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Developing a Hydrogen Economy in Ohio: Challenges and Opportunities

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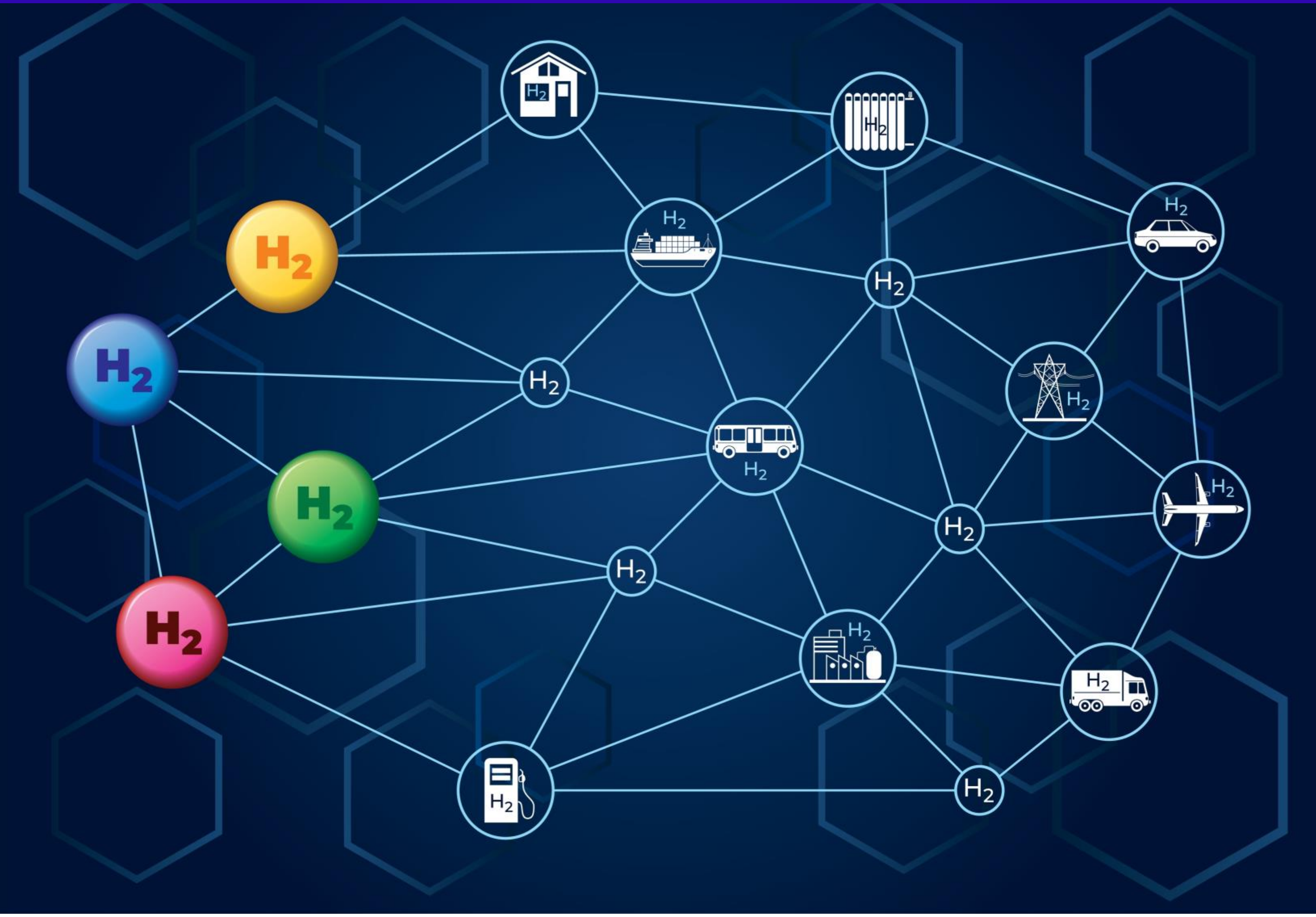

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THE MIDWEST HYDROGEN CENTER OF EXCELLENCE — *A Key Initiative of the Renewable Hydrogen Fuel Cell Collaborative*
JobsOhio
Maxine Goodman Levin College of Urban Affairs
SARTA

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Executive Summary

As hydrogen-based economies are beginning to gain traction around the United States, Ohio finds itself in a position to lead. Ohio has several key advantages over other states in ramping up a hydrogen economy, beginning with its already significant industrial hydrogen market, led by the steel, petrochemical and fertilizer industries. In the coming years, Ohio will see these industrial markets grow, and can leverage them to capture developing power generation, transportation and chemical hydrogen markets. This will be so because Ohio is also in a position to cost-effectively generate, store and deliver large volumes of hydrogen to supply these markets. This includes finding markets for carbon dioxide captured from hydrogen generation.

In its June 2021 "Hydrogen Energy Earthshot" Request for Information, the U.S. Department of Energy identified three sectors as likely to be affected by accelerated growth in the hydrogen economy: transportation, power generation and chemical manufacturing. Ohio has a strong interest in each of these sectors. In addition, a bi-partisan Infrastructure Investment and Jobs Act was passed in November 2021—with $9.5 billion in spending on systems that improve the production, delivery, and use of clean hydrogen. Together, these actions point to an opportunity for Ohio to be a burgeoning hydrogen hub. With its abundance and diversity of resources for making hydrogen and its myriad end users in the transportation, power generation, and industrial sectors, Ohio is positioned to be a hydrogen economy leader. This report was commissioned jointly by JobsOhio and Stark Area Regional Transit Authority to examine Ohio's opportunities for economic development relating to the hydrogen economy.

Ohio Has Ample Hydrogen Generation Capacity

Ohio has ample resources for hydrogen generation. About 95% of hydrogen worldwide is made from steam methane reformation (SMR). Currently, Ohio is producing around 161,000 metric tons/year of hydrogen through SMR, using natural gas as its feedstock. Ohio could produce far more hydrogen through SMR: if 15% of its natural gas production were repurposed for hydrogen generation, it would provide local markets with about 2.5 million metric tons (MMT) of hydrogen per year. This would be more than what will be needed near term in Ohio, but is comparable to what will likely be required for projected 2050 Ohio markets.

Although Ohio probably can meet all of its hydrogen markets through SMR, it would not be desirable to do so. First, SMR produces a considerable amount of byproduct carbon dioxide, which, if not properly managed, will hinder energy companies in realizing their targets for reducing greenhouse gas emissions.[1] SMR-based carbon dioxide emissions will need to be economically captured and used or sequestered (called "blue hydrogen"). And second, it is unclear if regional natural gas reservoirs can sustain current rates of production beyond 2050. As regional natural gas fields deplete over time, extraction costs will rise as wells are drilled into increasingly difficult areas to produce, driving up the cost of natural gas-based hydrogen.

Ohio can reduce its dependence upon SMR through electrolysis, a method whereby water is split into its hydrogen and oxygen components using electricity. If the power for electrolysis comes from renewable sources, it is referred to as "green hydrogen;" if from nuclear, it is called "pink hydrogen." Electrolysis-based hydrogen is beginning to become cost-competitive with SMR, and will be most attractive if the source of electricity is carbon-free. Notably, electrolysis is not the only way to make green hydrogen. Hydrogen from biomass, landfill gas or other renewable sources is also referred to as "green," even though these sources may deploy SMR processes. Ohio also has ample biomass potential for making green hydrogen.

Over the next several years, Ohio's primary source of carbon-free electricity is likely to be from its nuclear power plants located in Perry and Oak Harbor, Ohio.[2] These plants have a total capacity of around 2176 MW.[3] If 15% of the capacity at these power plants were repurposed to make hydrogen via electrolysis, it could provide around 60,000 metric tons of hydrogen per year. Based upon U.S. Energy Information Agency (EIA) expected growth rates for renewable power, Ohio projects to be able to generate around 5,000 MW of utility-scale renewable power by 2050. Diverting 15% of this generation capacity to hydrogen production could yield up to an additional 136,000 metric tons annually via electrolysis. Together, electrolysis from nuclear and renewable power generation in Ohio could supply nearly 200,000 metric tons of hydrogen per year by 2050, assuming a 15% repurposing rate.

Importantly, hydrogen made in Ohio will have important advantages compared to hydrogen made in other states. The major costs of making hydrogen from SMR (natural gas) and electrolysis (electricity) are favorable in Ohio. Natural gas in Ohio sells for below national (Henry Hub) rates, and Ohio's commercial and industrial electrical power rates are among the lowest in the nation. Byproduct hydrogen from chemical processes – the lowest cost hydrogen - is not

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[1] For example, *see* Marathon Petroleum's target for lowering its carbon intensity from operations by 2030. https://www.marathonpetroleum.com/Sustainability/Lowering-Carbon-Intensity

[2] Ohio currently has 1,582 MW of operational, utility-scale wind and solar power capacity. An additional 444 MW in solar generation for the grid is under construction (no additional wind-based generation is currently under construction). This additional renewable generation is projected to come online no later than the first half of 2023 (*see* https://nationalgridrenewables.com/yellowbud/; *see also* https://hardinsolar.invenergy.com/).

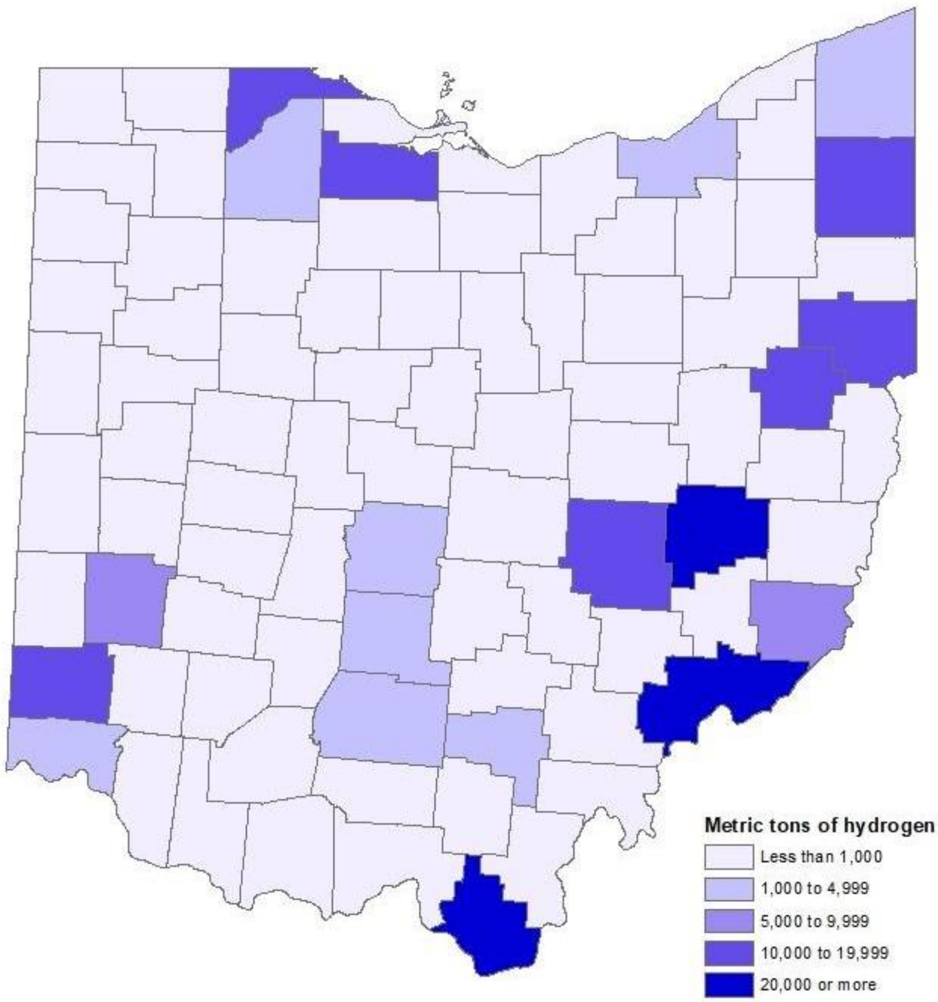
[3] https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/constellation-spin-off-underscores-nuclear-s-role-in-us-decarbonization-effort-68401652

currently a major supply source in Ohio, but may become so if an ethane cracker is built in the state. Such a cracker is already being built close to the Ohio border near Pittsburgh, PA.

Ohio's Hydrogen Markets Are Large and Growing

Ohio will need this hydrogen as its chemical manufacturing industries grow and new markets for transportation and electricity generation develop. Electric power markets for hydrogen are currently being developed, including a hydrogen-burning plant at the Long Ridge Energy Terminal in Monroe County, Ohio. Ohio is likely to be among the first states to blend hydrogen and natural gas. U.S. National Labs project that in the coming years, hydrogen/natural gas blends will include up to 20% hydrogen before the hydrogen content begins to have a corrosive effect on infrastructure. The Ohio stationary power generation market, driven by hydrogen blends, is projected to require around 250,000 metric tons annually by 2050, assuming natural gas prices rise to over $6/MMbtu. That is likely to happen as reserves are depleted in Appalachia, and as the demand for natural gas as a feedstock for hydrogen grows. If mandates constraining carbon dioxide emissions are passed, hydrogen requirements will be significantly higher than this. The counties that are likely to require the most hydrogen for power generation are Guernsey, Lawrence and Washington.

Annual Hydrogen Consumption for Power Generation in Ohio by 2050
Assuming No Carbon Dioxide Regulation

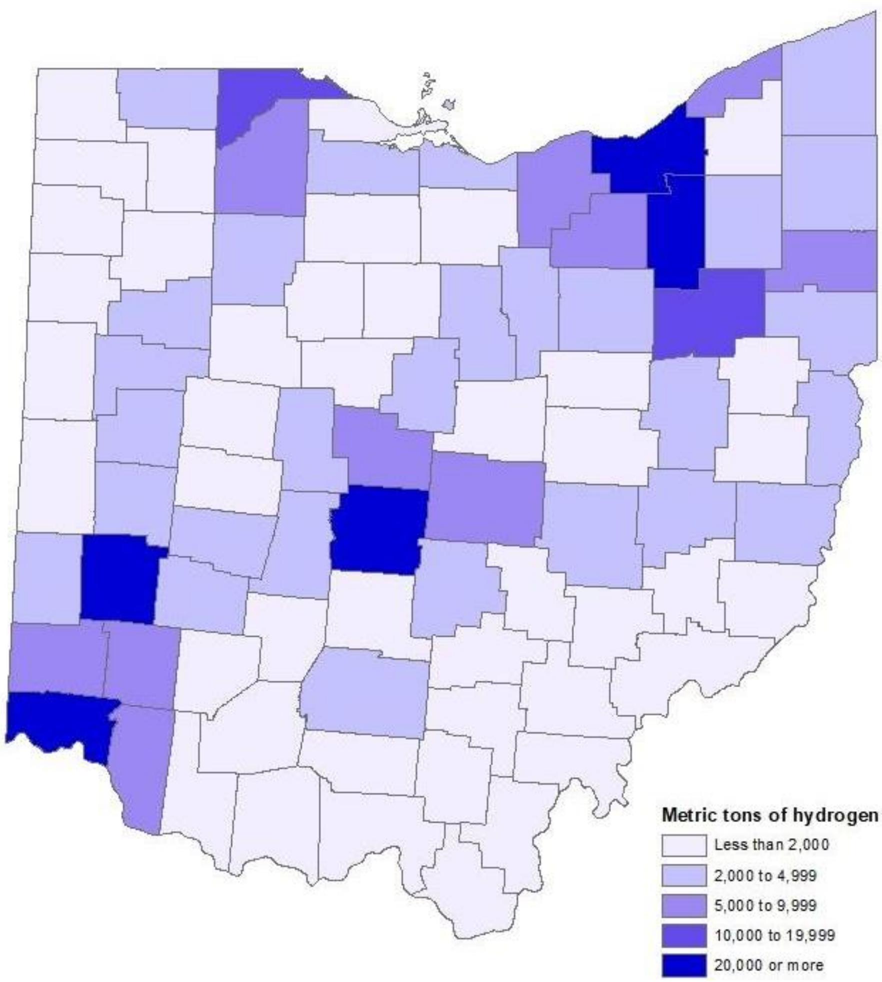


Another growing market in Ohio will be hydrogen fuel cell electric powered vehicles. Ohio already has one fleet of fuel cell electric buses, plus a public refueling station, in Canton, Ohio (Stark Area Regional Transit Authority). Statewide hydrogen consumption for transportation is projected to be around 450,000 metric tons per year by 2050, based upon a projected 12.2% market share of all vehicles, assuming Ohio does not become a zero-emission vehicle (ZEV) state. If ZEV standards are adopted, that market share would likely be more than 33%, with hydrogen consumption for vehicles alone over 1.2 MMT/year. Hydrogen fuel cell forklifts, which have already realized significant market penetration, will consume another 20,000 metric tons/year by 2050.

Vehicle consumption of hydrogen will be greatest where there is the most traffic. Accordingly, it follows that the counties with the greatest populations—Cuyahoga, Franklin, Hamilton, Lucas, Summit, and Montgomery—will be the biggest hydrogen markets for transportation. Stark County will be the early leader in hydrogen consumption for vehicles, insofar as it already hosts a fleet of fuel cell electric buses and the only public refueling station in Ohio. Because of refueling logistics, near-term vehicle hydrogen consumption is likely to be co-located with transit depots and along interstates, where heavy duty (e.g. Class 8) trucking fleets can be readily refueled.

Fuel cell bus refueling at Stark Area Regional Transit Authority

Projected Annual Hydrogen Consumption in Ohio for Fuel Cell Electric Vehicles by 2050 Assuming No Regulation of Carbon Dioxide



Chemical manufacturers, however, are likely to be the biggest consumers of hydrogen in Ohio for the near-term future. Ohio already has a significant hydrogen market for oil refining, metal refining, and ammonia production. Petroleum refiners are among the largest hydrogen consumers in the nation, and Ohio has four refineries. Ohio refiners are projected to need over 200,000 metric tons of hydrogen per year by 2050.

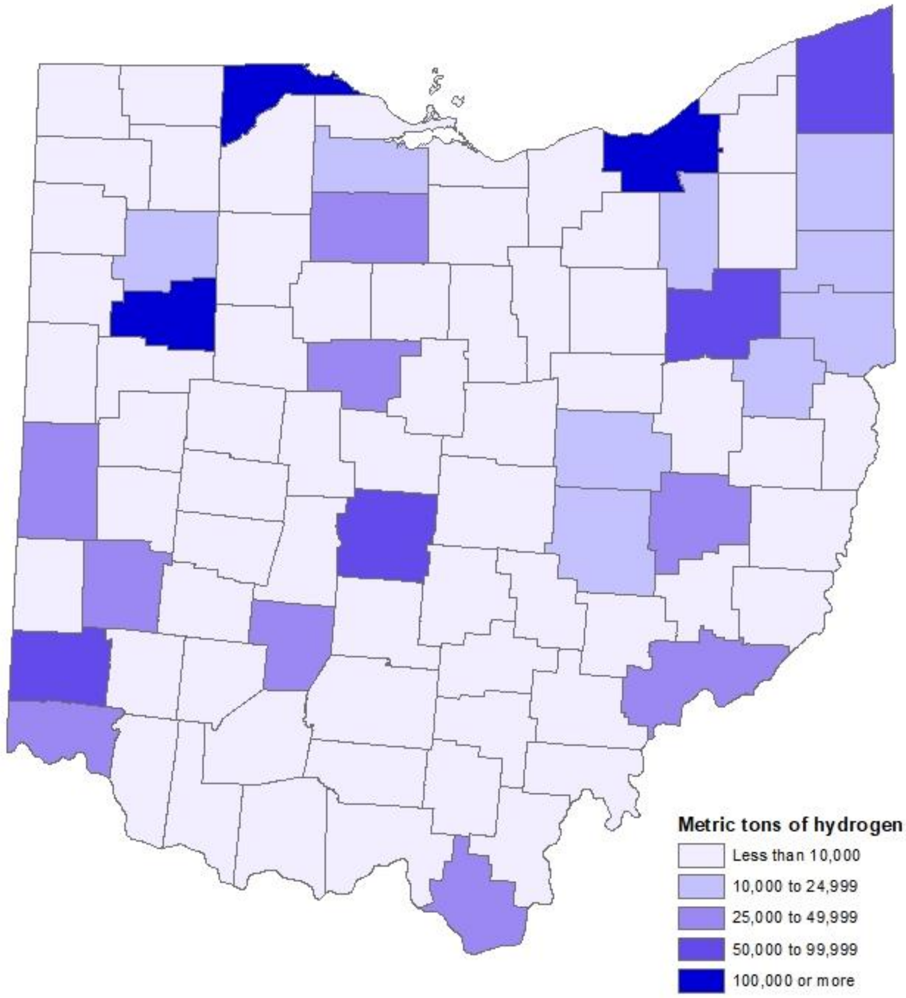
The primary driver of growth in hydrogen consumption for metal refining has been the adoption of Direct Reduction of Iron (DRI), a process that uses hydrogen instead of coke as a reducing agent, thereby producing high quality iron with low carbon emissions. Already 5% of the world's steel is made through DRI, and the industry appears to be replacing traditional reduction strategies with DRI. Toledo has an operational DRI plant, and Ashtabula may soon follow. Growing hydrogen demand in Ohio to supply DRI is expected to reach nearly 400,000 metric tons per year by 2050.

Ammonia is the second most produced chemical in the world, and is a major consumer of hydrogen. Lima, Ohio has a large ammonia production facility. That facility projects to require about 120,000 metric tons of hydrogen per year by 2050. Other manufacturing markets that consume hydrogen include paper, plastics, nonmetallic production, computer/electronics, appliances, chemicals, transportation equipment and machinery. These industries together project to consume around 10,000 metric tons of hydrogen in Ohio per year by 2050.

Based upon the rate of growth demonstrated over the past ten years, the total Ohio hydrogen market, including industrial, transportation and electricity generation, is projected to be about 2 million metric tons per year by 2050, ***without carbon regulation*. ** Should regulation be adopted that constrains carbon dioxide emissions, the total Ohio hydrogen market will be much higher. For instance, if fuel cell vehicles achieve 33.3% market penetration, and if natural gas/hydrogen blend for power generation reaches 33.3% hydrogen, the total Ohio consumption will be over 3 MMT/year.

The counties that project to have the largest total hydrogen markets are Lucas, Cuyahoga, and Allen. Should an ethane cracker be built along the Ohio River, such as has been proposed for Belmont County, a hydrogen hub would likely develop therewith due to the large amounts of byproduct hydrogen produced.

Total Projected Annual Hydrogen Consumption in Ohio by 2050
(With No Carbon Dioxide Regulation)



Markets for carbon dioxide are likely to play a role in hydrogen development in Ohio – especially for steam methane reformation. Technology exists now that can cost effectively recover carbon dioxide from the SMR process. Absent regulation of carbon dioxide emissions, the challenge will will lie in economically disposing of that captured carbon dioxide.

The most cost-effective disposal strategy is sequestration through use. Ohio has a number of carbon dioxide markets that can permanently sequester carbon dioxide. One of the largest markets for carbon dioxide is for enhanced oil recovery (EOR) processes,[4] and Ohio has aging oil fields that are candidates for this process. The life cycle of using carbon dioxide to drive oil production can create net-negative emissions, and Ohio's oil fields could become large carbon dioxide sinks. While EOR has not been used extensively in Ohio, recent studies by Battelle

[4] https://iea.blob.core.windows.net/assets/50652405-26db-4c41-82dc-c23657893059/Putting_CO2_to_Use.pdf

indicate that this extraction method could yield more than twice the production from the state's oil-producing geologic formations than has been withdrawn to date via primary recoveries.[5]

Ohio has other industries, including urea manufacturing, that require carbon dioxide. New technologies such as Ready-Mix Concrete also promise opportunity for sequestration of carbon dioxide. Another option for disposing of carbon dioxide is deep injection into the subsurface, in what are called "Class 6 wells," which are currently regulated by USEPA in most states. Ohio appears to have the appropriate subsurface geology to support Class 6 well injection, but does not currently have regulatory primacy to permit such wells. Obtaining state regulatory primacy will be important to streamlining the permitting process.

Hydrogen Infrastructure Will Initially Develop Around Large Markets.

It is generally cheaper to transport electricity or natural gas than hydrogen. As a result, early hydrogen hubs are likely to form near markets, especially where generation capacity exists. This will also be where hydrogen storage, pipeline, and refueling infrastructure will likely first emerge. Because diesel trucking of hydrogen emits considerable carbon dioxide, pipelines are the cleanest way to transport hydrogen. However, until a network is developed comparable to the current natural gas system, hydrogen pipelines may not be cost effective except for larger markets, such as 100,000 metric tons per year. For smaller, distributed markets, the most cost-effective strategy to transport hydrogen may be by truck, either through tube trailers (gas) or in tanks (liquid).

The cost of hydrogen pipelines may drop considerably by converting existing natural gas pipelines into hydrogen lines. It is projected that this can be done for most pipelines for around 15% of the cost of building new hydrogen pipelines. Because of their large industrial markets, it is anticipated that hydrogen pipeline networks are likely to emerge first in Lucas or Allen Counties. One exception to early markets driving pipeline development might be in and around ethane crackers, where large volumes of low-cost byproduct hydrogen could attract hydrogen pipeline and storage infrastructure.

Ohio's Hydrogen Timeline

The following table provides a timeline comparison of hydrogen markets and generation for Ohio based upon a "no carbon regulation" model that forecasts a market of 2 MMT/year by 2050. As can be seen, natural gas will likely be the principal source of hydrogen generation in Ohio for the next 30 years. This would be true even if Ohio utilities were to repurpose half of their carbon-

[5] *See* https://www.osti.gov/biblio/1773046. *See also* https://www.mdpi.com/1996-1073/13/23/6215.

free power generation to making hydrogen. To meet the growing hydrogen market, Ohio will likely need to ramp up both its fractional share of repurposed power generation and its capacity for renewable power (assuming no new nuclear plants are built). Even without internalizing the costs of carbon dioxide emissions, hydrogen from electrolysis could approach the cost of SMR hydrogen over the next 30 years, as renewable power and electrolysis technologies improve, and as the cost of extracting natural gas goes up.

Projected Ohio Annual Hydrogen Consumption and Production (Metric Tons)
Assuming: No Carbon Dioxide Regulation and Markets Supplied by 15% of Nuclear and Renewable Power, and Remaining Market Supplied by Natural Gas (SMR)

		2030	2040	2050
Hydrogen Consumption	Power generation	31,100	88,400	251,200
	FCEVs	2,900	35,400	430,600
	Forklifts	4,700	8,400	12,700
	Oil refining	188,700	202,400	217,000
	Metal refining	23,900	96,600	391,000
	Ammonia production	114,200	119,600	125,400
	Biofuels	400	7,900	148,000
	Synthetic hydrocarbons	63,600	85,800	397,700
	Other Mfg. markets	8,100	9,100	10,300
	Total Consumption	**437,600**	**653,600**	**1,983,900**
Hydrogen Production	Electrolysis via Nuclear Power	9,300	50,700	59,600
	Electrolysis via Renewable Sources	86,600	112,800	135,900
	Natural Gas (SMR)	341,700	490,100	1,788,400

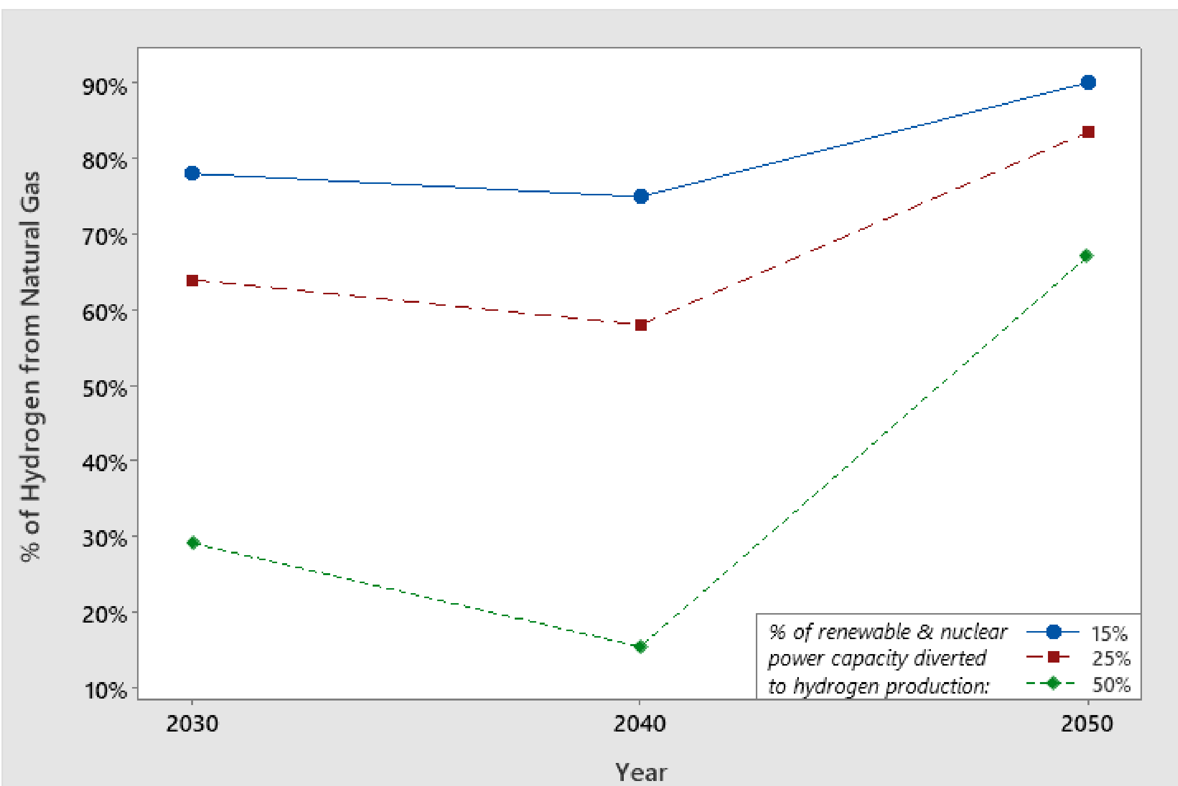
Note 1: Natural gas production of hydrogen is determined by subtracting the amount of hydrogen generated from repurposing 15% of nuclear and renewable power from the total expected market. Current SMR capacity in Ohio is about 161,000 metric tons annually. Projections assume nuclear power repurposing ramps up to 15% by 2050, using an "S" curve for new products (and assumes overall nuclear power capacity will not grow). For renewable power, we assumed Ohio's growth will follow the EIA national annual growth rate projections for renewable power (3.9% for solar and 0.7% for wind). Currently, repurposing 15% of existing and under construction renewable power would generate about 55,000/yr metric tons of hydrogen.

Note 2: The U.S. Energy Information Administration (EIA) identifies the following as sources of renewable energy: Conventional Hydroelectric Power; Geothermal; Municipal Waste; Wood and Other Biomass; Solar Thermal; Solar Photovoltaic; and Wind. Among these, only solar photovoltaic and wind are included in our renewable projections.

For Ohio to supply a 2 MMT/year market entirely through electrolysis, it would require that Ohio dedicate 11 gigawatts of renewable or nuclear power capacity, running 24/7 (which clearly renewable cannot do), to hydrogen generation. To meet the more likely 3 MMT/year scenario where carbon is regulated, it would require about 16 gigawatts of capacity — at the same time that the grid will be pressed to provide power to support battery electric vehicles. Indeed, because a zero-emission vehicle market will require electricity for both hydrogen and battery electric vehicles, to provide 100% of those markets with carbon free electricity would require Ohio to at least double the size of its current statewide generation capacity of 29 MW. For this reason, it is hard to envision a scenario for Ohio where natural gas is not a principal source for hydrogen over the next 30 years.

As can be seen from the chart below, even if Ohio were to repurpose 50% of its projected renewable and nuclear power capacity, hydrogen derived from natural gas would still represent more than 70% of the hydrogen required to meet the more conservative demand of 2 MMT/year by 2050. Further, repurposing 50% of nuclear and renewable power for hydrogen would have a significant effect on the grid -- Ohio already imports nearly 25% of its power.

Percent of Hydrogen from Natural Gas to Meet Demand Potential Under Three Scenarios for Repurposing Projected Renewable and Nuclear Power to Make Hydrogen

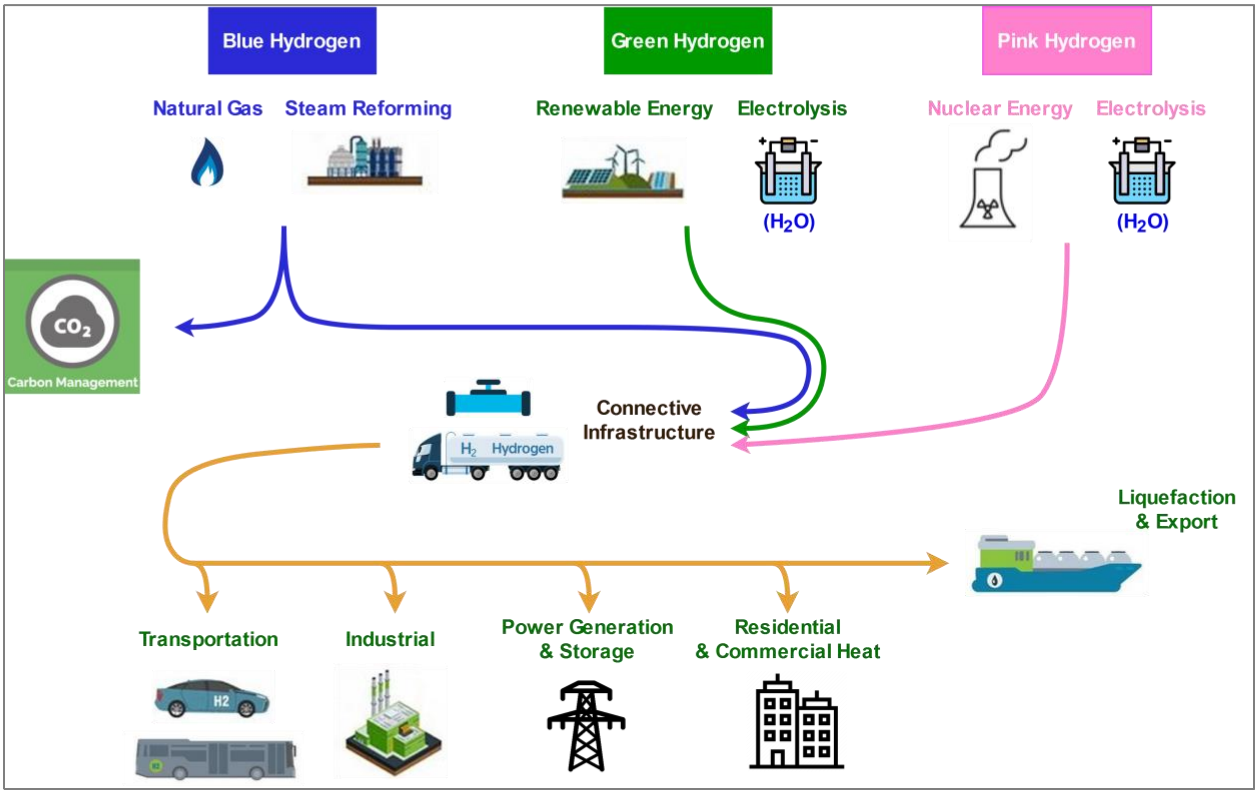


The result is that Ohio's industries, policy makers and economic development entities will need to plan for the development of all available hydrogen sources to supply Ohio's anticipated hydrogen demand. To meet the demand for natural gas-based hydrogen responsibly, Ohio will need to develop strategies for using or sequestering carbon dioxide captured from steam methane reforming processes. Ohio will also need to ramp up its renewable power generation fleets to replace natural gas over time, as natural gas resources are depleted.


SMR of natural gas to make hydrogen.

It is clear that over the coming decades Ohio will have to adopt an "all of the above" strategy for sourcing hydrogen to meet its market demand - embracing natural gas, biomass and electrolysis as sources. Yet this does not mean that Ohio's stakeholders and policy makers are not facing some important decisions. The "no carbon regulation" market timeline above suggests that industrial and natural gas markets will be early adopters, while vehicles will come later. This in turn suggests that hydrogen infrastructure can wait until zero emission mandates are passed. But this would be a risky strategy. Low or no carbon emission mandates could get passed at any time. Stakeholders will want to invest into the hydrogen infrastructure that will provide the best return on their investment, but they may not have the luxury of waiting until the lowest risk strategies are clear. Improvements in technology or changes in regulations could shift the economics quickly, and opportunities could be lost.

Hydrogen Economy Flowchart



1.0 Introduction/Background.

1.1 Factors Leading to Growth of the Hydrogen Economy

Climate-related risks, together with structural changes in energy markets, have placed the hydrogen economy in the forefront of planning for Ohio's policy makers and economic development thought leaders. This report examines Ohio's opportunities for economic development relating to the hydrogen economy. This report looks at hydrogen generation, storage and infrastructure assets in Ohio, together with local hydrogen markets, and considers how these are likely to play out in the coming years. The report does not consider the role that hydrogen import or export might play in this opportunity, although this will likely be an important aspect of the hydrogen economy. Projecting how hydrogen import or export will be accomplished is difficult to do. However, the recent increase in natural gas exports from the region,[6] together with the development of major new hydrogen shipping ports in the Netherlands,[7] suggest that ports and other transportation infrastructure may require significant investment.

In November 2020, the U.S. Department of Energy (DoE) published a Hydrogen Program Plan, noting that in undertaking that research, "[f]or the first time, a coalition of major industries teamed together to develop an industry-led roadmap on the potential for hydrogen in the United States."[8] The DoE determined that hydrogen, as a "versatile energy carrier and chemical feedstock," offered strategies that would enable innovations that can "help decarbonize three of the most energy intensive sectors of our economy: transportation, electricity generation, and manufacturing." Further, the wide range of applications where the use of hydrogen is either growing or has the potential for significant future demand was such that private industry had "projected a potential $2.5 trillion global market for hydrogen technologies by 2050." The roadmap concluded that by 2050, the "U.S. hydrogen economy could lead to an estimated $750 billion per year in revenue and a cumulative 3.4 million jobs."[9]

The DoE followed this up in June 2021 by announcing its "Hydrogen Energy Earthshot," the first of a series of strategic investments into new energy technologies designed to "look beyond incremental advances," and to instead aim "at the game-changing breakthroughs that will secure American leadership in enabling net-zero carbon technologies." Hydrogen was chosen for the

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[6] "U.S. Liquified Natural Gas Exports Grew to Record Highs in First Half of 2021," *Today in Energy*, Energy Information Agency, July 27, 2021, https://www.eia.gov/todayinenergy/detail.php?id=48876.
[7] *See, e.g*. https://www.portofamsterdam.com/en/business/cargo-flows/liquid-bulk/h2-hydrogen.
[8] "Department of Energy Hydrogen Program Plan," November 2020, found at: https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf
[9] *Id*. at 4.

first Earthshot technology because of its potential in diverse applications across multiple sectors, and because "it can provide substantial environmental and economic benefits, as well as improved energy security and resiliency."[10] In the fall of 2021, Congress passed a bipartisan infrastructure bill that targeted nearly $10 billion to support scaling up the hydrogen economy, including $8 billion for development of "clean hydrogen hubs."[11] The bill was signed into law by President Biden in November 2021.

Ohio has a strong interest in each of the three industries the DoE identified as most affected by the hydrogen economy: transportation, power generation and chemical manufacturing (a fourth market -- commercial and residential heating -- was further identified in the bipartisan infrastructure bill). Ohio's economy has traditionally been dependent upon transportation related manufacturing, as well as energy intensive industries such as steel, glass and chemicals. Ohio's economy likewise relies heavily upon hydrogen as a chemical feedstock or reducing agent. For these reasons, JobsOhio and Stark Area Regional Transit Authority have jointly commissioned this study to examine the opportunities and challenges the hydrogen economy will bring to Ohio.

It has been understood for a number of years that the transition from internal combustion to electric drive engines could have a disruptive effect on the Ohio manufacturing economy. In the early 2000s, Ohio's manufacturing economy faced significant threats from high hydrocarbon prices, climate change regulation, and wars with rogue oil regimes. Oil prices had risen to $150/barrel, and oil imports made up over half of the US trade deficit. Ohio responded to these threats with the redirection in 2002 of its Third Frontier Program, which program began to invest heavily into, among other technologies, the development of fuel cells and their supply chain.[12]

Yet the transition from internal combustion engines to fuel cell electric engines has been slow to develop. Today, nearly 20 years after the creation of the Third Frontier, only two hydrogen vehicle refueling stations exist in Ohio: one 400 kg/day facility at Stark Area Regional Transit Authority's bus depot in Canton, Ohio, and a small 12 kg/day one at the Center of Automotive Research at Ohio State University.

The coming decade will change this narrative. Driven in part by climate change concerns, the transition to a hydrogen economy has begun to accelerate in Ohio. In 2021 several

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[10] https://www.energy.gov/articles/secretary-granholm-launches-hydrogen-energy-earthshot-accelerate-breakthroughs-toward-net

[11] *Department of Energy Fact Sheet,* https://www.energy.gov/articles/doe-fact-sheet-bipartisan-infrastructure-deal-will-deliver-american-workers-families-and-0. The infrastructure bill includes another $10 billion for carbon capture and sequestration strategies. *See id*.

[12] https://www.energytechnologiesinc.com/pressRelease/news/Press_Release_3rd_TFFC_Grant.php

transportation, power generation, and chemical manufacturing projects using hydrogen were already operational or about to begin operations in Ohio.

But responding to the threat that rising carbon intensity poses to human health is not the only reason for the hydrogen economy moving forward now. Problems that have frustrated ramping up a hydrogen economy for the last 20 years – the cost and reliability of fuel cell technology, and the cost of making and delivering hydrogen – have largely been ameliorated. Fuel cells today are sufficiently durable, long lasting, and cost effective to be competitive with internal combustion engines.[13] Moreover, due to the advent of shale development in Appalachia, the cost of hydrogen feedstock (natural gas) is lower today than 20 years ago, thereby making hydrogen generation inexpensive. The U.S. Energy Information Agency forecasts modest natural gas price increases over the next 20 years,[14] although geopolitics and a rapidly growing export market may cause the EIA to change its future forecasts.

Recent cost reductions in hydrogen generation through electrolysis are also promising. Improvements in the technology, together with low electricity prices, suggest an economical new source of zero emission hydrogen could power the industrial, electricity and transportation sectors in the 21st century. Wholesale electricity costs in 2021 are particularly attractive for wind and nuclear power generation; off-peak power from these sources can be repurposed from the grid to making hydrogen, which can then be stored or transported to local markets. Such hydrogen generation could be a critical component to a net-zero carbon emission energy economy.

Industrial use of hydrogen in Ohio is already significant and growing. Ohio uses large amounts of hydrogen in petrochemical, fertilizer and steel manufacturing. In addition, hydrogen will increasingly be blended with natural gas for use in electricity or thermal generation. We are also likely to see hydrogen used for grid storage over the coming decades: due to a growing information economy, modern models for the grid require increased reliability, while at the same time relying more on intermittent, renewable power sources. Hydrogen at scale will be required to support the electricity storage mix necessary to enable the data-driven grids of the 21st century, which must provide 99.999% or better uptime.[15]

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[13] Honda, for instance, has an 8-year warranty on its fuel cell sedan, the Honda Clarity. *See* https://www.kbb.com/honda/clarity-fuel-cell/2019/base-style/?vehicleid=443592&intent=buy-new

[14] For reference case forecasts of natural gas prices, see the Energy Information Administration's Annual Energy Outlook 2019. Energy Prices by Sector and Source (table). https://www.eia.gov/outlooks/aeo/data/browser

[15] The operational performance of information technology (IT) systems is generally evaluated according to "uptime," the percentage of time a particular system is operational. In IT, it is one of the most vital metrics associated with the performance of mission-critical systems. The higher the uptime, the more available and better performing the system. Uptime is traditionally measured in nines, which correlates to an expected amount of downtime over a given period. Five nines, or 99.999%, corresponds to approximately 5 minutes of downtime per

1.2 Challenges for Ohio.

Due to low-cost electricity and natural gas supplies, Ohio has advantages over other states in hydrogen generation costs. This will, itself, attract companies in the industrial gas business to Ohio. However, it will be a challenge to develop the necessary infrastructure to support Ohio's hydrogen markets. For hydrogen to be competitive with diesel as a transportation fuel in Ohio, prices will need to be around $7/kg at the pump (assuming that there continues to be no cost for emitting carbon dioxide). This estimate is based upon a diesel cost of about $3.50/gallon. These prices are likely to be achievable in the next decade,[16] at least for "gray hydrogen" (i.e., hydrogen generated by steam reformation of natural gas without carbon capture).

The "Hydrogen Shot" proposed by the DoE, however, seeks to drive down the cost of generating *carbon free* hydrogen to below $1/kg. Carbon free hydrogen either must be "green" (generated by carbon free electricity or from renewable natural gas) or "blue" (generated by steam methane reformation (SMR) with carbon capture and sequestration). According to the International Energy Agency, hydrogen from steam reformation in 2021 without carbon capture cost between $1-3/kg to make, and from clean energy electrolysis $2.5-6/kg. Carbon capture would add another $0.50/kg to the cost of SMR,[17] with significant additional costs for sequestration, depending upon the availability of local carbon dioxide markets. The Hydrogen Shot seeks to reduce these costs by 80% in the next decade.

But generation is only part of the cost problem Ohio will need to resolve. In general, it is less expensive to transport natural gas or electricity than hydrogen, so hydrogen generation that is closer to the market would be economically optimal. Hydrogen infrastructure will need to be developed in a manner that minimizes transportation, storage and delivery costs. Table 1 below sets forth a projected intermediate term (i.e. this decade) price at the pump scenario for Ohio, based upon projected costs for generation (terminal), storage, transportation and refueling infrastructure. Notably, under this scenario, 2/3 of the cost of fuel at the pump comes from storage, transportation and refueling infrastructure. The Hydrogen Shot strategy has not set

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year and is a highly valued level of system availability often recommended for mission-critical applications and in performance-sensitive industries like finance and ecommerce. *See* https://www.nefiber.com/blog/five-nines-uptime-sla-mean/

[16] Prices for hydrogen at the pump in California are projected to be comparable to gasoline by 2025, according to the California Energy Commission. *See* S. Edelson, Green Car Reports, June 9, 2020. https://www.greencarreports.com/news/1128428_report-hydrogen-fuel-cell-price-parity-with-gasoline-2025

[17] D. Snieckus, "Green Hydrogen Leads Off US Energy Earthshots," Recharge Global News, June 7, 2021, https://www.rechargenews.com/energy-transition/green-hydrogen-leads-off-us-energy-earthshots-in-all-hands-on-deck-technology-call/2-1-1021584

forth specific goals for this infrastructure yet, but rather it plans for reducing these costs by establishing a "framework and foundation for deployment" through the American Jobs Plan.[18]

Table 1. Intermediate-term Hydrogen Distribution Costs for Transportation (2018$)

Hydrogen Dispensed Per Day Per Station (kg)	Terminal Cost ($/kg)	Geologic Storage Cost ($/kg)	Compressed H_2 Truck-Tube Cost ($/kg)	Refueling Station Cost ($/kg)	Total Cost ($/kg)
1,000	$2.90	$0.79	$2.80	$1.20	$7.69
2,000	$1.98	$0.60	$1.70	$0.63	$4.92

Source: The Authors (based on Argonne's Hydrogen Delivery Scenario Analysis Model)[19]

1.3 Timeline.

Projecting when hydrogen infrastructure will get built in Ohio is difficult, given the uncertainty regarding carbon dioxide emission regulation. We have a general sense of how the build out is likely to proceed, however. We know that near-term hydrogen will likely be supplied principally by natural gas via SMR. We also know that hydrogen infrastructure like SMR plants and pipelines have a useful life span of up to 50 years, and once built, those assets will not readily be discarded. Accordingly, Ohio is likely to be dominated by natural gas-based hydrogen for some time. Indeed, natural gas assets already exist in Ohio that could catalyze a hydrogen economy over the next ten years, thus enabling Ohio to be a leader in hydrogen development. These assets also include an existing industrial hydrogen market supplied by natural gas.

We also know that there will likely be a transition at least in part from natural gas to carbon-free forms of hydrogen, like those coming from electrolysis using nuclear and renewable power. How soon these are developed, and what fraction of the hydrogen they can supply, may depend upon regulation of carbon dioxide emissions. Even without regulation, however, we can project that they will likely provide an increasing share of hydrogen production, and by 2050 may even approach that provided by natural gas.

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[18] *Id.* As of August 2021, the American Jobs Plan was, in principal part, placed into in the proposed bipartisan Senate bipartisan infrastructure bill, which was passed into law, and the Senate reconciliation budget plan, which has not as of this writing been passed into law.

[19] Henning, Mark; Thomas, Andrew R.; Triozzi, Michael; and Psarras, Peter, "How the Midwest Can Lead the Hydrogen Economy: Matching Generation Assets to Distribution Markets in Planning Hydrogen Refueling Infrastructure for Trucking and Transit" (2020). Urban Publications. 0 1 2 3 1656. https://engagedscholarship.csuohio.edu/urban_facpub/1656. (See also Argonne National Laboratory. Hydrogen Delivery Scenario Analysis Model (HDSAM) User Guide. https://hdsam.es.anl.gov/files/hdsam-guide. See also http://ieahydrogen.org/Activities/Task-28/Task-28-report_final_v2_ECN_12_2_v3.aspx).

To most people the hydrogen economy means the adoption of hydrogen to power transportation, primarily through fuel cell electric vehicles. Absent a zero-emission vehicle mandate, this market will make up a relatively small share of the near-term total market. However, by 2050 transportation is expected to be the largest consumer of hydrogen in Ohio, with or without carbon regulations. In the near term, light duty vehicles will likely transition to battery electric propulsion, while heavy duty will transition to fuel cell electric. For this reason, and due to fleet refueling logistics, public transit is expected to be among the largest early users of hydrogen in Ohio, consuming over 500 kg/day by 2030.[20] But we also project that heavy duty trucks (Class 8) (heavy duty) will be a major early consumer of hydrogen in the region, where refueling infrastructure can be built along interstate corridors. The Pittsburgh to Chicago I76/I80 corridor, for instance, is projected to use around 1,200 kg/day by 2030, and about 20,000 kg/day by 2040, even without zero emission mandates.[21]

As will be set forth below, for Ohio, the Study Team projects a 12.2% overall vehicle market penetration rate by 2050, assuming no zero emission vehicle mandates. That penetration rate would require about 430,000 metric tons of hydrogen annually in Ohio. If the penetration rate reaches 33%, which is likely if Ohio becomes a zero-emission vehicle state, Ohio will require around 1.2 million metric tons (MMT) of hydrogen annually to satisfy demand from fuel cell electric vehicles.

2.0 Hydrogen Generation Opportunities for Ohio

2.1 Generation Technologies and Strategies

As hydrogen has begun to play a more significant role in the energy economy of the United States, several production pathways have developed to supply the need for hydrogen resources. These various pathways for the creation of hydrogen have differing levels of technological maturity, economic viability, and environmental impact. It has become common to refer to these different production methods using “color” labels that indicate their level of environmental sustainability. A brief overview of the methods of production and their economic and environmental viabilities is given below.

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[20] *Id*. at 35. A recent study by Foothill Transit (Southern California) found that hydrogen fuel cell electric buses would provide that transit agency with a significantly lower cost life cycle fleet replacement than battery electric buses.

[21] *Id.*

Table 2. Estimated Generation Cost and Carbon Intensity of Various Strategies for Large-Scale Hydrogen Generation (2021)

Hydrogen Generation Technology	Generation cost ($/kg H_2)	Carbon Intensity ($gCO_2e/MJ\ H_2$)
SMR (gray)[a]	1.00 – 2.14	99
SMR with carbon capture (blue)[b]	1.20 – 3.16	20
H_2O electrolysis with renewable energy (green) or nuclear (pink)[b]	2.80 - 7.00	11
BiCRS[a]	5.00 - 6.00	-127

a Authors' analysis. SMR refers to "Steam Methane Reforming." BiCRS refers to "Biomass Carbon Removal and Storage." MJ refers to Megajoule.
b Liguori, S.; Kian, K.; Buggy, N.; Anzelmo, B. H.; Wilcox, J., Opportunities and Challenges of Low-Carbon Hydrogen via Metallic Membranes. *Progress in Energy and Combustion Science* 2020, *80*, 100851.

2.1.1 Steam Methane Reformation (SMR) -- Gray Hydrogen

At present, 95% of the hydrogen used in the United States is produced from Steam Methane Reformation (SMR).[22] The SMR process passes pressurized natural gas and heated steam over a catalyst (typically supported nickel) to generate hydrogen, carbon dioxide, carbon monoxide, and other trace compounds. Unreacted carbon monoxide is converted to hydrogen via the high temperature water gas shift reaction, and the resulting mixture is fed to a pressure swing adsorption unit where 85-90% of the hydrogen is recovered at over 99.9% purity.[23]

SMR is already used on an industrial scale to produce economically competitive hydrogen, although the cost to produce hydrogen via SMR depends in part on the cost of the natural gas that is used as a feedstock. A study conducted by the National Renewable Energies Laboratory (NREL) estimates that existing facilities in the East North Central census region of the United States can produce 1 million metric tons (MMT) of hydrogen annually at a cost of $1.44 per kg.[24] Although widely used and technologically efficient, the SMR process is carbon intensive, emitting

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[22] Department of Energy, Office of Energy Efficiency & Renewable Energy, 2021. H*ydrogen Production: Natural Gas Reforming,* available at: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming
[23] Collodi, G.; Azzaro, G.; Ferrari, N. *Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS*; IEAGHG: 2017. *See*: https://www.sciencedirect.com/science/article/pii/S1876610217317277
[24] Ruth, Mark F., Jadun, Paige, Gilroy, Nicholas, Connelly, Elizabeth, Boardman, Richard, Simon, A. J., Elgowainy, Amgad, and Zuboy, Jarett. *The Technical and Economic Potential of the H2@Scale Hydrogen Concept within the United States*. National Renewable Energy Laboratory. United States: 2020. Around 10 MMT are produced nationally per year. *Id.*

between 8 to 12 kg of carbon dioxide equivalents (CO_2e) per kg of hydrogen produced.[25] The carbon dioxide produced by SMR may be mitigated through carbon capture, as described below.

2.1.2 Coal Gasification -- Brown Hydrogen

Hydrogen can be produced from coal via the process of gasification, which converts solid coal into synthetic gas using a high temperature mixture of steam and a controlled amount of oxygen gas. The resulting synthetic gas blend, composed of hydrogen and carbon monoxide, can then be used as a starting block for a number of chemical pathways, or separated to produce pure hydrogen. Coal gasification requires 8.6 kg of coal to produce one kg of hydrogen and the process produces significant amounts of solid waste and carbon dioxide as byproducts.[26] Specifically, the carbon intensity of hydrogen generation using coal gasification has been estimated at between 19 and 25 kg CO_2e per kilogram of hydrogen, depending on the coal feedstock. The vast majority of these emissions (~97%) arise from the gasification process, with only minimal contributions encountered in upstream coal extraction, processing and transport.[27]

Ruth et al. estimate that coal gasification can yield hydrogen at a levelized cost of $2.04–$2.15/kg (or $2.43–$2.54/kg if hydrogen transportation costs are factored in).[28] In addition to the drawback of the high levels of carbon dioxide and solid waste produced by coal gasification, the high capital costs of the process compared to SMR render it only economically efficient at large scales.

2.1.3 Fossil Fuel-Based Production with Carbon Capture -- Blue Hydrogen

Since most current hydrogen production currently entails producing high volumes of carbon dioxide as a byproduct, there has been significant research into technologies that would capture and store carbon dioxide before it is released into the atmosphere. For processes involving high levels of carbon dioxide production as a byproduct (such as SMR or coal gasification), the carbon dioxide can be physically absorbed and separated using solvents such as Selexol™. Research has

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[25] *See* Rocky Mountain Institute, 2020. *Hydrogen's Decarbonization Impact for Industry*. Available at https://rmi.org/wp-content/uploads/2020/01/hydrogen_insight_brief.pdf

[26] Ruth, Mark F., Jadun, Paige, Gilroy, Nicholas, Connelly, Elizabeth, Boardman, Richard, Simon, A. J., Elgowainy, Amgad, and Zuboy, Jarett. *The Technical and Economic Potential of the H2@Scale Hydrogen Concept within the United States*. National Renewable Energy Laboratory. United States: 2020.

[27] Burmistrz, P.; Chmielniak, T.; Czepirski, L.; Gazda-Grzywacz, M., Carbon footprint of the hydrogen production process utilizing subbituminous coal and lignite gasification. *Journal of Cleaner Production* 2016**,** *139*, 858-865. *See*: https://www.sciencedirect.com/science/article/pii/S0959652616312604?via%3Dihub

[28] Ruth, Mark F., Jadun, Paige, Gilroy, Nicholas, Connelly, Elizabeth, Boardman, Richard, Simon, A. J., Elgowainy, Amgad, and Zuboy, Jarett. *The Technical and Economic Potential of the H2@Scale Hydrogen Concept within the United States*. National Renewable Energy Laboratory. United States: 2020. *See:* https://www.nrel.gov/docs/fy21osti/77610.pdf

suggested that a facility producing hydrogen via SMR and using Selexol™-based carbon capture processes could produce hydrogen at a cost of $0.99--$3.24/kg once constructed, depending on the size, output, and efficiency.[29]

It is important to note that capturing carbon dioxide from SMR is not a new technology. The Air Products SMR carbon, capture and utilization (CCUS) project at the Valero Port Author refinery in Texas began operation in late 2012, capturing 1 MMT of carbon dioxide per year from SMR hydrogen generation for delivery to an adjacent enhanced oil recovery operation. Shell's Quest Project in Alberta Canada commenced in 2015 and uses an amine absorption technology to capture carbon dioxide for underground storage. Several other projects await in the pipelines, demonstrating that blue hydrogen is safe, technically feasible, and economic given sufficient support (e.g., revenue from the sale of carbon dioxide or tax credits for sequestration).

2.1.4 Production from Renewable Resources (Green Hydrogen) and Nuclear Power (Pink Hydrogen)

In the fossil-fuel derived routes mentioned above, carbon dioxide will always be a by-product of hydrogen generation because the source of hydrogen is a hydrocarbon: by definition, this source contains hydrogen and *carbon*. One strategy to reduce direct generation of carbon dioxide is to eliminate carbon from the feedstock. Hydrogen can be produced from water in electrolytic cells, where the byproduct is oxygen gas. While this process solves the problem of *direct* CO_2 emissions, careful selection of the energy source for the electrolysis process is necessary to ensure minimization of indirect emissions associated with electricity production. For example, electricity taken from the grid has an average carbon intensity of approximately 700 g CO_2e/kWh, whereas electricity from solar, nuclear and wind power has a footprint of 25, 12, and 11 gCO_2/kWh, respectively.[30]

Hydrogen production through electrolysis can be accomplished using proton exchange membrane (PEM), alkaline or solid oxide electrolyzers. Of these methods, alkaline electrolyzers are the most technologically mature. Recent research by the International Renewable Energy Agency (IRENA) indicates that the investment cost for producing hydrogen using these methods equates to a production cost of about $2.03/kg on average for facilities with electrolyzer upfront

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[29] Henning, Mark; Thomas, Andrew R.; Triozzi, Michael; and Psarras, Peter, "How the Midwest Can Lead the Hydrogen Economy: Matching Generation Assets to Distribution Markets in Planning Hydrogen Refueling Infrastructure for Trucking and Transit" (2020). Urban Publications. 0 1 2 3 1656.

[30] Pacala, S.; Al-Kaisi, M.; Barteau, M. A.; Belmont, E.; Benson, S. M.; Birdsey, R.; Boysen, D.; Duren, R.; Hopkinson, C.; Jones, C., Negative emissions technologies and reliable sequestration: a research agenda. Washington, DC: The National Academies Press: 2018. https://www.nationalacademies.org/our-work/a-research-strategy-for-ocean-carbon-dioxide-removal-and-sequestration

costs of $500/kW that operate at 15% capacity.[31] Current capital costs per kW range from $500 to $1,000 for alkaline electrolyzers, and $700 to $1,400 for PEM electrolyzers.[32] For electrolyzers with upfront costs of $770/kW operating at the same capacity, IRENA estimates a hydrogen production cost of $3.75/kg. Based on IRENA's analysis, the use of grid electricity adds about $0.50/kg more to the cost of hydrogen production for every $0.01/kWh charged for electricity.[33] In Ohio, where the all-in cost of electricity for large industrial users has recently averaged around $0.06/kWh, the use of grid electricity to produce hydrogen via electrolysis would therefore add $3.00/kg more to the production cost, totaling $5-6/kg.[34] Small scale commercial power from the grid in Ohio sells on average for about $0.10/kWh, which would add $5/kg to the cost, making the total price around $7-8/kg for generating hydrogen through electrolysis. For this reason, onsite hydrogen production, such as might occur at a refueling station, might benefit from onsite power generation.

2.1.5 Byproduct Hydrogen from Ethane Cracking

In addition to producing hydrogen for merchant sale and industrial purposes, several major industrial processes also produce hydrogen as a byproduct. Ethane cracker plants are among the most promising of these producers of byproduct hydrogen. Ethane steam cracking is a process that reforms ethane gas into ethylene, polyethylene, and other light olefins by applying heated steam to the feedstocks in order to strip the hydrogen atoms from the natural gas. A 2018 study conducted by the Energy Systems Division of Argonne National Laboratory estimated that 3.5 MMT of byproduct hydrogen could be produced each year by cracker plants in the United States, although at present, the vast majority of this hydrogen is either vented or burned for heat at the point of production.[35] The Argonne study estimated that the cost of rendering this byproduct hydrogen as a marketable commodity would be $0.9–1.1/kg.[36] Harnessing this byproduct hydrogen for sale at potential markets has the added benefit of producing a fraction of the greenhouse gas emissions normally produced through the SMR process of hydrogen production.[37]

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[31] *See* International Renewable Energy Agency, 2020. *Green Hydrogen Cost Reduction: Scaling Up Electrolysers to Meet the 1.5°C Climate Goal* (Figure 1). Available at https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

[32] *Id.* (Table 6).

[33] *Id.* (Figure 1).

[34] *See* https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

[35] Lee, Dong-Yeon, and Elgowainy, Amgad. *By-product hydrogen from steam cracking of natural gas liquids (NGLs): Potential for large-scale hydrogen fuel production, life-cycle air emissions reduction, and economic benefit*. United States: 2018. Web. doi:10.1016/j.ijhydene.2018.09.039.

[36] *Id.*

[37] *Id.* The range is between 15-91% of carbon dioxide made through SMR, depending upon circumstances.

The economic feasibility of using byproduct hydrogen from steam cracking will depend on the proximity of ethane cracker plants to potential markets and the cost of installing new hydrogen delivery infrastructure. Steam ethane cracking produces relatively small amounts of hydrogen, outputting only 0.076 units of hydrogen by mass for every unit of ethylene that is produced, as the production of hydrogen is not the primary goal of these facilities.[38] At high levels of production, however, this byproduct hydrogen could become a marketable commodity.

There are several regional cracker facilities either planned or already actively under construction, including a proposed facility in Belmont County, Ohio. One actively under construction in 2021 is the Shell Oil Company ethane cracker plant in Beaver County, Pennsylvania, which sits adjacent to the Ohio state line. Its expected output is 1.6 million metric tons of polyethylene per year, which could in turn yield as much as 121,600 metric tons of byproduct hydrogen annually. As steam cracking becomes a larger part of Ohio's energy economy, further studies will show how efficiently byproduct hydrogen can be incorporated into nearby industrial markets.

2.2 Ohio Assets for Hydrogen Generation

The state of Ohio has multiple natural and industrial resources that make it well-suited for several of the hydrogen production methods outlined in the above section. Seven hydrogen production facilities are currently in operation within the state of Ohio, including plants operated by Air Products in Cincinnati and Middletown, plants operated by Linde in Lima and Oregon, Ohio, and a Praxair plant in Painesville. Each of these plants uses Steam Methane Reformation to generate hydrogen. These facilities supply nearby industrial centers with gaseous hydrogen for use in oil refining and chemical production and have a combined output capacity of over 440,000 kg/day.[39] In addition, many industrial facilities produce and consume hydrogen onsite rather than purchasing it for delivery by industrial gas suppliers. Because transportation and storage costs can be relatively high, the economic viability of hydrogen production will depend considerably upon its proximity to hydrogen markets. Ohio's markets in relation to potential sources of hydrogen will be discussed more in the sections below. An overview of Ohio's potential resources for the generation of hydrogen is outlined below.

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[38] *Id*. at 9

[39] According to data compiled by the Hydrogen Analysis Resource Center. See *Merchant Hydrogen Plant Capacities in North America*. Available at https://h2tools.org/hyarc/hydrogen-data/merchant-hydrogen-plant-capacities-north-america

2.2.1 Natural Gas Resources

Natural gas is the most common feedstock for the process of Steam Methane Reforming which remains the most prevalent method of hydrogen production globally. Renewable natural gas, typically found at landfills, can be another source for SMR, but to date it has not commonly been purposed for generating hydrogen. Ohio's significant natural gas resources can be an important asset in future hydrogen production. Due to the advent of shale development, natural gas production in Ohio increased over thirty-fold between 2012 and 2019 and Ohio currently has 26,894 natural-gas-producing wells in operation.[40] Most of Ohio's natural gas production is sourced from Utica Shale wells in the southeastern portion of the state. In 2019, wells in the state of Ohio produced 2.6 trillion cubic ft (TCF) of natural gas. Every thousand cubic feet (mcf) of natural gas can produce around 6.4 kg of hydrogen via SMR. If 15% of that production was repurposed for hydrogen, it would supply 2.5 million metric tons per year at current production rates. The Energy Information Agency (EIA) estimates future commercial production of 34 TCF of natural gas during the life of the Utica.[41] Hydrocarbon recovery technology will have to be improved, or production imported from other formations, to maintain a rate of production required to meet expected hydrogen markets in 2050.

It should be noted that Ohio's natural gas industry provides the state with much more than just a feedstock for SMR, however. Even before the development of shale gas, Ohio had a mature natural gas storage and transportation infrastructure. This has been developed further since the Utica and Marcellus shale formations began production. As will be discussed later, infrastructure may in part be retrofitted for use with hydrogen.

2.2.2 Nuclear Resources

Nuclear energy plants can provide a source of inexpensive, carbon free electricity for use in hydrogen generation through the process of electrolysis. There is potential for Ohio's two nuclear power stations to divert some of their power to the generation of hydrogen, especially during off-peak grid demand. A DOE-funded project is currently being piloted at the Davis-Besse Nuclear Power Station near Toledo, Ohio to produce hydrogen via low-temperature PEM electrolysis. The Davis-Besse Nuclear Power Station and its sister plant in Perry, Ohio (near

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[40] US Energy Information Administration, June 2020. *Ohio State Energy Profile,* available at https://www.eia.gov/state/print.php?sid=OH

[41] *Id.* In 2019 the U.S. Geologic Survey estimated the "technically recoverable reserves" in the Utica-Point Pleasant formation to 38 TCF, and over 200 TCF including the Marcellus, which formation does not produce much in Ohio, but does in neighboring states. https://triblive.com/news/pennsylvania/report-amount-of-marcellus-utica-natural-gas-higher-than-in-2011/. What is "technically" recoverable may or may not be "commercially" recoverable, depending upon prices.

Cleveland) are both located close to significant industrial, commercial and transportation markets, making them well-suited for both hydrogen and grid power generation.

The Davis Besse Nuclear Power Station is capable of producing 908 MW of electricity, much of which could be repurposed for the production of hydrogen.[42] The PEM electrolyzer being piloted with the Davis Besse Nuclear Power Plant has the capacity to convert 2 MW of power to 800-1000 kg of hydrogen per day.[43] Using this conversion factor, if 15% of the power produced at Davis Besse were diverted for hydrogen production, 68,100 kg of hydrogen could be produced daily (using 500 kg/MW). The Perry Nuclear Generating Station, which has a capacity of 1,268 MW, could likewise generate 95,100 kg/day by repurposing 15% of its power away from the grid to hydrogen, for an Ohio total of over 59,600 metric tons per year.

2.2.3 Potential Renewable Energy Resources

By the end of 2021, Ohio had 480 MW of utility-scale solar power generation capacity,[44] with an additional 444 MW under construction.[45] Among the largest operational solar projects in the state are the Hillcrest Solar Farm in Brown County, Ohio which can generate 200 megawatts of power, and the Hardin Solar Energy Center in Hardin County, Ohio which can generate 150 megawatts. Solar fields could be used to generate hydrogen either through photovoltaic processes that are currently being developed or through electrolysis. The EIA also considers Ohio to have access to a moderate level of potential wind-based energy generation, mainly from winds off the shores of Lake Erie or from wind farms in western Ohio.[46] As of December 2021, more than 450 onshore wind turbines were in operation in Ohio, with the capacity to generate 1,102 megawatts of electricity.[47]

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[42] Using the MW capacity of the Davis Besse Nuclear Power Sation made publicly available by the Bechtel Corporation and found at https://www.bechtel.com/projects/davis-besse-nuclear-power-station/

[43] See University of Toledo, 2020. *Sustainable Energy Economy Workshop: Research & Development of Light Water Reactor and Hydrogen Hybrids*. Available at https://www.utoledo.edu/engineering/docs/EnergyWorkshopReport_Feb26_2020.pdf

[44] *See* EIA's Monthly Electric Generator Inventory for December 2021 (https://www.eia.gov/electricity/data/eia860m/). EIA considers utility-scale generating facilities to be those where total generation capacity is one megawatt (MW) or greater.

[45] https://opsb.ohio.gov/wps/wcm/connect/gov/b504e379-4a4ba-49e4-aa35-dba759ffee7f/Solar+Map+and+Stats02252022.pdf?MOD=AJPERES&CONVERT_TO=url&CACHEID=ROOTWORKSPACE.Z18_K9I401S01H7F40QBNJU3SO1F56-b504e379-4a4ba-49e4-aa35-dba759ffee7f-nZGTr41

[46] *Supra,* fn 41. *See also* https://opsb.ohio.gov/wps/wcm/connect/gov/c48eaa05-9f80-4a6b-bae1-f4cdc6717207/Wind+Map+and+Stats02222022.pdf?MOD=AJPERES&CONVERT_TO=url&CACHEID=ROOTWORKSPACE.Z18_M1HGGIK0N0JO00QO9DDDDM3000-c48eaa05-9f80-4a6b-bae1-f4cdc6717207-nZHfq2N

[47] *Id.*

Solar facilities tend to produce power during peak electric load demand, and as a result solar power is often more valuable being sold into the grid. Wind power, however, generates significant off-peak electricity, making the production of hydrogen more economically attractive. Since wind-based resources are less dependent on the time of day, it may be possible to divert a portion of generation potential during non-peak hours to the production of hydrogen. Several of Ohio's potential wind farm areas may be located offshore in Lake Erie, as in the case of the proposed 21-megawatt Icebreaker Wind project which has been approved for construction by 2022.[48]

Nationally, the EIA projects electricity generating capacity from solar and onshore wind to grow, respectively, 3.9% and 0.7% annually on average over the next 30 years according to the agency's 2022 *Annual Energy Outlook* Reference case projections. [49] Applying these growth rates to Ohio's power generation capacity from solar and onshore wind that will likely be available by the first half of 2023,[50] the state projects to have 5.0 GW of utility-scale renewable generation capacity by 2050. Diverting 15% of this capacity to electrolytic hydrogen production could yield 135,900 metric tons annually based on a production rate of 500 kg per day per MW, assuming the generation could be run 24/7. Clearly renewable cannot be, so it would require either storage or a larger percentage of capacity to meet 15% of overall electricity generated. Regulatory uncertainty in the state around renewables, especially for wind siting offsets, may also limit the ability of wind and solar to provide this level of generation capacity over the long run.[51]

2.2.4 Biomass and Emerging Technologies

Ohio also has significant biomass resources that can be used to generate hydrogen. This biomass can be found in the form of wood waste, agricultural detritus, municipal waste, and other organic waste material. A significant portion of the biomass available in Ohio is currently being processed into approximately 38,000 tons of wood pellets each year, much of which is burned for power generation or heating.[52] Currently, 17 power plants in Ohio burn biomass-based resources to generate electricity.[53] The further development of biomass reforming technology would allow for this biomass to also be converted into hydrogen through gasification or microbial

[48] *See* permitting details made publicly available by the Ohio Siting Board for the Icebreaker Wind Facility (Case Number: 16-1871-EL-BGN), available at https://opsb.ohio.gov/wps/portal/gov/opsb/cases/16-1871-el-bgn

[49] EIA's Reference case projections assume current laws and regulations, and includes current views on economic and demographic trends and technology improvements. *See* EIA Data Browser. Annual Energy Outlook 2022 [*Table 16. Renewable Energy Generating Capacity and Generation*]. https://www.eia.gov/outlooks/aeo/data/browser.

[50] *Supra,* fns 2 and 41.

[51] *See* https://www.eenews.net/articles/volatile-place-new-laws-thwart-ohio-renewables/.

[52] US Energy Information Administration, June 2020. *Ohio State Energy Profile*. Available at https://www.eia.gov/state/print.php?sid=OH

[53] *Id.*

fermentation.[54] The Department of Energy considers microbial biomass conversion to be potentially commercially viable as a mid- to long-term strategy for hydrogen production, and the ready availability of biomass resources in Ohio make this a future option for Ohio. More detail about biomass hydrogen generation is set forth below discussing emerging technologies.

Two emerging hydrogen technologies hold considerable promise in Ohio for the use of biomass to make hydrogen: hydrogen from biomass with carbon removal and storage (BiCRS) and hydrogen from methane pyrolysis, also known as *turquoise* hydrogen. Recent studies published separately by Lawrence Livermore National Laboratory[55] and Princeton University[56] cite the leveraging of vast waste biomass resources within the region to serve as a source of hydrogen, either via gasification or fast pyrolysis of biomass. Importantly, in these processes the by-product CO_2 is captured and secured safely underground.

The key advantage in this route is that the produced hydrogen is assigned a negative carbon footprint over its lifecycle due to emissions accounting protocols associated with the capture and storage of CO_2 derived from biomass resources.[57] This could become an important feature if climate change requires urgent action, or if net-zero requirements become difficult to meet. With no commercially available technologies to directly remove carbon dioxide from the air, accounting for negative carbon emissions may be the best alternative. Ohio is projected to yield roughly 3.6 million dry tons of biomass in 2025, with the top ten counties – and the amount of hydrogen that can be generated therefrom – listed in Table 3 below.[58] Total projected biomass capacity for Ohio in 2025 is 159,549 metric tons per year. Biomass hydrogen production is a promising source of green hydrogen, but currently too uncertain to be included in this Study as contributing to the total hydrogen capacity projections for Ohio.

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[54] *See* U.S. Department of Energy Office of Energy Efficiency & Renewable Energy. *Hydrogen Production: Microbial Biomass Conversion*. Available at https://www.energy.gov/eere/fuelcells/hydrogen-production-microbial-biomass-conversion.

[55] Baker, S.; Peridas, G.; Stolaroff, J.; Goldstein, H.; Pang, S.; Lucci, F.; Li, W.; Slessarev, E.; Pett-Ridge, J.; Ryerson, F. *Getting to Neutral: Options for Negative Carbon Emissions in California*; Lawrence Livermore National Laboratory (LLNL) Livermore, CA, 2019

[56] E. Larson; C. Greig; J. Jenkins; E. Mayfield; A. Pascale; C. Zhang; J. Drossman; R. Williams; S. Pacala; R. Socolow; EJ Baik; R. Birdsey; R. Duke; R. Jones; B. Haley; E. Leslie; K. Paustian; Swan, A. *Net-Zero America: Potential Pathways, Infrastructure, and Impacts, interim report*; Princeton University, Princeton, NJ, 2020.

[57] Specifically, since this CO_2 is biogenic in nature and captured for geologic storage, it is considered a carbon dioxide removal technology

[58] Langholtz, M. H.; Stokes, B. J.; Eaton, L. M., 2016 Billion-ton report: Advancing domestic resources for a thriving bioeconomy, Volume 1: Economic availability of feedstock. *Oak Ridge National Laboratory, Oak Ridge, Tennessee, managed by UT-Battelle, LLC for the US Department of Energy* 2016**,** *2016*, 1-411. For county-level projections, see the study's data mapping tool at https://bioenergykdf.net/executive-summaryoverview?chapterNumber=1&tabNumber=2#panel-a8d8e1aa-af4a-41f3-bb02-e925f558fafe.

Table 3. Year 2025 Waste Biomass and Hydrogen Generation Potential for Ohio.

County	Waste biomass potential (dry tons)	H_2 generation potential (metric tons)[59]
Cuyahoga	355,647	15,809
Franklin	320,261	14,236
Hamilton	216,163	9,609
Summit	149,467	6,644
Montgomery	143,414	6,375
Lucas	118,062	5,248
Stark	107,502	4,779
Butler	102,833	4,571
Lorain	83,891	3,729
Mahoning	70,649	3,140
All other counties	1,921,338	85,407
Total	**3,589,227**	**159,549**

Source: The Authors (based upon Langholtz et al.)

Turquoise hydrogen generation creates hydrogen through hydrocarbon pyrolysis (thermal decomposition) at high temperatures to produce hydrogen and carbon. Unlike for blue hydrogen production, the carbon byproduct is not gaseous carbon dioxide, but instead solid carbon, obviating the need to manage the CO_2. The produced solid carbon has a number of industrial and commercial uses, from soil amendment to incorporation into tire manufacturing. While this option is less mature and potentially energy intensive due to the elevated pyrolytic conditions, it holds promise for regions with prohibitive CO_2 sequestration costs.

3.0 Hydrogen Markets and Consumption Potential in Ohio

3.1 Natural Gas Blending: Opportunities for Power Generation and Heating

There is a potential market for hydrogen to be used as a supplement for natural gas stocks in existing pipelines. By displacing some of the natural gas in an existing pipeline with hydrogen, the carbon emissions created by the burning of natural gas could be significantly reduced.[60] Recent studies indicate that converting natural gas pipelines to carry a blend with up to 20% hydrogen may require only modest modifications to transmission pipelines and end-use applications.[61] This admixture can then be used in place of pure natural gas by facilities seeking to reduce their

[59] Assumes hydrogen from Municipal Solid Waste (MSW) at ~ 0.049 metric tons of hydrogen per metric ton of MSW (more than 80% of Ohio's biomass is projected to be from MSW); *see* https://bioenergykdf.net/executive-summaryoverview?chapterNumber=1&tabNumber=2#panel-a8d8e1aa-af4a-41f3-bb02-e925f558fafe.

[60] See *US Drive Hydrogen Delivery Technical Team Roadmap*. (2017).

[61] Melaina, M W; Antonia, O; Penev, M, *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues,* National Renewable Energy Lab. (NREL), Golden, CO (2013).

environmental impact. Alternatively, the blended hydrogen could be separated back out by the end-use facility through the process of Pressure Swing Adsorption.[62] According to a 2020 analysis by Argonne National Laboratory, a 20% blend of hydrogen in natural gas pipelines could create a national demand of 44,000 metric tons per day (16 MMT/yr) of hydrogen by 2050.[63]

Absent a carbon tax on fossil-based energy or subsidy for zero-carbon alternatives, hydrogen will have to compete directly with natural gas on cost. The amount of hydrogen blended into the existing natural gas pipeline network will therefore also depend on the price of natural gas. The EIA, under its AEO2020 Reference case representing its best assessment of how U.S. and world energy markets will operate through 2050, projects a natural gas price of $4.68/MMBtu for industrial use and $4.16/MMBtu for electric power generation by 2050 (both prices in 2020 dollars, and both assume that current laws and regulations remain unchanged throughout the reference period).[64] On a higher heating value basis, this corresponds to hydrogen prices of $0.71/kg and $0.63/kg for high-volume industrial and electric power consumers, respectively.[65] Under the reference case for natural gas, and assuming that the DoE is able to meet its target cost of $1/kg for clean hydrogen over the next decade,[66] additional intervention would still likely be necessary for hydrogen to see high high-volume natural gas blending applications requiring pipeline distribution.

There is reason to believe, however, that the EIA reference case for natural gas price may be low, given how much natural gas is now being exported,[67] how much will be needed to create hydrogen, and the rate of reserve depletion in Appalachia. Repurposing 15% of natural gas to make hydrogen through SMR – the amount likely required to meet demand even under the no carbon regulation scenario – will have a significant effect on supply. Between the depletion of lower cost reserves (the estimated 34 TCF of commercial reserves in the Utica, for example, are

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[62] *Id.* This will likely require some PSA technology improvements. The current economics of separating hydrogen from natural gas through PSA are disadvantageous.

[63] A. Elgowainy, M. Mintz, U. Lee, T. Stephens, P. Sun, K. Reddi, Y. Zhou, G. Zang, M. Ruth, P. Jadun, E. Connelly, R. Boardman, *Assessment of Potential Future Demands for Hydrogen in the United States* (2020).

[64] U.S. Energy Information Administration. (2021). *Annual Energy Outlook 2021* (Table 3.Energy Prices by Sector and Source). https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2021&cases=ref2021~aeo2020ref&sourcekey=0. Accessed September 10, 2021.

[65] The following parameters were assumed in comparing the higher heating values of natural gas and hydrogen: the energy content of methane in Ohio is 1.1 MMBtu/Mcf; the higher heating values of methane and hydrogen are 36.4 MJ/m^3 and 142.2 MJ/kg, respectively [*See* Ragland, K. W., & Bryden, K. M. (2011). Combustion engineering (Table 2.2). Boca Raton, FL: CRC press.].

[66] *See* DoE Hydrogen Energy Earthshot Initiative. https://www.energy.gov/articles/secretary-granholm-launches-hydrogen-energy-earthshot-accelerate-breakthroughs-toward-net

[67] C. Riley, "U.S. becomes world's top exporter of liquified natural gas," https://www.cnn.com/2022/01/05/energy/us-lng-exports/index.html. Henry Hub prices for natural gas were over $5/mmbtu in January 2022, however the EIA projects it will average under $4/mmbtu in 2022-23. https://www.eia.gov/todayinenergy/detail.php?id=50898

being depleted at a rate of 2.7 TCF/year) and the increased demand for natural gas, EIA's low natural gas supply scenario of $7.39/MMbtu (industrial) and $6.82/MMbtu (electric power) for 2050 may be a better forecast. Under that scenario, natural gas prices would support blending of clean hydrogen at hydrogen generation costs in the $1/kg range. This all, of course, assumes that the generation will take place at or near a major pipeline, or at the tailgate of a natural gas processing plant.

Ohio is likely to host some of the first large-scale hydrogen-natural gas blend consumers. Near-term plans are already underway to add hydrogen to the fuel mix for a natural gas-fired power plant at Long Ridge Energy Terminal.[68] Hydrogen does not provide carbon emissions when combusted. As such, its use aligns with the power generation industry's growing desire to reduce carbon emissions, especially if the hydrogen is produced from renewable sources.[69]

While experts project that natural gas/hydrogen blends can include up to 20% hydrogen, it is difficult to know if they will in fact reach that volume absent some value placed upon carbon emissions. However, we can make some projections of future hydrogen consumption based upon natural gas-based power generation in Ohio at the county level, which will provide a large portion of the natural gas consumption in Ohio (industrial, commercial and residential uses are also significant consumers). Assuming that hydrogen was sufficiently inexpensive such that it constituted 20% of the fuel mix for gas-fired power generation in the state, we can merge Energy Information Agency 923 fuel consumption survey data[70] (greater than 1 MW) together with the U.S. Department of Energy data on CHP plant consumption[71] (below 1 MW) to estimate the volume of natural gas required to supply generation as it exists in Ohio in 2021.

There are additional large-scale natural gas power plants currently under construction. These include the 1,875 MW Guernsey Power Station, the 1,105 MW South Field Energy Center, the 485 MW Long Ridge Energy Center, and the 105.5 MW CHP plant on the campus of Ohio State

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[68] Mark Williams and Beth Harvilla, Feb 3, 2021: "Long Ridge Power Plant in Ohio to Use Hydrogen and Natural Gas," *Columbus Dispatch.* Available at https://www.dispatch.com/story/business/2021/02/03/long-ridge-power-plant-ohio-use-hydrogen-natural-gas/4230621001/

[69] See General Electric Company, 2019. Power to Gas: *Hydrogen for Power Generation,* available at https://www.ge.com/content/dam/gepower/global/en_US/documents/fuel-flexibility/GEA33861%20Power%20to%20Gas%20-%20Hydrogen%20for%20Power%20Generation.pdf

[70] *See* https://www.eia.gov/electricity/data/eia923/. EIA-923 survey data provides annual data on fuel consumption for power generation at the plant level. This data encompasses all U.S. electric power plants with a generator nameplate capacity of 1 MW or greater, including combined heat and power (CHP) plants, along with the technology basis for that generator (e.g., natural gas, nuclear, solar, etc.).

[71] *U.S. Department of Energy Combined Heat and Power and Microgrid Installation Databases* available at https://doe.icfwebservices.com/chp

University.[72] Annual fuel consumption for these plants was estimated based on the annual fuel consumption per MW of nameplate generator capacity for existing gas-fired plants as gathered from the EIA-923 data. Because these plants will begin operations in the next few years, their consumption was added to the existing volumes consumed for electricity in Ohio. However, there are new plants that have been permitted, including one in Harrison County, that are likely to be added to Ohio's natural gas-based power generation fleet. Those plants will be added to future maps looking at likely hydrogen consumption or power generation.

The EIA further projects an overall 3.5% increase in the volume of natural gas consumed for electric power generation from 2020 to 2050.[73] We applied this growth to the current facility-level consumption for gas-fired plants (plus plants under construction) in Ohio to arrive at projected future natural gas consumption, 20% of which was assumed to be hydrogen by volume (and converted to mass). It is important to note that these projections do not account for energy losses resulting from the lower energy content of hydrogen per unit volume compared to natural gas. The conversion of hydrogen's volume to its mass was based on a factor of 2.37 kg per thousand cubic feet (mcf) at 68°F.[74]

The results of this analysis appear below in Figure 1, where we project annual hydrogen consumption by 2050 for power generation at the county level. Altogether, projected state-wide hydrogen consumption under this scenario is 251,200 metric tons annually. Notably, the consumption does not correlate directly with population centers in Ohio. This is because large scale natural gas plants are not generally located in heavily populated counties.

In the Bipartisan Infrastructure Bill passed in November of 2021, an additional market that is very similar to power generation was targeted for development: residential and commercial heating. The likely early markets for heating will be for boilers that use blended hydrogen and natural gas, and as such, the markets will be similar to that for power generation. Hydrogen-tolerant boilers and burners have been deployed in the United Kingdom and are available from such companies as Beckett Thermal Solutions in North Royalton, Ohio. Further, there is evidence that the public will support hydrogen heating markets.[75] But projections for this market are difficult because of

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[72] Ohio Siting Board, April 2021. *Power Siting Gas Generation & CHP Case Status,* available at https://opsb.ohio.gov/wps/wcm/connect/gov/b1eb9b14-cdc0-4389-81a2-9a5c52cc85aa/Natural+Gas+Map+and+Stats.pdf?MOD=AJPERES&CONVERT_TO=url&CACHEID=ROOTWORKSPACE.Z18_M1HGGIK0N0JO00QO9DDDDM3000-b1eb9b14-cdc0-4389-81a2-9a5c52cc85aa-nz5Ub2G

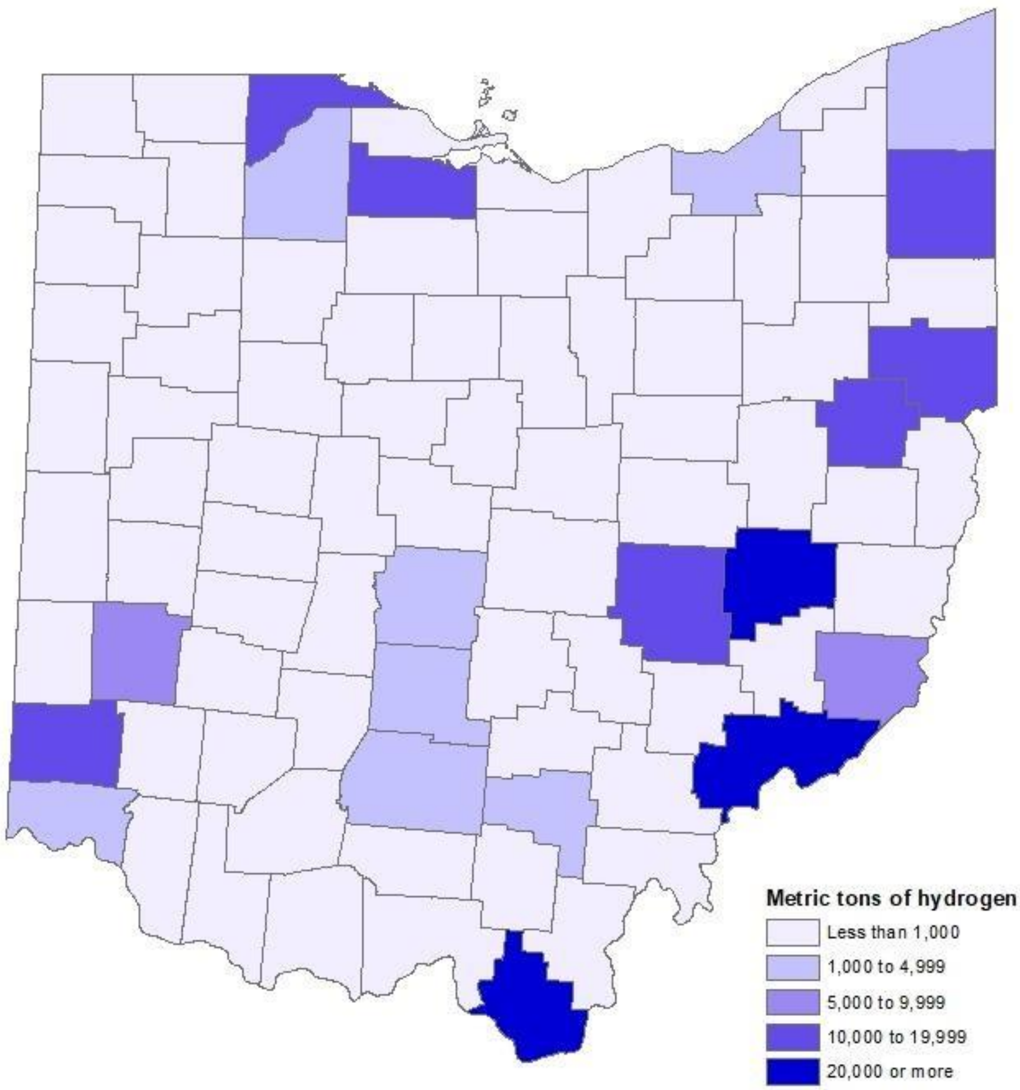
[73] Based on author's calculations of EIA data. Energy Information Administration, February 2021. *Annual Energy Outlook 2021,* available at https://www.eia.gov/outlooks/aeo/production/sub-topic-03.php.

[74] Hydrogen Analysis Resource Center, *Hydrogen Conversions Calculator,* available at https://h2tools.org/hyarc/calculator-tools/hydrogen-conversions-calculator

[75] Leeds Beckett University News, June 2020, found at: https://www.leedsbeckett.ac.uk/news/0620-research-finds-public-would-support-hydrogen-energy/

the uncertainty of its near-term adoption. As a result, we have followed the example of Argonne National Lab and excluded it from this market study.[76] This market may, however, develop rapidly and could be comparable to the electricity generation market in size if it does.

Figure 1. Projected Annual Hydrogen Consumption for Electricity Generation fueled by Natural Gas Blends by 2050, by County



Source: The Authors (based on EIA data and projections).

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[76] Elgowainy, M. Mintz, U. Lee, T. Stephens, P. Sun, K. Reddi, Y. Zhou, G. Zang, M. Ruth, P. Jadun, E. Connelly, R. Boardman, **"**Assessment of Potential Future Demands for Hydrogen in the United States," October 29, 2020, found at: https://greet.es.anl.gov/publication-us_future_h2 (finding that "Several demand sectors are not included in this report, either because the application is not sufficiently well-defined at this time or because it is spread over many different processes, complicating any assessment. These include heating.").

3.2 Hydrogen-Powered Vehicles

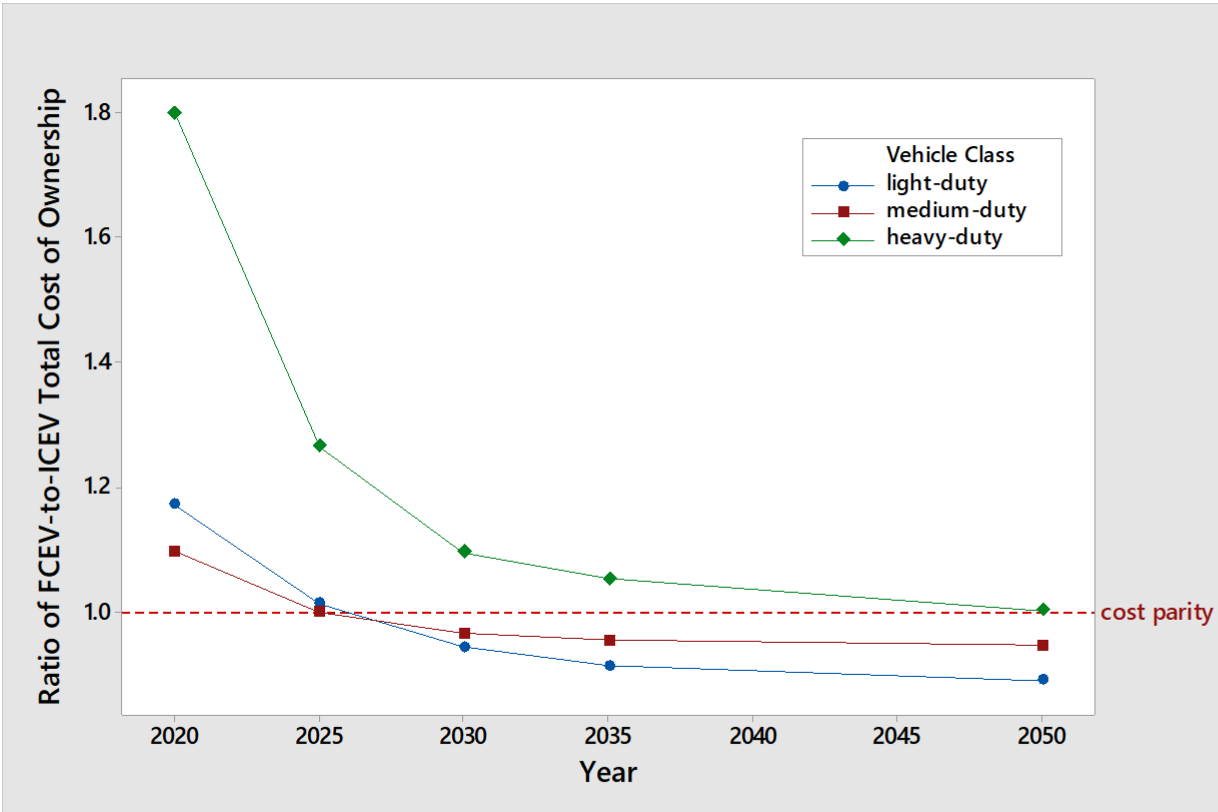
Hydrogen-powered fuel cell electric vehicles (FCEVs) are emerging as a viable alternative to fossil fuel-powered cars, trucks, and transportation fleets. Also included in this analysis are hydrogen-powered forklift vehicles, which are replacing battery electric forklifts commonly now used indoors, such as in warehouses, due to rapid refueling capabilities.

A 2021 study by Argonne National Laboratory on the total cost of ownership (TOC) for vehicles with different size classes and powertrains indicates the near-term convergence in total costs to purchase and operate FCEVs are comparable to those costs for fossil-fuel powered internal combustion engine vehicles (ICEVs).[77] Using its *Autonomie* vehicle system simulation tool, Argonne modeled—among other powertrains—the total lifetime cost to own and operate a representative light-duty gasoline ICEV (a small Sport Utility Vehicle), a representative medium-duty diesel ICEV (a class 4 delivery truck), a representative heavy-duty diesel ICEV (a class 8 tractor trailer), as well as FCEV variants for these vehicle class sizes. Figure 2 illustrates some of the results from Argonne's cost modeling, where cost parity for light and medium-duty FCEVs in relation to their fossil-fuel counter parts is projected to be realized by 2025. Heavy-duty FCEVs are likely to take longer to achieve comparable parity (although heavy duty FCEVs will likely to the zero-emission vehicle of choice due to their range and short refueling time). However, Argonne projects the difference in TOC between heavy-duty FCEVs and ICEVs to decrease substantially over the next decade, with FCEV TOC shrinking from being 80% greater than ICEV TOC currently, to 10% greater by 2030.[78]

[77] Andrew Burnham, David Gohlke, Luke Rush, Thomas Stephens, Yan Zhou, Mark A. Delucchi, Alicia Birky, Chad Hunter, Zhenhong Lin, Shiqi Ou, Fei Xie, Camron Proctor, Steven Wiryadinata, Nawei Liu, and Madhur Boloor, *Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains,* Energy Systems Division, Argonne National Laboratory, (April 2021).

[78] Argonne's analysis did not include "soft" costs, such as value of driver preferences for comfort, performance, styling etc., and no costs external to purchasing and operating the vehicle, such as costs due to congestion, pollution, or noise impacts were included.

Figure 2. Ratio of FCEV-to-ICEV Total Cost of Ownership by Vehicle Class Size



Data Source: Argonne National Laboratory (2021).

A 2020 analysis by Argonne estimates that if 18% of light-duty cars and 26% of light-duty trucks were powered by hydrogen fuel cells, then a hydrogen price at the pump of $5.03 per kg could support an annual national consumption potential of 11.7 MMT for use in these vehicles.[79] If the proportion of hydrogen-powered light-duty vehicles were to reach 41% of all passenger vehicles, then the potential demand could be as high as 21.4 MMT each year. Additionally, if 22% of medium- and heavy-duty vehicle fleets could be powered by hydrogen fuel cells, these same hydrogen prices would correspond to an annual national hydrogen consumption potential of 1.4 MMT from medium-duty vehicles and 5.2 MMT from heavy-duty vehicles.[80] It is difficult to accurately predict the range of policy decisions, technological advances, and consumer preferences that may affect the advent of these vehicles, but their cumulative potential hydrogen demand should be considerable in the coming years.

[79] *See* A. Elgowainy, M. Mintz, U. Lee, T. Stephens, P. Sun, K. Reddi, Y. Zhou, G. Zang, M. Ruth, P. Jadun, E. Connelly, R. Boardman, Assessment of Potential Future Demands for Hydrogen in the United States (2020). This price at the pump is consistent with DoE's long-term cost targets for making hydrogen competitive with conventional fossil fuels.

[80] *Id.*

Hydrogen-powered fuel cell forklifts are further along in their product life cycle than on-road FCEVs. Based on DoE progress reports and program records for its Hydrogen Program, growth in this segment has been upwards of 30% annually, going from 6,087 deployments in 2013 to at least 30,000 deployments by 2019.[81] This would seem to be a relatively large number of deployments given the 17,345 establishments in the warehousing and storage subsector (NAICS 493) as of 2019.[82] Companies whose facilities deploy fuel cell forklifts include Amazon, Coca-Cola, FedEx, and Walmart.[83]

3.2.1 Projected Hydrogen Consumption in Ohio for FCEVs

We projected future hydrogen consumption for on-road FCEVs in Ohio at the county level. To accomplish this, we looked at Argonne National Lab and National Renewable Energy Laboratory (NREL) models for likely fuel cell vehicle market penetration rates, and applied them to Ohio on a county by county basis. Traffic patterns in those counties were determined from data collected by the Ohio Department of Transportation, together with growth rates projected by the Federal Highway Administration.

Argonne projects a long-run market penetration rate of 22% across all types of FCEVs (light/medium/heavy duty) by 2050.[84] However, this is for the entire country. States such as California and others that have adopted similar zero-emission vehicle (ZEV) mandates are likely to realize higher FCEV market penetration than states such as Ohio that have no ZEV support policies. It is important to account for these differences so that a projection of future FCEV stock in Ohio is not overly optimistic.

An analysis by the National Renewable Energy Laboratory (NREL) indicates that non-ZEV states[85] are projected as a whole to contain 42.1% of the light-duty FCEV vehicle stock by 2050 under a National Expansion scenario.[86] Under this scenario, the most ambitious that NREL considered in modeling market growth for FCEVs, the highest levels of FCEV adoption are achieved through

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[81] DOE Hydrogen and Fuel Cells Program Record, 2013. *Industry Deployed Fuel Cell Powered Lift Trucks,* available at https://www.energy.gov/sites/default/files/2014/03/f9/13008_industry_lift_truck_deployments.pdf
DOE Hydrogen and Fuel Cells Program, *FY 2019 Annual Progress Report,* available at https://www.hydrogen.energy.gov/pdfs/progress19/introduction_2019.pdf
[82] County Business Patterns, 2019. https://www.census.gov/programs-surveys/cbp/data/tables.html
[83] DOE Hydrogen and Fuel Cells Program Record, 2013. Industry Deployed Fuel Cell Powered Lift Trucks, available at https://www.hydrogen.energy.gov/pdfs/18002_industry_deployed_fc_powered_lift_trucks.pdf
[84] Elgowainy et al., 2020. *Assessment of Potential Future Demands for Hydrogen in the United States*. Argonne National Laboratory.
[85] States with ZEV supportive policies included CA, CT, ME, MD, MA, NJ, NY, OR, RI, and VT.
[86] Melaina, M., B. Bush, M. Muratori, J. Zuboy and S. Ellis, 2017. National Hydrogen Scenarios: How Many Stations, Where, and When? Prepared by the National Renewable Energy Laboratory for the H2USA Locations Roadmap Working Group. https://www.nrel.gov/docs/fy18osti/71083.pdf.

strong policy support initiatives implemented at the city, state, and national levels, and also through aggressive supply chain coordination and infrastructure planning.[87] Applying the share of FCEV vehicle stock in non-ZEV states from NREL's analysis to Argonne's projection of 68 million light-duty FCEVs on the road nationally by 2050 yields a projected vehicle stock of 28.7 million light-duty FCEVs in non-ZEV states.[88]

To understand what proportion of all future light-duty vehicle stock these 28.7 million FCEVs might represent across non-ZEV states, recent state-level vehicle registration counts were gathered from the Federal Highway Administration (FHWA).[89] National growth rate projections for light-duty vehicle stock from Argonne's VISION model were applied to the current vehicle registration counts for non-ZEV states to arrive at an estimated 235.1 million total light-duty vehicles on the road in these states by 2050.[90] This results in a projected long-run market share of 12.2% for light-duty FCEVs in non-ZEV states such as Ohio. Following Argonne's methodology for assessing future hydrogen demand for transportation, the long-run market penetration of fuel cell medium- and heavy-duty vehicles in Ohio was assumed to be consistent with that of light-duty FCEVs.[91]

This 12.2% long-run market share was applied to projected total vehicle miles traveled in Ohio by 2050 to arrive at an estimate of future vehicle miles traveled in the state annually by FCEVs. Current vehicle miles traveled by road segment was gathered from the Ohio Department of Transportation's Transportation Information Mapping System (TIMS).[92] In addition to allowing for summation of vehicle miles traveled by county, this data source also classifies miles traveled according to three broad categories of vehicle class sizes: cars, single unit trucks, and

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[87] NREL also considered two other scenarios in its analysis of future FCEV deployment: 1) an Urban Markets scenario where FCEV markets are driven by a combination of consumer demand, initiatives implemented by individual cities, and stakeholder focused on the most promising urban markets; and 2) a State Success scenario where a higher level of FCEV market adoption than in the Urban Markets scenario, with FCEV sales primarily driven by state-level Zero Emission Vehicle (ZEV) mandates and other market support mechanisms, which are complemented by strong stakeholder planning and coordination in ZEV states.

[88] *See Supra*, Elgowainy et al., 2020.

[89] See Federal Highway Administration, 2018. Table MV-1 State Motor-Vehicle Registrations. https://www.fhwa.dot.gov/policyinformation/statistics/2018/mv1.cfm. For light-duty truck counts by state, see Federal Highway Administration, 2018. Table MV-9 Truck and Truck-Tractor Registrations. https://www.fhwa.dot.gov/policyinformation/statistics/2018/mv9.cfm

[90] *See* https://www.anl.gov/es/vision-model. Argonne projects average annual growth of approximately 0.5% for light-duty vehicle stock through 2050.

[91] *Supra*, Elgowainy et al., 2020.

[92] https://www.transportation.ohio.gov/wps/portal/gov/odot/programs/technical-services/transportation-information-management/tims

combination trucks.[93] This current number of vehicle miles traveled by class size was multiplied by the Federal Highway Administration's (FHWA's) most recent 30-year forecast of projected annual growth in vehicle miles traveled based on baseline economic growth, which includes separate projections for light-duty vehicles, single-unit trucks, and combination trucks.[94]

Finally, to arrive at the amount of hydrogen required to fuel these vehicles over these distances, fuel efficiencies for the three size classes of FCEV were assumed. Based on Argonne's 2020 *Assessment*, average fuel economy for light-duty FCEVs is projected to be 82.3-miles-per-gasoline gallon equivalent by 2050.[95] A conversion factor of 1.019 gasoline-gallon-equivalent (gge)/kg was applied to this rate of fuel consumption to present it in terms of miles per kg of hydrogen (83.9 miles/kg).[96] Similarly, Argonne projects a fuel economy of 33 miles/kg and 14.7 miles/kg for single unit trucks and combination trucks, respectively.[97]

The results of this analysis appear below in Figure 3 where projected annual hydrogen consumption by 2050 for on-road FCEVs is at the county level. Altogether, projected state-wide annual hydrogen consumption under this scenario is 430,578 metric tons. For on-road vehicles, Counties with large populations correlate with the highest consumption.

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[93] The "cars" category includes miles traveled by light-duty pick-up trucks. *See* https://www.dot.state.oh.us/Divisions/Planning/SPR/ModelForecastingUnit/Documents/OH_Cert_Traffic_Manual.pdf

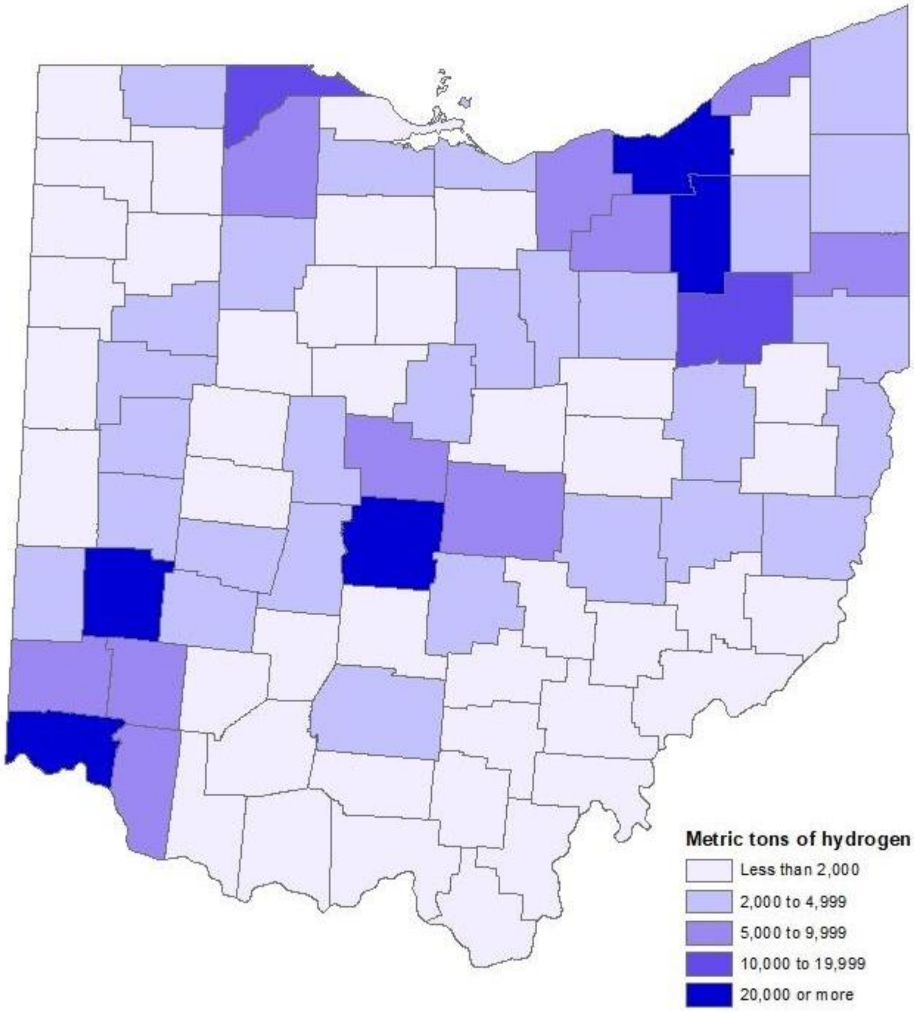
[94] https://www.fhwa.dot.gov/policyinformation/tables/vmt/vmt_forecast_sum.cfm

[95] By this time, Argonne projects FCEV passenger cars to have a fuel economy of 100 mpgge and light truck FCEVs to have a fuel economy of 64 mpgge. The projected fuel economy of 82.3 mpgge for all light-duty vehicles is based on a weighted average given the share of cars and light trucks currently on the road in Ohio and the projected national growth in the stock of these vehicles under Argonne's VISION model. *See* FHWA *Highway Statistics Series 2018*, Table MV-1. https://www.fhwa.dot.gov/policyinformation/statistics/2018/mv1.cfm. *See also* https://www.anl.gov/es/vision-model

[96] https://atb.nrel.gov/transportation/2020/index.html?t=eh

[97] *Supra,* Elgowainy et al., 2020.

Figure 3. Annual Hydrogen Consumption by 2050 for On-Road FCEVs by County



Source: The Authors (based on Argonne, NREL, and FHWA data and projections)

3.2.2 Projected Hydrogen Consumption for Fuel Cell Forklifts

An analysis was also undertaken by the Study Team to project hydrogen consumption potential for fuel cell forklift deployments in Ohio. This projection was based on the current ratio of operators to vehicles for forklifts, also known as industrial trucks or lift trucks,[98] and occupational forecasts developed by the Ohio Department of Job and Family Services (ODJFS) using data from the U.S. Bureau of Labor Statistics (BLS).

First, the total number of forklifts currently deployed in the U.S. was estimated. The Industrial

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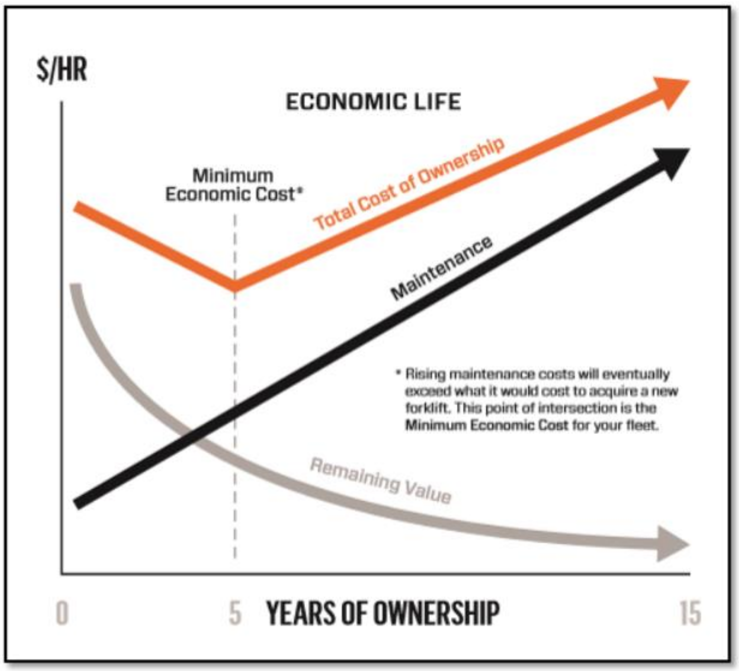
[98] https://www.osha.gov/powered-industrial-trucks

Truck Association (ITA), which represents 90% of forklift manufacturers in North America, regularly releases total annual forklift shipments in the U.S. by its members, with currently available data covering 1995 through 2020.[99] To translate these annual shipments to an estimate of total forklifts currently in operation, an economic life for forklifts was assumed.[100] Based on information from Toyota's Forklifts Division, forklifts were assumed to have an average economic lifespan of 5 years (see Figure 4).[101] Based on data for ITA-member forklift shipments in the U.S. over the 5-year span of 2016-2020, representing 90% of the market, the total population of forklift deployments was estimated at approximately 1.2 million units.

Figure 4. Economic Lifespan of Forklifts



Source: Toyota Forklifts.

Next, annual estimates for the number of forklift operators were gathered from the BLS. Among other occupations, the BLS publishes U.S. employment levels for Industrial Truck Operators, which from 2016-2020 averaged a little under 600,000.[102] Based on this occupational data and the forklift shipment data from ITA, there has been an average of about 1.9 forklifts per Industrial Truck Operator. There are likely additional employees at a given facility that are trained and licensed to operate a forklift (e.g., an Operator's Supervisor) but who do not fall within the BLS

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[99] https://www.indtrk.org/market-intelligence

[100] The *economic life* of a forklift is distinct from its *useful life*. A forklift's useful life is the maximum time for which it can run, while its economic life is the time for which it is economically sensible to run based on the cost to operate and maintain it. *See* https://www.toyotaforklift.com/resource-library/material-handling-solutions/finance/forklift-economic-life-vs-forklift-useful-life

[101] https://www.toyotaforklift.com/blog/what-is-the-economic-life-of-a-forklift

[102] https://www.bls.gov/oes/current/oes537051.htm

classification for an Industrial Truck Operator, which would explain why there are more forklifts than Operators.

The ODJFS, using BLS employment data, develops estimates of employment levels by occupation for the state overall and by county.[103] According to ODJFS estimates, there were 32,510 Industrial Truck Operators in Ohio in 2019 (the most recent year for which these estimates are available).[104] Based on the previously described ratio of forklifts-to-Operator, this represents 61,283 forklifts for that year.

The ODJFS also forecasts annual employment growth in the state by occupation. Employment growth for Industrial Truck Operators is projected to be 0.43% annually over the next decade.[105] Assuming this occupational growth rate remained constant beyond the next decade, Ohio would be projected to have 37,085 Industrial Truck Operators by 2050. Assuming the current ratio of forklifts-to-Operators also remained constant, this would represent 69,908 forklift deployments in the state by 2050.

The number of hours these forklifts were assumed to operate during the week is based on recent data from the U.S. Census Bureau's Quarterly Survey of Plant Capacity Utilization (QPC) for the manufacturing sector. According to the QPC, the average plant was in operation 69.9 hours per week from 2016-2020.[106] Applying this rate to all facilities in Ohio where forklifts are in operation, and assuming it remains constant into the future, leads to a projection of 254.1 million operation hours for forklifts in the state by 2050.

The proportion of these forklift-hours projected to be attributable to hydrogen-powered forklifts is based on the Fuel Cell & Hydrogen Energy Association's (FCHEA's) 2019 *Roadmap to a U.S. Hydrogen Economy*. Based on the *Roadmap*'s ambitious scenario for fuel cell forklift adoption rates—which assumes strong measures at the federal and state levels to support the growth of hydrogen—fuel cell forklifts will represent 20% of forklift sales by 2030, increasing to 59% of sales by 2050.[107] The Study Team projected the number of fuel-cell powered fork lifts by 2050, based upon the assumption that the economic life of vehicles will continue to average 5 years, and that 50% of fork lifts will be hydrogen powered. Based upon these assumptions, and the weekly average operation of forklifts, fuel cell forklifts in Ohio were projected to operate altogether around 127 million hours annually by 2050.

[103] https://ohiolmi.com/Home/CountyOccupationReport
[104] https://ohiolmi.com/Home/DS_Results_OES
[105] https://ohiolmi.com/_docs/PROJ/Ohio/Ohio_Job_Outlook_2018-2028.pdf
[106] https://www.census.gov/programs-surveys/qpc.html
[107] https://www.fchea.org/us-hydrogen-study

An assumed fuel efficiency for hydrogen-powered forklifts in terms of kg/hour was applied to their projected hours of operation to arrive at a projection for hydrogen consumption potential among these vehicles. An evaluation of early-stage, DoE-sponsored deployments of fuel cell forklifts during the early 2010s described 140,000 kg of hydrogen being dispensed for vehicles that logged 1.25 million hours of operation, for a fuel efficiency of 0.112 kg/hour.[108] More recently, the European Commission's Fuel Cells and Hydrogen Joint Undertaking described a future potential fuel efficiency of 0.10 kg/hour for fuel cell forklifts.[109] This fuel efficiency of 0.10 kg/hour was applied to the projection of fuel cell fork lift hours in Ohio, resulting in a hydrogen consumption potential of 12,705 metric tons by 2050. Figure 5 shows the spatial distribution of this projection for hydrogen-powered forklifts by county.

In 2018, the U.S. Department of Energy reported that more than 21,000 hydrogen-powered forklifts were already in operation in the United States.[110] This figure included over 1,000 hydrogen fuel cell powered forklifts operating in the state of Ohio, comprised of fleets of more than 150 units at the Honda plant in Marysville, Ohio and over 250 units at the Walmart facility in Washington Court House, Ohio.[111] The number of hydrogen-powered forklifts is expected to increase further as companies such as Amazon have begun to invest significantly in the construction and operation of new warehouses and in hydrogen-powered forklifts. As the market penetration of hydrogen-powered forklifts continues to expand along the projections outlined in the FCHEA's *Roadmap*, these forklifts will continue to be a significant source of demand for hydrogen production.

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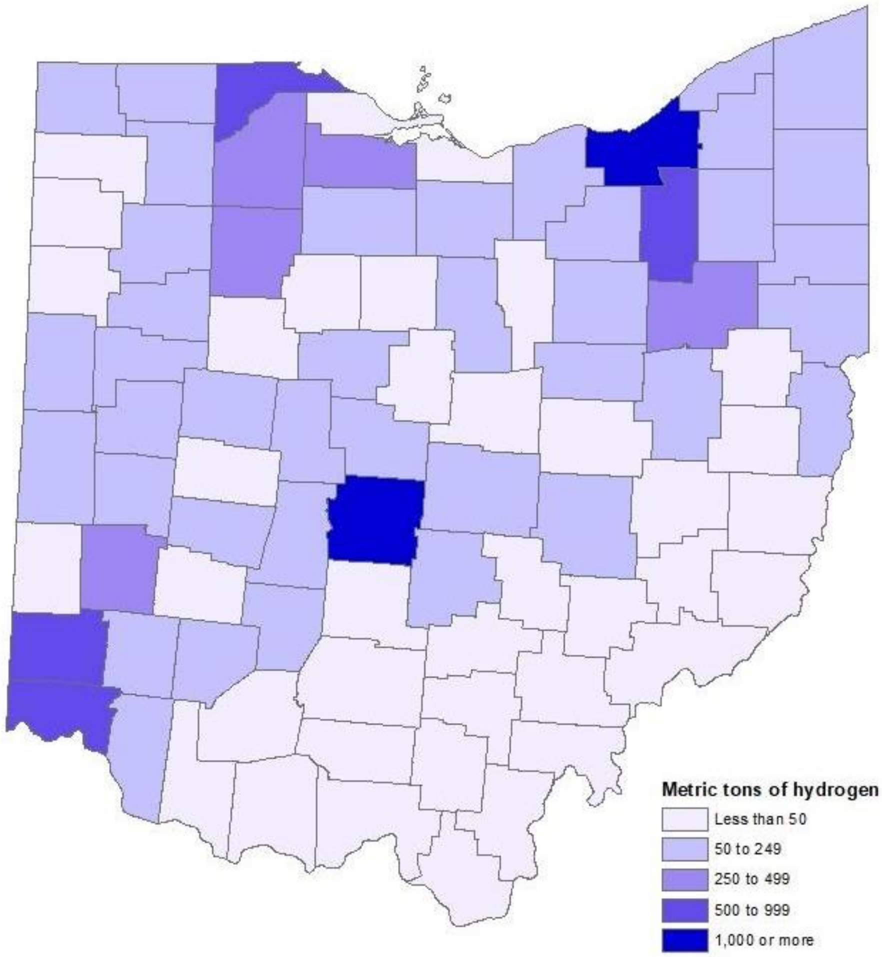
[108] https://www.nrel.gov/docs/fy13osti/56408.pdf

[109] https://www.fch.europa.eu/sites/default/files/FCH%20Docs/171121_FCH2JU_Application-Package_WG2_Material%20handling%20equipment%20%28ID%202910567%29%20%28ID%202911653%29.pdf

[110] https://www.hydrogen.energy.gov/pdfs/18002_industry_deployed_fc_powered_lift_trucks.pdf

[111] *See* Hydrogen Roadmap for the U.S. Midwest Region, July 2017, available at http://e67ti2w9ws71al8xmnhsozd3.wpengine.netdna-cdn.com/wp-content/uploads/sites/64/2017/11/hydrogen_roadmap_for_the_midwest_20170721.pdf

Figure 5. Projected Annual Hydrogen Consumption for Fuel Cell Forklifts by 2050, by County



Source: The Authors (based on data from trade associations and various state & federal agencies).

3.3 Feedstocks and Other Industrial Uses

3.3.1 Oil Refining

Oil refining remains the largest market for hydrogen, consuming around 10 MMT in the United States each year.[112] This hydrogen is largely used for hydrocracking (the production of diesel fuel from more complex hydrocarbon chain products and waxes) and hydrotreating (the removal of sulfur impurities from feedstocks). The 10 MMT used each year by these processes are supplied by roughly 4 MMT of byproduct hydrogen and 5.9 MMT of hydrogen produced specifically for industrial use or sale (known as "on-purpose hydrogen"). A 2020 Argonne National Laboratory

[112] Mark F. Ruth, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A.J. Simon, Amgad Elgowainy, and Jarett Zuboy, *The Technical and Economic Potential of the H2@Scale Concept within the United States,* National Renewable Energy Laboratory (NREL), (October 2020).

study calculated that the consumption potential for on-purpose hydrogen can be expected to increase to 7.5 MMT annually by 2050 as lower-quality crude oil begins to be used as feedstock and as the demand for diesel fuel increases compared to gasoline.[113]

A moderate growth of 7% is expected over the next decade, enabled by tighter pollutant regulations but tempered by low growth in oil demand.[114] Since there is no cost-effective substitute for hydrogen in the processes of hydrocracking and hydrotreating, Elgowainy et al. have determined that a relatively high market price of $3.00 per kg of hydrogen can sustain this expected growth in demand.[115] However, it is important to note that hydrogen cost strongly influences refining margins, hence the business case remains challenging for using higher cost, low-carbon sources of hydrogen, e.g. the blue or green routes described previously herein, in refining operations. Ohio has four petroleum refining facilities reporting to the EPA Greenhouse Gas Reporting Program, yielding roughly 4.8 MMT CO_2e per year.

Ohio's four petroleum refineries are in Lima, Canton, and two in Toledo.[116] Based on a facility-level analysis of current hydrogen consumption and expected growth in hydrogen demand by refineries, Argonne projects total annual potential hydrogen demand at these Ohio-based facilities of 217,000 metric tons by 2050.[117] This amount is included in the total hydrogen market set forth in Figure 8 at the end of this section.

3.3.2 Metal Refining

There is potential for hydrogen to be increasingly used in the production and refinement of steel. Direct Reduction of Iron (DRI) is a more efficient process than traditional blast furnace refining, though it needs further upgrading (through electric arc furnace processing) to bring the sponge iron to market. Roughly 90 MMT of steel was produced from DRI-EAF in 2018, or around 5% of global production.[118] Instead of using coke as a reducing agent, DRI involves the direct treatment of iron ore with natural gas, synthetic gas, or hydrogen. This results in both a higher quality of pig iron and steel as well as lower carbon dioxide emission rates than current technologies.

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113 Elgowainy et al., *Assessment of Potential Future Demands for Hydrogen in the United States*. Argonne National Laboratory, (2020).

114 https://www.iea.org/reports/the-future-of-hydrogen

115 Elgowainy et al, *supra.*

116 Two additional refineries—one in Catlettsburg, KY, and the other in Newell, WV—border the state along the Ohio River.

117 Personal correspondence with Argonne relating to Ohio-specific results from *Assessment of Potential Future Demands for Hydrogen in the United States* (2020).

118 World Steel Association, *World Steel in Figures*, available at https://www.worldsteel.org/en/dam/jcr:96d7a585-e6b2-4d63-b943-4cd9ab621a91/World%2520Steel%2520in%2520Figures%25202019.pdf

As long as the cost of natural and synthetic gas remains lower than the cost of hydrogen, DRI processes will predominantly use only limited amounts of Hydrogen mixed in with other feedstocks. At a price threshold price of $1.70 per kilogram, it would become cost-efficient for a mixture of up to 30% hydrogen to be used, resulting in a potential annual demand of 4 MMT of hydrogen by 2050.[119] At a price of $0.80/kg, it would become economically viable to use 100% hydrogen in the DRI process without any admixture of synthetic or natural gas, increasing the consumption potential to 12 MMT.[120] It should be noted that in this scenario, the H2@Scale report released by the NREL specifically lists the region around Lake Michigan and Lake Erie among the three main regions of the US where demand for hydrogen for use in metal refining is most prominent.[121]

Ohio already has one operational iron production plant in Toledo using a DRI process, while a second one in Ashtabula is in development. Figure 6 includes additional plants in Ohio that could also consume hydrogen as a reducing agent in producing iron and steel. Argonne projects that growing demand for hydrogen in metal production could lead to a combined consumption potential at these facilities of 391,000 metric tons annually by 2050.[122]

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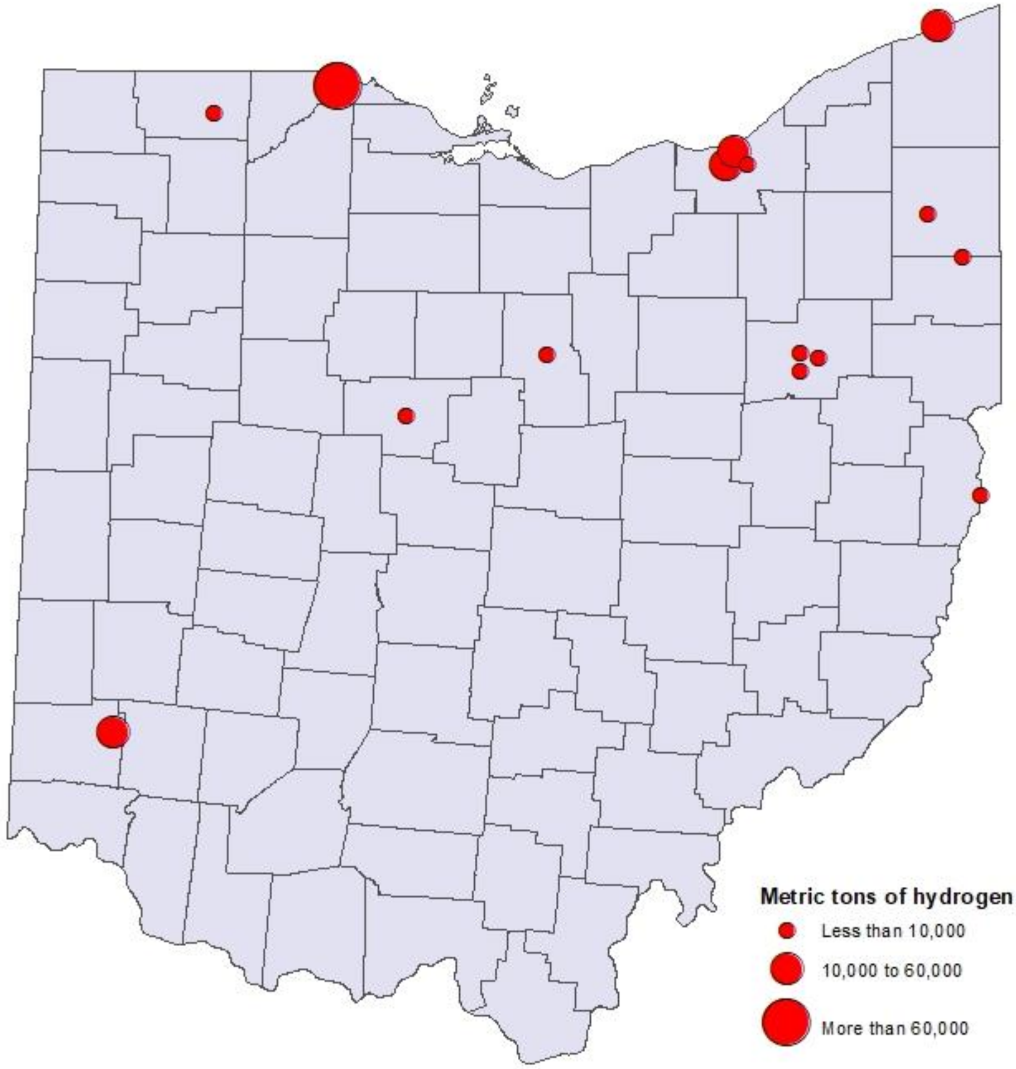
119 Mark F. Ruth, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A.J. Simon, Amgad Elgowainy, and Jarett Zuboy, *The Technical and Economic Potential of the H2@Scale Concept within the United States,* National Renewable Energy Laboratory (NREL), (October 2020).

120 *Id.*

121 *Id.* at 17.

122 Personal correspondence with Argonne relating to Ohio-specific results from *Assessment of Potential Future Demands for Hydrogen in the United States*, (2020). Argonne's analysis did not include the recently developed Ashtabula plant. The Study Team estimated potential hydrogen consumption at this location based on projected production there of 526,739 short tons per year (equivalent to 477,850 metric tons) and Argonne's assumption from its 2020 *Assessment* of 0.1 MT of hydrogen being required to reduce 1 MT of iron ore. For the Ashtabula site's projected annual production, *see* https://www.epa.gov/nsr/petmin-usa-incorporated.

Figure 6. Hydrogen Consumption Potential for Metal Refining in Ohio by 2050



3.3.3 Ammonia Production

Ammonia is the second most produced chemical in the world behind sulfuric acid. Synthesized in the Haber-Bosch process, ammonia manufacturing is a high-volume user of hydrogen, totaling between 3 and 4 MMT in North America in 2018.[123] Most of this hydrogen is sourced from natural gas, with the cogenerated CO_2 captured for captive use in urea formation. Urea (and ammonium nitrate) represent the largest use of ammonia in fertilizer production, with a host of other mixed uses including explosives, synthetic fibers and other materials. Elgowainy et al. project a 1%

[123] https://www.iea.org/reports/the-future-of-hydrogen.

annual increase in demand to 3.6 MMT each year by 2050 at a threshold price of $2.00 per kg.[124] Since hydrogen is necessary for the production of ammonia, the demand for hydrogen is somewhat inelastic. At a relatively high price of $3.00 per kg, hydrogen demand for use in ammonia production would still be 2.5 MMT annually.[125] A further discussion of ammonia as an energy carrier is set forth below in the section on infrastructure.

There is only one ammonia production facility in Ohio. However, this plant, located in Lima, has the 9th highest production capacity out of 32 such facilities in the U.S. at 612,000 metric tons annually.[126] This translates to a current annual consumption potential for hydrogen of 109,000 metric tons, given that 0.178 kg of hydrogen is needed to produce 1 kg of ammonia.[127] Assuming 15% growth in capacity from now to 2050 based on Argonne's projections for the U.S. ammonia industry,[128] 125,350 metric tons of hydrogen would be needed annually to produce ammonia at this facility by 2050.[129] This amount is included in the total consumption projection map set forth in Figure 8 below.

3.3.4 Biofuels

As the efficiency and performance of biofuels advance, they have the potential to become an effective alternative for fueling aircraft and maritime shipping. The production of these biofuels often consumes hydrogen, mainly through a process called catalytic fast pyrolysis, which uses hydrogen to convert biomass into usable biofuels.[130] While hydrogen is necessary for the production of biofuels via this process, the hydrogen used in catalytic fast pyrolysis is often supplied as a byproduct from other processes rather than purchased specifically for this purpose. Elgowainy et al. assume that the chemicals that generate this byproduct hydrogen could be used more cost-effectively for other purposes, and that on-purpose hydrogen could be purchased specifically for use in biofuel production.[131] Their data project a potential national annual

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[124] Elgowainy et al., *Assessment of Potential Future Demands for Hydrogen in the United States*. Argonne National Laboratory, (2020).
[125] *Id.*
[126] U.S. Geological Survey. *Metals and Minerals: U.S. Geological Survey Minerals Yearbook* [Nitrogen], (2020). https://www.usgs.gov/centers/nmic/nitrogen-statistics-and-information
[127] *See* Elgowainy et al, *supra.*
[128] *Id.*
[129] Personal correspondence with Argonne relating to Ohio-specific results from *Assessment of Potential Future Demands for Hydrogen in the United States*, (2020).
[130] Mark F. Ruth, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A.J. Simon, Amgad Elgowainy, and Jarett Zuboy, The Technical and Economic Potential of the H2@Scale Concept within the United States, National Renewable Energy Laboratory (NREL), (October 2020).
[131] Elgowainy et al., *Assessment of Potential Future Demands for Hydrogen in the United States*. Argonne National Laboratory, (2020).

hydrogen demand of 8.7 MMT for use in biofuels by 2050 if the price of hydrogen is assumed to be $3.00/kg or lower.

The Study Team undertook an analysis to project hydrogen demand for biofuel production in Ohio. In making this projection, the Study Team followed a methodology outlined by NREL in its recent report on the techno-economic potential for wide-scale hydrogen production and utilization in the U.S.[132] Ohio's portion of the 8.7 MMT in hydrogen demand for biofuel production annually by 2050 was allocated according to its biomass resource availability as determined by the U.S. Department of Energy.[133]

According to the DoE's estimates, Ohio possesses 1.7% of the country's biomass resource.[134] Therefore, following NREL's methodology, Ohio was assumed to have 1.7% of the country's hydrogen demand for biofuel production by 2050, which would be around 148,000 metric tons annually. Following NREL's method, regional biofuel production was distributed uniformly to locations with oil refining, ammonia production, metals refining, or SMR-based hydrogen in the state. These locations will likely have the industrial infrastructure to support biofuel production.[135] Regional biofuel production was also distributed to locations with existing biorefineries in Ohio.[136] Following NREL, the 148,000 metric tons in annual hydrogen demand for biofuel production was allocated evenly to these locations. This amount of annual hydrogen consumption potential for the production of biofuels is included in the map of total hydrogen consumption by 2050 as set forth in Figure 8 below.

3.3.5 Synthetic hydrocarbons

Hydrogen can be reacted with carbon dioxide to create synthetic hydrocarbons, such as methanol, which may become a viable alternative to fossil fuels. (The production process for methanol has the added benefit of requiring carbon from CO_2 as another component part, which could help spur growth in the market for captured carbon.) If the energy used to make hydrogen is renewably sourced, the recycling of CO_2 that would otherwise be released into the atmosphere can result in carbon-neutral synthetic hydrocarbons.[137] Argonne estimates that only 11% of potential concentrated CO_2 emissions from industrial sources such as ammonia and ethanol

[132] https://www.nrel.gov/docs/fy21osti/77610.pdf
[133] *See* https://www.energy.gov/eere/bioenergy/2016-billion-ton-report
[134] *Id.*
[135] *Id.*
[136] *See* https://ohioline.osu.edu/factsheet/fabe-6602
[137] https://www.pnas.org/content/116/25/12212

production are currently captured and sold into the merchant market to be used for applications such as food processing.[138]

At a threshold price of \$1.73/kg the potential demand nationally for hydrogen in methanol production is projected to be 6 MMT annually by 2050.[139] Hydrogen could further be used in methanol-to-gasoline conversion, which would create an estimated additional demand of 8 MMT of hydrogen annually by 2050, although the price of hydrogen would need to be extremely inexpensive for this process to be economically viable with current technologies.[140] Cost minimization of synthetic fuel production depends largely on the availability of concentrated supplies of CO_2. Among the sources of this concentrated CO_2 in Ohio are one of the larger ammonia plants in the U.S. and a collection of ethanol plants.[141] Argonne projects future potential hydrogen demand at these Ohio-based facilities related to synthetic fuel production of 317,400 metric tons annually.[142]

Potential hydrogen demand in the state could also come from a recently constructed methanol plant in Toledo.[143] Global demand for methanol, which can be used directly as an alternative transportation fuel or blended into gasoline to increase combustion efficiency and reduce air pollution, is projected to increase 5.5% annually in the near-term, driven largely by the automotive and construction sectors.[144] Assuming this trend were to continue beyond the near-term, a doubling of the current \$20.4 billion global market could occur by the early 2030s.

An analysis was performed to estimate the hydrogen consumption potential of the methanol plant in Toledo. According to Ohio EPA records, the facility has a maximum daily methanol production capacity of 75,400 gallons, equivalent to about 226 metric tons.[145] For purposes of projecting hydrogen market for methanol in Ohio, the Study Team assumed operations of 147 hours per week, based on the average plant hours for companies within its overarching NAICS

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[138] Elgowainy et al., *Assessment of Potential Future Demands for Hydrogen in the United States*. Argonne National Laboratory, (2020).
[139] Mark F. Ruth, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A.J. Simon, Amgad Elgowainy, and Jarett Zuboy, *The Technical and Economic Potential of the H2@Scale Concept within the United States,* National Renewable Energy Laboratory (NREL), (October 2020).
[140] *Id.*
[141] *See* Figure ES.4, Elgowainy et al., *Assessment of Potential Future Demands for Hydrogen in the United States*. Argonne National Laboratory, (2020).
[142] Personal correspondence with Argonne relating to Ohio-specific results from *Assessment of Potential Future Demands for Hydrogen in the United States*, (2020).
[143] https://www.toledoblade.com/business/energy/2019/07/03/alpont-chemical-manufacturing-plant-oregon-plans-to-keep-distribution-local/stories/20190620145
[144] https://www.marketsandmarkets.com/Market-Reports/methanol-market-425.html
[145] https://edocpub.epa.ohio.gov/publicportal/ViewDocument.aspx?docid=648002. A conversion factor for methanol of 2.996 kg per US gallon was assumed. *See* https://www.aqua-calc.com/calculate/volume-to-weight

industry (NAICS 325199) as gathered from the Census Bureau's Quarterly Survey of Plant Capacity.[146] This represents projected annual methanol production potential of nearly 72,000 metric tons. Given that about 4.25 metric tons of methanol output can be produced per metric ton of hydrogen input,[147] this translates to a present-day hydrogen consumption potential of about 16,900 metric tons annually. Argonne projects a nearly 4-fold increase in hydrogen consumption for U.S. methanol production between now and 2030, driven largely by growing demand for the chemical in the building and construction industry.[148] Assuming that the Toledo methanol plant follows projected industry trends, its annual hydrogen demand potential by 2030 is estimated at 63,000 metric tons.

Beyond 2030, demand for hydrogen as a feedstock in industrial processes (such as the production of methanol) is expected to increase 27.5% overall by 2050 according to the Fuel Cell & Hydrogen Energy Association's *Roadmap to a U.S. Hydrogen Economy*.[149] Applying this rate of growth to the estimated hydrogen consumption potential at the Toledo methanol plant in 2030 yields a projected annual hydrogen demand by 2050 of 80,300 metric tons at this location.

The amounts of annual hydrogen consumption potential for the production of synthetic hydrocarbons in Ohio are included in the map of total hydrogen markets for 2050 set forth in Figure 8 below.

3.3.6 Other Manufacturing Markets

Outside of major uses like ammonia production and petroleum refining, other industrial uses for hydrogen constitute roughly 10% of global consumption and 4% in the U.S. Whether used as a hydrogenating agent in food production, as a coolant for large electrical generators, or as a searching agent to check for leaks in manufacturing plants, hydrogen has a role in an increasing number of industrial applications.[150]

The Study Team estimated the current level of hydrogen consumption in Ohio for these "Other" industrial uses (i.e., industrial hydrogen consumption outside of manufacturing oil, ammonia, iron, biofuel, and synthetic hydrocarbon production) and projected what future hydrogen

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[146] https://www.census.gov/programs-surveys/qpc.html
[147] *See* Elgowainy et al., *Assessment of Potential Future Demands for Hydrogen in the United States*. Argonne National Laboratory, (2020).
[148] *Id.*
[149] *See* Fuel Cell & Hydrogen Energy Association (FCHEA). (2019). "Roadmap to a US Hydrogen Economy." http://www.fchea.org/us-hydrogen-study. The FCHEA *Roadmap* estimates growth in hydrogen demand for "ambitious" scenarios under favorable assumptions.
[150] https://www.thechemicalengineer.com/features/uses-of-hydrogen-in-industry/

consumption for these applications might be. The U.S. Bureau of Economic Analysis (BEA) publishes a series of input-output tables showing the relationships between all industries in the U.S. economy and all commodities that these industries produce and use.[151] One of these tables, the direct requirements table, shows the input of commodities that an industry requires to produce a dollar of output. However, none of these tables include hydrogen as a standalone commodity for a given industry's set of production inputs. Instead, input-output data for hydrogen is aggregated with other industrial gases such as carbon dioxide, helium, and oxygen.[152]

To separate hydrogen as a commodity from other gases produced by the Industrial Gas Manufacturing industry (NAICS 325120), the Study Team deployed a method for disaggregating input-output sectors into subsectors that was initially developed at Argonne and extended by researchers at the University of Cambridge.[153] This method allows for disaggregating sectors into an arbitrary number of new sectors when the only available information about the newly formed sectors is their output weights.[154] The U.S. Census Bureau's Economic Census corresponding with the BEA's most recent detail-level benchmark input-output tables[155] includes such a measure of output for each commodity produced by Industrial Gas Manufacturing in terms of *product shipment value*, which is the dollar value of products sold by manufacturing establishments.[156] According to this Economic Census, argon and hydrogen combined represented 18.4% of product shipments for Industrial Gas Manufacturing.[157] Based on research by Markets & Markets, a company that DoE has referenced in estimating the size of the U.S. hydrogen market,[158] the hydrogen market was about 3 times the size of the argon market around the time of the most recent BEA detail-level, benchmark input-output table.[159] This implies that hydrogen represented around 13.8% of output for Industrial Gas Manufacturing.

With an assumed level of output for hydrogen, and the output for all other gases within Industrial Gas Manufacturing combined as a second subsector, the Argonne-Cambridge disaggregation

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[151] https://www.bea.gov/data/industries/input-output-accounts-data
[152] Industrial gas manufacturing falls under NAICS 325120.
[153] *See* Wolsky, A. M. (1984). Disaggregating input-output models. *The Review of Economics and Statistics*, 283-291. *See also* Lindner, S., Legault, J., & Guan, D. (2012). Disaggregating input–output models with incomplete information. *Economic Systems Research*, *24*(4), 329-347.
[154] *Output* here refers to gross output, which is the sum of *value added* and *intermediate inputs* for a given industry.
[155] https://apps.bea.gov/iTable/itable.cfm?reqid=58&step=1. The BEA's detail-level input-output tables allow for the most granular analysis of commodity use by industries at the 5- and 6-digit NAICS code level.
[156] https://www.census.gov/manufacturing/m3/definitions/index.html. The BEA similarly characterizes *output* as an industry's sales or revenues. *See* https://www.bea.gov/help/faq/1197
[157] The U.S. Census Bureau did not separate product shipment values for the two gases for its public release.
[158] https://www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf
[159] *See* https://www.marketsandmarkets.com/Market-Reports/argon-gas-market-99838454.html. *See also* http://solarhydrogeninc.com/hydrogen-generation-market-worth-138-2-billion-by-2019/

method was applied to the BEA detail-level direct requirements table.[160] Table 4 shows the resulting estimated spending on hydrogen as an input per $1,000 of product output for Other Manufacturing industrial uses under this analysis for subsectors at the 3-digit NAICS level.

Table 4. Hydrogen Use Per $1,000 of Output for Various Industrial Subsectors

NAICS Code	Subsector Description	Spending on H_2 per $1,000 of output
322	Paper Manufacturing	$0.24
325	Chemical Manufacturing	$0.32
326	Plastics and Rubber Products Manufacturing	$0.50
327	Nonmetallic Mineral Product Manufacturing	$0.29
333	Machinery Manufacturing	$0.12
334	Computer and Electronic Product Manufacturing	$0.40
335	Electrical Equipment, Appliance, and Component Manufacturing	$0.31
336	Transportation Equipment Manufacturing	$0.12
339	Miscellaneous Manufacturing	$0.05

Source: The Authors.

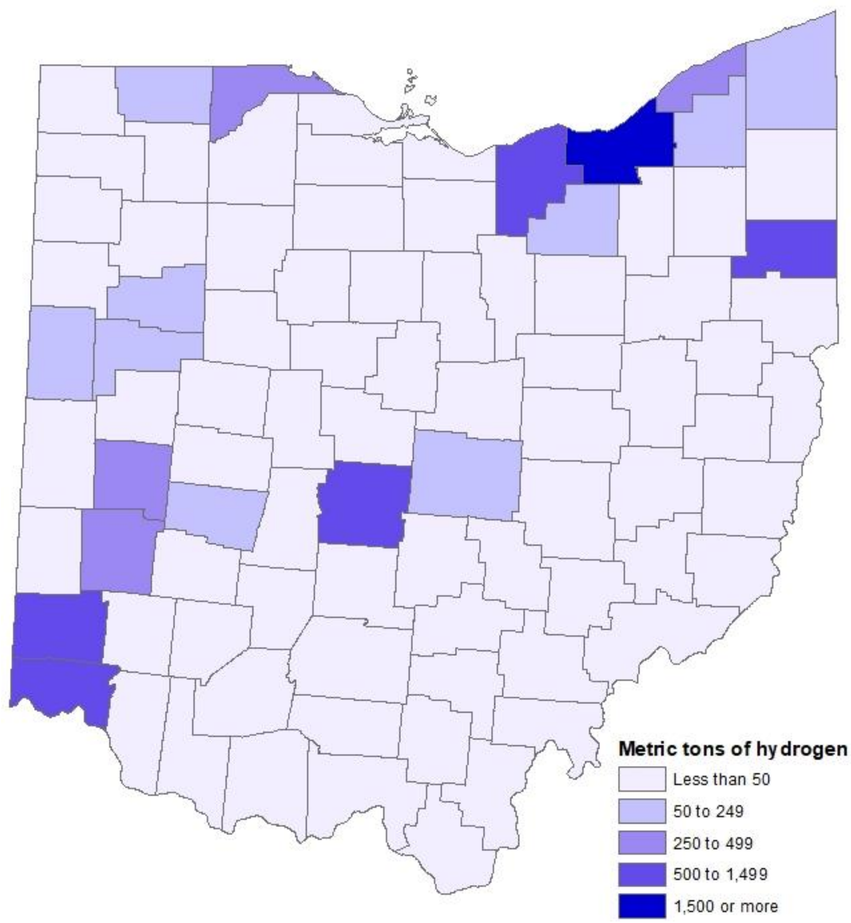
These estimated rates of hydrogen consumption per $1,000 of output were then applied to revenue estimates by both county and industry in Ohio to determine the amount of hydrogen used by these industries. Revenue estimates for specific industries by county were derived from U.S. Census Bureau data. First, data was collected for the ratio of payroll-to-revenue at the national level for the manufacturing industries of interest.[161] Then data was collected on annual payroll per industry by county in Ohio. [162] The ratio of payroll-to-revenue at the national level was then applied to the county-level payroll data for Ohio to arrive at an estimate of revenue by county for the manufacturing industries of interest within the state. The results gleaned from deploying the Argonne-Cambridge disaggregation model (a measure of hydrogen used per $1,000 of gross output[163]) were then applied to these revenue estimates to derive an estimate for annual consumption of hydrogen in kilograms for "Other Manufacturing Markets," given the

[160] MATLAB and the R package 'hitandrun' were used to implement the Argonne-Cambridge method.
[161] The Census Bureau's Annual Survey of Manufactures (ASM) provides national estimates for both payroll and sales revenue for the manufacturing sector at the 6-digit NAICS level https://www.census.gov/programs-surveys/asm.html
[162] County-level payroll data by industry was gathered from the Census Bureau's County Business Patterns program. https://www.census.gov/programs-surveys/cbp.html
[163] Gross output is principally a measure of sales or revenue from production. *See* https://www.bea.gov/help/faq/1197

$/kg cost to produce hydrogen.[164] Altogether, current industrial use of hydrogen for these Other Manufacturing Markets was estimated at approximately 7,200 metric tons annually in the state.

To project future consumption potential, the expected overall growth in demand for hydrogen as a feedstock in industrial processes from 2030 to 2050—based on FCHEA's *Roadmap to a U.S. Hydrogen Economy*—was annualized.[165] The resulting average annual growth rate of 1.2% was applied to all years between now and 2050. Annual consumption of hydrogen for Other Manufacturing Markets in Ohio is projected at 10,300 metric tons under this analysis. Figure 7 shows the spatial distribution of this projection by county.

Figure 7. Projected Other Industrial Hydrogen Annual Consumption by County (2050)



Source: The Authors (based on Argonne and FCHEA models and various economic databases).

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164 The Bureau of Economic Analysis benchmark input-output tables used for this analysis are in 2012 dollars. According to the DoE, the cost of hydrogen production in 2012—not including compression, storage, or dispensing—was $1.74/kg. *See* https://www.hydrogen.energy.gov/pdfs/12024_h2_production_cost_natural_gas.pdf

165 *See* Fuel Cell & Hydrogen Energy Association (FCHEA). (2019). "Roadmap to a US Hydrogen Economy." http://www.fchea.org/us-hydrogen-study.

3.4 Combined Total Ohio Hydrogen Consumption

Altogether, the Study Team projected an annual combined Ohio hydrogen consumption potential by 2050 of 1.98 million metric tons across industry, transportation, and stationary power generation. This represents around 2.7% of the 74.7 MMT hydrogen demand potential that Argonne projects nationally by the middle of the century, assuming that hydrogen becomes price competitive with substitutes such as natural gas,[166] and assuming that there is no new regulation of carbon dioxide emissions. According to Argonne, the top two hydrogen applications, representing 44% of the demand potential nationally by 2050, will be for FCEVs and injection into natural gas streams.[167] For transportation applications, Ohio is limited in its hydrogen demand potential by a lack of zero emission vehicle (ZEV) credits. California, with its robust ZEV program, is projected to have a market penetration for FCEVs of around 54% by 2050 based on a similar analysis as that performed in Section 3.2.1 on projected hydrogen consumption for FCEVs in Ohio. Were Ohio to implement a ZEV program of its own, expected hydrogen consumption for FCEVs in the state would increase 350,000 metric tons for every 10-percentage-point increase in market share beyond the 12.2% that the Study Team projected. At a long-run market penetration of one-third, for example, FCEVs would alone consume nearly 1.2 MMT of hydrogen annually by 2050 rather than the 0.43 MMT under a non-ZEV market penetration of 12.2%.

Hydrogen consumption from blending with natural gas, especially for power generation, was limited in this report to a concentration of 20%. Beyond this concentration level, there is a great deal of uncertainty regarding the long-term impact of such a blend on pipelines and end-use appliances. NREL, through a project known as HyBlend™, is currently leading a research collaborative in conjunction with five other national laboratories to better understand the compatibility of pipelines and appliances with gas blends composed of greater than 20% hydrogen.[168] Were the HyBlend™ project to show that higher concentrations of hydrogen could be blended into the natural gas network without having a deleterious effect on pipelines or appliances, the expected hydrogen consumption in Ohio for power generation would increase 125,000 metric tons for every 10-percentage-point increase in hydrogen concentration level beyond the 20% that the Study Team assumed. At a concentration level of one-third hydrogen, for example, power generation would consume nearly 420,000 metric tons of hydrogen annually by 2050 rather than the 251,000 metric tons under a blend that was 20% hydrogen.

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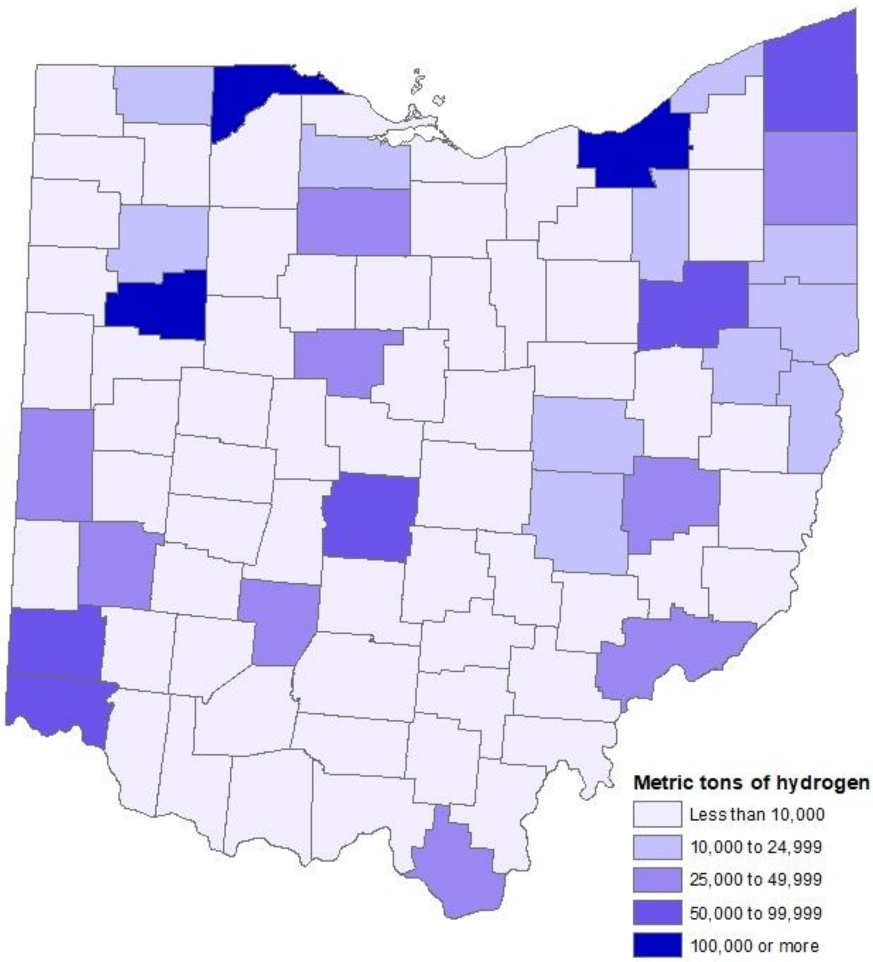
[166] *See* Elgowainy et al., *Assessment of Potential Future Demands for Hydrogen in the United States*. Argonne National Laboratory, (2020).
[167] *Id.*
[168] https://www.nrel.gov/news/program/2020/hyblend-project-to-accelerate-potential-for-blending-hydrogen-in-natural-gas-pipelines.html

A mapping of the total Ohio-specific hydrogen demand potential projected by the Study Team appears below in Figure 8, by County. Total projected Ohio demand is set forth in Table 7 in the Conclusion. Greatest projected hydrogen consumption rates generally correlate to counties with large populations, however large-scale industrial markets will likely control the locations where hydrogen infrastructure hubs develop. As will be discussed in a later section, the location of carbon markets may also play a role in where hydrogen hubs develop.

Figure 8. Total Projected Ohio Annual Hydrogen Consumption for 2050 by County



4.0 Hydrogen Infrastructure Development in Ohio.

4.1 Delivery Methods.

Hydrogen delivery strategies will play a significant role in the development of hydrogen. As discussed earlier, driving down the price of hydrogen generation is only a piece of the hydrogen economy puzzle. Hydrogen fuel cell vehicles, for instance, require the transportation, storage and dispensing of hydrogen – all of which makes up over 2/3 of the cost of hydrogen delivered at the pump. A great deal of infrastructure planning will be required to build a hydrogen economy in Ohio. Ohio does, however, have incumbent infrastructure that can be used to enable a more rapid adoption than might be available in other states. This includes existing natural gas storage and distribution systems that could in part be converted to hydrogen.

4.1.1 Pipelines

The Congressional Research Service has reported that the United States has 1,608 miles of dedicated hydrogen pipelines operating currently, mostly along the Gulf Coast and serving major industrial centers.[169] The Hydrogen Analysis Resource Center reports that as of 2016, only 9.2 miles of hydrogen pipeline have been constructed in Ohio, serving refineries in Lima, Ohio, although the National Pipeline Mapping System (NPMS) also reports several additional short hydrogen pipelines operating in conjunction with the BP Toledo facility in Lucas County and near Steelyard Commons in Cuyahoga County.[170] Hydrogen pipelines are an economically feasible option for supplying hydrogen for large-scale operations with sustained demand. The cost of building new hydrogen pipelines in urban areas has been estimated at around $600,000 per kilometer, including materials, rights-of-way, and installation.[171] These high capital costs make pipeline transportation efficient only when there is a reliable, long-term, large-scale industrial demand.

The majority of hydrogen pipelines currently in use were purpose-built for the transportation of hydrogen, but recent research has looked into the potential to retrofit existing natural gas lines for use in hydrogen transportation. This strategy could exploit a significant pre-existing infrastructure investment, as approximately 300,000 miles of natural gas pipeline currently exist in the United States. A white paper published in 2020 by Siemens Energy along with German natural gas companies Nowega and Gascade has reported that converting natural gas pipelines into hydrogen pipelines would cost only 10% to 15% of the estimated construction cost of purpose-built hydrogen pipelines.[172] However, there are several factors that make the pipeline transportation of hydrogen more expensive than the pipeline transportation of natural gas. Pipelines carrying hydrogen have the potential to become embrittled due to the chemical

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[169] Congressional Research Service, March 2, 2021. *Pipeline Transportation of Hydrogen: Regulation, Research, and Policy*.

[170] Based on data from the Hydrogen Analysis Resource Center, 2016. *Hydrogen Pipelines September 2016,* available at https://h2tools.org/hyarc/hydrogen-data/hydrogen-pipelines
Data from the National Pipeline Mapping System can be found at https://www.npms.phmsa.dot.gov/

[171] Siemens Energy, 2020. *Hydrogen infrastructure – the pillar of energy transition,* available at https://assets.siemens-energy.com/siemens/assets/api/uuid:3d4339dc-434e-4692-81a0-a55adbcaa92e/200915-whitepaper-h2-infrastructure-en.pdf

[172] *Id.*

nature of hydrogen, which can cause malfunctions or failure over time. In addition, due to the small size of hydrogen molecules, there is likely to be a greater leakage rate from pipelines that were intended for natural gas usage.

One way to facilitate the transition of existing natural gas pipelines into use in the transportation of hydrogen would be to mix proportions of hydrogen into the natural gas feedstocks. In this way, both hydrogen and natural gas could be transported together as an admixture along the same pipelines and either separated out or used in tandem by end-use facilities. An NREL study has researched the potential for mixing percentages of hydrogen into existing natural gas pipelines and found that very few modifications would be required for existing natural gas pipelines to carry hydrogen mixtures of 5% to 15%[173] (and possibly as high as 50% depending on conditions). Hydrogen transported as a mixture with natural gas could potentially be separated back out at the site of the end user through a process known as Pressure Swing Adsorption, but this process would add an additional $3.30 to $8.30 per kg to the delivery cost.[174] As a result, there has not yet been significant planning to blend hydrogen and natural gas for purposes of transporting hydrogen, except for purposes of burning the blended mixture to make electricity or thermal energy. As discussed earlier, this strategy promises to significantly reduce the carbon footprint of burning natural gas without significantly diminishing its utility.

4.1.2 Trucking

In addition to transportation via pipeline, hydrogen in the United States is also commonly transported by overland trucking in either gaseous or liquid form. Liquid tanker trucks with capacities of 4,000 kg to 5,000 kg are able to cost-effectively deliver hydrogen within 600 miles of its source point. Tube trucks, which carry hydrogen in its gaseous form and have around 800 kg of capacity, are cost-effective within a range of 200 miles.[175] This makes trucking the currently preferred option for short-to-mid-range hydrogen transportation.

Transporting hydrogen in liquid form entails the risk of some loss through boil-off, especially during loading and unloading. In addition, the process of liquefying hydrogen for transportation also adds as much as $1.00 per kg to the cost of production.[176] Liquefication also significantly

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[173] Melaina, M W, Antonia, O, and Penev, M. *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues*. United States: N. p., 2013. Web. doi:10.2172/1068610

[174] *Id.*

[175] *See* U.S. DRIVE Partnership, Hydrogen Delivery Technical Team Roadmap, (2017).

[176] Siemens Energy, 2020. *Hydrogen infrastructure – the pillar of energy transition,* available at https://assets.siemens-energy.com/siemens/assets/api/uuid:3d4339dc-434e-4692-81a0-a55adbcaa92e/200915-whitepaper-h2-infrastructure-en.pdf

increases the amount of energy (compression and cooling) used in the hydrogen storage process, rendering the transportation process more carbon intensive than it would otherwise be. Transporting pressurized hydrogen gas cylinders in tube trailers is a widely available and economically viable option for hydrogen delivery. These tube trucks are the most common method of hydrogen transportation over short distances, although they must carry a lower payload than trucks transporting liquid hydrogen. While transporting hydrogen via truck requires more labor and cost per delivery, this method also requires significantly less initial capital investment than the construction of pipelines. For this reason, trucking is generally used at small, initial scales, and most hydrogen currently being delivered in Ohio and the broader Midwest region is transported via trucks rather than pipelines.

4.2 Optimal Delivery Strategies in Ohio

The optimal method for delivering hydrogen from the point of production to the point of final use largely depends on the quantity of hydrogen being delivered and the distance between the two points. An analysis was undertaken to evaluate under what circumstances trucking or pipeline delivery might be the lowest cost method of transporting the quantity of hydrogen consumption projected per county as seen in Figure 8. Argonne's Hydrogen Delivery Scenario Analysis Model (HDSAM) was used for this cost estimation.[177] HDSAM allows for the simulation of not only present-day scenarios present based on default values for currently available technology cost and performance, but also for future scenarios where the effect of design improvements and increased production volume can lower component costs.[178] Technology cost and performance assumptions are combined with financial assumptions to calculate the contribution of these components to the delivered cost of hydrogen on a $/kg basis. The resulting output from simulating a delivery pathway scenario in HDSAM allows for the separate costs of transport, storage, and conditioning activities to be distinguished from each other.

There are endless scenarios that HDSAM can simulate. For the sake of simplicity, the Study Team limited the distances under analysis to 100 km (~60 miles) and 400 km (~250 miles). The Study Team modeled the levelized cost of hydrogen under HDSAM's "Urban" market type (HDSAM also allows for examination of Rural Interstate market types). The Urban market type models the cost of delivery from a centralized hydrogen production facility to the edge of an urban area (i.e., the city gate). HDSAM's "High" production volume option was selected to model future scenarios where the effects of technological improvement and higher production volumes are likely to reduce component costs. Default financial parameters were selected for the discounted cash

[177] https://hdsam.es.anl.gov/index.php?content=hdsam
[178] https://hdsam.es.anl.gov/files/hdsam-guide

flow analysis that HDSAM performs and included a real after-tax discount rate of 10% and a 30-year analysis period.

The cost per kg to deliver hydrogen via truck and newly constructed pipeline was simulated for each county in Ohio based on its projected hydrogen consumption as described in Section 3. Table 5 summarizes and compares the results of modeling these scenarios in HDSAM. At 400 km, delivery by new pipeline is projected to be cheaper, on average, than truck delivery at quantities greater than 200,000 metric tons per year (*Truck* delivery method in Table 5 is the cheaper of tube trailer or liquid tanker). At all other quantity and distance combinations, truck delivery is projected to be the cheaper option.

Table 5. Comparison of Projected Costs of Hydrogen Delivery for 2050: New Pipelines versus Trucking

	Average Delivery Cost ($/kg) by Distance and Pathway			
	100 km		400 km	
Annual demand (metric tons per year)	***Truck***	***New Pipeline***	***Truck***	***New Pipeline***
200,000 or more	$2.54	$2.58	$3.37	$2.98
100,000 to 199,999	$2. 50	$2.73	$3.29	$3.65
50,000 to 99,999	$2.49	$2.91	$3.28	$4.41
25,000 to 49,999	$2.54	$3.31	$3.30	$6.05
10,000 to 24,999	$2.70	$4.26	$3.41	$9.79
5,000 to 9,999	$2.86	$5.79	$3.56	$15.22
Less than 5,000	$3.00	$8.85	$3.70	$24.28

Source: The Authors (based on Argonne HDSAM model).
Note: Delivery costs are in 2021 dollars.

As indicated earlier, a less expensive means of pipeline delivery may be realized by converting natural gas to hydrogen pipelines. A follow-up HDSAM simulation of hydrogen delivery costs was run for each county reflecting conversion costs outlined in the aforementioned Siemens study on retrofitting natural gas pipelines.[179] In particular, the cost of retrofitting natural gas distribution and transmission lines was assumed to be 15% of the cost of installing new such lines.[180] Table

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[179] Siemens Energy, 2020. *Hydrogen infrastructure – the pillar of energy transition,* available at https://assets.siemens-energy.com/siemens/assets/api/uuid:3d4339dc-434e-4692-81a0-a55adbcaa92e/200915-whitepaper-h2-infrastructure-en.pdf

[180] The Siemens cost estimate of retrofitted natural gas pipeline being 15% that of the cost of new construction is based on the experience of transmission system operators. The 2016 *Leeds City Gate Project* report, funded by the United Kingdom's Office of Gas and Electricity Markets to evaluate the feasibility of retrofitting natural gas pipeline for hydrogen use in Leeds, England, estimated costs equivalent to around $13.4 million (US) to convert natural gas distribution lines within the city for hydrogen use. This represents no more than 14% of the cost for new hydrogen distribution pipeline construction for a similarly sized urban area based on HDSAM modeling. *See* Northern Gas

6 summarizes the results of modeling this second set of scenarios in HDSAM. At 400 km, delivery by converted pipeline is projected to be cheaper, on average, than truck delivery at quantities greater than 50,000 metric tons per year within a given county. At 100 km, delivery by converted pipeline is projected to be cheaper than truck delivery at quantities greater than 25,000 metric tons per year. Truck delivery is projected to be the cheaper option at all other quantity-distance combinations.

Table 6. Comparison of Projected Costs of Hydrogen Delivery: Repurposed Natural Gas lines to Trucking

	Average Delivery Cost ($/kg) by Distance and Pathway			
	100 km		**400 km**	
Annual demand (metric tons per year)	***Truck***	***Retrofitted Natural Gas Pipeline***	***Truck***	***Retrofitted Natural Gas Pipeline***
200,000 or more	$2.54	$2.01	$3.37	$2.14
100,000 to 199,999	$2. 50	$2.09	$3.29	$2.41
50,000 to 99,999	$2.49	$2.18	$3.28	$2.72
25,000 to 49,999	$2.54	$2.37	$3.30	$3.42
10,000 to 24,999	$2.70	$2.89	$3.41	$5.21
5,000 to 9,999	$2.86	$3.81	$3.56	$8.33
Less than 5,000	$3.00	$6.20	$3.70	$15.87

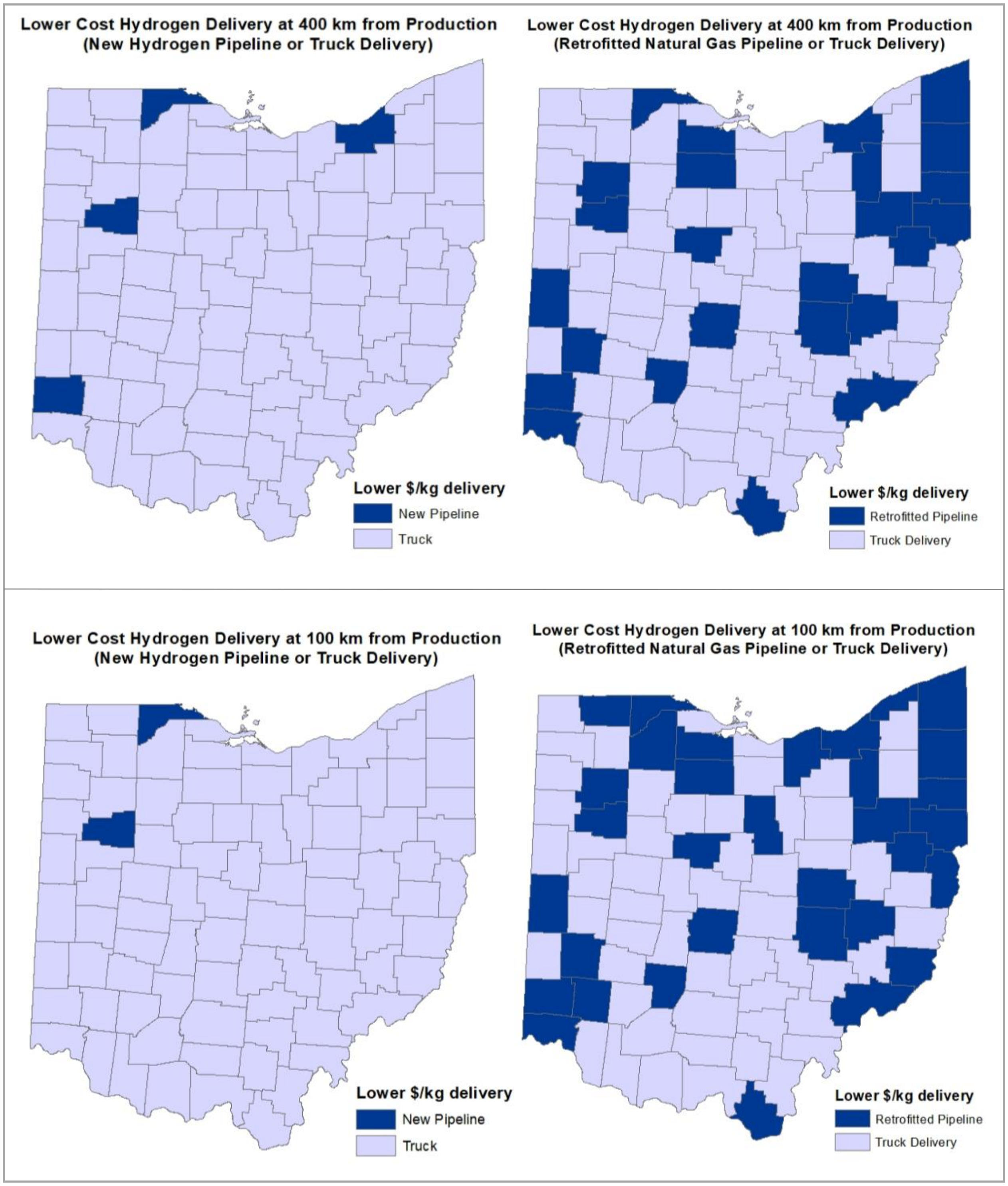
Source: The Authors (based on Argonne HDSAM model).
Note: Delivery costs are in 2021 dollars.

Figure 9 sets forth optimal delivery pathways in Ohio by County, based upon the total hydrogen markets projected for each County by 2050. This is intended to be illustrative of where pipeline infrastructure will likely first get built in Ohio, based upon the projected costs of pipeline versus trucking transportation. Since some of the County-wide consumption may not be at a single end point for delivery, this necessarily assumes that delivery can be enhanced by a local tube truck distribution system. That may not be an accurate assumption. Importantly, this analysis also assumes that there are no regulatory changes constraining carbon dioxide emissions. The economics of pipeline versus trucking of hydrogen could change significantly if regulation requires accounting for the costs of carbon dioxide emissions. Pipelines could significantly reduce carbon dioxide emissions compared to trucking.

Networks, 2016. *H21 Leeds city gate project*, available at https://www.h21.green/wp-content/uploads/2019/01/H21-Leeds-City-Gate-Report.pdf

Figure 9 also illustrates the change in optimal delivery pathways when retrofitting existing natural gas pipelines rather than building new hydrogen lines. These Figures show the lower cost delivery option resulting from the HDSAM scenario modeling given the projected annual hydrogen consumption within each county, assuming delivery distances between points of production and consumption of 400 km and 100 km. At 400 km, retrofitting natural gas pipelines increases the number of counties from 4 to 25 where pipeline delivery of hydrogen could be the cheaper option. At shorter distances, lower upfront costs compared to trucking may present additional opportunities for converting natural gas pipelines for hydrogen delivery (although whether this pathway is optimal still depends on sufficient volume). At 100 km, retrofitting natural gas pipelines increases the number of counties where pipeline delivery may be cheaper from 2 to 33.

Figure 9. Optimal Hydrogen Delivery at 400 km and 100 km: New Pipeline, Retrofitted Pipeline, or Truck Delivery



Source: The Authors.

4.3 Ammonia and Other Alternative Carriers

While pipeline transport may be considered the most efficient (and cleanest) means of hydrogen transport, the high capital costs associated with pipeline infrastructure may make this option unlikely for most hydrogen delivery in early stages of the hydrogen economy. Hence, trucking may be considered a more viable near-term solution. Yet there are economic and energetic losses associated with hydrogen liquefaction, as well as increased emissions. One potential solution to this problem exists in the use of hydrogen *carriers*, i.e., molecules or materials that embody hydrogen in their chemical or physical form. Ideal carriers must be inexpensive to carry – meaning in a liquid or solid state at atmospheric temperatures and pressures. It should have a high hydrogen density, require little energy and cost on both upstream (production) and downstream (cracking) conversion, and meet safety specifications regarding potential leakage and benign interaction with storage and transport infrastructure.

A number of carriers have been proposed for hydrogen transport including ammonia, hydrocarbons, formic acid, methanol and metal hydrides. Carriers like ethanol and methanol bind hydrogen in strong covalent bonds and are less likely to be converted back into hydrogen at location. Ammonia has surfaced as a popular hydrogen carrier option due to its low-cost production, ease of transport, higher hydrogen density (ammonia contains 40% more hydrogen per weight basis than methanol) and established safety protocols due to existing widespread usage and distribution. Some have proposed using ammonia directly: recently, Mitsubishi Power began construction of a 40 MW gas turbine fired entirely by ammonia (which produces no carbon dioxide as a byproduct).

Alternatively, ammonia can be "cracked" at the site of use to reproduce gaseous hydrogen. However, more efficient cracking mechanisms must be developed to ensure the economic viability of this route as the net energy losses in cracking are considerable and from several sources, including ammonia boil-off losses, heating to cracker temperature, and heat for ammonia dissociation. These collective losses point to a total cracker efficiency of around 76% in a best-case scenario. Altogether, the round-trip efficiency for ammonia as a hydrogen carrier (from energy to hydrogen to ammonia back to energy) ranges from 19 – 50%, with the higher end observed in the direct use of ammonia.[181] These efficiencies are comparable to those observed in similar energy vectors like methanol and liquid hydrogen, suggesting ammonia could serve as a suitable hydrogen carrier, especially in regions with existing ammonia infrastructure.

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[181] Giddey, S.; Badwal, S. P. S.; Munnings, C.; Dolan, M., Ammonia as a Renewable Energy Transportation Media. *ACS Sustainable Chemistry & Engineering* 2017**,** *5* (11), 10231-10239.

4.4 Hydrogen Refueling Infrastructure

In order to support the widespread use of hydrogen fuel cell vehicles in Ohio, a network of refueling stations would need to be constructed. There is currently only one publicly accessible hydrogen fueling station in Ohio, operated by Stark Area Regional Transit Authority in Canton, Ohio. This station was installed by SARTA in 2018 to supply what is now a fleet of 20 fuel cell electric buses and paratransit vans (requiring around 400 kg/day). In addition to the SARTA refueling station, Ohio State University's Center for Automotive Research operates a privately accessed, 12 kg/day capacity refueling facility, which uses on-site electrolysis to generate hydrogen.[182] While hydrogen fueling stations are very limited in the Midwest, a network of 48 publicly accessible hydrogen fueling stations has been established so far in California, demonstrating that a level of infrastructure is sustainable if demand is significant enough.[183]

Constructing hydrogen refueling stations requires considerable initial capital investment. Sandia National Laboratories has calculated that the equipment costs for constructing a refueling station capable of dispensing 100 kg/day can be estimated at $894,256, including compressors, dispensers, and storage tanks.[184] This cost estimate increases to $1,033,203 for a refueling station with an output of 200 kg/day and $1,157,439 for a refueling station providing 300 kg/day.

In addition to refueling stations that service medium and heavy-duty vehicles such as city buses and trucking fleets, there is a developing network of hydrogen refueling facilities dedicated to supplying industrial fleets of forklifts. The use of hydrogen fuel cells to power forklifts in storage and shipping warehouses has increased significantly in recent years. Several facilities in Ohio already operate fleets of more than one hundred hydrogen-powered forklifts, and each of these facilities requires the capacity to operate and refuel its forklift fleet for daily use. A further discussion of the current and projected use of hydrogen-powered forklifts can be found above in section 3.2.2.

4.5 Hydrogen Storage Infrastructure

Hydrogen has a smaller molecular structure and a less dense gaseous form than complex hydrocarbons, creating additional challenges to its large-scale storage. More space is required to store large amounts of hydrogen due to its low density, and its small structure leads to greater leakage rates from storage facilities. In order to be stored in significant quantities without

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[182] *See* Ohio State University Center for Automotive Research at https://car.osu.edu/hydrogen-fueling-station

[183] *See* US Department of Energy Alternative Fuels Data Center https://afdc.energy.gov/states/oh

[184] https://www.hydrogen.energy.gov/pdfs/18002_industry_deployed_fc_powered_lift_trucks.pdf

necessitating excessive storage volumes, hydrogen can be compressed as a gas, cooled into a liquid form, or bound to a material sorbent. The most common way to store hydrogen for short-term use is as compressed gas in steel or aluminum cylinders. These vary in cost of storage from $600 per kg to $1,450 per kg depending on pressurization, which can range from 135 bar to 950 bar of pressure.[185] The high cost of pressurization and storage contributes significantly to the overall cost of hydrogen delivery.

In addition to storage in pressurized cylinders, large quantities of hydrogen gas can be stored in certain types of underground geological caverns or deep saline aquifers. Ohio currently has approximately 391,000 million cubic feet of natural gas in underground storage, which can serve as a model for the underground storage of hydrogen.[186] According to data collected by the EIA, there are 24 underground storage fields in Ohio that are currently being used to store natural gas resources. These underground fields have a combined storage capacity of approximately 576 billion cubic feet and comprise about 6% of all total underground storage capacity in the United States. These could potentially also be used for the storage of hydrogen. However, the small molecular size of hydrogen leads to an expected loss rate of 1-3% of stored hydrogen per year.[187] Additionally, with limited storage in Ohio, hydrogen producers will have to compete with natural gas and ethane producers for storage space.

Salt caverns, which are relatively abundant in Ohio and throughout much of the Midwest, have a high potential for use in hydrogen storage. Due to the physical properties of salt molecules, the walls that line salt caverns are relatively difficult for hydrogen molecules to penetrate, leading to lower loss rates.[188] A 2014 analysis estimated the levelized cost of hydrogen storage in salt caverns to be approximately $1.62 per kg of hydrogen due to the relative ease of recovery.[189]

Three salt caverns are presently being used for hydrogen storage in the United States and there is potential for this usage to expand with upcoming projects. The Long Ridge Energy Terminal being constructed in Hannibal, Ohio has plans to deploy salt caverns as hydrogen storage in addition to above-ground storage tanks. Depleted oil and natural gas reservoirs also have the potential to be used for the large-scale underground storage of hydrogen. Ohio has ample

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185 *See* p. 23 of U.S. DRIVE Partnership, *Hydrogen Delivery Technical Team Roadmap*, (2017).
186 US Energy Information Administration, June 2020. *Ohio State Energy Profile*. Available at https://www.eia.gov/state/print.php?sid=OH
187 T. Tsoutsos, *Stand-Alone and Hybrid Wind Energy Systems*, Woodhead Publishing Series in Energy (2010)
188 Alexander Lemieux, Karen Sharp, & Alexi Shkarupin, *Preliminary Assessment of Underground Storage Sites for Hydrogen in Ontario, Canada*, International Journal of Hydrogen Energy 4 vol. 4 (2019).
189 Anna S. Lord, Peter H. Kobos, & David J. Borns, *Geologic Storage of Hydrogen: Scaling Up to Meet City Transportation Demands,* International Journal of Hydrogen Energy vol. 39 (2014).

depleted reservoirs, and a number are being used already for natural gas storage. It is unclear, however, how suitable these will be for hydrogen storage.

5.0 Role of Carbon Dioxide in Ohio's Emergent Hydrogen Economy

Ninety-Five percent of the hydrogen produced in the United States is made from natural gas reformed in large central plants.[190] This process of steam-methane reformation (SMR) separates hydrogen from a methane molecule yielding a stream of hydrogen gas by the application of heat and pressure. One of the byproducts of this production method is leftover carbon dioxide (CO_2), which if released into the atmosphere, adds to the greenhouse effect that raises global temperatures.[191] On average, this type of hydrogen production emits 9 kg of CO_2 for every kg of hydrogen produced.[192]

Any strategy for hydrogen development should therefore account for net CO_2 emissions from a comprehensive life-cycle perspective if it is to be effective in curtailing atmospheric CO_2 levels. One alternative to the SMR process is to use electricity derived from renewable sources such as the sun to split a water molecule into its constituent parts: oxygen and hydrogen. Another option is to capture the carbon produced via SMR and to either store it underground in geologic formations such as salt caverns or in depleted oil and gas reservoirs[193] or to use it as a feedstock to make other things such as synthetic aggregates, synthetic fuels, or new materials such as carbon fiber.[194] This approach, referred to as carbon capture, utilization and storage (CCUS) is particularly attractive in regions where there is an absence of suitable underground reservoirs for storage, to generate revenue through the valorization of CO_2 into a marketable product, or to displace fossil feedstocks (e.g., for plastic manufacturing) toward the creation of a circular carbon economy.[195]

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[190] Hydrogen and Fuel Cells Technologies Office. U.S. Department of Energy.

[191] National Oceanic and Atmospheric Administration. U.S. Department of Commerce. (2020). *Climate Change: Atmospheric Carbon Dioxide*. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

[192] Argonne National Laboratory. (2019). *Updates of Hydrogen Production from SMR Process in GREET 2019.* https://greet.es.anl.gov/publication-smr_h2_2019

[193] *See* Intergovernmental Panel on Climate Change. (2005). *IPCC Special Report on Carbon dioxide Capture and Storage* (Chapter 5). https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter5-1.pdf

[194] *See* Center for Climate and Energy Solutions. (2019). *Carbon Utilization: A Vital and Effective Pathway for Decarbonization.* https://www.c2es.org/document/carbon-utilization-a-vital-and-effective-pathway-for-decarbonization/

[195] P. Psarras, C. Woodall, & J. Wilcox (2021), "The Role of Carbon Utilization," *CDR Primer*, edited by J. Wilcox, B. Kolosz, J. Freeman. *See also* Núñez-López, V., et al. Gulf Coast Carbon Center. University of Texas at Austin. (2019). *Environmental and Operational Performance of CO2-EOR as a CCUS Technology: A Cranfield Example with Dynamic LCA Considerations*. https://www.osti.gov/pages/biblio/1493096

Hydrogen production from natural gas in combination with CCUS – i.e. "blue" hydrogen -- is expected to be the least-cost, low-carbon option for clean hydrogen in the near term, especially in regions where inexpensive natural gas is readily available.[196] U.S. natural gas prices, which rebounded from historic lows in 2021 to nearly $4.00/mmbtu in early 2022, are nonetheless projected to remain relatively low over the next decade, driven in large part by the continued development of shale plays in states such as Ohio, Pennsylvania, and West Virginia.[197] Blue hydrogen has been proposed by intergovernmental organizations such as the International Renewable Energy Agency (IRENA) as a bridging solution: as the cost of producing hydrogen from renewable power decreases, it can offer the prospect of continuity to fossil fuel producers while also helping to achieve climate objectives at acceptable costs.[198]

For blue hydrogen generation (as well as for the BiCRS option), it is important to find offtake partners for the carbon dioxide. Proximity of the source-sink CO_2 partnership is crucial to minimizing delivery costs. In general, small-scale transport of CO_2 in compressed tanker trucking costs between $0.16 and 0.18/metric ton of CO_2 per mile transported.[199] Larger scale transfer is more economical with pipeline, but the economies of scale favor trucking when the volume is under 500,000 metric tons CO_2/year, regardless of distance transported.[200] Accordingly, low-cost CO_2 disposal is a function of both cost-efficient CO_2 capture at the point-source and close proximity to the end-user.

Existing or new markets for carbon dioxide could significantly accelerate the hydrogen economy in Ohio. The beneficial reuse of carbon dioxide (CO_2 utilization, or CCU) has been practiced for decades in the United States. Currently, over 70 million metric tons of CO_2 are used for chemical and physical purposes including as a precursor for polymers, in fire suppression, as an inert gas in welding and food storage, in beverage carbonation, in concrete building materials (curing and as an aggregate replacement), and in fertilizer production.[201] However, by far the largest use of CO_2 in the United States is for enhanced oil recovery (EOR) where annually roughly 65 million metric tons of CO_2 are injected into the subsurface for the purpose of enhancing the recovery of crude oil. The next largest use of CO_2 is in urea manufacturing, consuming nearly 5 million metric

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[196] International Energy Agency. (2019). *Transforming Industry through CCUS*. https://webstore.iea.org/download/direct/2778

[197] *See* U.S. Energy Information Administration. U.S. Department of Energy. (2020). *Annual Energy Outlook 2020*. https://www.eia.gov/outlooks/aeo/. More recent EIA forecasts project prices to be under $4.00/mmbtu in 2023.

[198] International Renewable Energy Agency. (2019). *Hydrogen: A Renewable Energy Perspective*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf

[199] Assuming 20 metric ton CO_2/payload.

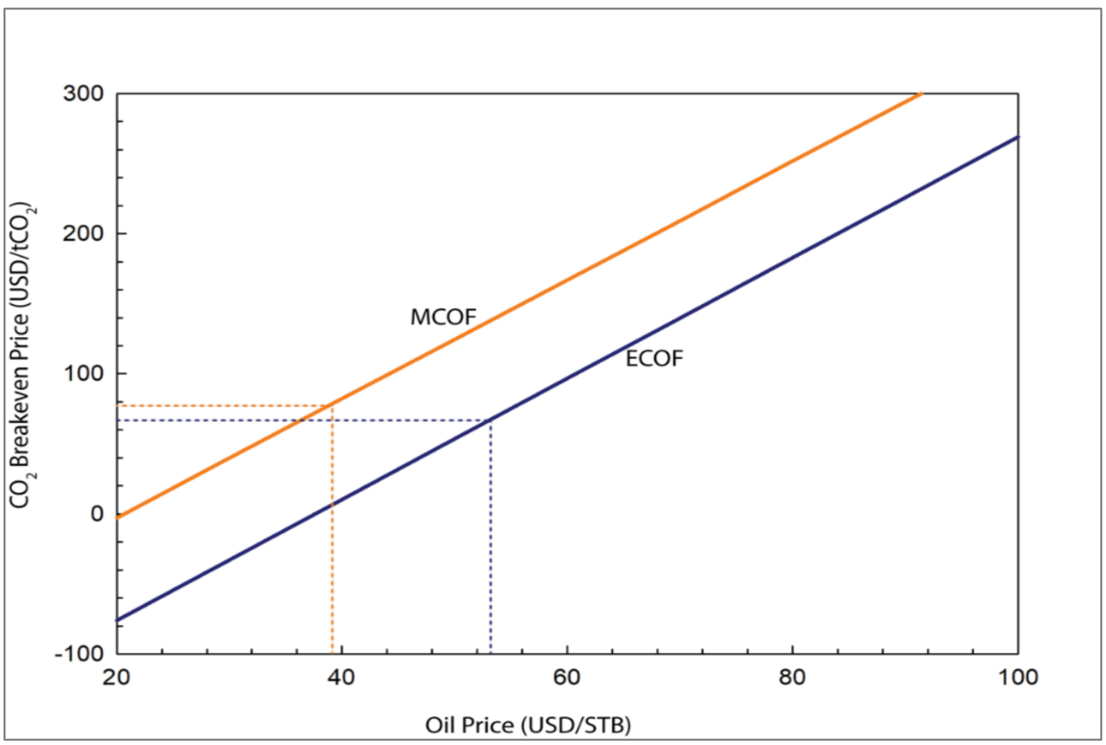
[200] Psarras, P. C.; Comello, S.; Bains, P.; Charoensawadpong, P.; Reichelstein, S.; Wilcox, J., Carbon Capture and Utilization in the Industrial Sector. *Environmental Science & Technology* 2017, ***51*** (19), 11440-11449.

[201] Psarras, Peter C., et al. "Carbon capture and utilization in the industrial sector." *Environmental Science & Technology* 51.19 (2017): 11440-11449.

tons CO_2 per year. Low-cost CO_2 disposal is a function of both cost-efficient CO_2 capture at the point-source and close proximity to the end-user.

Ohio has existing urea manufacturing markets and potential EOR markets. Urea manufacturing in Ohio currently consumes around 315,000 metric tons of carbon dioxide per year.[202] Ohio also has a number of aging oil fields that could benefit from enhanced oil recovery, including the East Canton (ECOF) and the Morrow County (MCOF) oil fields. A chart of break-even prices for each, as a function of oil sales price and variance in field characteristics, is set forth below. If the hydrogen plant is within 10 miles of the ECOF, for instance, delivery would be estimated to be around $2/metric ton carbon dioxide (assuming CO_2 is treated as a cost-free byproduct of hydrogen generation). The break-even point for oil sales at that price would be around $45/barrel. Given 2021 oil prices of between $50 and $80/barrel, essentially any CO_2 generated in Ohio through SMR with carbon capture should be profitable in a partnership with either the East Canton or Morrow County fields.

Figure 10. CO_2 Breakeven Price as a Function of Oil Price for Enhanced Oil Recovery CO_2 Derived from Small Scale Reformed Natural Gas (2020)



Source: The Authors.

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[202] Psarras, P. C.; Comello, S.; Bains, P.; Charoensawadpong, P.; Reichelstein, S.; Wilcox, J., Carbon Capture and Utilization in the Industrial Sector. *Environmental Science & Technology* 2017, *51* (19), 11440-11449.

Other carbon markets exist in Ohio. Ohio is currently the 7th largest producer of aggregate in the US, producing roughly 120 million metric tons of aggregate per year, primarily for use in concrete, asphalt and road pavement, and railroad ballast. The majority of these aggregates are produced in-state and within 50 miles of end use. Synthetic aggregate can be formed from the reaction of captured CO_2 with an appropriate alkaline feedstock. These feedstocks exist currently in the form of various industrial wastes like steel slag, cement kiln dust, coal fly ash, and air pollution control residue (APCR). According to the EPA greenhouse gas reporting protocol, Ohio has one cement facility, 14 iron and steel production facilities, and 11 coal-fired power plants, all capable of producing alkaline industrial waste.

Additionally, in 2019 Ohio produced approximately 15 million metric tons of municipal solid waste, of which approximately 11% was incinerated to form APCR. Synthetic aggregate is unique in that it combines CO_2 use and CO_2 storage into one step, securing CO_2 into a stable mineral form and providing a high-demand commodity. Though synthetic aggregate is projected to have a slightly higher cost than the current selling price for aggregate in the US by +17%, a premium may apply to carbon-derived goods, especially those (like synthetic aggregates) that store CO_2 permanently. The flexibility of use, high volume demand, and co-benefits position synthetic aggregate as a major user of CO_2 in Ohio and beyond.

Additionally, hydrogen is the primary co-feedstock in most CO_2 conversion pathways, especially those leading to synthetic hydrocarbons; hence, hydrogen can see a local boost in demand where captured CO_2 is readily available, and perhaps an enhanced demand in regions where geophysical, social or political barriers to CO_2 storage exist. Conversion of CO_2 into valuable products for the generation of revenue, displacement of fossil feedstocks, or as an alternative surficial storage mechanism, is generally viewed as more favorable in regions with identifiable barriers to storage. Importantly, these barriers are expected to be widespread in the near-future as geologic storage in Ohio is still immature and permitting requirements (Class VI wells) remain difficult and time-consuming to obtain.

One interesting use for carbon dioxide in Ohio is for Ready Mix Concrete, which is already deployed in construction operations around the state. The utilization rate of CO_2 in ready-mixed concrete (RMC) is low, typically under 1% by mass, but sufficient to be a sink for small scale, distributed hydrogen generation. RMC plants tend to be dispersed, lower volume operations, with an average shipment distance of 32 miles (compare to the average distance of 546 miles for all industrial commodities). Given these considerations, a typical RMC plant using CO_2 as an input will have a demand for CO_2 between 340 and 1700 metric tons/year. This pairs well with small scale blue hydrogen operations, such as might be found onsite at a refueling station.[203]

6.0 Conclusion

Conservative projections (i.e. the assumption that there will be no regulation of carbon dioxide emissions in the near future) indicate that Ohio will be a major market for hydrogen markets and generation. Assuming consumption growth similar to that experienced in Ohio over the last 10 years, the Study Team projects an Ohio hydrogen market of around 2 MMT/year by 2050. This is consistent with the projections from the U.S. Department of Energy, which projects 20-40 MMT/year nationally by 2040.[204] Following Ohio's estimated 5% share of national manufacturing output, Ohio would have between 1-2 MMT/year by 2040.

Assuming the natural gas currently produced from the Utica in Ohio and the nuclear power currently generated are both maintained and 15% of this is repurposed form hydrogen generation, Ohio will be able to meet the projected 2050 demand of 2 MMT/year with locally produced hydrogen. However current Energy Information Agency projections suggest that Utica production may decline significantly by 2050. Likewise, Ohio's two nuclear power plants are scheduled for retirement before 2050. Accordingly, Ohio may need to consider strategies to maintain natural gas production and/or nuclear generation in the coming years. Alternatively, Ohio will need to build and repurpose power from renewable sources, such as wind, solar or biomass power, to make hydrogen.

Table 7 below compares the projected major markets for hydrogen to the 15% repurposing strategy in the coming years. In the near term, oil refining and ammonia production will continue to be the major markets for hydrogen. However, by 2050 fuel cell electric vehicles, metal refining, power generation and synthetic hydrocarbons will be the major markets.

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[203] Psarras, Peter; Henning, Mark; and Thomas, Andrew R., "Economics of Carbon Capture and Storage for Small Scale Hydrogen Generation for Transit Refueling Stations" (2020). *Urban Publications*. 0 1 2 3 1675. https://engagedscholarship.csuohio.edu/urban_facpub/1675

[204] Testimony of S. Satyapal before the United States Senate, February 2022, https://www.energy.senate.gov/services/files/FE1C53B0-3925-46E3-B1D3-B8E2C0DD92B6.

Table 7. Projected Ohio Annual Hydrogen Consumption and Production (Metric Tons) Assuming: No Carbon Dioxide Regulation and Markets Supplied by 15% of Nuclear Power and Renewable Power, and Remaining Market Supplied by Steam Methane Reformation

		2030	2040	2050
Hydrogen Consumption	Power generation	31,100	88,400	251,200
	FCEVs	2,900	35,400	430,600
	Forklifts	4,700	8,400	12,700
	Oil refining	188,700	202,400	217,000
	Metal refining	23,900	96,600	391,000
	Ammonia production	114,200	119,600	125,400
	Biofuels	400	7,900	148,000
	Synthetic hydrocarbons	63,600	85,800	397,700
	Other Mfg. markets	8,100	9,100	10,300
	Total Consumption	**437,600**	**653,600**	**1,983,900**
Hydrogen Production	Electrolysis via Nuclear Power	9,300	50,700	59,600
	Electrolysis via Renewable Sources	86,600	112,800	135,900
	Natural Gas (SMR)	341,700	490,100	1,788,400

Source: The Authors.

Note 1: Natural gas production of hydrogen is determined by subtracting the amount of hydrogen generated from repurposing 15% of nuclear and renewable power from the total expected market. Current SMR capacity in Ohio is about 161,000 metric tons annually. Projections assume nuclear power repurposing ramps up to 15% by 2050, using an "S" curve for new products (and assumes overall nuclear power capacity will not grow). For renewable power, we assumed Ohio's growth will follow the EIA national annual growth rate projections for renewable power (3.9% for solar and 0.7% for wind). Currently, repurposing 15% of existing and under construction renewable power would generate about 55,000/yr metric tons of hydrogen.

Note 2: The U.S. Energy Information Administration (EIA) identifies the following as sources of renewable energy: Conventional Hydroelectric Power; Geothermal; Municipal Waste; Wood and Other Biomass; Solar Thermal; Solar Photovoltaic; and Wind. Among these, only solar photovoltaic and wind are included in our renewable projections.

It is important, however, to note the implications of this conservative estimate for Ohio's hydrogen markets. When presented with the complexities of determining the external costs of carbon dioxide emissions, and unable to agree upon what those costs really are, society assigns no external cost whatsoever. That model is clearly no longer sustainable. Corporations are joining academic, national lab and other institutions calling on government to deploy strategies to constrain carbon emissions.

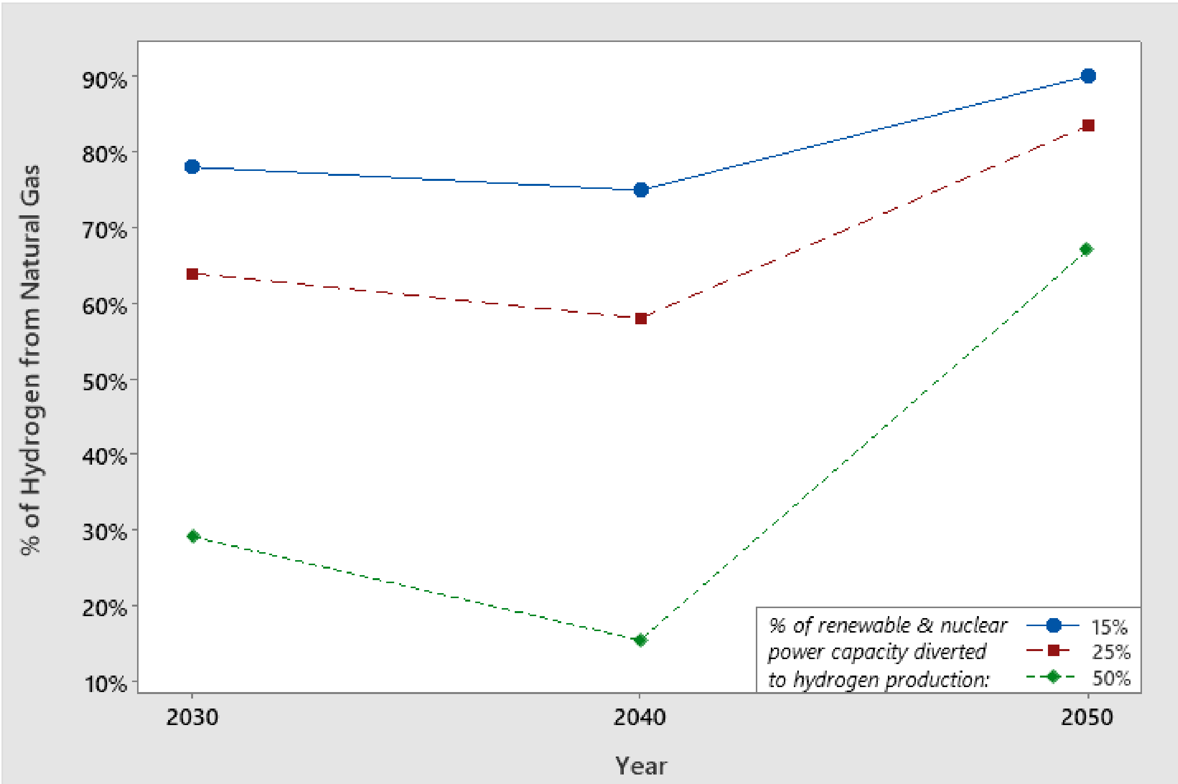
In August 2021, the United Nations issued a report calling for dramatic and immediate action.[205] After yet another summer of record heat, drought and wildfires, including June temperatures in Canada that reached 120°F, a consensus has begun to develop that will likely lead to action in the coming decade, including the widespread adoption of zero emission vehicle standards.

In an energy economy that puts costs on carbon dioxide emissions, a 2 MMT/year hydrogen market projection for 2050 for Ohio is likely to be too low. The fuel cell electric vehicle market, for instance would itself be around 1.2 MMT/year if such vehicles reach a 33.3% market share, rather than the 12% market share projected with no zero emission standards. Likewise, a hydrogen/natural gas blend of 30% hydrogen instead of 20% for power generation would increase consumption by over 100,000 metric tons/year. Other uses, such as for metal refining, would likely also ramp up consumption as companies use hydrogen to reduce carbon emissions. The result is that a 3 MMT/year market is a more likely prognosis for Ohio in 2050.

Ohio will likely be looking to supply this larger 3 MMT/year market at the same time that natural gas production from Utica Shale and other Appalachian formations are in decline. Ohio will need to develop a green hydrogen strategy to prepare for this scenario. Based upon current projections for Ohio generation capacity, if the state repurposed 50% of its nuclear and utility scale renewable power fleets to make hydrogen for a 2 MMT/year market, it would still be required to support 70% of its hydrogen from steam methane reformation by 2050 (see Figure 11 below). A 3 MMT/year market will only require more natural gas. Further, 50% repurposing of nuclear and renewable power will put a significant strain on Ohio's grid, which already imports around 25% of its power.

[205] IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press. See: https://www.ipcc.ch/report/ar6/wg1/.

Figure 11. Percent of Hydrogen from Natural Gas Required to Meet Demand Potential Under Three Scenarios for Repurposing Renewable and Nuclear Power



Source: The Authors.

Accordingly, Ohio industries will need to plan for both blue and green hydrogen sources to supply Ohio's anticipated hydrogen demand. It will need to develop strategies for using or sequestering carbon dioxide captured from steam methane reforming processes. And it will need to ramp up its green power generation fleets to replace natural gas over time. This will include extending the life of its nuclear power plants, and significantly increasing its fleet of utility scale renewable power.

Indeed, if Ohio were to supply just half of its projected 2 MMT/year hydrogen market from carbon-free electricity, it would need to increase its utility-scale renewable power fleet to more than 4 Gigawatts (GW) by 2050 (and probably much more, since renewable cannot be run 24/7).[206] This will include extending the life of its nuclear power plants, and significantly increasing Ohio's fleet of utility-scale renewable power systems. If Ohio were to try to supply the entire hydrogen market with carbon free electrolysis, it would require a fleet of around 11

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[206] By 2050, one-half the hydrogen market will be about 991,950 metric tons per year. Assuming 500 kg/day/MW, or 182.5 metric tons/year/MW, electricity generation capacity of 5,435 MW would be needed to satisfy such a projected H2 demand.

GW by 2050, operating 24/7 making hydrogen (which renewable cannot do). If emission regulations are passed, and the Ohio markets were to reach 3 MMT/year in 2050, it would require about 16 GW total renewable and nuclear power, operating 24/7, to meet this market. Since Ohio will not likely increase its nuclear power load, this means most of the power would come from intermittent sources, meaning the total capacity would need to be much higher than 16 GW.

Notably, this low or no carbon emission market size assumes only a 33% hydrogen fuel cell vehicle market penetration. That would mean that battery electric would, under a zero-emission mandate, represent most of the rest of the vehicle market. This, too, will require a significant amount of renewable power to meet that load. In 2021, Ohio's generating plants together have a nameplate capacity of about 29 GW (Ohio also imports about 24% of its load).[207] To meet zero emission mandates and the anticipated hydrogen and battery electric markets without natural gas would mean that Ohio would likely have to at least double the size of its current generation fleet with intermittent renewable power over the next 30 years. For this reason, natural gas is likely to continue to play a major role in hydrogen generation in Ohio in the coming decades.

[207] *See* Table 10, Supply and Disposition of Electricity, of the EIA's State Electricity Profile for Ohio at: https://www.eia.gov/electricity/state/ohio.