource, the 2008 Great Lakes Compact regulates large diversions of water outside the Great Lakes Basin. See Figure 6 below for a map of the Great Lakes Basin.

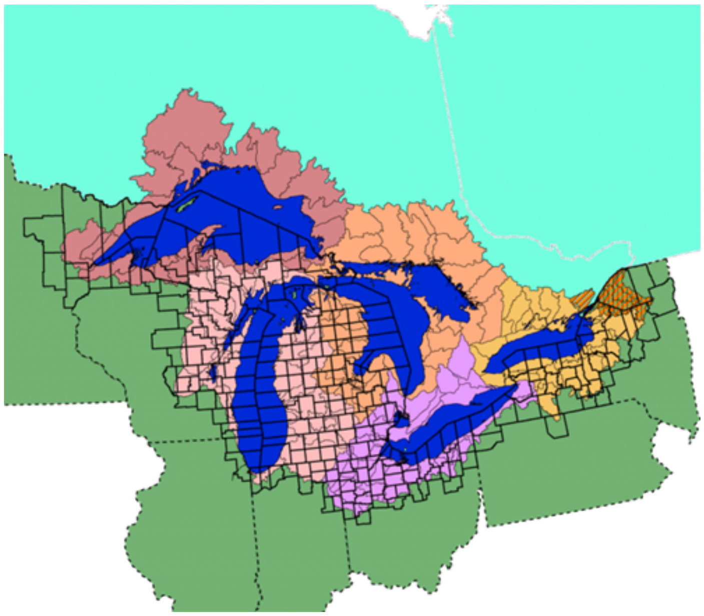

Figure 6- Great Lakes Basin (with sub-basins shown)

Generally, cities and industrial users taking water from the Great Lakes but not sending it outside the Basin (i.e. - local potable water distribution) are subject to state permits and regulations. However, diversions partially or wholly outside the Great Lakes Basin can trigger additional regulations of the Great Lakes compact, for example the approval of all Great Lakes Governors and the input of Ontario and Quebec for new consumptive uses exceeding five million gallons a day. A recent case involving a Foxconn factory in Wisconsin required seven million gallons of water a day, although an administrative law judge ruled in favor of the diversion. It should be noted that Illinois has a diversion exemption of 2.1 billion gallons per day.

Additionally, hydrogen production using water within the Great Lakes Basin may become an emerging regulatory and legal issue, and hydrogen project developers should consider this in their planning. This hydrogen may be shipped to a distant corner of the state for use. When used in a fuel cell, this hydrogen will release water into the atmosphere, effectively diverting water from within to outside the Great Lakes Basin. Although the Midwest is centered on the Great Lakes, Earth's second largest freshwater bodies by volume, these examples highlight the complicated multi-national regulatory structures that protect these waters.

Ammonia as Hydrogen Carrier

Ammonia is a compound consisting of nitrogen and hydrogen with the formula of NH_3. At room temperature, ammonia is a colorless gas with a pungent, irritating odor. In its pure form, it is referred to as anhydrous ammonia and readily absorbs moisture. The Haber-Bosch process combines nitrogen and hydrogen to produce ammonia, and the hydrogen is typically sourced from an SMR, using fossil fuels as a feedstock and releasing CO_2 into the atmosphere.

The presence of hydrogen within an ammonia molecule implies that ammonia can be decomposed to produce H_2 at the point of use. Following transport in ammonia form, the hydrogen would be removed through a chemical "cracking" process. Alternately, applications for direct use of ammonia as a hydrogen-rich fuel are also in use. Advantages include transportation of a higher energy density, less volatile fluid at much lower pressures than the comparable H_2 gas. This makes ammonia very attractive for overland and marine shipping as well as storage. There is a growing interest in using ammonia as a carbon-free fuel for combustion applications or as a hydrogen-carrier for use with fuel cells due to its high volumetric energy density (15.3 MJ/L), its high hydrogen content (17.6 wt%) and the existing infrastructure for distribution and storage.

Nevertheless, ammonia production would need to become carbon neutral for ammonia to serve as a hydrogen carrier in a decarbonized economy, either through the use of green hydrogen as a feedstock (Green Ammonia), or carbon capture onto the SMR (Blue Ammonia). Currently, the United States has only one blue ammonia plant, the Dakota Gasification Co. in Beulah, North Dakota, which utilizes coal as a feedstock, then captures and sequesters carbon dioxide by piping it to nearby oil fields for enhanced oil recovery.

Several U.S. ammonia producers are considering or investing in capturing carbon dioxide at their facilities to produce blue ammonia including CF Industries at its Donaldsville, LA, and Yazoo City, MS, plants and Iowa Fertilizer Co. at its Weaver, IA, plant. Air Products recently announced the construction of a $4.5B, 20 million m^3/day plant to produce blue hydrogen for producing ammonia and use in other products in Ascension Parish, LA.[4] CF Industries recently announced that it will build an electrolyzer plant at its Donaldsville, LA, facility to

[4] "Landmark Louisiana Clean Energy Complex" - https://www.airproducts.com/campaigns/la-blue-hydrogen-project

produce green hydrogen providing enough hydrogen to produce 20,000 tons of green ammonia annually.[5]

Carbon Capture Considerations

Technology Overview of Carbon Capture Utilization and Storage (CCUS)

Reforming and partial oxidation of methane, methanol, and ethanol using catalysts are among the processes that are frequently used for the production of hydrogen. However, reforming and partial oxidation results in the production of CO_2. Various biomass sources, such as sludge from wastewater, algae, and agricultural and municipal wastes, can also be used as potentially low-cost substrates for bio-hydrogen production. Although these will not lead to a net increase in carbon release, they nevertheless do release CO_2. Exploring ways to capture and utilize CO_2 will play a significant role in developing a hydrogen economy. Reforming biomass and capturing the carbon will in fact have a negative carbon intensity.

The world's consumption of energy from all fuel sources except coal will increase through the year 2040. Renewables are the world's fastest-growing energy source, with consumption increasing by an average of 2.3%/year between 2015 and 2040. Although consumption of non-fossil fuels is expected to grow faster than fossil fuels, fossil fuels will still account for a majority of energy use in 2040. Natural gas is the fastest-growing fossil fuel in the projections, with other fossil fuel percentages decreasing by 2040.[6]

There are two major sources of anthropogenic CO_2 production from fossil fuels, mobile and stationary. Capturing CO_2 from mobile sources is extremely challenging and requires significant research. In stationary sources including industrial and power plants, CO_2 is usually generated through combustion or gasification and becomes part of the mixture of gases. The major challenge is separating CO_2 from other gases in the mixture using economically competitive processes, and then regenerating it in the concentrated form for utilization and/or sequestration. Today, liquid-based technology for CO_2 capture is commercially available; however, these liquid-based processes have shortcomings including low operating temperature and high heat for regeneration, which demand a high energy penalty.

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[5] "CF Industries Commitment to a Clean Energy Economy" - https://www.cfindustries.com/globalassets/cf-industries/media/documents/cf-commitment-to-a-clean-energy-economy.pdf

[6] EIA Annual Outlook 2022- https://www.eia.gov/outlooks/aeo/

On the other hand, solid sorbents have a demonstrated lower energy penalty due to CO_2 sorption at higher temperature and CO_2 regeneration at temperatures not significantly higher than the sorption temperature and at possibly lower pressure. Furthermore, chemical looping and the use of oxygen in place of air in combustion and gasification processes results in the direct production of a concentrated CO_2 stream. In such processes gas containing CO_2 typically enters the bottom of the fluidized bed absorber and reacts with fresh sorbent in the bed. The CO_2-laden particles flow up the riser and flow to the regenerator fluidized bed, where CO_2 is released from the sorbent particles by heating up the spent sorbent using concentrated solar energy or steam. The regenerated sorbent particles then move to the fluidized bed absorber to complete the loop.

In general, all CO_2 capture technologies have their own advantages and limitations, but their stability and removal efficiency are the main challenges and opportunities for future research to improve the performance and reduce the cost and energy required for CO_2 separation.

Regional CO_2 Pipelines

Two large CO_2 pipelines are proposed running west from Illinois and Iowa. The Midwest Carbon Express CO_2 pipeline, proposed by Iowa-based Summit Carbon, plans to sequester CO_2 from 31 Iowa Ethanol plants and transport west to North Dakota for sequestration. The Heartland Greenway Pipeline, developed by Dallas-based Navigator CO_2 ventures would also extend westward but would reach as far east as central Illinois.The pipelines would transport carbon dioxide captured from ethanol and other industrial emitters.

Development of pipelines will be one of the keys to a regional hub and must integrate the pipeline developer and operator companies capable of scaling these projects. Pipelines would need to connect CO_2 producers such as SMR sites with offtakers requesting CO_2 feedstock, or diverting to sequestration sites.

Regional CO_2 Sequestration options

Illinois State Geological Survey (ISGS) recently completed final preparations for a small-scale field test of enhanced oil recovery through carbon dioxide (CO_2) injection at the Loudon Oil Field near St. Elmo in Fayette County. The "huff 'n' puff" test will inject CO_2 into an oil reservoir, then extract oil from the same well. Data gathered through this basic test will give a strong indication of the feasibility of enhancing the recovery of oil through CO_2 injection in Illinois' many mature oil fields.

The Midwest Geological Sequestration Consortium (MGSC), Archer Daniels Midland Company (ADM), and Schlumberger Carbon Services collaborated to drill a 7,230 ft well and inject and permanently store CO_2 from the ADM ethanol plant at Decatur, Illinois. The Illinois Basin-Decatur project inject one million metric tonnes of CO2 over a three year period into the Mt. Simon Sandstone. Numerous monitoring and verification methods are being used to evaluate the potential of carbon sequestration in the Illinois Basin. The target reservoir is the Cambrian Mt. Simon Sandstone, a thick sandstone reservoir with an overlying shale seal.

Regional, as well as local, geologic and geophysical characterization of the target reservoir is necessary for successful completion of a sequestration project.
In addition, the potential for sequestering CO_2 in the largest bituminous coal reserve in the United States (Illinois Basin) is being assessed in southeastern Illinois as part of the DOE's Regional Sequestration Partnership program by ISGS. The main objectives of this test are to determine CO_2 injection rates and storage capacity. See Figure 7 below for a survey of Midwest storage capacity according to the Great Plains Institute.

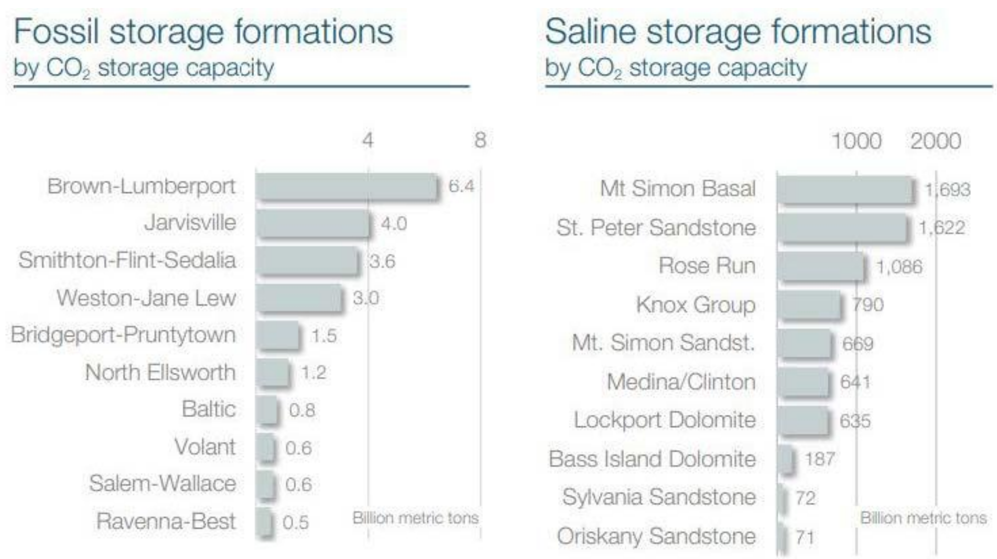

Figure 7- Midwestern Carbon Sequestration Capacity[7]

<u>Regional CO_2 offtakers</u>
Although carbon capture discussions often center on underground long-term carbon sequestration, the full name "carbon capture utilization and sequestration" (CCUS) is becoming more common. CCUS acknowledges that CO_2 is itself a valuable feedstock and

[7] "An Atlas of Hydrogen Hubs" - https://carboncaptureready.betterenergy.org/analysis/

industrial input to a wide variety of industries, some of which are more mature than others. CO_2 may be used as feedstock to production of chemicals such as methanol, ethylene, or carbon monoxide, or further processing into end products such as plastics or sustainable aviation fuel (SAF). The most economical approach will vary depending on the source, geographic location, shipping options, and potential offtakers. Many processes using CO_2 as a reactive feedstock also require hydrogen as a chemical feedstock input. See Figure 8 below for a summary of these options from the Royal Society.

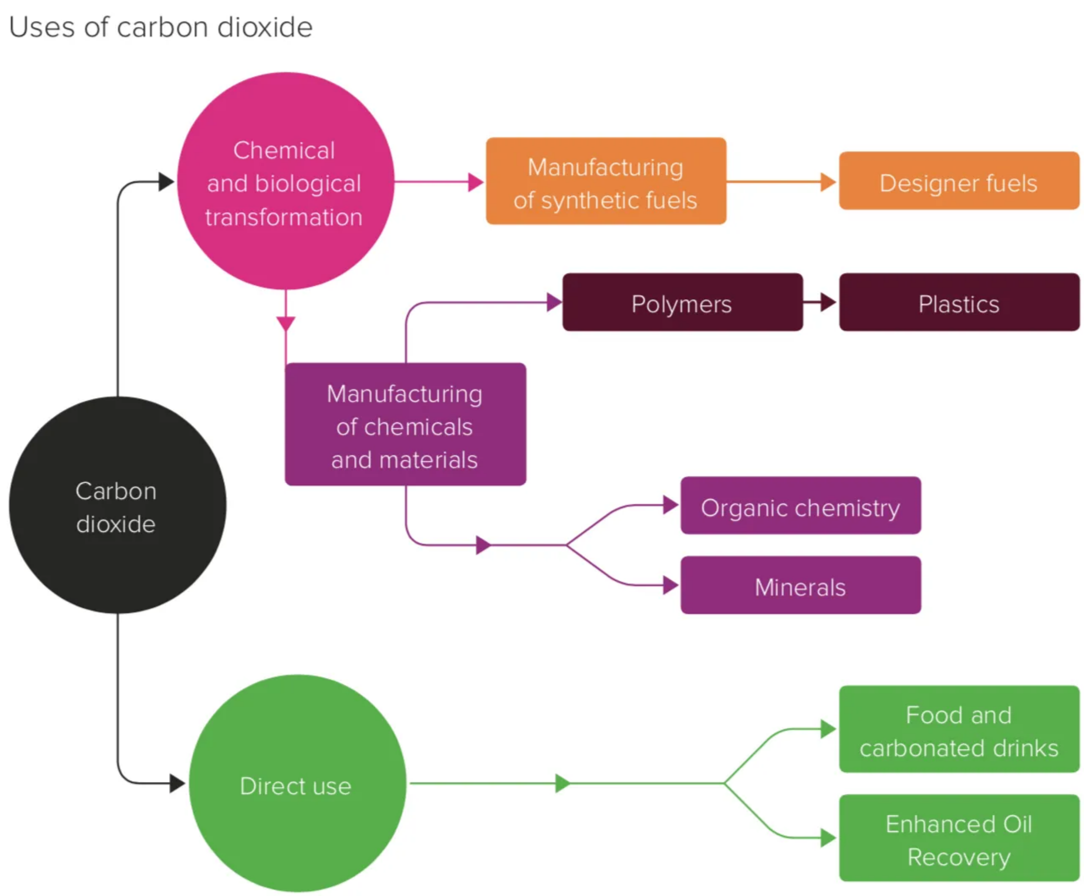

Figure 8 - Uses of CO_2 following Carbon Capture, the Royal Society[8]

As a heavily industrial region, this implies that the Midwest can not only produce and consume clean hydrogen. The Midwest is also in a very good position to build a circular economy in which carbon capture of fossil-based hydrogen will capture CO_2 and use it as feedstock to a variety of potential industries that already consume CO_2, reducing the carbon footprint of those industries as well. This provides another pathway for the “hard to decarbonize” sectors of the economy.

[8] “The Potential and Limitations of Using Carbon Dioxide” - https://royalsociety.org/~/media/policy/projects/carbon-dioxide/policy-briefing-potential-and-limitations-of-using-carbon-dioxide.pdf

Section 4: Hydrogen Delivery and Storage Considerations

Mobile Delivery vs. Pipeline considerations

The dedicated US hydrogen pipeline system is not very extensive, covering approximately 1600 miles throughout the entire country.[9] In comparison, the natural gas pipeline system covers approximately 350,000 miles. Nearly 2/3 of the dedicated hydrogen pipelines are concentrated along the Gulf Coast, connecting several existing hydrogen producers and consumers in Texas and Louisiana. Within the Midwest, an approximately 15 mile pipeline runs between fossil-based hydrogen production and consumption facilities in Northwest Indiana.

While the expansion of new dedicated hydrogen pipelines are an option for hydrogen transport, extensive work has been done to review the repurposing of the existing natural gas transmission and distribution pipeline system. An operator may inject hydrogen into the existing pipeline system, transporting a volumetric blend with a lower carbon intensity. End users such as combustion turbines or building water heaters may use this decarbonized gas to lower their operating footprint. Alternatively, the gas pipeline system may be repurposed to transport hydrogen with end users extracting H_2 from the gas and utilizing it in their process. Extraction of hydrogen is currently possible with one of three technologies - Pressure Swing Absorption (PSA), membrane separation, and Electrochemical Hydrogen Separation (EHS).[10] Finally, portions of an existing pipeline may be decommissioned for natural gas use, isolated from the main natural gas network, and repurposed as new hydrogen pipelines.

While pipelines are the most cost effective means for transporting large quantities of hydrogen, truck delivery is still the most common because the hydrogen pipeline network has not been extended much beyond the US Gulf Coast. Trucking is often provided in high pressure tube trailers. Long distance transport may lead to evaluation of ultra-low temperature cryogenic hydrogen and transport in cold liquid form in order to maximize the amount of hydrogen mass transported by a given vehicle.

Any organization participating in the hydrogen economy must consider the most financially viable approach to production, storage, and consumption. Various factors may come into play beyond the availability of pipeline and truck transport. For example, constraints in the electrical transmission system may incentivize a producer to produce onsite and ship a

[9] "Gaseous Hydrogen Delivery" - https://www.energy.gov/eere/fuelcells/gaseous-hydrogen-delivery
[10] "Blending Hydrogen into the Natural Gas Pipeline Network" - https://www.nrel.gov/docs/fy13osti/51995.pdf

longer distance. The lack of a hydrogen or natural gas pipeline nearby may lead an end-user to procure from an ammonia supplier and install the necessary equipment to crack the ammonia into hydrogen for onsite consumption.

Natural gas transmission pipelines map

The Midwestern natural gas pipeline system is extensive. See Figure 9 below. An argument to be made for siting hydrogen production projects near these pipelines for short interconnection distance. As noted above, gas availability may be used in an SMR to produce blue hydrogen. Gas transmission companies may consider repurposing existing natural gas pipelines for hydrogen, and hydrogen producers may consider siting more closely to these locations. If hydrogen blending becomes widespread, proximity to any natural gas pipeline becomes favorable. If additional hydrogen or CO_2 pipelines are built, the existing right of way (ROW) of these natural gas pipelines provides a natural corridor for expansion.

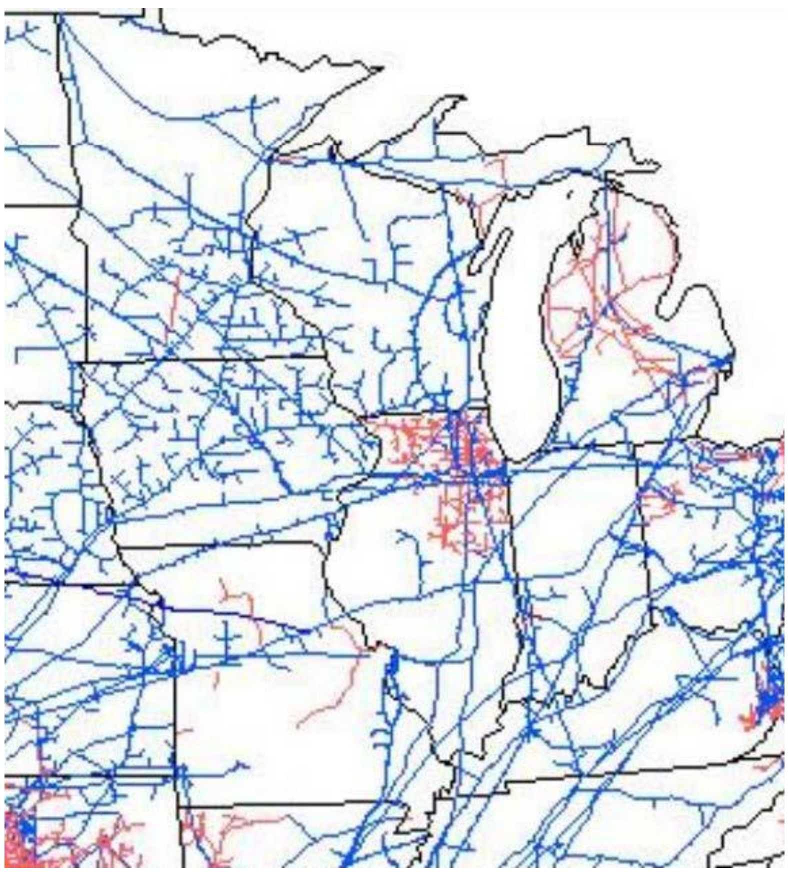

Figure 9 - Midwest Natural Gas Pipelines (Blue - interstate, Red - intrastate)[11]

[11] "Blending Hydrogen into the Natural Gas Pipeline Network" - https://www.nrel.gov/docs/fy13osti/51995.pdf

Ammonia pipelines map

Ammonia can serve as a hydrogen carrier and can be transported at large scale through the ammonia pipeline systems of the US. Ammonia cracking enables ammonia to serve as a medium for transporting hydrogen. There are over 2,000 miles of ammonia pipelines currently in operation in the U.S. The NuStar Energy pipeline runs from the Gulf Coast to the midwestern corn belt region, transporting about 1.5 million tons of anhydrous ammonia annually. The 1,100 mile Magellan Midwestern Partners pipeline servicing the Plains states was decommissioned in 2019. See Figure 10 below for a map of the major ammonia pipelines in the Midwest, as well as industrial ammonia and fertilizer production facilities.

Figure 10 - Map of Midwestern Nitrogen (N- Ammonia, Urea, Fertilizer) facilities and proximity to Pipelines (Purple - NuStar, Yellow - Magellan) and or river ports[12]

FERC interstate pipeline considerations

A dedicated hydrogen pipeline is not subject to the Natural Gas Act, and therefore not subject to Federal Energy Regulatory Commission (FERC) jurisdiction. There is no federal authority to approve the siting of dedicated hydrogen pipelines, although federal approvals

[12] "Fertilizer Production," Argus Media - https://www.argusmedia.com/en

may be required for siting of specific pipeline segments.[13] For example, authorization for water crossings from the Army Corps of Engineers, permission for a route that crosses federal lands from the Bureau of Land Management, or consultation with Native American tribes to identify historic or cultural sites. In this respect, hydrogen pipelines are similar to oil pipelines and intrastate natural gas pipelines, which also are under state jurisdiction. Developers seeking to construct hydrogen pipelines must seek separate approvals from the individual states through which the pipeline would pass, with each state having its own distinct statutory requirements for such approval. This approach is in contrast to the siting of interstate natural gas pipelines, the siting of which must be approved by FERC under Section 7(c) of the Natural Gas Act. Since hydrogen is not regulated within the Natural Gas Act, however, dedicated hydrogen pipelines are subject to environmental, land use, and rights of way laws.

Construction and operation of hydrogen infrastructure is subject to pipeline safety regulations administered by The Pipeline and Hazardous Materials Safety Administration (PHMSA), which operates within the Department of Transportation (DOT). PHMSA's focus is public safety; its charter is to prescribe "minimum safety requirements for pipeline facilities and the transportation of gas." (49 CFR Part 192.1.) PHMSA has regulated pipelines in the United States since 1970 under its authority to regulate “gas.”[14] (49 CFR Part 192.) Those regulations define "Gas" as "natural gas, flammable gas, or gas which is toxic or corrosive." (49 CFR Part 192.3.)

Many studies in the early-to-mid 2000s addressed the future of hydrogen infrastructure in the United States as the country looked to hydrogen as an alternative to oil for the transportation sector, but no specific authority for economic regulation of hydrogen infrastructure has yet been written into law.[15] However, hydrogen pipelines may fit within the regulatory framework for “miscellaneous” non-oil, non-gas, non-water pipelines administered by the Surface Transportation Board (STB) under the Interstate Commerce Commission Termination Act (ICCTA).[16] There also has been some suggestion that as hydrogen is increasingly used as a fuel, FERC may have jurisdiction under the “old” Interstate Commerce Act (ICA). 49 U.S.C. App. § 1, *et seq.* (1988).

[13] “Pipeline Transportation of Hydrogen” - https://crsreports.congress.gov/product/pdf/R/R46700

[14] https://primis.phmsa.dot.gov/comm/hydrogen.htm
[15] https://www.energy.gov/sites/prod/files/2014/03/f11/delivery_infrastructure_analysis.pdf
[16] https://www.venable.com/-/media/files/publications/2021/05/whitepaper_hydrogen_pipelines.pdf

Gas pipeline blending considerations

Clean hydrogen can be injected into the existing natural gas pipeline system, producing a blend that reduces the carbon footprint of whatever end-use application uses the hydrogen. For example, burning a blended fuel within a commercial office building's natural gas boiler will lower the carbon footprint for heating the building.
Various end-use and transport technical issues have been raised and are under investigation by a variety of research organizations, including Chicago-based Gas Technology Institute and the National Renewable Energy Laboratory. For example, maximum hydrogen blend percentages for safe operation of home appliances such as stoves is under review.

Safe transport within pipelines is another consideration. Hydrogen is the smallest molecule in the universe, which allows it to leak much more easily than other gasses. Small cracks along pipelines, or gaps found in aging pipe flanges and gaskets may provide leak points for the escape of flammable hydrogen. Additionally, technical reviews have been performed regarding the concern about embrittlement - the tendency for hydrogen to cause certain pipeline materials to become more brittle and prone to failure. Solutions such as pipe coatings have been developed, and certain pipeline materials may be more prone to embrittlement than others. Work is underway to address these issues, especially within Europe where there is in fact a large-scale effort underway to repurpose the natural gas transmission network for large-scale hydrogen delivery.[17]

There are several ongoing pilot projects around the United States. New Jersey Resources (NJR) began operating its green hydrogen pilot project in 2021, using solar to power electrolyzers and produce hydrogen for blending into existing natural gas pipelines. The HyBlend project is a large study of hydrogen pipeline blending, led by the National Renewable Energy Lab along with 20 industrial partners and 5 other national labs - Sandia, Pacific Northwest National Lab, Oak Ridge, National Energy Technology Lab, and Illinois's Argonne National Lab. The team will investigate three areas- technical compatibility of blending with the existing pipeline system and its materials, lifecycle emissions of a blending approach, and the techno-economic analysis of hydrogen blending.[18]

17 https://www.acer.europa.eu/events-and-engagement/news/repurposing-existing-gas-infrastructure-pure-hydrogen-acer-finds

18 https://www.energy.gov/eere/fuelcells/hyblend-opportunities-hydrogen-blending-natural-gas-pipelines

Underground Storage Options

Underground salt formations are generally considered the most viable option for underground storage of large hydrogen volumes because the risk of leakage is very low, and the lack of oxygen within underground caverns prevents combustion. Hydrogen storage has been performed safely since the 1980's, beginning with Chevron's Phillips Clemens Terminal in Texas. Solution-mined salt caverns are developed through the hollowing out of natural underground salt formation via water injection and brine removal. Figure 11 shows that Michigan has natural geology that is beneficial for storing hydrogen. Connecting Michigan hydrogen storage into a broad Midwestern piping network should be considered as a central aspect of a Midwestern hydrogen strategy, especially with proximity to the major potential hydrogen demand at the southern tip of Lake Michigan. While future salt formations may be discovered in surrounding states, only Michigan has the large-scale proven and characterized salt available for project development.

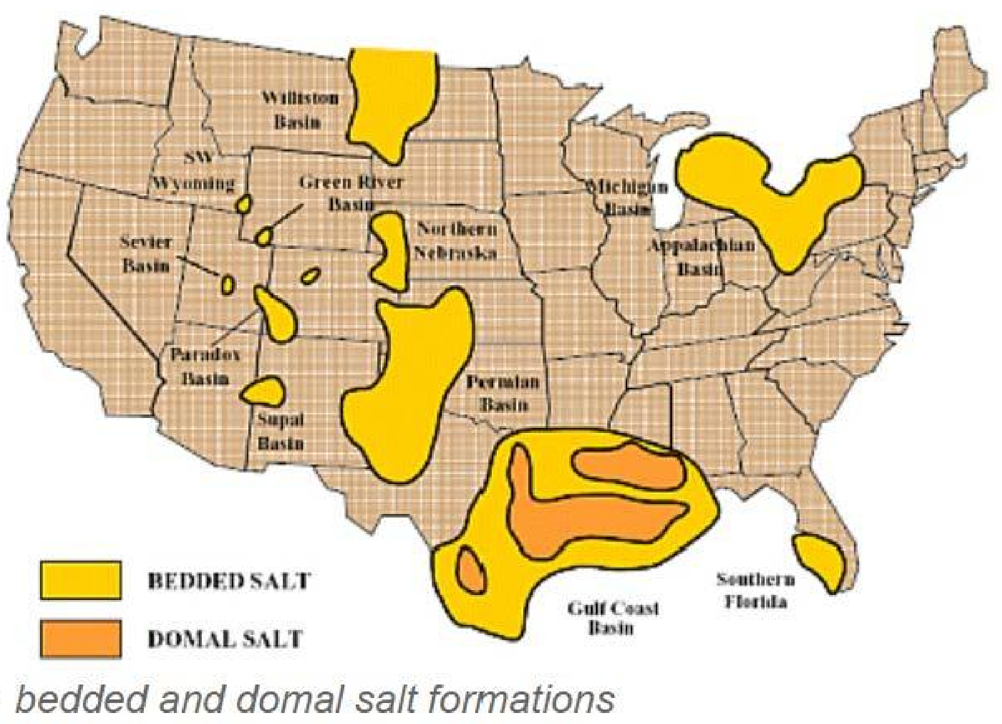

Figure 11 - Michigan Salt Formations For Potential Midwestern Hydrogen Storage[19]

[19] "Cavern Roof Stability in Bedded Salt" - https://netl.doe.gov/node/2638

Michigan salt is bedded salt, in comparison to the domal salt of the Gulf Coast. Generally, the shape of the bedded salt formations requires that the storage domes are created as sideways-oriented storage caverns deep underground. These are generally more expensive than domal salt, which can be developed into vertical caverns. Nevertheless, bedded salt formations as found in Michigan are a viable option for storing large volumes of hydrogen underground.

Section 5: Hydrogen End Use Considerations

Review of current end-use adoption forecasts

Although increased supply and buildout of transport infrastructure are critical to support increased consumption of clean hydrogen, the competitiveness of end-use applications will be the true driver of the market. Individual decisions will be made by public and private capital program managers and individual consumers. They will evaluate the available technology for a given application and select the technology that likely has the lowest total cost of ownership and simplest perceived operation and maintenance, all while helping to achieve decarbonization goals.

A variety of analyses have been performed to forecast potential costs for hydrogen end-use. Two prominent reviews are highlighted below as a snapshot of current thinking. The reader may review each in greater depth through the original sources.
First, McKinsey has reviewed multiple end-use applications in its work for the Hydrogen Council, a global consortium of energy provider and services companies. McKinsey analyzed the potential total cost of ownership for decarbonized hydrogen feeding a hydrogen-based technology, such as hydrogen-fueled fuel cell electric vehicle (FCEV) trucks in heavy duty applications, or decarbonized replacement of fossil-based hydrogen feedstock in ammonia production.

See Figure 12 below for a distribution of cost competitiveness. Technologies toward the right side of the chart are expected to be more cost competitive compared to a conventional alternative, such as FCEV's being more competitive against diesel long-haul trucks. Technologies toward the top of the chart are expected to be more competitive compared to another low carbon alternative, such as FCEV's being more competitive against battery electric vehicles (BEV's). McKinsey's analysis would indicate that the technologies and markets to the upper right quadrant are therefore most likely to be cost competitive first.

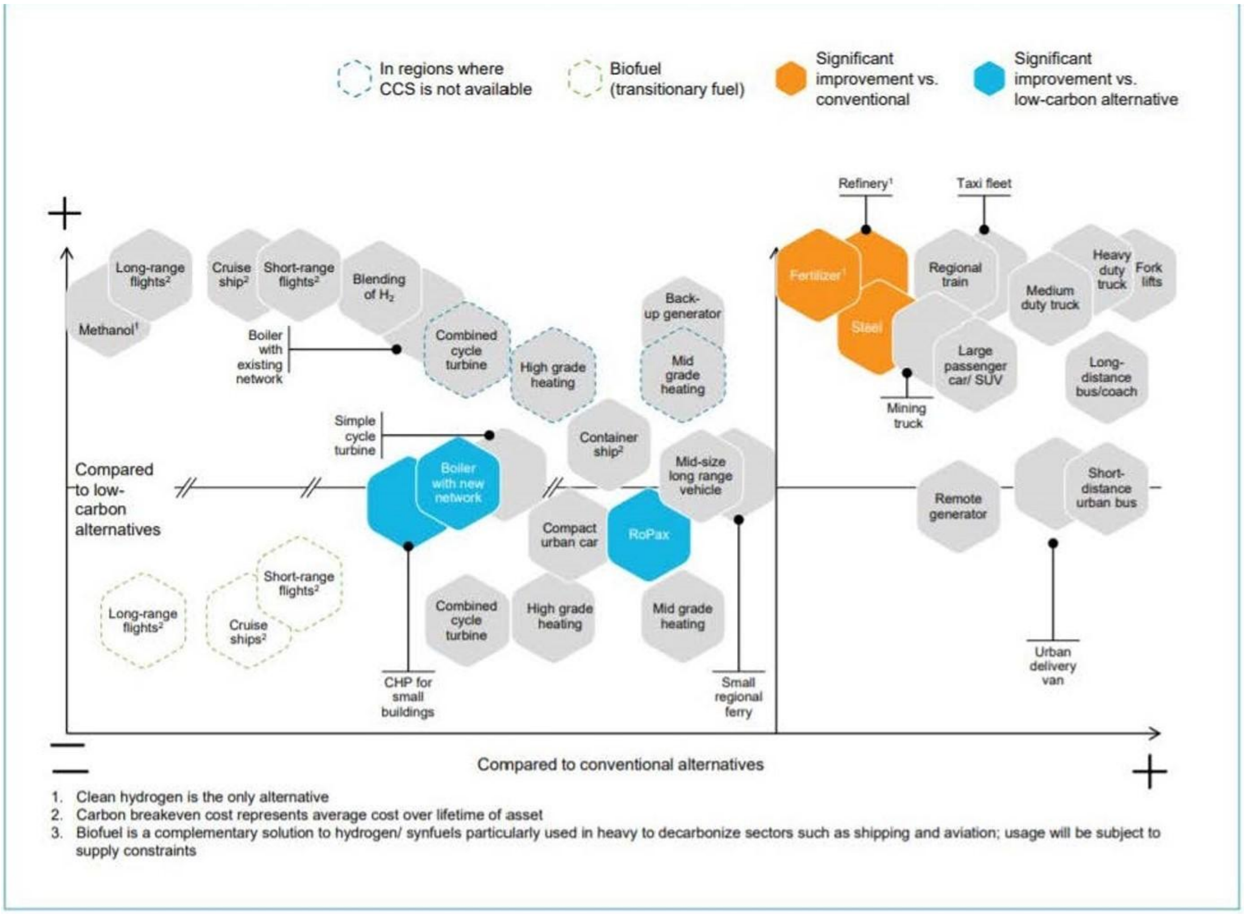

Figure 12 - 2030 H_2 Competitiveness per End Use Application[20]

Second, Bloomberg New Energy Finance founder Michael Liebreich, currently CEO of Liebreich Associates issues the "Hydrogen Ladder" shown below in Figure 13. The Hydrogen Ladder demonstrates the expected competitiveness of end-use applications in the coming decades. At the top, he places the unavoidable applications such as fertilizer/ammonia and /petrochemical (i.e. - hydrogenation and hydrocracking). These applications currently utilize hydrogen in large quantities globally, and this hydrogen is almost unanimously produced from fossil fuels through SMR. Replacing this existing hydrogen demand with clean, decarbonized hydrogen is the most immediate application and is a strong opportunity for the Midwest.

Liebreich argues that other heavy transport such as shipping may be best approached through hydrogen in ammonia form, an opportunity for a location such as the Illinois

[20] https://hydrogencouncil.com/en/hydrogen-insights-2021/

International Port District. At the low end of the ladder are the applications he views as uncompetitive. One example is home heating via hydrogen when the alternative, electric heat pumps, is available and gaining acceptance. He also notes fuel-cell cars as an unlikely application when battery electric vehicle cars have begun gaining widespread national acceptance.

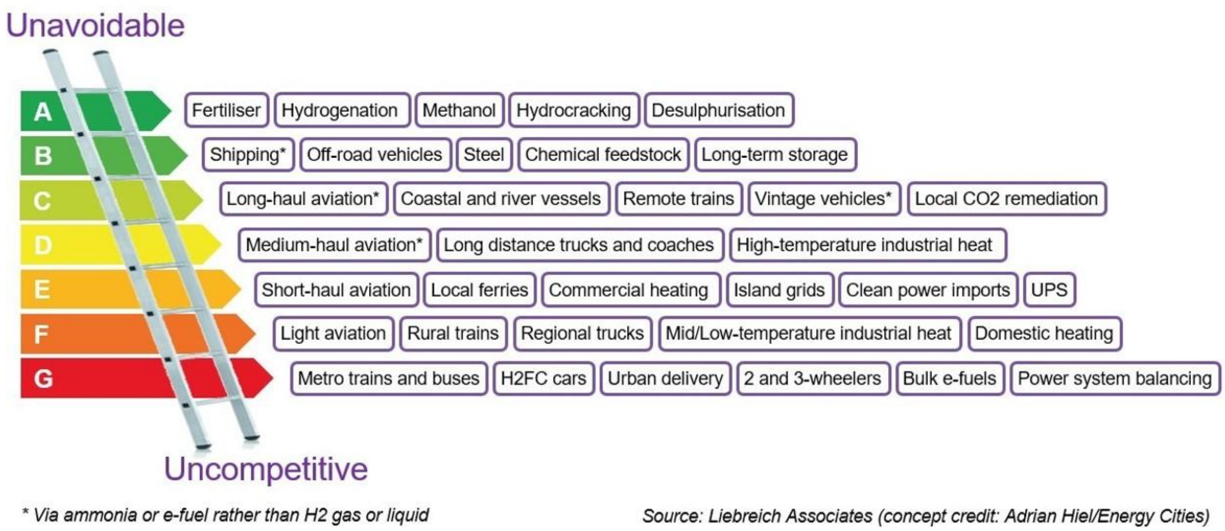

Figure 13 - Liebreich Associates Hydrogen Ladder, Version 4.01[21]

Although no single analysis is a predictor of the future, both agree on the use of clean hydrogen to replace fossil-based hydrogen and decarbonize the ammonia, petrochemical, and potentially steel industries of the Midwest. For these reasons, they are likely the core offtakers of a Midwestern hydrogen hub. The Great Plains Institute reached a similar conclusion in their *Atlas of Hydrogen Hubs* publication, noting the importance of the concentrations of industrial offtakers especially within Illinois but spreading as well to Indiana and Iowa. See Figure 14 below.

[21] https://www.linkedin.com/pulse/clean-hydrogen-ladder-v40-michael-liebreich/

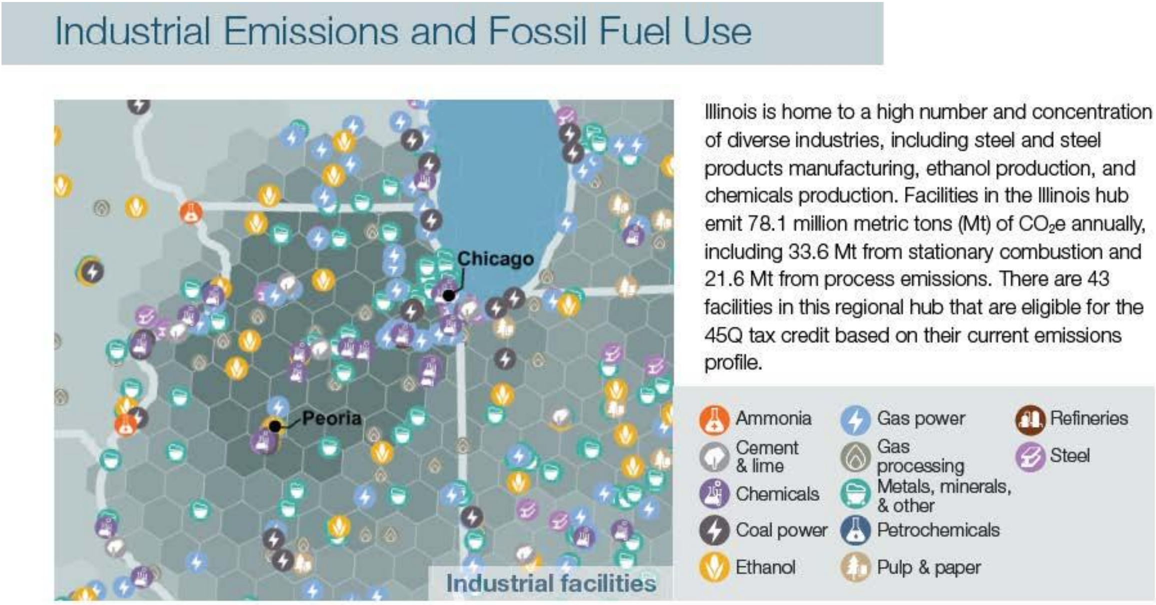

Figure 14 - Potential Heavy Industry Hydrogen Consumers in a Midwestern Hub, GPI[22]

Regional Heavy industry

<u>Regional Ammonia</u>

China is currently the largest ammonia producer, accounting for 29% of global production in 2019, followed by Russia (10%), the United States (9%), the Middle East (9%), the European Union (8%) and India (8%).[23] U.S. production of ammonia was estimated to be about 17 million metric tons in 2019. Ammonia is produced by 16 companies at 35 facilities in the United States. Most ammonia plants are in states along the Gulf Coast region due to the availability of low cost natural gas.

Illinois-based (Northbrook) CF Industries is the largest producer of ammonia in the U.S. accounting for approximately 40% of the total U.S. production. However, Illinois itself does not have significant production facilities. Other major producers include Nutrien, Koch Industries, OCI, Yara, and Dyno Nobel. The largest plant in the U.S. is in Donaldsville, LA, which produces nearly one-fourth of the total U.S. production. The Upper Mississippi, Illinois River, and Ohio River provide miles of navigable river to bring ammonia into the Midwest. The vast majority of the ammonia is 'imported' from the New Orleans area via barge or pipelines. The imported ammonia is typically produced at one of the following

[22] "An Atlas of Hydrogen Hubs" - https://carboncaptureready.betterenergy.org/analysis/
[23] https://www.ammoniaenergy.org/articles/decarbonising-fertiliser-production-in-iowa-via-ccs/

facilities: CF's Donaldsonville, LA; CF's Verdigris, OK; Nutrien's Geismar, LA; or a series of ammonia plants in Trinidad and Tobago that are owned by Yara, Nutrien, Koch, and CF.

Large ammonia plants in the midwestern region are in Port Neal, IA, (CF Industries), Weaver, IA, (Iowa Fertilizer Co.), East Dubuque, IL (Coffeyville Resources, CVR) and Fort Dodge, IA (Koch Industries, Inc.), and Wever, IA (OCI). The OCI and CVR plants are located on the Illinois/Iowa border. All participate in manufacturing hydrogen in North America through steam methane reformation, converting the hydrogen to anhydrous ammonia, storing anhydrous in large volume storage tanks (> 15,000 short tons of anhydrous ammonia), and allowing their customers to distribute full truck loads (20 tons) from wholesale terminals to the corn producing farms.

Illinois is currently a top three consuming state for anhydrous ammonia, not including industrial use. The vast majority of ammonia consumption within the state is direct injection into the soil to provide the nitrogen nutrient to corn. The top consuming ammonia states are, in order, Iowa, Illinois, Nebraska, Indiana, and North Dakota. Illinois currently consumes roughly 1 million short tons of ammonia in anhydrous form for agriculture consumption almost exclusively used for fertilizer application on corn producing farms. Since hydrogen composes 17.5% by weight of ammonia, Illinois currently consumes 159,000,000 kg of H_2 in the agriculture sector.

Regional steel production

Carbon plays three vital roles in steelmaking serving as a fuel for heating, a reducing agent, and an alloying agent, with coke being the major carbon source. Steelmaking generates about 1.85 metric tons of CO_2 per metric ton of steel produced. Worldwide, the steel industry produced 1.86 billion metric tons of steel in 2020 accounting for about 7% of the world's energy use and generating over 3 billion metric tons of CO_2, corresponding to 7-9% of all human-made greenhouse gas emissions. The U.S. steel industry produces about 80-90 million metric tons annually, accounting for ~2% of the U.S. energy use and ~4% of the U.S. CO_2 emissions. Given the projected growth in global steel demand, it has been estimated that the steel industry must reduce its CO_2 emissions from 1.85 to 0.02 metric tons of CO_2 per metric ton of steel produced by 2050.

With the major steel production capacity along the southern tip of Lake Michigan, Indiana has been the top steel-producing state for the last 40 years.[24] Currently there are three major integrated steel mills located in northwest Indiana. The Gary Works, located in Gary,

[24] https://www.insideindianabusiness.com/articles/indiana-again-tops-us-in-steel-production

IN and owned by Pittsburgh-based US Steel, is one of the largest fully integrated steel mills in the U.S. with an annual production capacity of 7.5 million tons. The Indiana Harbor Works, located 20 miles southeast of Chicago in East Chicago, IN and owned by Cleveland-based Cleveland-Cliffs, is the largest fully integrated steel mill in the U.S. with an annual production capacity of 9.5 million tons. The Burns Harbor Works, located 50 miles southeast of Chicago in Burns Harbor, IN, has an annual production capacity of nearly 5 million tons. Burns Harbor is also owned by Cleveland-Cliffs.

There is a growing interest in the steel industry to use hydrogen for reducing iron ore to metallic iron as an option for reducing CO_2 emissions in the steel industry. Currently, there is no commercial steel making process that solely employs hydrogen as the reducing agent. The direct reduced iron (DRI) process, developed by Midrex and HYL-Energiron, employs a mixture of H_2 and CO, referred to as syngas, produced by reforming natural gas as the reducing agent. There are about 100 DRI processes deployed worldwide. When integrated with the electric arc furnace process, CO_2 emissions are reduced by 35-40% compared to the conventional blast furnace route.

There are a number of processes being demonstrated in Europe that solely use hydrogen (>95% hydrogen) as the reducing agent:

- ArcelorMittal is demonstrating a modified DRI process at its Hamburg Germany plant that will use a reducing gas containing more than 95% hydrogen. The hydrogen is produced by steam reforming methane and separating the hydrogen from the carbon monoxide/carbon dioxide. The plant is expected to produce 100,000 metric tons of iron by 2025.
- Swedish steelmaker, SSAB, is developing HYBRIT (Hydrogen Breakthrough Ironmaking Technology) which replaces coke with hydrogen and attempts to decarbonize every step of the steelmaking process. Initial demonstrations used hydrogen produced by reforming natural gas but are now investigating using hydrogen produced by electrolyzing water using wind-generated electricity. SSAB expects the process to be in commercial production by 2026 with a carbon footprint of less than 5% of that of the conventional steelmaking process.
- Austrian steelmaker Voestalpine is developing a hydrogen plasma process for reducing iron ore. The process uses hollow graphite electrodes in a conical reactor to generate the plasma. The major drawback with these new process technologies is that they cannot be deployed in existing blast furnaces.
- German steelmaker thyssenkrupp Steel is investigating the direct injection of hydrogen into a blast furnace using the existing tuyeres for introducing the hydrogen.

The amount of hydrogen needed for the reduction process varies with the degree of hydrogen preheating. The reduction of iron ore with hydrogen is an endothermic reaction whereas the reduction of iron ore with carbon monoxide is an exothermic reaction which is why the hydrogen is preheated. To fully reduce one metric ton of iron ore requires between 0.08 to 0.12 metric tons of hydrogen depending on the technology employed, the reaction temperature, and the reaction off-gas available for preheating the hydrogen assuming no excess hydrogen is needed.

Regional petroleum production

Petroleum refineries are the largest consumer of hydrogen in the U.S., consuming 68% of the hydrogen produced annually (about 10 million metric tons of hydrogen). Hydrogen consumed in petroleum refining comes from three different sources: hydrogen purchased from merchant plants, hydrogen produced as a by-product during naphtha reforming, and hydrogen produced on or near the site by steam reforming natural gas.

There are three major refineries in the Chicagoland area:

- The BP Whiting refinery located in northwestern Indiana is the largest refinery in the Midwest with the capacity to process 440,000 barrels of crude oil every day. Whiting's hydrogen demand is approximately 200 million cubic feet per day (mmscfd).
- The ExxonMobil Joliet Refinery located about 40 miles southwest of Chicago in Channahon, IL, has the capacity to process 250,000 barrels of crude oil every day.
- The CITGO Lemont Refinery located in Lemont, IL, has the capacity to process 177,000 barrels of crude oil every day.

All three refineries currently purchase merchant hydrogen produced by steam reforming of natural gas without carbon capture. According to the U.S. Department of Energy Energy Information Agency, there is 120 mmscfd of merchant H_2 production capacity at the Whiting Refinery, 60 mmscfd of merchant H_2 production capacity at the CITGO Lemont Refinery, and 18 mmscfd of merchant H_2 production capacity at the ExxonMobil Joliet Refinery.

Regional Heavy transport

Chicago is one of the world's major multimodal hubs, with traffic passing through via barge, rail, truck, and air. Below we review regional considerations centered around these heavy transportation actors and their intersection at the Illinois Port District.

Hydrogen Considerations in the Maritime Industry

Although the marine propulsion technologies utilizing hydrogen are currently in the pre-commercial development and demonstration stages, it is expected that hydrogen fuel cell vessels will be capable of transporting sizable portion of the goods currently moved by diesel-powered boats in the next 10-20 years. Unlike passenger vehicles, or some medium- and heavy-duty trucks that can be practically and powered by battery-electric technologies, inland waterway vessels will not be easy to electrify due to the unique and very demanding duty cycles and the amount of energy storage required onboard. Additionally, current development is progressing for maritime engines capable of burning ammonia as fuel. German engine supplier MAN has plans to install an ammonia engine by 2024.

A typical workboat is powered by 1,000 – 4,000 hp engines, and each carries up to 100,000 gallons of diesel fuel onboard. These do not have a practical pure-electric solution. Hydrogen or ammonia have high potential to displace the diesel fuel currently powering the inland workboats. The current cost of hydrogen and lack of hydrogen or ammonia fueling infrastructure at ports are current barriers to adoption. Other barriers slowing down the adoption of zero-emission technologies in the marine industry are: very long asset turnover cycles (30-50 years); apprehension towards new, unproven technologies, a lack of regulatory roadmap, and lack of incentives. This current white paper may bring focus to this issue for the region.

Port Districts may act as large “anchor tenants” to spur the development of a regional hydrogen economy. Ports are the unique nexus of multiple modes of transportation, energy consumers, pre-existing infrastructure and high traffic. For these reasons, ports are an excellent scalable blueprint for hydrogen hubs. Ports of Los Angeles and Long Beach, with years of State of California funding support, have been evaluating and demonstrating multiple hydrogen-based technologies, such as drayage trucks, cargo-handling equipment and hydrogen fueling stations. Hydrogen-powered vessel development projects have been kicked-off in the last couple years and are ongoing, however there are none currently in operation.

This concept is being evaluated by multiple ports globally, such as Port of Auckland in New Zealand, Port of Rotterdam in Netherlands or Port of Cromarty Firth in Scotland. Figure 15 below illustrates the concept in Scotland.

Figure 15 Concept of Hydrogen Hub Centered Around Marine Port

The Illinois International Port offers a unique opportunity in the heart of the continental United States, with access to robust energy sources, industrial energy consumers (steel, ammonia, petrochemicals), transportation energy users (intermodal terminals, rail, marine and on-highway transport), and airports. The IIPD and its tenants also have high potential to consider large-scale use of hydrogen for barges, rail, and heavy trucking that interfaces with the port. The location within 50 miles of all the major steel production facilities along the southern tip of Lake Michigan provides an ideal concentration of potential hydrogen demand in one geographic location.

The Illinois International Port should be clearly understood by regional hydrogen suppliers. The Port is one of the key reasons that Chicago is one of the world's busiest multimodal hubs with major potential for decarbonization of its operations.

The Port District has a rich history and has been an important part of the industrial and economic development of the City of Chicago and the surrounding areas. The Port District owns three locations in the southeast side of Chicago totaling over 1600 acres - Iroquois Landing, Lake Calumet Harbor, and Harborside International Golf Center.

As an inland waterway port, the IIPD provides connectivity to the waterways of the Great Lakes as well as the Mississippi River System via the Chicago Area Waterway System

(CAWS). Traffic at the IIPD is split between domestic and international traffic. Domestic traffic is primarily barge traffic traveling via the Mississippi River System. International traffic at the IIPD primarily consists of Great Lakes vessels and barges from Canada, as well as vessels from Eastern Europe that access the Great Lakes through the St. Lawrence Seaway. It is feasible to access the IIPD via the Gulf of Mexico by transferring cargo to barge to traverse the Mississippi River system.

The Port District has 28 miles of coastline along Lake Michigan. The lake is part of Marine Highway 90. Additionally, the following navigable waterways flow through the port district - the Chicago Sanitary & Ship Canal, the Chicago River, the Chicago River North Branch, and the Calumet River and Channel. These waterways are part of Marine Highway 55. See Figure 16 below for the various IL Public Port Districts, including the IIPD. Although IIPD is the largest, these other ports also provide the opportunity to build hydrogen or ammonia fueling infrastructure. More broadly within the Midwest, other major ports exist such as the twin ports of Duluth-Superior (Minnesota/Wisconsin), which together are considered the largest freshwater port in the world.

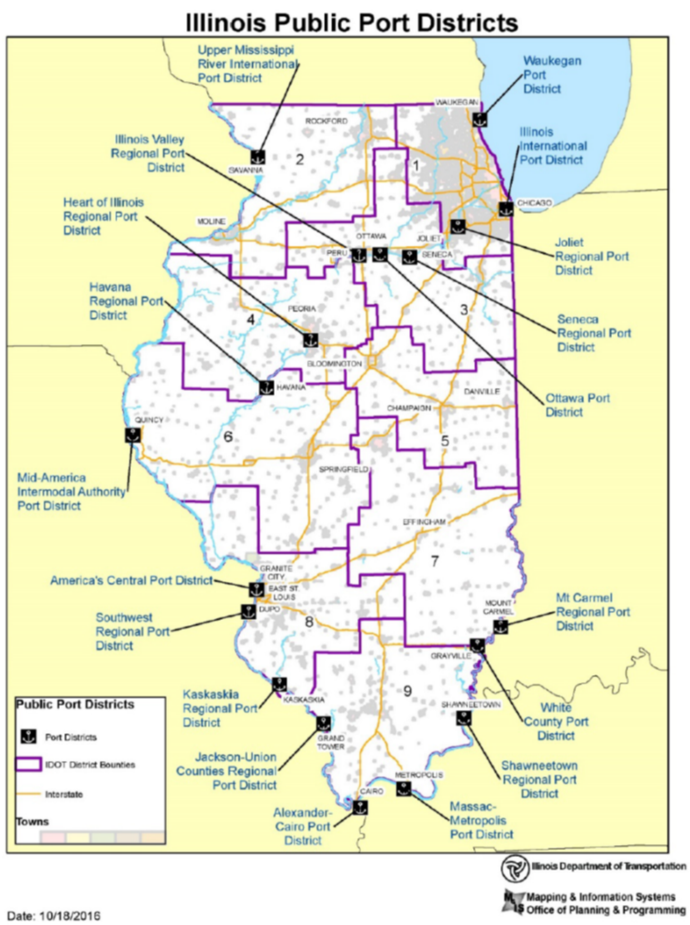

Figure 16 - Illinois Port Districts

The port also has access to all of North America via rail and interstate highway connections. Several interstates, state routes, and US highways traverse the port district. Included within these routes are a total of 20.8 Critical Urban Freight Corridor miles within the port district.

The IIPD has access to all North American markets and ports via rail. The Lake Calumet Area is directly served by the Norfolk Southern (NS) railroad on the east side of the port facilities and by the BNSF Railway Co., CSX Transportation, Grand Trunk Corporation (Canadian National's operations), Norfolk Southern, Soo Line Corporation (Canadian Pacific's operations), and Union Pacific Railroad with direct access provided through the Class III rail operator, Chicago South Shore and South Bend (CSS), on the south side of Lake Calumet. Iroquois Landing is a Canadian National (CN) transload and distribution center. Through these connections, rail users at IIPD facilities have access to the Chicago Rail Terminal, where six of the seven Class I railroads operate.

In 2017, approximately 760 million tons of goods valued at $1.6 trillion were transported to, from, through, and within Cook County, with truck and rail freight comprising 93 percent of total tonnage and value. The Chicago Area Waterway System (CAWS), which accounted for seven percent of total traffic by weight, had a disproportionate share of inbound traffic due to its role in bringing in raw materials such as steel, lumber, and aggregates to the region. About six million tons worth $9 billion dollars moved on the waterway system through Lake Calumet and Calumet Harbor combined, where the IIPD is located.

There are over 50 private operators providing a variety of freight and maritime services, including shipments of bulk products (e.g., food products, grain), aggregates (e.g., limestone, cement), metals, general warehousing and storage, and mooring/fleeting services. Due to these multimodal connections, users of the IIPD have multiple modes through which to access all major markets of the world.

Hydrogen considerations in long-haul trucking

Trucking is the most important freight mode in Illinois, responsible for transporting 54.1 percent of the total Illinois freight tonnage.[25] The interstate network handles the bulk of the truck traffic in Illinois, with more than half of the interstate miles carrying truck percentages at 25 percent or greater. Tractor-trailer combination trucks traveled close to 5.6 billion

[25] https://idot.illinois.gov/Assets/uploads/files/Transportation-System/Reports/OP&P/Freight/IDOT_Freight_Plan_ExecSummary_v9.pdf

miles[26] across Illinois in 2020, of which estimated 2.1 billion were carrying cargo passing through the state. This equates to 350 million gallons of diesel, which can be displaced by 262,500 tons of hydrogen on an annual basis, for a through-state long-haul transportation alone. The long-haul transport originating in Illinois, or arriving in Illinois could account for another 150,000 tons of hydrogen on an annual basis.

Establishing a robust hydrogen production and fueling infrastructure along the interstate network could capture a significant portion of this energy demand and production. Although it is difficult to speculate on the technology adoption and transition scenarios, it is widely expected that strong policy support, technology development and infrastructure investments can lead the heavy-duty transportation sector to a 100% zero-emission transition by 2045-2050. Maintaining early policy and financial incentives will help the industry reach a self-sustaining tipping point due to increased production and falling costs. Retaining that support will continue to accelerate the transition ahead of the 2045-2050 time frame.

Within the greater Midwest region, hydrogen production for heavy trucking is already under development. The Wabash Valley Resources project - the repurposing of an old gasification plant located 175 miles south of Chicago in West Terre Haute, IN - is relevant to Chicago's regional multimodal conversation. Phoenix-based fuel cell electric vehicle (FCEV) truck manufacturer Nikola motors has announced the investment of $50M in the project in order to develop a steady supply of hydrogen for expanded Midwestern hydrogen FCEV truck fleet presence. Wabash Valley produces a carbon-negative hydrogen through the use of biomass. Additionally, St. Louis-based Anheuser-Busch previously announced a large FCEV hydrogen truck order from Nikola and utilized a Nikola Tre FCEV to deliver beer for distribution within the Los Angeles region ahead of the 2022 Super Bowl. NY-based FCEV truck manufacturer Hyzon Motors built its Innovation Center and fuel cell assembly plant in the Chicago suburb of Bolingbrook.

<u>Hydrogen considerations in buses</u>

There are 87 fuel cell buses in operation in the U.S. with about two-thirds of the buses operating in California. In the Midwest, Ohio's Stark Area Regional Transit Authority (SARTA) has 20 hydrogen fuel cell buses in operation. The Illinois Champaign-Urbana Mass Transit District County bus system has two hydrogen fuel cell buses currently in operation. In late 2020, CUMTD installed a 1 MW onsite electrolyzer system fed by an onsite solar field, with onsite compression and storage of 7500 psig hydrogen. This operational system

[26] https://idot.illinois.gov/Assets/uploads/files/Transportation-System/Reports/OP&P/Travel-Stats/2018_ITS.pdf

self-produces its own green hydrogen and feeds two fuel cell buses, with plans to expand and add another 13 in the next 5 years. The general setup illustrates the potential for a decentralized model of hydrogen production. On the other hand, Chicago Transit Authority (CTA) has pledged to electrify its bus fleet by 2040, illustrating the ongoing competition between various transportation decarbonization options even within the same state.

Hydrogen considerations in freight rail

The northeastern portion of Illinois is the hub of the nation's railway system. All seven Class I railroads, as well as 38 other railroads, operate in Illinois. Rail accounts for 37% of all freight movement in Illinois. The rail industry faces very similar barriers to decarbonization as described above for the marine industry. Railroad operators and Federal Railroad Administration (FRA) , the government institution responsible for regulating the railroad industry, are in general very conservative when adopting new technologies. Safety considerations are paramount. Nevertheless, the last few years have demonstrated significant progress towards evaluation and adoption of low-carbon and zero-emission technologies in rail transport.

See Figure 17 below for distribution intermodal rail facilities in Illinois, including 20 within the Chicago area. Switcher locomotives at these intermodal yards may be the best candidates for hydrogen conversion in a short-term (5-10 years), although this will require coordinated policy support and financial incentives. A robust Illinois hydrogen supply, capable of feeding these intermodal yards as well as the other potential hydrogen offtakers in the Chicagoland area, would enable transition to fuel cell electric locomotives.

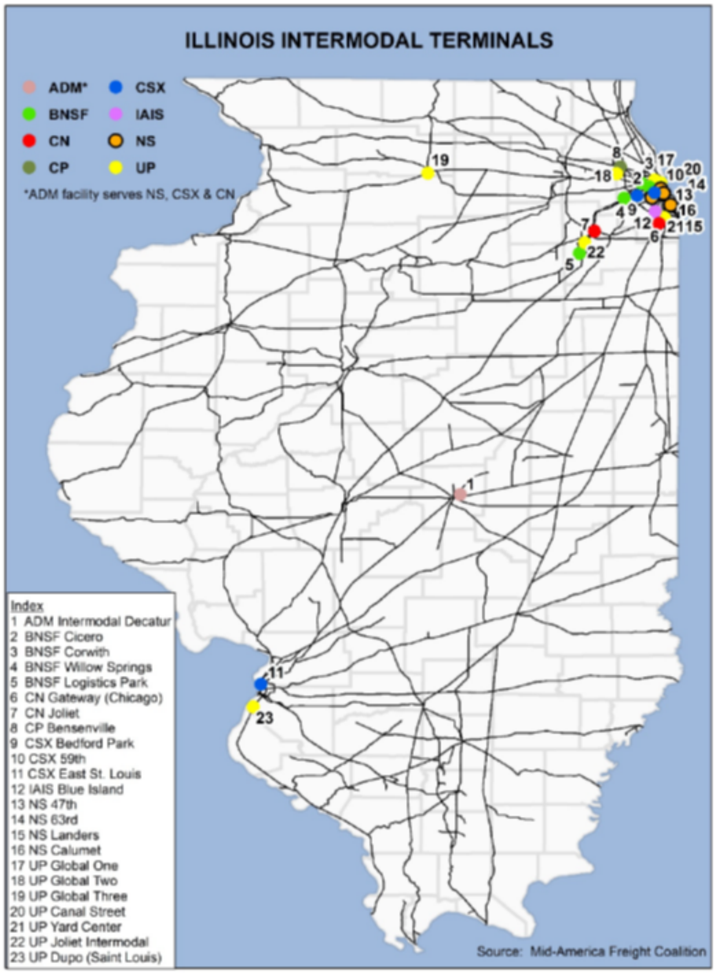

Figure 17 - Intermodal Rail Yards in Illinois

Technological developments and demonstration projects in the rail industry are progressing more quickly than the marine industry, with numerous railroads (nationally and globally) testing and operating battery-electric and hydrogen fuel-cell locomotives. Due to infrastructure limitations, the early adopters will be regional railroads operating switching locomotives. They can rely on local fueling solutions and control their own risks. Simultaneously, long-haul railroads will include prototype locomotives in a consist of 4-5 locomotives.

In the near term, diesel-powered locomotives are expected to continue serving as primary or redundant traction power, but Indiana-based Cummins Engine was the world's first and still only company to develop and implement fuel cell drive trains in commercial operation. Partnering with French railcar manufacturer Alstom since 2016, Cummins has powered the Alstom Coradia iLint trains which have provided commercial service in Germany since 2018.

Cummins broke ground on a German fuel cell production facility in 2021 to provide fuel cells for hundreds of additional hydrogen locomotives throughout Europe.

Currently, U.S. locomotive manufacturers Progress Rail (formerly EMD) and Wabtec (formerly GE) are also developing hydrogen fuel cell prototype locomotives. The Canadian Pacific Railway working with Canadian fuel cell manufacturer Ballard recently converted an existing diesel locomotive to a hydrogen fuel cell locomotive. This locomotive is currently in operation in Canada. Canadian Pacific plans to convert two more diesel locomotives to hydrogen fuel cell locomotives. Illinois-based Gas Technology Institute (GTI) is working with the Sierra Northern Railway to convert one of its diesel switcher locomotives to a hydrogen fuel cell locomotive for use at the Port of Sacramento, CA.

Hydrogen considerations in aviation

The global aviation sector contributes approximately 2-3% of global CO_2 emissions, and decarbonization is a key strategic focus of all major airlines. The use of pure hydrogen aircrafts is under development and is attracting the attention of major operators. For example, ZeroAvia received $35M investments from both United Airlines and Alaska Air Group in late 2021. However, pure hydrogen aircrafts are in the early stages of design and pilot testing. These are not yet globally scalable solutions.

The more near-term role for hydrogen in the aviation sector is through manufacturing of Sustainable Aviation Fuel (SAF). SAF is a “drop-in fuel,” liquid fuel that can be blended with existing jet fuel without any modifications to existing aircraft design. It can therefore be deployed through the existing global aircraft fleet, providing an immediate carbon footprint reduction if it can be produced at competitive prices. SAF currently accounts for only 0.1% of all global fuel consumed, both because supply is insufficient and pricing is not yet competitive.[27] DOE, DOT, and the USDA jointly launched the Sustainable Aviation Fuel Challenge in 2021 to provide government-wide coordination for increased production and reduced cost.

The particular relevance of SAF to a Midwest hydrogen economy is its production method. SAF can be manufactured from a variety of feedstocks, including municipal solid waste, used cooking oil, and a variety of plants. Additionally, SAF can be produced from clean hydrogen plus captured CO_2. As home to both the 6th busiest airport in the world by seats (O’Hare) and a second major airport (Midway), decarbonization of Chicago’s aviation sector also provides the potential for large SAF demand within a Chicago-area hydrogen hub.[28]

[27] https://www.iea.org/reports/aviation
[28] “Busiest Airports in the World” - https://www.oag.com/busiest-airports-world

Given the variety of other regional hydrogen production and carbon capture projects under discussion, it follows that the Midwest has the potential to become both a major producer and consumer of SAF. The aviation sector can be a key stakeholder in a regional hydrogen economy.

Regional Power Generation

Natural-gas fired power plants are distributed throughout the entire US and especially concentrated within the Midwest. While nuclear provides the greatest electric capacity within Illinois, several "simple cycle" and "combined cycle" natural gas power plants exist within Illinois and surrounding states. See Figure 18 below from the Energy Information Administration for the distribution of Midwestern natural gas power plants.

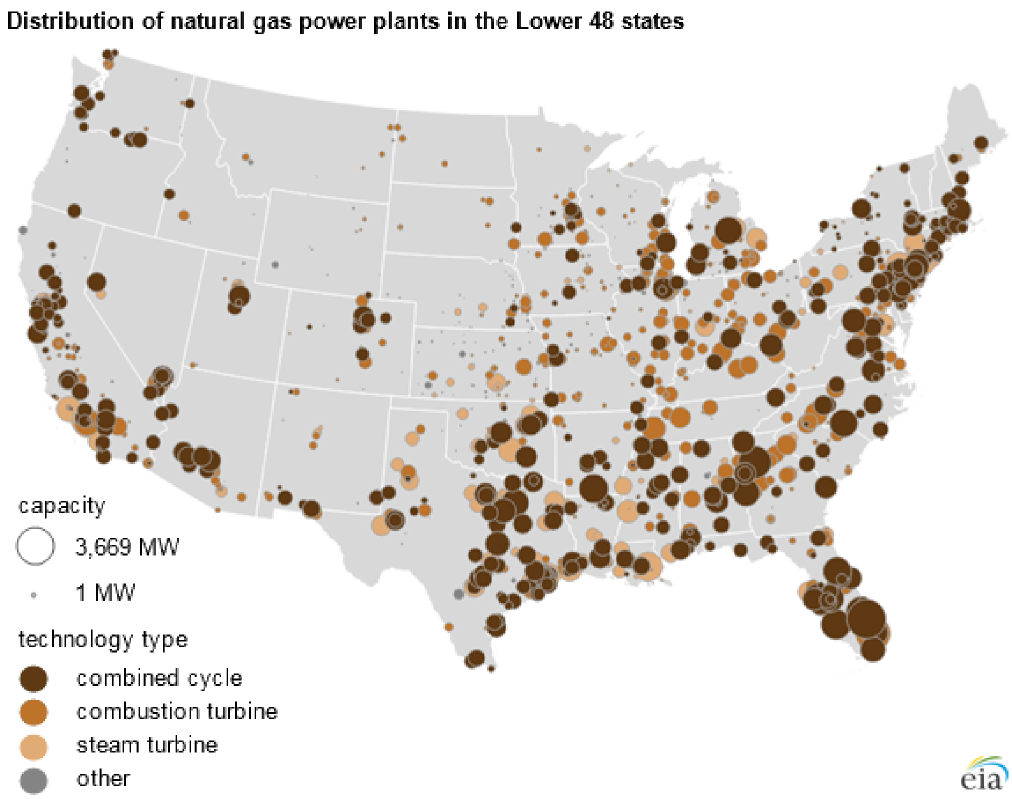

Figure 18 - Distribution of Natural Gas Power Plants in the US

Natural gas-fired power plants utilize combustion turbines to burn a fuel, spinning a turbine and an associated electric generator to produce electricity. The original equipment manufacturers (OEM's) of these turbines, such as Siemens or Mitsubishi Hitachi Power Systems (MHPS), are actively developing modifications to burn increasingly larger blends of natural gas and hydrogen. All OEM's are claiming a transition to 100% hydrogen in the coming decades, with test blends of up to 30% hydrogen underway in various pilot projects around the US. In short, while natural gas-fired power generation is dominant in the power sector today due to abundant supply of low-priced natural gas, climate change considerations are driving the market to decarbonize in the coming decades. OEM's are accelerating their efforts to demonstrate that a hydrogen-powered fleet is possible.

Two key considerations must be taken into account when discussing hydrogen in the power generation sector. First of all, as illustrated in Figure 19 below, increasing the volumetric blend of hydrogen does not lead to an equivalent reduction in carbon footprint. Early blend percentages such as the 30% pilot blends listed above only lead to a 10% reduction in carbon footprint. Nevertheless, these reductions will reduce the carbon footprint of the region, especially for existing assets.

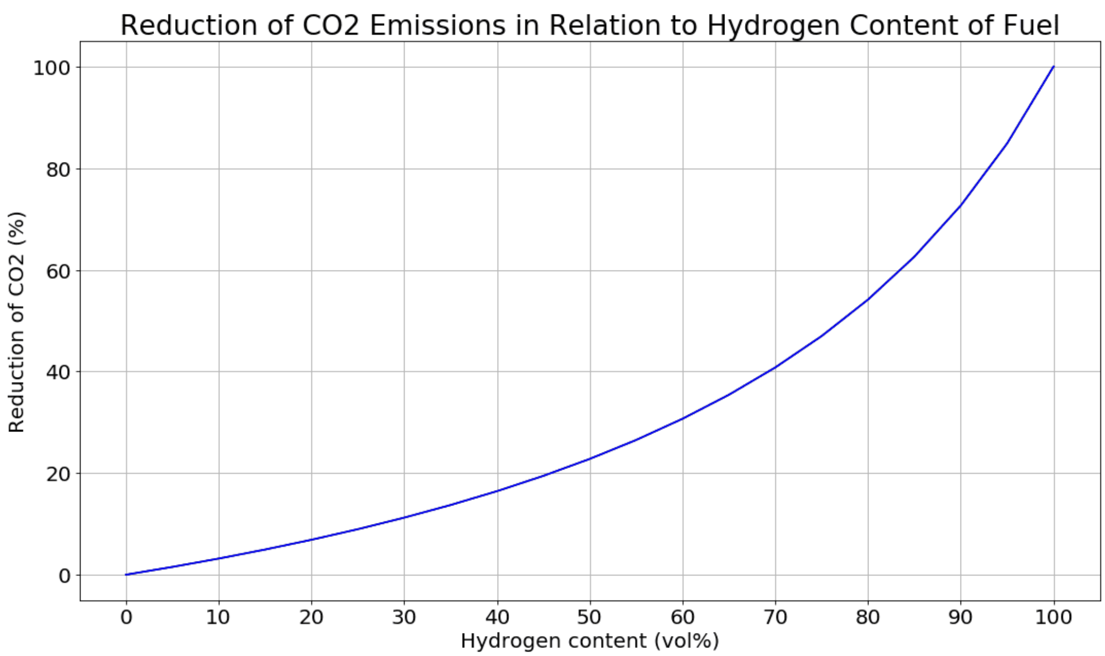

Figure 19 - Hydrogen Blend vs. Carbon Footprint Reduction in Combustion Turbines[29]

The second consideration is storage. Even if hydrogen is directly piped into a power generating facility, it must be stored somewhere as an intermediate buffer. This is similar to the way that natural gas connected to the US natural gas pipeline system is stored in large volumes underground and drawn into the system as needed. New underground hydrogen storage is therefore a critical consideration as noted above. The hydrogen

29 https://www.powermag.com/ready-for-the-energy-transition-hydrogen-considerations-for-combined-cycle-power-plants/

storage approach most commonly discussed is the hollowing out of salt caverns within naturally occurring underground salt formations. The need for large volumes of underground storage is especially true for power generation, where one of the important use cases is the use of “seasonal shifting” - producing hydrogen in the Summer when solar energy may be plentiful and storing that hydrogen underground for months, potentially drawing from it for use in Winter when natural gas prices are high due to increased heating demand.

Large-scale power generating projects in the Midwest are also considering hydrogen beyond the pilot scale. According to the website of Houston-based energy developer Emberclear, the 1100 MW Lincoln Land Energy Center project is currently under development near Springfield, IL. The Lincoln Land Energy Center’s stated goal is to utilize, in the relatively near-term, a 30% hydrogen blend in its Siemens combustion turbines, with a targeted transition toward 100% over the next 20 years as clean hydrogen becomes commercially available. NYC-based New Fortress Energy’s 485 MW Long Ridge natural gas power plant in eastern Ohio is also publicly stating a commitment to 100% hydrogen transition in the next decade. While Lincoln Land is located within central Illinois, we note that the Long Ridge project is located within the Midwest (Ohio) but near Pittsburgh and West Virginia. This is itself a viable hydrogen hub region centered in proximity to the Marcellus Shale region, reinforcing the importance of geographic proximity for hydrogen hub partnerships.

Other uses of hydrogen

As illustrated above in both McKinsey’s and Leibreich’s market forecasts, hydrogen has many potential end-use applications. However, the existence of a technical solution does not necessarily imply that it will become the dominant technology in a market. In every sector, there are several potential competing pathways to decarbonization, each vying for dominance within the coming decades. The “low hanging fruit” markets for clean hydrogen are those such as ammonia and petrochemicals that already consume large volumes of unabated grey hydrogen. As a valuable molecule that is already used as chemical feedstock within an established market, the transition to cleaner “green” or “blue” hydrogen in these markets is what Liebreich calls unavoidable.

Beyond these markets, however, clean hydrogen will compete with several alternatives and may or may not gain an appreciable market share. For example, the owner of a residential building may replace its natural gas-fired water heater with electric heat pumps powered by a renewable electric grid. Alternately, they may evaluate an emerging technology such as a hydrogen-fueled water heater. Fuel cell passenger vehicles and battery electric vehicles is another example of a technology competition, one that has persisted for decades but has largely shifted in favor of battery electric vehicles in recent years. In each sector, for specific end-use applications, these competitions will play out in the coming decades. The large first-movers for clean hydrogen such as ammonia, petrochemical, and heavy transport, will help to scale up production capacity. These economies of scale are expected to bring down the costs of clean hydrogen, potentially impacting these other markets.

Section 6: Equity Considerations

With the emergence of a regional hydrogen economy, stakeholders have the opportunity to consider equity from the beginning. Historically institutional and structural racism has led to generations of negative impacts on BIPOC (Black, Indigenous, and People of Color) communities. While equality traditionally means “to provide the same for all,” “equity” implies that we do not start from the same place and must make additional adjustments to overcome intentional and unintentional barriers. A hydrogen economy provides a few key areas to consider equity in planning as described below.

Air Quality Impacts

Chicago provides an example of the air quality issue that is common throughout Midwestern industrial and post-industrial cities. More than four in 10 Chicagoans are living with unhealthy air, with most of those numbers coming from Chicago’s industrial southeast side and heavy transport / intermodal districts on the south and west sides. “The American Lung Association’s 2019 “State of the Air” report revealed that Chicago ranked the 18th most city in the nation for ozone pollution. The 20th annual report found that Chicago had a weighted average of 14 unhealthy ozone days between 2015-2017, which is significantly higher than the average of 9.8 unhealthy days from last year’s report.[30]

As described above, Chicago hosts 6 out of the 7 Class I railroads through a series of intermodal hubs. 19 intermodals/inland ports are in the region with 8 located within the city limits. Of these 8 Chicago intermodal facilities all but one is in primarily low income and communities of color. See Figure 21 below for distribution of multimodal facility locations within Chicago.

[30] https://www.lung.org/media/press-releases/new-report-chicago-now

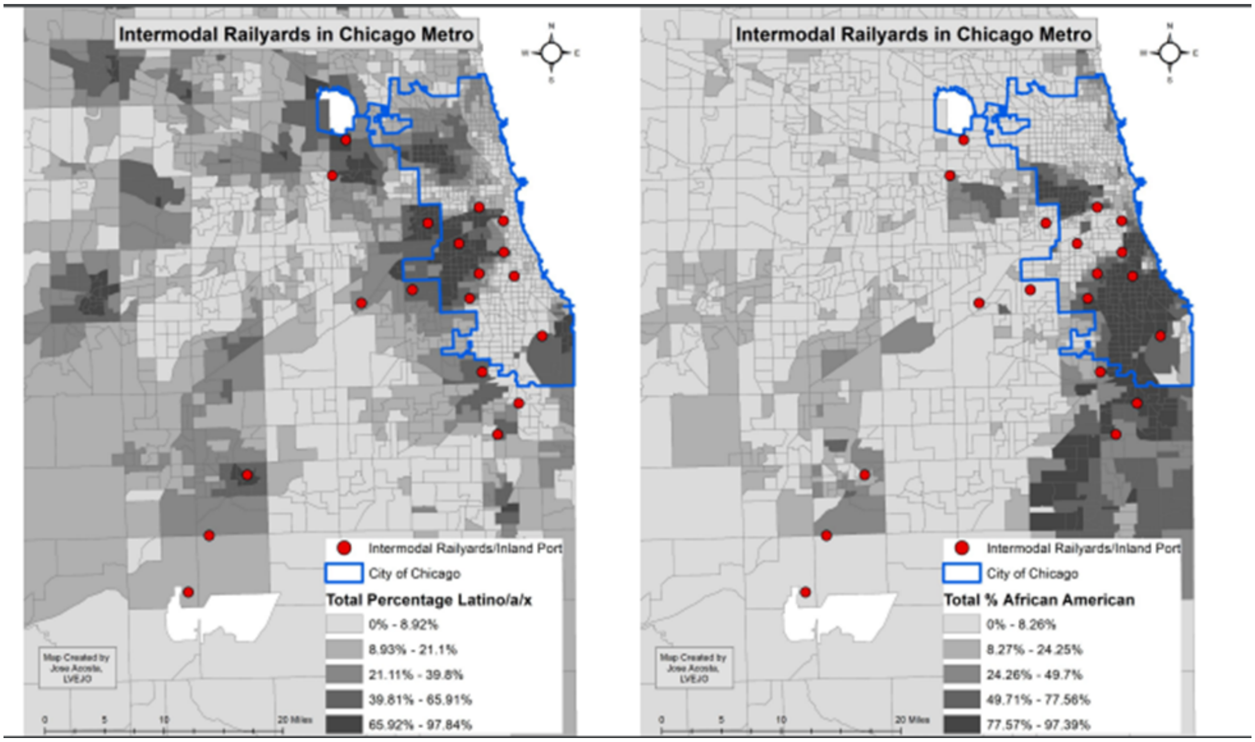

Figure 21 - Multimodal facilities and Latino / African-American Population Distribution

Distribution hubs of this nature rely heavily on diesel on-road and off-road engines to move products from one transport to another. In locomotive lingo these engines stay in the modal yard exclusively and are called "switchers". The Environmental Protection Agency (EPA) in 1998 promulgated final exhaust emission standards for oxides of nitrogen (NOx), hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM) and smoke for newly manufactured and remanufactured locomotives and locomotive engines.

These new regulations found switcher locomotives rated into "tiers" based on the amount of pollutants they produce. Engines produces prior to 2001 are tier 0 and produce over twice as much NOx, HC, and CO as the newer Tier 3 engines.[31] It is unknown how many Tier 0 locomotives are still in use in the Chicagoland area. Although fleet managers can no longer add new tier 0 engines to their fleet, it is still standard practice to rebuild and use these older locomotives if possible. See Figure 22 below for the impact of these hubs on the air quality of the surrounding neighborhoods, all of which are majority African-American and Latino.

[31] https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100OA09.pdf

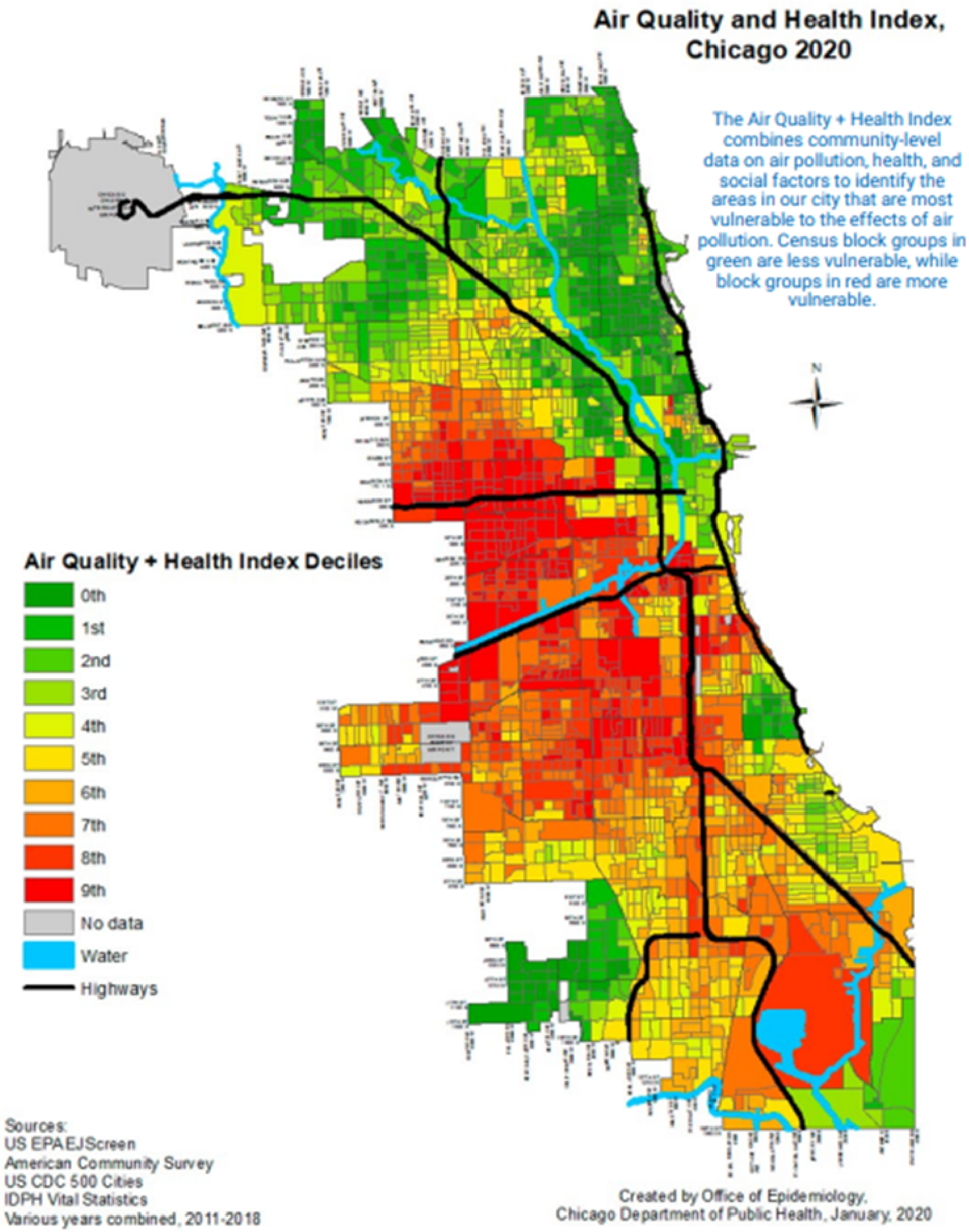

Figure 22 - Air Quality Distribution in Chicago Neighborhoods.

There is a need for a long-term solution to this persistent problem which disproportionately impacts disadvantaged communities. The application of hydrogen technologies at the nation's Midwest freight hub is an equitable step in the right direction. The use of hydrogen fuel cells for transport emit only water vapor as a byproduct. As with the use of battery electric vehicles, air quality in neighborhoods around heavy transport corridors would be expected to improve a great deal. Whether battery electric vehicles or hydrogen fuel cell electric vehicles will become the more prominent technology remains to be seen. However, either would have an immediate impact on air quality in Chicago's black and brown communities. This pattern would be repeated throughout the Midwest and should be reviewed as a model.

Workforce Development and Job Creation

Developing a viable workforce to support the transition to a clean hydrogen economy is critical, but it is equally crucial to ensure that the benefits of the hydrogen transition are distributed throughout all communities. Workforce development must be an ongoing process to educate and empower the current workforce. School curricula should also adapt to introduce the concept of a hydrogen economy, raising the interest of students from the next generation of workers. Exposure to STEM (science, technology, engineering, and mathematics) is an equity issue and one that must be addressed early as economies decarbonize so as not to further exacerbate the disparities.

Government investments into training of underrepresented populations in the energy industry includes lower income individuals, women, ethnic/racial minorities and veterans. These are necessary to address the current disparity in the energy work force, which has historically been dominated by white males. Workforce development initiatives will pave the way not only for job creation but for long-term career advancements. Various curricula should cover both the hard and soft skills involved with working in clean energy.

Critical investments into workforce development provide an opportunity to create economic prosperity for communities that have been denied opportunities for centuries. Design of these programs can enable a direct pipeline into the workforce. Within Illinois, for example, the Climate and Equitable Jobs Act (CEJA) specifically focuses on workforce development hubs as a model for building this transition. Since job growth provides the opportunity to build wealth within communities, additional community programming should be available to assist with building skills around wealth management and investments.

In 2020, 61 percent of the jobs in the green energy economy were held by white Americans. [32] Renewable Energy jobs are an opportunity for high-wage employment in the communities served, including communities that have historically been excluded from employment opportunities in the energy sector. It is not only important to create jobs in the underrepresented communities but also to ensure that these are career-track jobs with a path toward upward mobility.

Previous job creation initiatives often centered around training for a single skill. This may create an oversupply of job seekers for particular roles that do not materialize. For example, some prior efforts to train solar installers occurred at moments when the solar industry had not yet matured sufficiently to hire the available workers. Companies should instead identify all possible job opportunities that can come from clean energy and then create a diverse training program focused on a broad cross-section of critical skills that will allow for continued career growth. A hydrogen economy in particular has the potential to touch many industries, with a variety of operating and construction skills around electrolyzers, tank farms, pipeline operations, the electric grid, transportation fleet maintenance, and more. All skills have a STEM component, again raising the importance of broad STEM training to ensure both licensed professionals (i.e. - Professional Engineer, PE) and skilled trades (i.e. - welders, electricians).

To ensure adoption, companies should be incentivized to hire, train, and develop a diverse workforce. In competitive procurements, equitable requirements should be set as a precondition for companies to be considered a compliant bidder.

Community Impacts

The history of systematic racism is evident in the location of current energy facilities. Existing power plants, oil and gas refineries, and energy generating facilities in general are most often located in BIPOC and/or low-income areas and often considered for siting because these are zoned as the existing heavily industrial areas. This was noted above in the discussion of poor air quality due to multimodal facilities on the south and west sides of Chicago, not only due to combustion emissions but also fugitive dust due to truck traffic. Serious health issues impact residents near these energy and transportation facilities, especially respiratory illness. Although communities may support cleaner energy sources in principle, they may also display a skepticism toward new development. While white males have historically led policy and business decision making, community stakeholder engagement from local communities will be crucial as the Midwest works to build an

[32] https://e2.org/wp-content/uploads/2021/09/E2-ASE-AABE-EEFA-BOSS-Diversity-Report-2021.pdf

equitable hydrogen economy. Some states have seen success in organizing energy committees to review and approve renewable projects. This gives residents of the community real, meaningful input, while also advancing the energy transition forward.[33]

This approach may lead to novel and unique results that can build community wealth. For example, many communities are becoming interested in the development of local community solar projects for self-generation and consumption, with potential sale into the grid for greening of the community's electric supply and possible additional community income. One unique approach that may be considered in a hydrogen economy is to provide community support for clean electricity to electrolyzer operators similar to the community solar model. Community solar could be used to "green" the power supply to the electrolyzer for clean hydrogen rather than for the community's own power consumption and thus may be used to help those operating electrolyzer farms seeking a renewable energy source. This novel use of community Power Purchase Agreements, even if third party intermediaries are needed, should be considered thoroughly in the regulatory process for effective project development. Ultimately, public policy and community support can be leveraged to help produce clean hydrogen equitably.

Section 7: Policy Considerations

Alignment with Federal, State, and Local Policy Priorities

As noted earlier, this white paper is being written in the context of a national race to develop clean hydrogen hubs. The Federal Infrastructure Bill includes an $8 Billion DOE program to support at least 4 regional clean hydrogen hubs in different regions of the US.. Current understanding is that this process will begin with a Funding Opportunity Announcement (FOA) in mid-May, 2022. In this context, Illinois bill SB-3613 "The Hydrogen Economy Act" was introduced and advanced out of committee in early February 2022. Illinois's passage of the Climate and Equitable Jobs Act (CEJA) in late 2021 provided the political environment that can help Illinois to succeed in the emerging hydrogen economy. The City of Chicago is also currently revising its Climate Action Plan is broadly seeking a path to decarbonize its buildings, transportation, and industrial sectors. While increased use of end-use electrification has been strongly considered in many of these discussions, the potential role of hydrogen should not be overlooked.

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33 https://kleinmanenergy.upenn.edu/wp-content/uploads/2020/08/KCEP-Balancing-Renewable-Energy-Singles-1.pdf

Local hydrogen regulatory production, delivery, and consumption barriers

Discussion of projects in various other states raises awareness of regulatory differences. For example, projects in Arizona were mentioned within this paper. Unlike Illinois, the regulatory framework in Arizona still utilizes the vertically integrated utility model. The regulators can simplify connection of a power generator to a hydrogen facility if they choose to do so. What may be possible in another state may be more difficult in Illinois or one of the surrounding Midwestern states, and these local barriers must be reviewed.

Various regulatory developments around the country should be tracked and evaluated to understand the lessons that they offer for the Midwest. For example, regulatory developments are driving the demand for clean hydrogen in power generation. In New York, after the 2019 adoption of the Climate Leadership and Community Protection Act, the state's "Green New Deal" legislation, environmental regulators declined to authorize a modification to a power plant's Clean Air act Title V permit to allow for replacement of existing turbines with cleaner, more efficient turbines that would eventually utilize hydrogen. By denying Danskammer Energy LLC's permit on October 27, 2021, the New York Department of Environmental Conservation cited the mandate to reduce greenhouse gas emissions from the power sector. This order is being appealed.

Another potential barrier requiring attention is electricity procurement. Federal and state regulators will need to collaborate to achieve regulatory solutions that expedite the connection of zero-carbon wholesale power to hydrogen electrolyzers, thus de-risking the development of clean hydrogen. One approach may be the sale of zero emission credits (ZEC's) to hydrogen producers. Another could involve FERC issuing a rulemaking or regulatory determination that the sale of electricity to a hydrogen producer qualifies as wholesale power in interstate commerce. Other stakeholders are likely to challenge such outcomes.

Funding Options

<u>Federal Funding</u>

The Department of Energy (DOE) Energy Earthshots include the Hydrogen Shot initiative to reduce the cost of green hydrogen to $1 per 1 kilogram in 1 decade ("1 1 1").[34] Across DOE offices the FY22 budget has an approximate $400 million for Hydrogen Shot activities, an increase from approximately $285 million in the FY21 budget. The DOE is funding hydrogen research and demonstration projects through the Hydrogen Fuel Cell

[34] https://www.energy.gov/eere/fuelcells/hydrogen-shot

Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy, the Office of Fossil Energy, the Office of Nuclear Energy, and the Office of Science. High Performance Computing (HPC4) for Manufacturing with support from the Office of EERE, AMO, and Office of Fossil Energy is an initiative for national laboratories to support materials and manufacturing innovations for challenges facing the US manufacturing industry. The program is funding projects up to $300,000 with a 20% cost share requirement.

As noted above, the DOE has laid the groundwork for the eventual award of $8B in hydrogen hub development to at least four regions. This is expected to proceed in phases, with Phase 1 beginning in the May 2022 timeframe for selection of initial studies, with subsequent phases potentially narrowing to 4 hubs each receiving funding over several years. Although the DOE has stated a plan for 4 hubs, a recent DOE RFI has implied that the final number may be closer to 6-10 hubs. This current paper has been written in the context of this award program. We note that the Midwestern region centered around Chicago as described within this paper is recognized as one of the likely 6-10 hubs.[35]

Tax Incentives

The Emergency Economic Stabilization Act of 2008 includes tax credits the lesser of 30% of project cost for qualified fuel projects, or $3,000/kW of nameplate capacity. Combined-heat-and-power-system properties can receive 10% of project cost. The American Recovery and Reinvestment Act of 2009 provides 30% tax credit for hydrogen fueling infrastructure capped at $200,000, a 30% tax credit for investment in fuel cell manufacturing, and residential fuel cell credit of $3,334/kW.

State

The Rebuild Illinois capital plan will invest $45 billion worth of investments, with some funded projects going towards hydrogen transportation projects. The Illinois Downstate Assistance program has also supported hydrogen transportation projects. The state of Illinois signed legislation in 2021 to establish the Clean Energy Jobs and Justice Fund to support low-income equitable access to clean energy, and the Illinois Finance Authority Climate Bank to create private/public partnership funding opportunities for clean energy projects. With the introduction of Illinois bill SB-3613 "The Hydrogen Economy Act," it is possible that additional hydrogen-specific funding may be forthcoming, at minimum to coordinate efforts around the pursuit of the $8B DOE hydrogen hub funds .

[35] https://www.nixonpeabody.com/en/ideas/articles/2022/03/01/hydrogen-hubs-are-coming

Regional

Organizations like the Renewable Hydrogen Fuel Cell Collaborative and the Midwestern Hydrogen Partnership have supported hydrogen development in the Midwest and worked with entities to pursue funding for hydrogen projects.

International

The German Federal Ministry for Business and Energy and Federal Ministry for Education and Research is funding green hydrogen projects in the United States through their 7th Energy Research Program (EFP) to meet the goals of the German National Hydrogen Strategy. The National Hydrogen Strategy is funding investments in hydrogen-powered vehicles, construction of hydrogen refueling infrastructure, fuel-cell powered transportation, creation of a center for hydrogen technology, development of international standards for hydrogen transportation applications systems, and global demonstration projects of green hydrogen.[36] The goal of the funding is to increase hydrogen generation technology adoption and allow German manufacturers to increase production of hydrogen generation systems to capture economies of scale in manufacturing. Eligible projects can receive up to 15 million euros in funding for module 1 projects and 5 million euros for module 2 projects.

Transportation

The Department of Transportation Federal Transit Administration announced approximately $182 million in funding in 2021 for low and no emissions buses and infrastructure. This program funding has supported the Champaign-Urbana Mass Transit District's hydrogen bus fleet conversion.[37]

Section 8: Conclusion

The Midwest, centered within the heavy logistical and industrial demand centers of the Chicagoland area, has the resources and industrial makeup to be one of the US and global centers of the emerging hydrogen economy. Initial efforts are underway, but scaleup requires coordination of plans and resources in order to develop a robust local hydrogen market.

The Midwest has the necessary energy production and infrastructure to produce large quantities of clean hydrogen and also to delivery, store, and consume it. Achieving

[36] https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6

[37] https://www.transit.dot.gov/lowno

hydrogen economies of scale provides a pathway to regional decarbonization, especially for the “hard to decarbonize” industries that do not easily lend themselves to an all-electric solution. These end-user industries especially include chemical feedstock-based industries currently consuming global hydrogen, such as ammonia and petrochemical, as well as the aviation industry through the use of Sustainable Aviation Fuel. The heavy transport industries - rail, trucking, shipping - may see technical advantages to pursuing hydrogen fuel cells or even ammonia-fuel engines. Regional coordination between the political, corporate, and nonprofit leadership within the Midwestern states of this paper is key to aligning incentives and leading the region to be greater than the sum of its parts.