H_2

Renewable Hydrogen in Iowa

SECOND EDITION

Assessing the prospects of a renewable hydrogen economy in Iowa with economic and employment projections, techno-economic modeling, and resource mapping.

ideal
ENERGY

Eric Johnson & Greg Wilson, PhD
Ideal Energy, LLC

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About this Report

Project Description

This report is part of a project intended to lay the foundation for industrial scale renewable hydrogen production in the state of Iowa. Key goals and deliverables for the project include:

- document renewable energy projects and other key resources in Iowa,
- identify opportunities associated with decarbonizing critical commodities such as ammonia,
- evaluate the current state-of-the-art in the renewable hydrogen industry and review up-to-date publicly funded research around the world,
- perform a techno-economic analysis for renewable hydrogen production in Iowa,
- construct a cost roadmap, and
- present key findings to public and private stakeholders.

About the Authors

Dr. Greg Wilson, PhD is one of the nation's leading renewable hydrogen experts. He was the director of the National Center for Photovoltaics (NCPV) at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) from 2011 to 2018. Prior to that he had a long career as a senior scientist and director of R&D projects at MEMC Electronic Materials.

After retiring from NREL, Dr. Wilson worked as a consultant in the renewable hydrogen field. It was in that capacity that he assisted with this project. He currently serves as Vice President of Science and Advanced Technologies at JERA Americas where he focuses on renewable hydrogen.

Dr. Wilson holds a doctorate of science and a master's degree in chemical engineering from Washington University in St. Louis as well as a bachelor's in chemical engineering from the Missouri University of Science and Technology.

Eric Johnson is a solar energy and renewable hydrogen subject matter expert. Through his consultancy, he has provided market research, analysis, and public-facing technical white papers to clients in the renewable energy industry since 2016. He has produced papers on subjects including peak shaving with battery energy storage systems, solar-driven demand charge reduction in university settings, and energy decarbonization using renewable hydrogen.

Johnson holds a bachelor's degree in history from Brown University.

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Report Sponsors

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About Ideal Energy

Ideal Energy is a veteran-owned, Iowa based energy company delivering quality solar and energy storage solutions to the Midwest. Ideal Energy's mission is to increase the security, sustainability, and vitality of our planet with future-facing renewable energy technology.

Since 2009, Ideal Energy has developed a portfolio of trailblazing projects, including the first battery energy storage system in Iowa, the state's first use of solar in conjunction with batteries for demand charge reduction, and many projects that were the largest in Iowa at the time. Awards include Iowa Environmental Council's Business Innovation award (two times), Solar Builder Magazine Project of the Year Award, and 1,000 Friends of Iowa Best Development Award (four times).

In addition to its work with solar power, Ideal Energy is now charting the path to a green hydrogen economy in Iowa and beyond.

About the Iowa Economic Development Authority

"The Iowa Economic Development Authority's (IEDA) mission is to strengthen economic and community vitality by building partnerships and leveraging resources to make Iowa the choice for people and business." IEDA is home to the Iowa Energy Office and the Iowa Energy Center which manage a diverse mix of state, federal and utility-funded programs and initiatives that provide energy-economic benefits for Iowa's citizens, businesses and organizations.

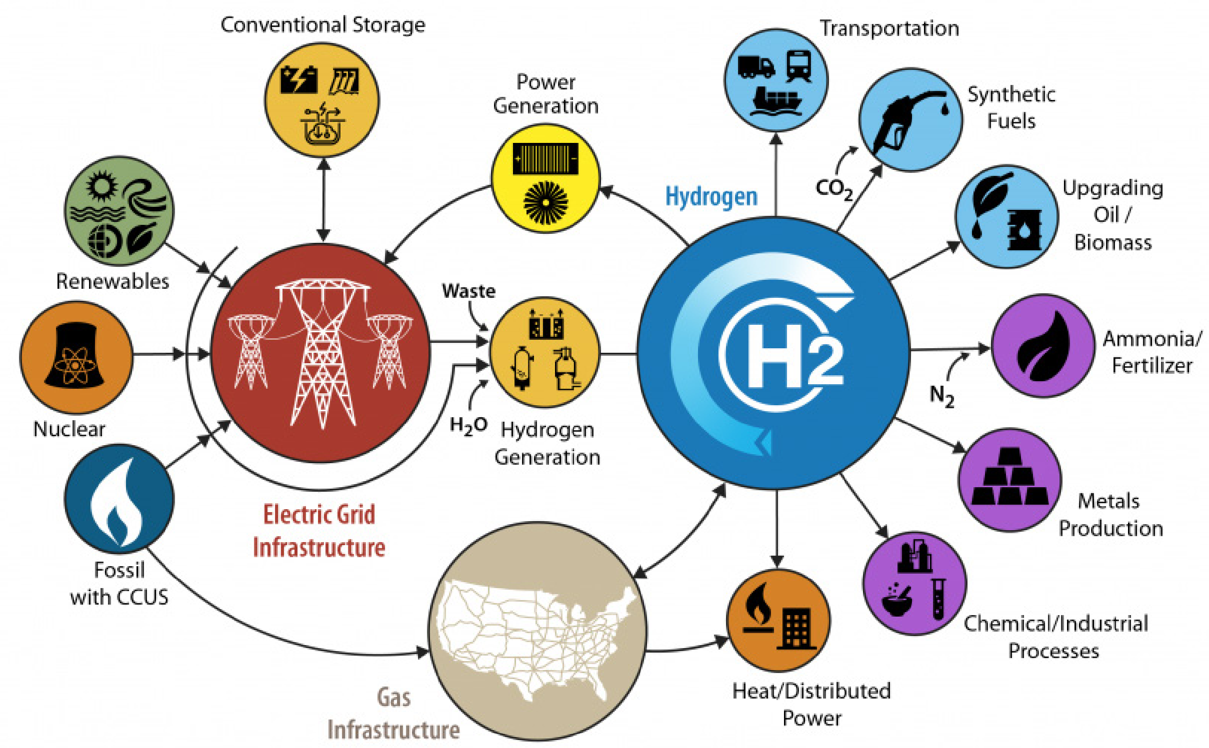
Through its business development and community development division, IEDA administers several state and federal programs, and deploys funds authorized by the Iowa Legislature. Since its inception in 2011, IEDA has assisted 567 projects, provided $83 million in direct financial assistance, and awarded $848 million in tax credits.

Executive Summary

Why Hydrogen?

The energy transition – the global changeover from fossil fuels to a renewable, carbon-free energy economy – will involve trillions of dollars of wealth creation. Iowa is in a unique position to lead the way and benefit from this transition.

To decarbonize energy the world needs both clean electricity and a carbon-neutral chemical energy carrier. A chemical energy carrier is necessary where electricity and batteries are not suitable, including applications like long-distance heavy transport, the chemical industry, heavy manufacturing, and long-term energy storage.



Renewable Hydrogen and Green Ammonia are Ideal Chemical Energy Carriers

Hydrogen (H_2) is a flammable, lighter-than-air gas with strong existing demand and a wide array of potential future uses. Ammonia (NH_3), which is made from hydrogen, is more stable and more energy-dense, ideally suited for long-term storage, and among the world's most in-demand chemicals due to its use as the principle ingredient in most fertilizers.

Renewable Hydrogen is Clean

Renewable hydrogen production requires only water, an electrolyzer, and a renewable power source such as a wind farm or solar array. The electrolyzer uses electricity to split water molecules into hydrogen and oxygen. **No pollution or greenhouse gases are emitted in this process.** Green ammonia, which is made from renewable hydrogen, is also carbon-free. In contrast, traditional brown ammonia production accounts for 1.8% of all CO_2 emissions worldwide.

Hydrogen is Versatile and In Demand

There is an existing market for hydrogen as the principle feedstock for ammonia production. Hydrogen can also be injected into the natural gas network, burned in power plants or industrial furnaces, used to power hydrogen fuel cells vehicles, and used to produce carbon-free fuels.

Hydrogen is used to make ammonia. Hydrogen is the primary feedstock for ammonia production. There is a vast, existing market for ammonia, especially among agrichemical manufacturers producing nitrogen fertilizers such as anhydrous ammonia. The ammonia market is valued at $74.61 billion and is expected to grow at a compound annual rate of 5.59% over the next five years.

Hydrogen in the natural gas grid. Hydrogen can be mixed with natural gas at up to 10% with no safety hazard, no impact to gas infrastructure, and no requirement to modify or replace end-use appliances like furnaces, boilers, stoves and ranges. European projects have already demonstrated the viability of this approach.

Hydrogen can be turned back into electricity. Hydrogen can be burned in modified peaking power plants. It can also be used in large, stationary fuel cells to provide peak demand reduction or grid stabilization services. Ammonia can be burned in modified coal power plants. Projects using each of these approaches are operational or under construction in the U.S., Europe, and Japan.

Renewable hydrogen is ideal for heavy transport and aviation. Hydrogen is a necessary ingredient in carbon-free fuels like renewable diesel, sustainable aviation fuel (SAF), and hydrotreated vegetable oil (HVO). Hydrogen can also power fuel cell electric vehicles (FCEVs), fuel cell locomotives, and fuel cell powered oceanic transport ships.

Hydrogen can Expand the Reach of Renewables

Electricity generation represents only 25–30% of global carbon emissions. The remaining 70–75% of emissions stem from difficult to decarbonize sectors, including heavy transport, steelmaking, and agrichemical processes. Emissions from these sectors cannot be easily addressed with solar power, wind power, or batteries, but they can be addressed with renewable hydrogen.

Iowa: the Persian Gulf of Renewable Hydrogen

- Iowa is extremely well-positioned to become a center of renewable hydrogen production and consumption. Iowa has abundant renewable energy resources, an existing agrichemical industry, and a huge demand for hydrogen products.

Iowa has Excellent Renewable Energy Resources

- **Iowa generates 57.51% of its electricity with wind – the highest percentage in the nation.** Iowa has 11,660 megawatts (MW) of installed wind capacity – second only to Texas.
- **The technical solar potential of Iowa ranks 16th in the nation, ahead of Florida and the Carolinas.** Iowa has 158.7 MW of installed solar capacity with another 1,349 MW approved or proposed.

Iowa has a Robust Agrichemical Industry

- Iowa is home to several agrichemical companies that produce nitrogen fertilizers from ammonia, including CF Industries and Iowa Fertilizer Company.
- The NuStar ammonia pipeline carries upwards of 30,000 barrels of ammonia per day to facilities in Iowa and neighboring states.

Iowa has Significant Local Demand for Hydrogen Products

- Iowa is a major agricultural state with the highest corn production in the nation and the second highest soybean production.
- With approximately 23,619,000 acres planted – more than any other state – demand for ammonia-based nitrogen fertilizers in Iowa exceeds 1.5 million tons per year.

Iowa has Potential Markets for Hydrogen in Transport, Manufacturing, and Natural Gas

- Iowa is a crossroads state for truck freight and a key refueling stop for trucks coming from and going to Chicago, St. Louis, Kansas City, Minneapolis, and Milwaukee.
- The busiest freight railway in the nation passes through Iowa.
- Iowa's manufacturing sector – which is the state's second largest industry and accounts for 18.4% its economy – could use hydrogen extensively with little modification to existing infrastructure.
- Replacing even 5% of Iowa's natural gas with hydrogen would create over 2.75 TW of hydrogen demand.

How Iowa Can Benefit

Renewable hydrogen can provide Iowa with billions of dollars in economic growth and thousands of jobs.

- With a renewable hydrogen industry in the state, Iowa could see a **$1.19 billion increase to its gross state product** (**GSP**) **by 2030 and a $6.375 billion GSP increase by 2050.**
- Research suggests Iowa's hydrogen industry could contribute **more than 7,000 new jobs by 2030, and up to 35,000 new jobs by 2050.**
- Employment factor is a measure of both direct and indirect jobs per terawatt-hour (TWh) that includes initial construction as well as ongoing operations. **The employment factor of renewable hydrogen surpasses wind energy and compares favorably with solar energy.**

ENERGY INDUSTRY	EMPLOYMENT FACTOR
Solar	1,000 jobs/TWh
Renewable Hydrogen	575-775 jobs/TWh
Wind	200-300 jobs/TWh

Is Renewable Hydrogen Competitive?

Renewable hydrogen is more expensive than hydrogen made from natural gas using steam methane reforming (SMR) in most situations. However, if electricity costs are low enough renewable hydrogen can be cheaper. Iowa has some of the lowest cost wind energy in the nation:

- Wholesale wind market value . . . $11-14 / MWh (MISO & SPP average)
- Power purchasing agreement (PPA) wind prices . . . $20 or below / MWh (average)

Ideal Energy's modeling shows that a renewable hydrogen production plant may be able to produce cost-competitive hydrogen in Iowa today.

- Renewable hydrogen price parity target . . . $2 / kg or less
- Modeled renewable hydrogen cost with $15 / MWh electricity . . . $1.69-1.99 / kg

In addition, Iowa has among the highest curtailment rates in the nation. Curtailed power is power that could have been generated, but was not due to insufficient demand, grid congestion, or other factors. Curtailed power can be used for renewable hydrogen production, which would drive prices even lower.

- Wind curtailment rate in Iowa . . . 5% (MISO average)
- Wind curtailment rates elsewhere . . . 0.1-4.6% (range of other ISOs)

Hydrogen Credits Will Make Renewable Hydrogen Even More Competitive

The Inflation Reduction Act creates a clean hydrogen production credit worth **up to $0.60/kilogram – or $3.00/kilogram** if labor requirements are met.

This technology-neutral 10-year credit will make renewable hydrogen significantly more cost-competitive with traditional "gray" hydrogen made from natural gas.

The credit amount is based upon the carbon intensity of the production process. The carbon intensity of wind-powered or solar-powered PEM is near zero, meaning renewable hydrogen will be eligible for the full credit amount.

This development promises to revolutionize the renewable hydrogen industry.

The H2Hub Program is a Once-in-a-Generation Opportunity for Iowa

The Infrastructure Investment and Jobs Act contains several provisions providing funding for renewable hydrogen projects. Some of the key provisions of the Infrastructure Act are as follows:

- Authorizes $9.5 billion in spending for clean hydrogen, including
    - $8 billion for development of large-scale Regional Clean Hydrogen Hubs,
    - $1 billion for Clean Hydrogen Electrolysis Research and Development,
    - $500 million for Clean Hydrogen Manufacturing and Recycling.
- Directs federal government to develop national hydrogen roadmap and strategy.
- Defines "clean hydrogen."

The Regional Clean Hydrogen Hub program, also known as H2Hub, calls for the creation of at least four hydrogen hubs. The Department of Energy defines a hydrogen hub as "a network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity." Hydrogen hubs are expected to have geographic diversity, feedstock diversity, and end-use diversity. At least one of the hydrogen hubs must focus on renewable hydrogen. ***Iowa is perfectly positioned to be the renewable hydrogen hub.***

Geopolitics of Renewable Hydrogen

The war in Ukraine has brought energy independence to the forefront of national security discussions – especially in Europe. To combat its dependence on Russian oil and gas imports Europe is pursuing a range of initiatives, including an aggressive program to import 10 million tons renewable hydrogen and produce an additional 5 million tons of renewable hydrogen domestically by 2030. This could accelerate adoption of renewable hydrogen in Europe by 10 years.

Rising Natural Gas Prices

Since mid-2020, natural gas commodity prices have increased approximately 5x, with nearly a 100% increase in just the last five months since the Ukraine invasion began. As natural gas prices rise, the cost of producing hydrogen from natural gas also increases. This makes renewable hydrogen more cost-competitive.

Recommendations

Iowa needs a comprehensive approach to building a renewable hydrogen industry. Ideal Energy has identified five key recommendations to do so:

1. **Investigate the opportunity to apply to the federal H2Hub program.** The Department of Energy's H2Hub program represents a unique opportunity to leverage federal funding to kickstart the renewable hydrogen industry within Iowa. Iowa has the resources necessary to support a strong application. To that end, the state could coordinate efforts by the state government, economic development organizations, private industry, and other stakeholders.

2. **Identify key resources, stakeholders, and potential partners within the state.** The state could identify key resources and existing infrastructure in three categories: production, transportation & storage, and demand. In addition, the state could identify potential project developers and partners, as well as other stakeholders.

3. **Address regulatory barriers.** A key challenge to the development of a renewable hydrogen industry in Iowa is the lack of a utility tariff specific to hydrogen production. Under current tariffs, wind energy – even if it is currently curtailed – has to be sold at rates that may be too expensive to be financially viable in a renewable hydrogen plant. Iowa leaders and energy industry stakeholders could explore the formation of state policy that proposes a flexible ratemaking mechanism that could provide a pathway for the adoption of low-carbon energy generation resources including renewable hydrogen.

4. **Leverage existing infrastructure to build momentum.** These key opportunities will help build momentum for renewable hydrogen's growth in Iowa.

    a. **Develop partnerships between wind farm owners and agrichemical companies.** Iowa has the second largest portfolio of wind energy assets in the nation. In addition, Iowa is home to several large-scale nitrogen fertilizer plants that require large feedstocks of ammonia. These two industries are a natural fit for renewable hydrogen project development.

  b. Use existing natural gas infrastructure to grow hydrogen demand and utilize future carbon markets. This will generate enough demand to absorb a considerable amount of renewable hydrogen production.

  c. Leverage storage and transportation infrastructure, including existing pipelines, to transport hydrogen and hydrogen products out of state. National Renewable Energy Laboratory data indicates that even with its significant existing demand for ammonia and fertilizer, Iowa has the potential to be a net-exporter of renewable hydrogen products.

5. **Deploy state-level incentives to scale up the hydrogen industry.** Iowa successfully used wind energy production tax credits, renewable energy tax credits, and solar energy system tax credits to grow the wind and solar industries in their critical early years. The Iowa government could once again implement state-level incentives, this time to stimulate hydrogen production. Possibilities include investment tax credits, production tax credits, and direct grants. Iowa can follow the Department of Energy's lead with regard to selection criteria and funding mechanism.

Introduction – Key Elements for a Hydrogen Economy in Iowa

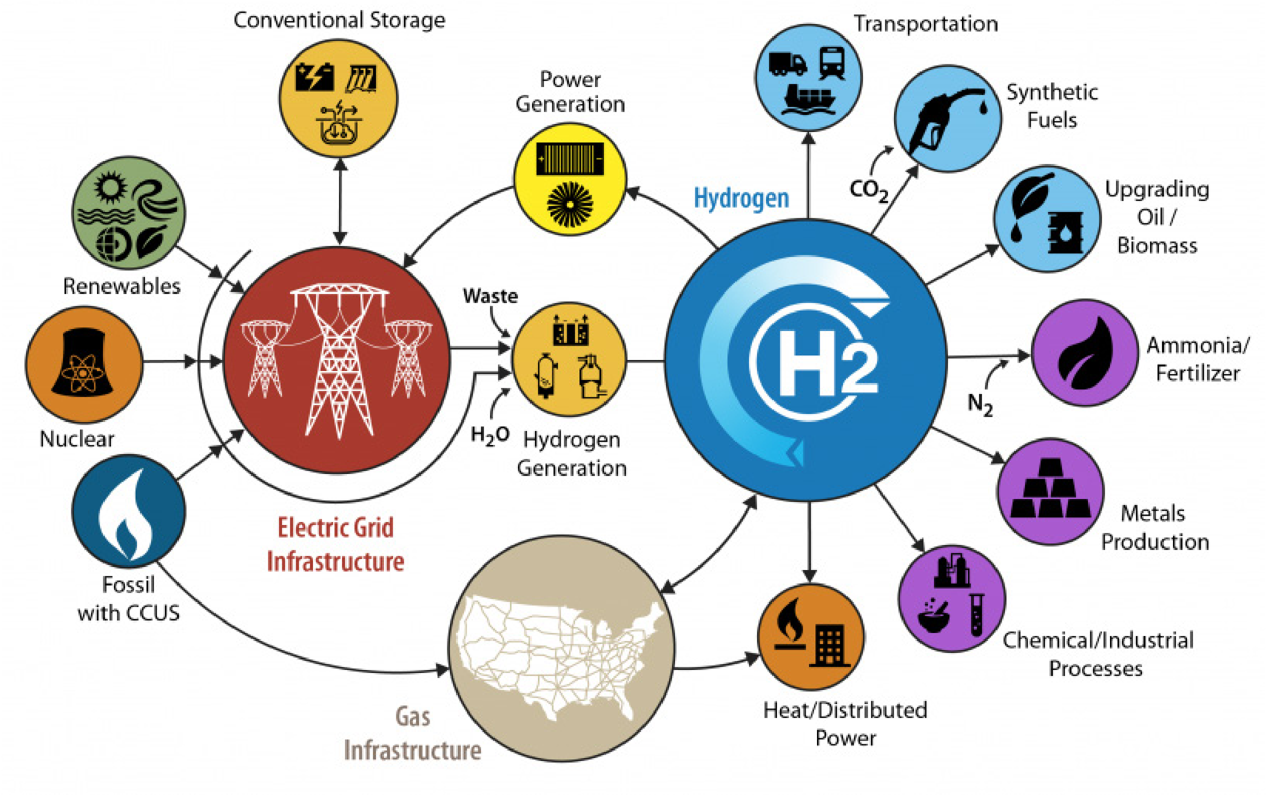


Figure 1. H2@Scale hydrogen economy flowchart.[1]

Introduction

H2@Scale, a U.S. Department of Energy initiative, offers a view of what a renewable hydrogen-based energy economy might look like. Iowa possesses all of the key elements needed for a successful renewable hydrogen economy: abundant and inexpensive wind and solar resources and existing markets for hydrogen and its derivative products, including ammonia.

Renewable hydrogen is already a proven technology. Research-scale projects at the Department of Energy's National Renewable Energy Laboratory (NREL) and commercial projects in Europe have demonstrated that renewable hydrogen can be produced profitably where renewable energy is low in cost and off-takers are available.

Research by Dr. Greg Wilson, a renewable hydrogen expert and consultant on this project, shows that a commercial project in Iowa may be profitable right now. If so, a successful project here could spark a hydrogen rush throughout the Midwest.

The growth potential for the renewable hydrogen industry is hard to overstate. "The world has an existing market for very large volumes of H_2 and ammonia and these markets will have to be supplied with new zero-carbon processes," said Wilson. "Beyond this, the H_2 market will grow substantially because H_2 will increasingly be used as fuel for heavy, long-distance transport, both truck and rail."[2]

In this report, Ideal Energy describes renewable hydrogen production technology, makes projections of the economic and employment impact of renewable hydrogen investment, performs a techno-economic analysis to estimate hydrogen production costs, provides maps and data to demonstrate the opportunity available within the state, assesses obstacles to renewable hydrogen deployment, and describes a path forward for Iowa.

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[1] "H2@Scale," U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office, accessed September 15, 2021, https://www.energy.gov/eere/fuelcells/h2scale.

[2] Greg Wilson, (Renewable Energy Expert, G.M. Wilson Consulting), interviewed by Eric Johnson via Zoom, May 12, 2020.

Part I – Economic and Employment Projections

Economic Impact

The Fuel Cell and Hydrogen Energy Association's (FCHEA) *Road Map to a US Hydrogen Economy* report estimates that the American hydrogen market could reach $140 billion in revenues by 2030 – an 8-fold increase over the $17.6 billion H_2 market of today. By 2050 annual revenues in the H_2 market could top $750 billion per year.[3] The majority of these revenues are expected to come from two steps in the value chain: hydrogen production, distribution, infrastructure, and retail; and manufacturing of specialized materials and components.[4] Approximately $330 billion of the predicted 2050 revenues are expected to come from exports.[5]

These figures assume a "broad rollout" of hydrogen with demand hitting 17 million metric tons (MMT) by 2030 and 65 MMT by 2050. In addition, the broad rollout scenario envisions 1.2 million in fuel cell vehicle sales, 4,300 hydrogen fueling stations, and $8 billion in annual investment by 2030.[6]

Iowa's share of this market depends on the degree of proactive uptake of renewable hydrogen by key stakeholders in the state. However, if **Iowa's share of hydrogen revenues simply tracks GDP, Iowa could see $1.19 billion in new economic activity by 2030 and $6.375 billion by 2050.**[7]

Employment Impact

The renewable hydrogen industry is so nascent in the United States that the most recent U.S. Energy and Employment Report (USEER 2021) report does not even list hydrogen as a standalone energy sector, either within the electric power generation category or the fuels category.[8] In fact, USEER 2021 only mentions employment figures related to renewable hydrogen in the context of fuel cell vehicles. However, it is possible to infer from other sources what kind of jobs impact renewable hydrogen might have in Iowa.

Employment Projections from U.S. National Data

Road Map to US Hydrogen Economy projects 700,000 hydrogen-related jobs by 2030 and 3.4 million by 2050.[9] These figures are based on employment factors ranging from 6.7 to 14.5 jobs per million USD in revenues, depending on industry sector. Hydrogen production jobs are estimated to fall at the lower end, at 6.7 jobs per $million, while manufacturing, machinery, and transportation jobs fall on the higher end of the spectrum.[10]

The U.S. labor force is 162.05 million[11] and the Iowa labor force is 1.68 million,[12] or approximately 1.03% of the national total. If these hydrogen jobs are distributed evenly across the U.S. labor force, **Iowa could see 7,210 new jobs by 2030 and 35,020 new jobs by 2050.**

Employment Projections from European Data

The Gas for Climate consortium commissioned a study to assess the job creation potential of hydrogen in the European Union. **They predicted an employment factor of 575-775 jobs per terawatt-hour (TWh) of renewable hydrogen.** Around one third of these jobs are expected to be high-skilled direct jobs[13] while the remaining two thirds are indirect jobs. One TWh of H_2 is roughly equivalent

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[3] FCHEA, "Road Map to a US Hydrogen Economy: Reducing emissions and driving growth across the nation," Fuel Cell and Hydrogen Energy Association (FCHEA), (date unknown), accessed November 15, 2021, https://www.fchea.org/us-hydrogen-study, 8.

[4] Road Map to a US Hydrogen Economy, 22.

[5] Road Map to a US Hydrogen Economy, 77.

[6] Road Map to a US Hydrogen Economy, 17-18.

[7] Iowa's gross state product (GSP) is approximately 0.85% of the U.S. GDP.

[8] Department of Energy, "United States Energy & Employment Report 2021," U.S. Department of Energy (2021), 9, 40.

[9] "Road Map to a US Hydrogen Economy," 8.

[10] "Road Map to a US Hydrogen Economy," 86.

[11] "United States Labor Force | Moody's Analytics," accessed December 8, 2021, https://www.economy.com/united-states/labor-force.

[12] "Iowa Labor Force | Moody's Analytics," accessed December 8, 2021, https://www.economy.com/iowa-united-states/labor-force.

[13] Gas for Climate, "Gas for Climate: Job creation by scaling up renewable gas in Europe," Gas for Climate & Navigant Netherlands B.V. (November 18, 2019), 10.

to 30,000 metric tons of H_2, or a daily production rate of 82,191 kg.[14]

Using this employment factor, it is possible to project the average job potential, including both direct and indirect jobs, for various plant sizes. **A small, distributed hydrogen plant producing 1,500 kg per day would contribute 10-14 jobs. A large, centralized plant producing 50,000 kg per day would contribute 350-471 jobs.**

Dutch researchers at New Energy Coalition and JIN Climate and Sustainability assessed the economic impact of renewable hydrogen in the Netherlands under three different scenarios on behalf of N.V. Nederlandse Gasunie, a Dutch natural gas network operator. They concluded that the difference between "Scenario 1" (a modest uptake of hydrogen in the Netherlands) and "Scenario 3" (in which the Netherlands becomes a renewable hydrogen hub) accounted for a net additional 98,300 jobs by 2050.[15]

Iowa's population is approximately 18.1% of the Netherland's and Iowa's GSP is around 19.4% of the Netherland's GDP. Extrapolating from the Gasunie research paper, **Iowa could potentially expect 17,792 to 19,070 net new jobs by 2050 if it becomes a hydrogen hub.**

Another Dutch report supports these figures. A paper by research consultancy CE Delft produced for Shell in 2021 concluded that renewable hydrogen could bring the Netherlands between 6,000 and 17,300 full time equivalent (FTE) jobs in 2030 and between 16,400 and 92,400 FTEs in 2050.[16]

Furthermore, according to Commissioner Kadri Simson of the European Commission, "experts have estimated that every billion [euros] of investment that we are able to attract in renewable hydrogen, will create 10,000 jobs along the supply chain."[17]

The *Hydrogen Roadmap Europe* report uses jobs estimates derived from jobs per million euros invested. Projections range from 10 to 15 jobs per million euros invested, depending on industrial sector. Based on these figures, Europe is projected to see 500,000 additional jobs associated with hydrogen production, distribution, and infrastructure by 2030, as well 350,000 jobs associated with end-use industries, including fuel cells.[18]

Under the "Ambitious Scenario," the report projects 820 billion euros in hydrogen-related annual revenue and 5.4 million new jobs for the European Union by 2050.[19] This is equivalent to three times the entire EU chemical industry today.

Employment Projections from NREL Demand Data

Using the the NREL's hydrogen demand projections and the Gas for Climate employment factor, Ideal Energy can project that producing enough hydrogen to meet the anticipated aggregate demand of a single 'high-demand'[20] county in Iowa with renewable hydrogen could generate 560-755 jobs, or more. Around one third of Iowa counties are classified by the NREL as high demand.[21]

NREL projects 106 million metric tons (MMT) of aggregate hydrogen demand per year in the United States with

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[14] The following calculation uses a conversion ratio of 120 megajoules (MJ) per 1 kg of hydrogen. Also note that 1 kWh is equal to 3.6 MJ.
Let h = kg H_2
h = TWh(1,000,000,000)(3.6)/120
h = 30,000,000

[15] Catrinus J. Jepma, Eise Spijker, and Erwin Hofman, "The Dutch Hydrogen Economy in 2050: An exploratory study on the socio-economic impacts of introducing hydrogen into the Netherlands energy system," N.V. Nederlandse Gasunie (Groningen, March 13, 2019), 8, 18.

[16] Cor Leguijt, Emiel van den Toorn, Amanda Bachaus, and Chris Jongsma, "Werk door investeringen in groene waterstof: Update en uitbreiding," CE Delft on behalf of Shell Nederland B.V. (April 2021), 4.

[17] "Keynote Speech by Commissioner Simson at the IRENA Assembly Ministerial Meeting on 'Renewables and Pathways to Carbon Neutrality,'" Text, European Commission, January 20, 2021, https://ec.europa.eu/commission/commissioners/2019-2024/simson/announcements/keynote-speech-commissioner-simson-irena-assembly-ministerial-meeting-renewables-and-pathways-carbon_en.

[18] FCH, "Hydrogen Roadmap Europe," Fuel Cells and Hydrogen 2 Joint Undertaking (January 2019), 58.

[19] Hydrogen Roadmap Europe, 10.

[20] "High demand" is defined by the NREL as 20,000+ kg/km2/year.

[21] Mark Ruth, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A.J. Simpson, Amgad Elgowainy *et al.*, *The Technical and Economic Potential of the H2@Scale Concept within the United States*, National Renewable Energy Laboratory (October 2020), 52.

a hydrogen economy, which is equivalent to approximately 3,533 TWh.[22] Using the Gas for Climate employment factor, 3,533 TWh of hydrogen could yield 2-2.7 million new jobs nationwide. Iowa's GSP is 0.85% of the U.S. GDP, indicating **Iowa could expect 16,943 to 22,873 jobs.**

Employment Projections from Midwest Data

As of 2015, there were 2,822 jobs in the hydrogen vehicle sector nationwide, according to the U.S. Energy and Employment Report (USEER),[23] although fewer than 40 of those are in manufacturing.[24] According to the *State of the States: Fuel Cells in America 2017* (January 2018) report, Iowa did not have any deployment of fuel cell technology other than in the *Small Stationary Fuel Cells* category (page 26). These are deployed by Iowa Telecom at an undisclosed location. Iowa does not yet have hydrogen stations, fuel cell buses, or any other commercial or government fuel cell applications. Iowa does have university R&D hydrogen projects, however.

Fuel cell jobs are expected to grow substantially, including in Iowa and the Midwest. The Renewable Hydrogen Fuel Cell Collaborative (RHFCC) –a public-academic partnership based in Ohio that advocates for hydrogen fuel cell vehicles in the Midwest – developed a roadmap projecting up to 65,000 new jobs in the hydrogen sector in the Midwest during the next 15 years related specifically to fuel cell vehicles.[25]

Although the RHFCC does not break down its projections by state, it is possible to make inferences from Iowa's population and economy compared to the Midwest as a whole. The Midwest is composed of 12 states (using the Census Bureau definition). It has a population of around 69 million people and an aggregate gross state product (GSP) of nearly $4.08 trillion. Iowa has a population of 3,190,369 and a GSP of a little over $194 billion.[26]

Iowa's population is approximately 4.62% of the Midwest's population and its GSP is around 4.76% of the Midwest's aggregate GSP. If the RHFCC's projected 65,000 hydrogen fuel cell jobs are distributed along a simple per capita or GSP basis, **Iowa could expect between 3,003 to 3,094 new jobs in the fuel cell sector alone.** Fuel cell sector jobs include jobs in research and development, manufacturing of fuel cells, manufacturing of fuel cell electric vehicles (FCEVs), FCEV maintenance, and hydrogen fueling station construction and operation jobs.

Uncertainty in Jobs Projections

Employment projections are heavily dependent upon the models underpinning them. For example, the employment multiplier used to estimate indirect jobs ranges from 1.5 to 5 in recent European models. This is a point of contention among experts.

In addition, according to Prof. Catrinus Jepma at the University of Groningen, Netherlands, **most renewable hydrogen jobs are related to end-use application, rather than hydrogen production, transport, or storage.** End-use applications in transportation and building heating produce the highest employment multipliers. Transportation jobs include not only the fuel cell jobs mentioned in the paragraphs above, but also jobs related to carbon-free biofuels production. Applications in heavy industry, the chemical industry, and the electrical generation industry have lower multipliers and yield fewer jobs overall.[27]

If Iowa succeeds in becoming a major hydrogen hub, it can capture a significant share of hydrogen production jobs, which tend to be among the higher-skilled, higher-paid hydrogen jobs available.

Hydrogen Jobs Compared to Other Renewables

Solar in Iowa. The solar industry in Iowa employed 870 people as of 2019. In 2019 solar job growth in Iowa was 16.5%, which was higher than in any other Midwest state. Nationally, solar installers are the third fastest growing profession. Nearly 100 businesses in Iowa are involved in the solar supply chain, as installers, manufacturers, and more.

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[22] Ruth *et al.*, 48.

[23] "United States Energy & Employment Report 2016," U.S. Department of Energy (March 24, 2016), 62.

[24] "United States Energy & Employment Report 2021," U.S. Department of Energy (2021), 138.

[25] "About Us | Renewable Hydrogen Fuel Cell Collaborative," accessed December 7, 2021, https://www.midwesthydrogen.org/about/.

[26] U.S. Bureau of Economic Analysis, "Gross Domestic Product: All Industry Totals," *various states (raw data)*, retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/categories/27281, November 29, 2021.

[27] "Hydrogen Tests Climate Policymakers with Its Job Potential," Energy Monitor, May 6, 2021, https://www.energymonitor.ai/tech/hydrogen/hydrogen-tests-climate-policymakers-with-its-job-potential.

Over $291 million has been invested in solar energy in Iowa and associated with the Iowa solar tax credit – the total amount invested is even higher.[28]

Wind in Iowa. The wind industry in Iowa directly employs 3,909 people as of 2019 and indirectly employs another 3,000 to 4,000 people. Roles include manufacturing, operations and maintenance, and engineering professionals. Wind turbine service technicians are projected to be the fastest growing occupation nationwide during the next decade. There are 53 Iowa companies involved in the wind industry. At least $19 billion has been invested in wind in Iowa to date with continued year-over-year growth expected.[29]

Ethanol in Iowa. Ethanol accounts for over $4.5 billion, or around 3%, of Iowa's GSP. The ethanol industry contributes, directly or indirectly, to 44,421 jobs in the state. Biodiesel contributes another $489 million and 3,875 jobs.[30]

The Gas for Climate paper cited above reports a global average employment factor of up to 1,000 jobs/TWh for solar projects based on data gathered in a 2015 Greenpeace study. The job employment factor of onshore and offshore wind energy projects ranges from 200 to 300 jobs/TWh.[31,32]

At 575-775 jobs/TWh, renewable hydrogen surpasses wind by a healthy margin and compares favorably with solar. Furthermore, renewable hydrogen production will drive additional investments in both solar and wind power.

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[28] "Iowa Solar Energy Fact Sheet," Iowa Environmental Council (January, 2021), accessed November 29, 2021, https://www.iaenvironment.org/news-resources/fact-sheets/energy-fact-sheets.

[29] "Iowa Wind Energy Fact Sheet," Iowa Environmental Council (March, 2021), accessed November 29, 2021, https://www.iaenvironment.org/news-resources/fact-sheets/energy-fact-sheets.

[30] John Urbanchuk, "Contribution of the Renewable Fuels Industry to the Economy of Iowa," Iowa Renewable Fuels Association (March 11, 2020), 7, accessed November 29, 2021, https://iowarfa.org/ethanol-center/ethanol-facts/ethanol-and-the-economy/.

[31] Gas for Climate, 12.

[32] J. Rutovitz, E. Dominish, and J. Downes, "Calculating global energy sector jobs: 2015 Methodology Update," Prepared for Greenpeace International by the Institute for Sustainable Futures (2015).

Part II – Renewable Hydrogen Technology

How Hydrogen is Made from Fossil Fuels

Right now, hydrogen is sourced almost exclusively from fossil fuels. Approximately 76% comes from methane and the remaining 24% from coal. Around 70 billion kilograms of hydrogen are produced worldwide every year from fossil fuel sources.

Steam methane reforming (SMR) using natural gas as a feedstock is the process responsible for most of the world's hydrogen supply and around 95% of the hydrogen in the U.S. Methane reacts with steam at high temperatures and under pressure to produce hydrogen and carbon monoxide.[33]

Extracting hydrogen from coal is also possible using a process called coal gasification. Coal is heated and blown through oxygen and steam. The resulting gas, call synthesis gas or syngas, is a combination of hydrogen and carbon monoxide. This process can be continued by adding more water, causing the water gas shift, which will yield additional pure hydrogen and carbon dioxide.

How Renewable Hydrogen is Made

Hydrogen can also be made using a process called electrolysis, which is the application of an electric current to force a chemical reaction to occur. Water decomposes into hydrogen and oxygen when subjected to electrolysis. To make renewable hydrogen, three things are needed: a renewable energy source, water, and an electrolyzer. (In a fuel cell, this reaction runs in reverse. Hydrogen combines with oxygen and releases water and electricity.)

There are three types of electrolysis technologies in use today: alkaline, proton exchange membrane, and solid oxide.

Alkaline Electrolyzer

In alkaline water electrolysis, two electrodes are submerged in water with alkaline electrolytes added. Alkaline electrolysis is the most mature electrolysis technology with the lowest long-term CAPEX. It is used for high-volume, steady-state production. However, it does not tolerate intermittent production very well, which makes it a less desirable choice to pair with renewable energy sources.[34]

HYDROGEN CHEMISTRY

HYDRO CARBON CHEMISTRY

STEAM METHANE REFORMING

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

COAL GASIFICATION

$$3C + O_2 + H_2O \rightarrow H_2 + 3CO$$

WATER GAS SHIFT

$$CO + H_2O \rightarrow CO_2 + H_2$$

RENEWABLE HYDROGEN CHEMISTRY

ELECTROLYSIS

$$2H_2O \rightarrow 2H_2 + O_2$$

FUEL CELLS

$$2H_2 + O_2 \rightarrow 2H_2O$$

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[33] "Hydrogen Production: Natural Gas Reforming," U.S. Department of Energy, accessed December 27, 2021, https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.

[34] Greg Wilson, "Renewable H_2 in Iowa: Technology Overview, Development & Partnering Opportunities," presentation, Fairfield, Iowa, June 16, 2020.

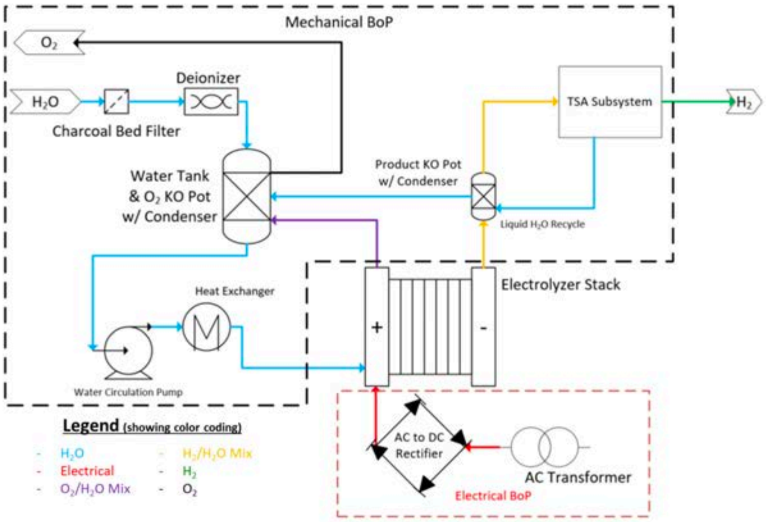

Figure 2. PEM electrolyzer system.[35]

Proton Exchange Membrane (PEM) Electrolyzer

Proton exchange membrane (PEM) electrolyzers use a solid polymer electrolyte rather than a liquid alkaline water solution. PEM electrolyzers are commercially viable, but less mature than alkaline water electrolyzers. The key advantage of PEM is that it is suited to intermittent production, making it a good choice for use with intermittent renewables like wind and solar.[36]

PEM electrolyzers are the focus of this paper. Most renewable hydrogen projects in development today use PEM electrolyzers. The state of PEM technology is similar to the state of battery energy storage technology circa 8 to 10 years ago; the technology is established, but demand needs to increase to drive prices down.[37]

The above schematic shows a generalized PEM electrolyzer system. It also identifies which parts of the system are considered the stack, the mechanical balance of plant, and the electrical balance of plant.

In the electrical generation industry, *stack* refers to the equipment directly involved in producing power. In the context of a renewable hydrogen plant, the stack is the PEM electrolyzer unit. It is often called the *electrolyzer stack*.

A PEM electrolyzer stack consists of three main components: a membrane-electrode assembly (MEA), a current collector, and bipolar plates. The MEA is made of a membrane, usually composed of a composite copolymer, that is coated with a catalyst on each side that separates the cathode from the anode. The current collector allows electrical current and product gases to flow out of the stack. The bipolar plates serve as electrodes and also circulate the water and gases.[38]

The term *Balance of Plant* (BoP) is used to describe parts of a power plant other than the generator. In this case, BoP refers to equipment not directly involved in producing hydrogen. *Mechanical BoP* includes water supply, plumbing, piping, heat exchangers, condensers, and so on. *Electrical BoP* includes any electrical equipment necessary to power the stack, which may depend upon the power source. In the schematic above, the PEM electrolyzer system is powered by grid-connected AC power.

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[35] David Peterson, James Vickers, Dan DeSantis, "Hydrogen Production Cost From PEM Electrolysis - 2019," Department of Energy (February 3, 2020), 3.

[36] Wilson, "Renewable H_2 in Iowa."

[37] Greg Wilson, presentation to Ideal Energy via Zoom, June, 16, 2020.

[38] Méziane Boudellal, *Power-to-Gas: Renewable Hydrogen Economy for the Energy Transition* (Berlin, Boston: De Gruyter, 2018), https://doi.org/10.1515/9783110559811, 81-84.

Solid Oxide Electrolyzer (SOEC)

Solid oxide electrolyzer cells (SOEC) are solid oxide fuel cells (SOFC) run in reverse in a regenerative mode. Like PEM they use a solid oxide, however the material used is different – usually zirconium dioxide, a ceramic. SOECs may offer higher efficiency and lower material cost than PEM, and because they are reversible they can be used to generate electricity from stored hydrogen without the need for a separate fuel cell or gas turbine power plant. However, they are still in the developmental stage.[39]

PEM Electrolyzer Manufacturers

As of 2021, notable manufacturers with electrolyzers in the 1 MW range or greater include Nel Hydrogen, Siemens, Cummins, Plug Power, and ITM Power.

The PEM electrolyzer manufacturing field is rapidly evolving. A wave of consolidation is currently sweeping the industry. In the past two years Cummins acquired Canadian PEM manufacturer Hydrogenics, Plug Power acquired Giner ELX, and GTT acquired AREVA H2Gen of France. Ideal Energy expects more acquisitions as larger firms move into the industry. Ideal Energy also expect additional multinational conglomerates to offer PEM electrolyzers as they expand their new energy portfolios, much as Siemens AG has done.

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[39] Wilson, “Renewable H2 in Iowa.”

Part III – Techno-economic Analysis

State of the Renewable Hydrogen Industry

As of late 2021, there are very few large, commercial-scale renewable hydrogen projects in the United States that are currently operational. Nearly all U.S. renewable hydrogen plants are research projects, small pilot/demonstration projects, or public-private partnerships that may not need to generate profits.

Several large-scale, multi-megawatt renewable hydrogen projects are in the planning or construction stages in the U.S. These include a 345 MW project in Texas that will produce 30 metric tons of green hydrogen per day,[40] a 5 MW hydroelectric-powered electrolyzer on the Columbia River in Wenatchee, Washington that is expected to supply the first public hydrogen fueling station in America,[41] and the Intermountain Power Project, a Utah coal-fired power plant in the process of converting to 30% renewable hydrogen and 70% natural gas.[42]

There are also a number of commercial projects operating in Europe, Asia, and Australia. In fact, 85% of large-scale renewable hydrogen are located in those three regions.[43]

The paucity of completed commercial-scale domestic projects leaves U.S. businesses considering renewable hydrogen with few projects to draw lessons from. A techno-economic analysis can help assess the viability of a renewable hydrogen project. Techno-economic models can be used to see what full-scale commercial production might look like financially.

Target Price

A key threshold in the techno-economic analysis is a production cost at or below $2/kilogram (kg) of hydrogen. This price threshold is important for several reasons. First, it is the price point at which renewable hydrogen becomes cost competitive with fossil fuel sources of hydrogen. Second, it is a stepping stone on the way to the Department of Energy's price target of $1/kg.

Most hydrogen is produced from natural gas using steam methane reforming (SMR). According to the Department of Energy, the average cost to produce hydrogen using SMR without carbon dioxide capture and storage (CCS) is $2.08/kg. SMR with CCS costs $2.27/kg.[44]

In addition, one kilogram of hydrogen has approximately the same energy content as one gallon of gasoline.[45] At retail price parity with gasoline or diesel, hydrogen could compete in the transportation market once vehicles and fueling infrastructure are more widely available.

With a production cost of around $2/kg, hydrogen would likely reach retail price parity with diesel. According to a Shell New Energies research paper, a $2/kg delivered cost would yield a $5.22/kg retail cost. Due to hydrogen fuel cell efficiencies, this represents price parity with heavy duty diesel at $3.20/gallon and with gasoline at $3.50/gallon.[46]

The $2/kg price point is also a stepping stone to the Department of Energy's recently announced target price of $1/kg by 2030.[47]

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[40] "Apex and Plug Power Partner on Largest Green Hydrogen PPA in the United States," Apex Clean Energy, July 14, 2021, accessed December 14, 2021, https://www.apexcleanenergy.com/news/apex-clean-energy-and-plug-power-partner-on-largest-green-hydrogen-power-purchase-agreement-in-the-united-states/.

[41] Mary Page Bailey, "Cummins to Install Largest Electrolyzer in the U.S. for Green H_2 Production in Washington State," *Chemical Engineering*, August 27, 2020, https://www.chemengonline.com/cummins-to-install-largest-electrolyzer-in-the-u-s/.

[42] Jeff St. John, "How Siemens Energy Is Targeting the US Green Hydrogen Opportunity," Green Tech Media, March 1, 2021, accessed December 14, 2021, https://www.greentechmedia.com/articles/read/how-siemens-energy-is-targeting-the-u.s-green-hydrogen-opportunity.

[43] "Hydrogen Deployment Accelerating with More Than $300 Billion in Project Pipeline; Including $80 Billion in Mature Projects - Hydrogen Council," *Https://Hydrogencouncil.Com/En/*, accessed November 29, 2021, https://hydrogencouncil.com/en/hydrogen-deployment-accelerating-with-more-than-300-billion-in-project-pipeline/.

[44] Office of Fossil Energy, "Hydrogen Strategy: Enabling a Low-Carbon Economy," Department of Energy, July 2020, retrieved https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf, 6.

[45] "Hydrogen Data," National Renewable Energy Laboratory, accessed November 22, 2021, https://www.nrel.gov/docs/gen/fy08/43061.pdf

[46] Jason Munster and Matthew Blieske, "Shell Hydrogen Refueling Station Cost Reduction Roadmap," Shell New Energies, December 12, 2018, retrieved https://www.hydrogen.energy.gov/pdfs/htac_dec18_06_munster.pdf, 3.

[47] "Hydrogen Shot," Department of Energy, accessed November 22, 2021, https://www.energy.gov/eere/fuelcells/hydrogen-shot

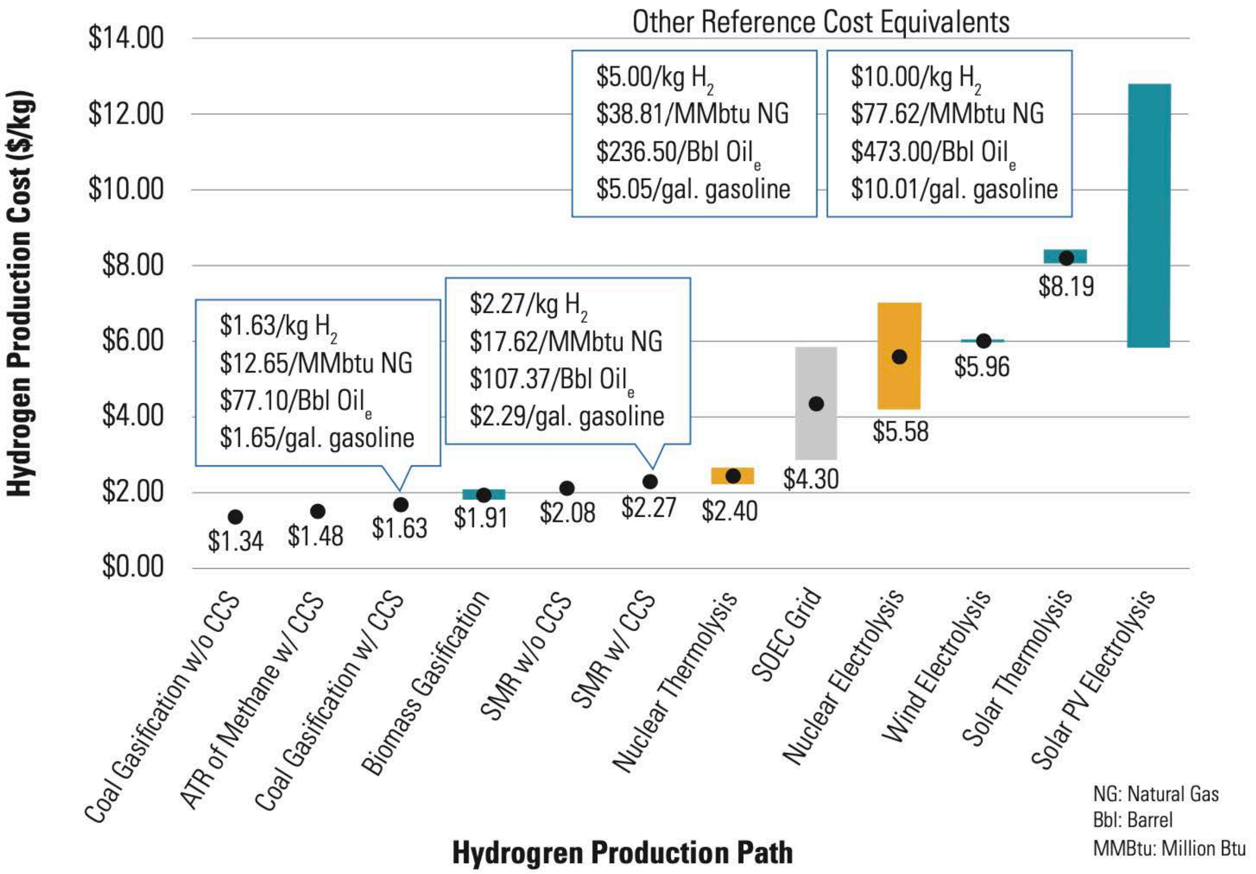

Figure 3. Current hydrogen production costs and cost averages by production method.[48]

"Getting green H_2 to $1/kg by the end of the decade will change the game entirely as new H_2 capacity will switch from blue to green when this cost target is hit," said Dr. Wilson.[49] Blue hydrogen is hydrogen made using SMR with CCS. Green hydrogen is fully carbon-free, renewable hydrogen.[50]

At present, most renewable hydrogen typically costs significantly more than $2/kg to produce. "In order to meet the goal of producing H_2 for less than $2.00/kg H_2 and to be competitive with H_2 production from steam methane reforming, further cost reductions are needed," Department of Energy researchers stated.

Ideal Energy will demonstrate that inexpensive electricity from Iowa's abundant wind resource may be able to provide just such cost reductions necessary to drive the price of renewable hydrogen to $2/kg or below.

About the Model

The Department of Energy developed two models to make financial projections for renewable hydrogen projects. These are known as H2FAST and the H2A 3.2018 Production Model. Renewable hydrogen expert Dr. Greg Wilson produced a simplified model – the Ideal Energy-Greg Wilson Simplified Model – derived from these DOE models for this project.

Existing Models: H2A 3.2018 and H2FAST

The H2A Production Model (H2A) is a comprehensive tool that can provide cost analyses of hydrogen production from a wide range of feedstocks and technologies, including biomass sources, natural gas, coal, emerging technologies,

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[48] *ibid.*

[49] Greg Wilson, email message to Eric Johnson, November 3, 2021.

[50] David Peterson, James Vickers, Dan DeSantis, "Hydrogen Production Cost From PEM Electrolysis - 2019," Department of Energy, February 3, 2020, 13.

and electrolyzers powered by renewable energy. H2A can model either large, central electrolysis-based production plants or small, distributed plants. It can model PEM electrolyzers or SOEC electrolyzers.

H2FAST "provides a quick and convenient in-depth financial analysis for hydrogen fueling stations."[51] It is more limited in scope. Everything in H2FAST is also in H2A with regard to electrolyzer details.

Ideal Energy-Greg Wilson Simplified Model

The Ideal Energy-Greg Wilson Simplified Model (IE-GW Simplified Model) is based on the H2A 3.2018 model. Compared to the more comprehensive H2A model, the IE-GW model is greatly simplified, and offers an approximation intended to produce levelized cost analyses.

This project – studying the viability of a commercial renewable hydrogen pilot project in Iowa – is highly focused in scope. Therefore, the model does not need to consider future scenarios, large plants, or sources of hydrogen other than PEM electrolyzers powered by renewable energy.

The IE-GW Simplified Model is focused on small, distributed PEM electrolyzer plants. It uses input criteria from the **H2A Projected Current Case – Distributed** scenario, but unlike H2A, it does not consider large, centralized plants or other hydrogen sources. Unlike H2FAST, the IE-GW Simplified Model does not consider hydrogen refueling stations.

This model is focused on producing levelized cost analyses. In a levelized cost model, all costs related to plant operations, depreciation of capital, and debt service over the life of the project are estimated and rolled into a net present value (NPV) number. The NPV of all hydrogen production over the life of the plant is then estimated. The levelized cost of hydrogen (LCOH) is equal to the NPV of all costs over the life of the plant divided by the NPV of all hydrogen production over the life of the plant.

H2A uses the same financial approach, but considers many more cost inputs with more variables related to cost. This level of detail may be important for a project developer analyzing small LCOH differences associated with design and operational decisions. Examples might involve decisions related to what kind of water treatment system will be used, or the terms of the maintenance agreement entered into with the electrolyzer manufacturer.

These details are beyond the scope of this project. This techno-economic analysis is focused on how the levelized cost of hydrogen changes with adjustments to overall CAPEX, cost of electricity, and how often electricity at various prices is available.

Comparisons of H2A versus the IE-GW Simplified Model show that over a fairly wide range of CAPEX, electricity cost, and capacity factor inputs the simplified approach achieves similar results to H2A with less complexity.[52]

Model Input

Reference Year & Recent Updates

In 2018, H2A was updated to version 3.2018. A number of changes were made, including to the reference year, feedstock costs, and federal tax rate:[53]

- Changed reference year dollars to 2016$.
- Updated plant start dates: current technology to 2015 and future technologies to 2040.
- Updated energy feedstock costs with AEO 2017 case. Costs were extrapolated beyond AEO forecast window using GCAM.
- Updated emissions factors with GREET 2015 values.
- Updated price indexes for GDP deflator, plant cost, labor cost, and chemical price until 2016.
- Updated federal tax rate to 21%.

Model Assumptions

The IE-GW Simplified Model assumptions are drawn from hydrogen production analysis work by the Department of Energy. There are two primary sources: the H2A Standard Economic Assumptions and the version of the H2A Production Model prepopulated with details for the current distributed electrolyzer plant scenario.

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[51] "H2FAST: Hydrogen Financial Analysis Scenario Tool," accessed December 21, 2021, https://www.nrel.gov/hydrogen/h2fast.html.

[52] Greg Wilson, email message to Eric Johnson, November 5, 2021.

[53] "H2A: Hydrogen Analysis Production Models," accessed November 1, 2021, https://www.nrel.gov/hydrogen/h2a-production-models.html.

The following are the **DOE H2A Standard Economic Assumptions**. These can be found in the Assumptions section of the Hydrogen Analysis (H2A) Project site.[54]

- Reference year dollars: 2016
- Debt versus equity financing: 40% equity
- After tax internal rate of return: 8% real
- Inflation rate: 1.9%
- Effective total tax rate: 25.7%
- Depreciation period and schedule: MACRS
- Central plant depreciation period: 20 yrs.
- Distributed depreciation period: 7 yrs.
- Delivery components: typically 5 years with a few exceptions
- Economic analysis period: Central plant production — 40yrs., Distributed production — 20 yrs., Delivery Components Model — 20 yrs.
- Decommissioning costs are assumed equal to salvage value

The H2A Current Distributed Hydrogen Production from PEM Electrolysis assumptions are shown at right. These can found within the H2A Current Distributed model spreadsheet.[55]

Plant Size

In addition, the IE-GW Simplified Model assesses a plant with a nominal production capacity of 5,850 kg H_2/day. Using the 85.6% long-term plant utilization rate from the H2A Current Distributed scenario assumptions, the model plant would yield approximately 5,008 kg H_2/day.

Electricity Cost

Electricity cost is the principle parameter investigated by the IE-GW Simplified Model. The key question was: Can hydrogen be produced cost-competitively using Iowa's inexpensive wind power?

ASSUMPTIONS		
Total Electrical Usage:	55.8	kWh/kg H2
Stack Electrical Usage:	50.4	kWh/kg H2
Process Water Usage:	3.5	gal/kg H2
Total CAPEX:	599.19	$/kW
Stack CAPEX:	342.11	$/kW
Mechanical BoP CAPEX:	136.08	$/kW
Electrical BoP CAPEX:	121.00	$/kW
Installation Cost:	12%	Percent of Total CAPEX
Stack Replacement Cost:	15%	Percent of Total CAPEX
Fixed O&M:	0.35	$/kg
Plant Service Life:	20	years
Stack Service Life:	7	years
Depreciation Period:	7	years
Initial Cell Voltage:	1.9	V
Stack Degradation Rate:	1.5	mV/1000 hours
Electricity Cost:	0.015	$/kWh
Process Water Cost:	0.002375	$/gal
Plant Capacity Factor:	97%	
Long-term Plant Utilization:	86%	
Discount Rate:	8.0%	

Table 1. Model assumptions. Source: IE-GW Simplified Model.[56]

To answer that question the model evaluated various electricity costs, including $0.00/kWh (to represent wind power that would otherwise be curtailed) and $0.015/kWh (a wholesale wind power price typical in the state of Iowa, according to Lawrence Berkeley National Laboratory reports).[57]

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[54] Hydrogen Program, "DOE H2A Analysis – DOE H2A Standard Economic Assumption," Department of Energy, accessed November 1, 2021, https://www.hydrogen.energy.gov/h2a_analysis.html#assumptions.

[55] "H2A Current Distributed Hydrogen Production from Polymer Electrolyte Membrane (PEM) Electrolysis (2019) version 3.2018," National Renewable Energy Laboratory, accessed October 26, 2021, https://www.nrel.gov/hydrogen/assets/docs/current-distributed-pem-electrolysis-2019-v3-2018.xlsm.

[56] The *stack* is the PEM electrolyzer. *Balance of Plant (BoP)* refers to equipment other than the PEM electrolyzer.

[57] Ryan Wiser and Mark Bolinger *et al., Wind Energy Technology Data Update: 2020 Edition.* (Lawrence Berkeley National Laboratory, August 2020), 62.

ALL COSTS & HYDROGEN OUTPUT OVER TIME

Item	Year	Output (kg)	Initial Total CAPEX	Stack Replacements	O&M Cost	Stack Electricity Cost	BoP Electricity Cost	Total Electricity Cost	Total Process Water Cost
Initial CAPEX	0	-	$7,623,192						
	1	1,827,774			$639,721	$1,565,822	$167,767	$1,733,588	$15,193
	2	1,827,774			$639,721	$1,576,726	$167,767	$1,744,492	$15,193
	3	1,827,774			$639,721	$1,598,840	$167,767	$1,766,607	$15,193
	4	1,827,774			$639,721	$1,632,715	$167,767	$1,800,481	$15,193
	5	1,827,774			$639,721	$1,679,166	$167,767	$1,846,932	$15,193
	6	1,827,774			$639,721	$1,739,309	$167,767	$1,907,076	$15,193
Stack Replacement	7	1,827,774		$1,046,426	$639,721	$1,814,606	$167,767	$1,982,373	$15,193
	8	1,827,774			$639,721	$1,565,822	$167,767	$1,733,588	$15,193
	9	1,827,774			$639,721	$1,576,726	$167,767	$1,744,492	$15,193
	10	1,827,774			$639,721	$1,598,840	$167,767	$1,766,607	$15,193
	11	1,827,774			$639,721	$1,632,715	$167,767	$1,800,481	$15,193
	12	1,827,774			$639,721	$1,679,166	$167,767	$1,846,932	$15,193
	13	1,827,774			$639,721	$1,739,309	$167,767	$1,907,076	$15,193
Stack Replacement	14	1,827,774		$1,046,426	$639,721	$1,814,606	$167,767	$1,982,373	$15,193
	15	1,827,774			$639,721	$1,565,822	$167,767	$1,733,588	$15,193
	16	1,827,774			$639,721	$1,576,726	$167,767	$1,744,492	$15,193
	17	1,827,774			$639,721	$1,598,840	$167,767	$1,766,607	$15,193
	18	1,827,774			$639,721	$1,632,715	$167,767	$1,800,481	$15,193
	19	1,827,774			$639,721	$1,679,166	$167,767	$1,846,932	$15,193
	20	1,827,774			$639,721	$1,739,309	$167,767	$1,907,076	$15,193

Table 2. Project financials. Source: IE-GW Simplified Model.

ITEM	NET PRESENT VALUE	COST NPV/OUTPUT NPV		PERCENT
Initial CAPEX NPV =	$7,058,510.99	$0.42	$/kg	21%
Stack Replacement NPV =	$1,866,054.09	$0.11	$/kg	6%
O&M NPV =	$6,280,874.10	$0.38	$/kg	19%
Electricity NPV =	$17,772,255.81	$1.07	$/kg	54%
Water NPV =	$149,170.76	$0.01	$/kg	0%
Total NPV =	$33,126,865.74	$1.99	$/kg	100%
Output NPV =	**$16,616,069**			

Table 3. Levelized cost of hydrogen (LCOH) results. Source: IE-GW Simplified Model.

Results

Project Financials

Ideal Energy's analysis indicates a small distributed plant with a nominal rating of 5,850 kg/day and access to $0.015/kWh electricity would have the financials shown in Table 3 over the lifetime of the plant.

Using these costs and hydrogen output figures the levelized cost of hydrogen in Iowa can be computed. To do so, the net present value of the lifetime costs of the plant is divided by the net present value of the lifetime hydrogen output of the plant.

Levelized Cost of Hydrogen for Distributed PEM Plant

The analysis shows that with electricity costs of $0.015/kWh a model plant could produce hydrogen at an LCOH of $1.99/kg. **This indicates that a distributed PEM electrolyzer plant may be able to produce cost-competitive renewable hydrogen in Iowa today.**

Total Installed CAPEX ($/kW)	Stack CAPEX ($/kW)	Electricity Cost $/kWh	Capacity Factor	LCOH ($/KG)		
				H2A v3.2018	H2FAST 2019	IE-GW Simplified Model
$599.00	$342.00	$0.0727	97%	$4.98	$4.47	
$599.00	$342.00	$0.0500	97%	$3.69	$3.38	
$599.00	$342.00	$0.0400	97%	$3.12	$2.90	
$599.00	$342.00	$0.0300	97%	$2.55	$2.42	
$599.00	$342.00	$0.0200	97%	$1.98	$1.94	
$599.00	$342.00	$0.0150	97%	$1.70	$1.69	$1.99
$599.00	$342.00	$0.0100	97%	$1.41	$1.45	
$599.00	$342.00	$0.0050	97%	$1.13	$1.21	
$599.00	$342.00	$0.0000	97%	$0.85	$0.97	
$599.00	$342.00	$0.0150	80%	$1.88		
$599.00	$342.00	$0.0150	60%	$2.21		
$599.00	$342.00	$0.0150	40%	$2.89		
$599.00	$342.00	$0.0150	20%	$4.92		
$599.00	$342.00	$0.0100	80%	$1.59		
$599.00	$342.00	$0.0100	60%	$1.93		
$599.00	$342.00	$0.0100	40%	$2.61		
$599.00	$342.00	$0.0100	20%	$4.64		
$599.00	$342.00	$0.0050	80%	$1.31		
$599.00	$342.00	$0.0050	60%	$1.65		
$599.00	$342.00	$0.0050	40%	$2.32		
$599.00	$342.00	$0.0050	20%	$4.35		
$599.00	$342.00	$0.0000	80%	$1.02		
$599.00	$342.00	$0.0000	60%	$1.36		
$599.00	$342.00	$0.0000	40%	$2.04		
$599.00	$342.00	$0.0000	20%	$4.07		

Table 4. Levelized cost of hydrogen (LCOH) at various electricity costs and capacity factors, with H2A 3.2018, H2Fast 2019, and IE-GW Simplified Model compared. Source: IE-GW Simplified Model.

Levelized Cost of Hydrogen and Electricity Cost

This table shows the levelized cost of hydrogen (LCOH) for various electricity costs and capacity factors. At an assumed 97% capacity factor, hydrogen falls below $2/kg with electricity costs at or below $0.02-0.015/kWh, depending on the model used.

This table also compares output from H2A 3.2018, H2FAST 2019, and the IE-GW Simplified Model. The IE-GW model produces similar output and is conservative compared to the Department of Energy's more comprehensive models.

		COST 1		COST 2				LCOH ($/kg)
Total Installed CAPEX ($/kW)	Stack CAPEX ($/kW)	Electricity Cost $/kWh	Time at Cost 1	Electricity Cost $/kWh	Time at Cost 2	Electricity Cost $/kWh	Capacity Factor	H2A v3.2018
$599.00	$342.00	$0.0150	80%	$0.00	17%	$0.0120	97%	$1.53
$599.00	$342.00	$0.0150	85%	$0.00	12%	$0.0128	97%	$1.57
$599.00	$342.00	$0.0150	90%	$0.00	7%	$0.0135	97%	$1.61

Table 5. Multiple electricity cost results. Source: IE-GW Simplified Model.

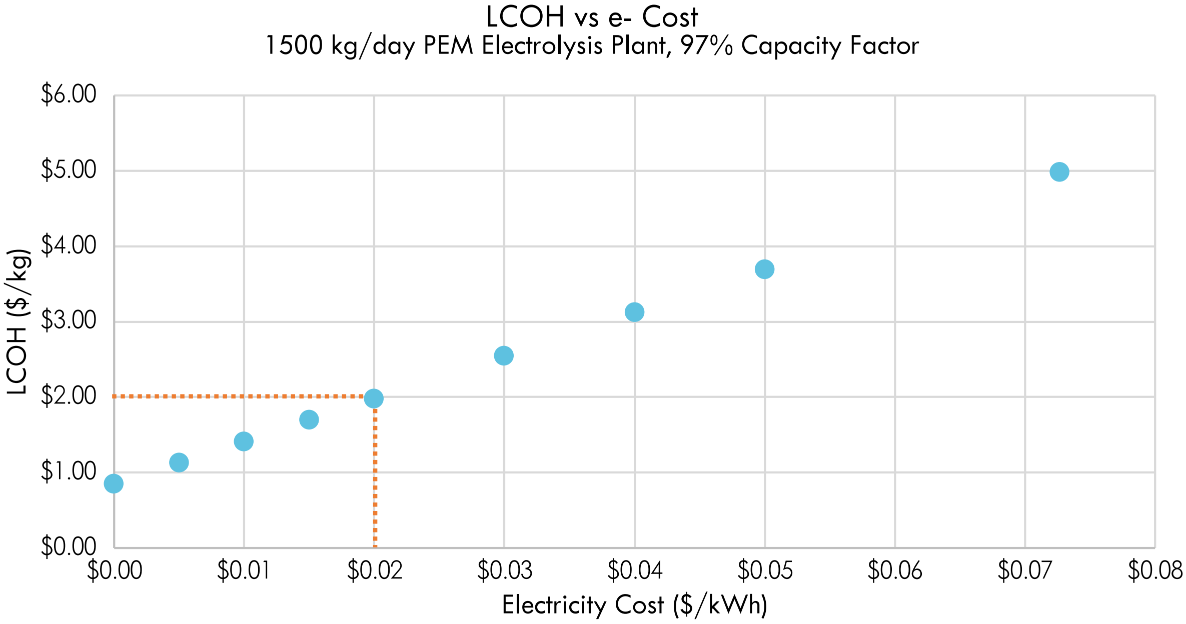

Figure 4. LCOH vs electricity cost. Source: IE-GW Simplified Model.

Table 5 shows the cost of hydrogen (using H2A 3.2018) under three different multiple electricity cost scenarios. Cost 1 is $0.015/kWh – a typical wholesale wind electricity price in Iowa. Cost 2 is $0.00/kWh, which represents the cost of curtailed wind energy.

The three scenarios model the final cost assuming the use of wholesale electricity (Cost 1) 80%, 85%, and 90% of the time, and no-cost, curtailed wind power (Cost 2) 17%, 12%, and 7% of the time. In each scenario the total capacity factor is 97%.

The greater the share of no-cost, curtailed wind power, the lower the cost of hydrogen production.

Sensitivity Analysis

Electricity cost is the single most significant parameter influencing the levelized cost of hydrogen. To produce hydrogen at $2/kg, it is crucial to have ready access to power at prices at or below $0.02/kWh. As can be seen in Figure 4, the LCOH falls below $2/kg at electricity costs of approximately $0.02/kWh (using H2A 3.2018).

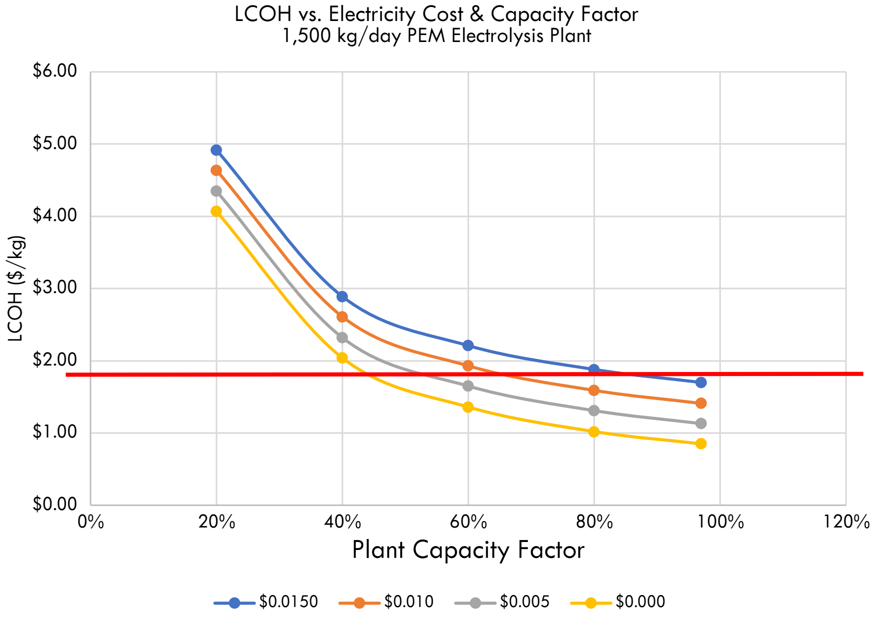

Figure 5. LCOH vs electricity cost and capacity factor. Source: IE-GW Simplified Model.

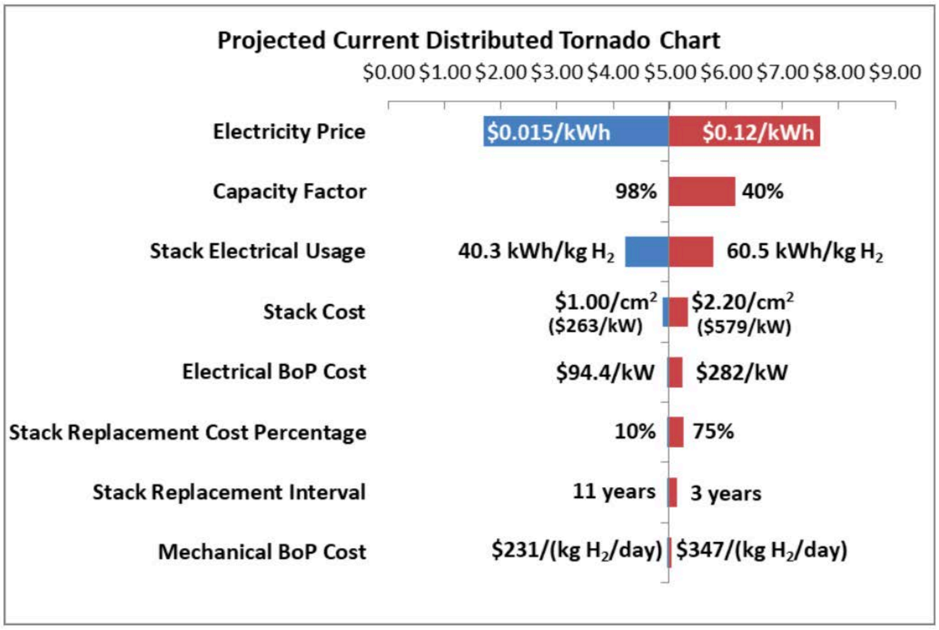

Figure 6. Tornado chart showing parameter sensitivities for the "Projected Current Distributed PEM Electrolysis" scenario.[58]

Figure 5 shows the sensitivity of LCOH to both electricity cost and capacity factor. A high capacity factor is needed to maintain sub-$2/kg prices with electricity costs of $0.015/kWh, while a lower capacity factor is sufficient with no-cost (curtailed) electricity. Department of Energy researchers arrived at similar conclusions. A sensitivity analysis published in "Hydrogen Production Cost From PEM Electrolysis - 2019" by David Peterson, James Vickers, and Dan DeSantis of the Department of Energy, shows that electricity cost is the single most significant factor in the production cost of hydrogen.

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[58] David Peterson, James Vickers, Dan DeSantis, "Hydrogen Production Cost From PEM Electrolysis - 2019," Department of Energy, February 3, 2020, 10.

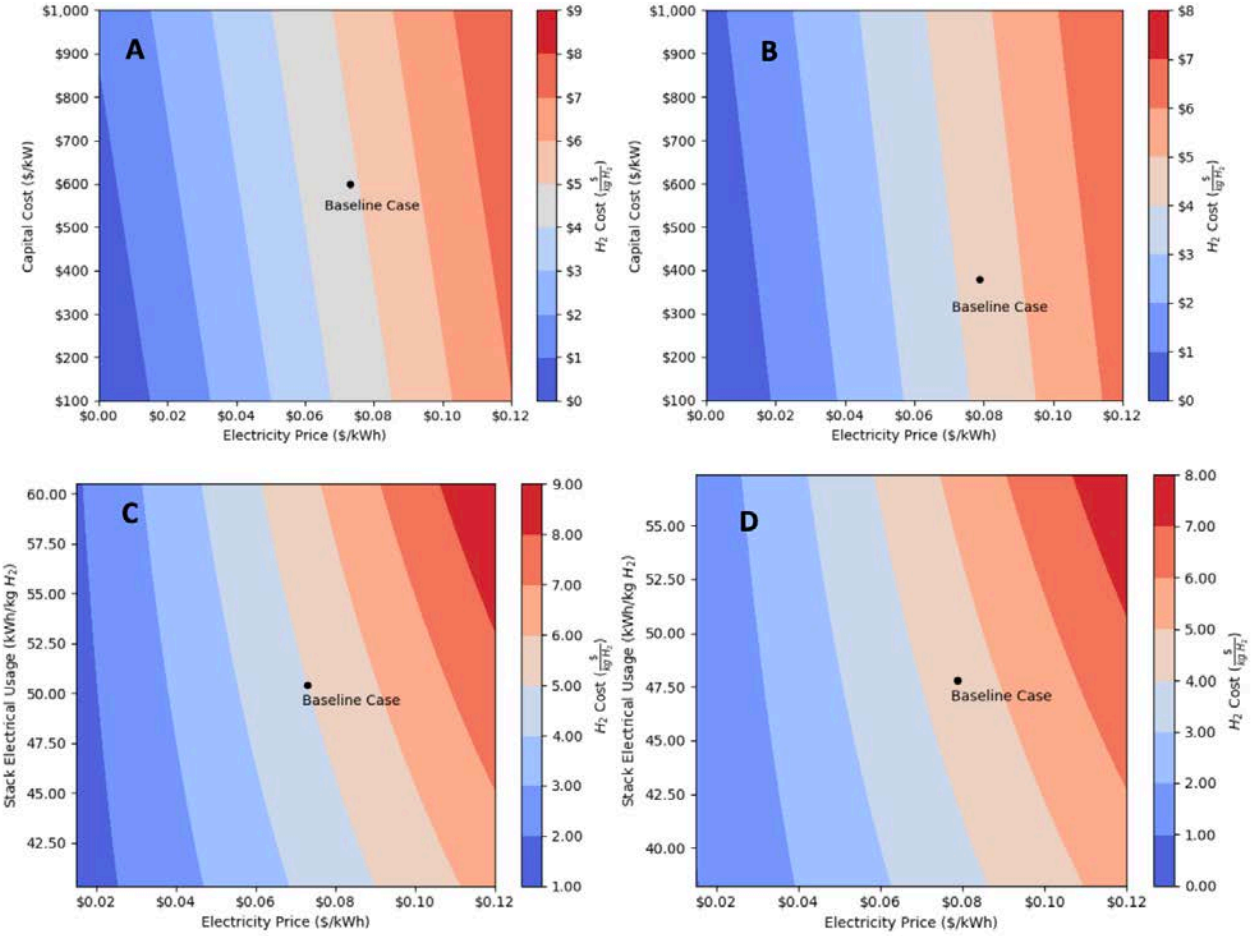

Figure 7. Contour plots showing H_2 production cost vs electricity cost, electrolyzer system capital cost, and stack electrical usage.[59]

Figure 6 shows hydrogen production cost sensitivity to various input parameters (using the H2A 3.2018 model). Tornado charts place the parameters with the highest sensitivity at the top. As can be seen here, electricity price has by far the most significant impact on hydrogen cost. Capacity factor and stack electrical usage are also significant.

In the contour plots shown above in Figure 7, hydrogen cost versus electricity cost and system cost is shown in (A) Projected Current Distributed PEM scenario and (B) Projected Future Distributed PEM scenario. H_2 cost versus electricity cost and stack electrical usage is shown in (C) Projected Current Distributed PEM scenario and (D) Projected Future Distributed PEM scenario. (Note: the IE-GW Simplified Model analyzes a scenario similar to A and C: the Projected Current Distributed PEM scenario.)

Discussion

Ideal Energy's results make clear that electricity cost is the most important factor in the levelized cost of hydrogen. These results are corroborated by Department of Energy research. Furthermore, these results show that with electricity prices at or below $0.015/kWh renewable hydrogen can be cost-competitive even when produced by a relatively small electrolyzer plant.

As will be demonstrated later in this report, Iowa is home to abundant and inexpensive wind energy with wholesale wind electricity prices around $0.015/kWh and a significant amount of curtailed wind power. **This is an extremely promising result, as it indicates that a renewable hydrogen pilot project in Iowa may be commercially viable right now.**

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[59] Peterson et al., 13.

Hydrogen Target Price Update

Renewable Hydrogen Competitiveness with Rising Natural Gas Prices

When this research project began, the target production cost for renewable hydrogen – the price at which renewable hydrogen would become competitive with fossil fuel hydrogen – was around $2.00/kg.

In 2020, according to the Department of Energy, the cost to produce hydrogen from natural gas using steam methane reforming without carbon capture and storage (SMR w/o CCS) was $2.08/kg and the cost with carbon capture and storage (SMR w/ CCS) was $2.27.[60]

Although this target price remains a near-term goal within the renewable hydrogen industry, the DOE launched an even more ambitious goal last year as part of its Hydrogen Shot initiative: $1/kg within one decade.[61]

However, both of these target prices ($2/kg in the short term and $1/kg by 2031) came about during a period of relatively low and relatively stable natural gas prices. Since the DOE's 2020 estimate of $2.07/kg for SMR w/o CCS, natural gas commodity prices have more than tripled and became more variable.

Natural gas feedstock costs are one of the biggest contributors to hydrogen cost. (Plant size is also a significant factor in cost.) What impact has this had on renewable hydrogen cost competitiveness? Could renewable hydrogen become competitive at production costs above $2/kg? If so, renewable hydrogen could become competitive even earlier than anticipated.

Estimating SMR Hydrogen Costs

Several researchers have developed formulas to estimate hydrogen production costs using SMR w/o CCS.

The Gray and Tomlinson equation is as follows:[62]

$$\text{Hydrogen Cost (\$/MMBtu)} = 1.27 \text{ x NG price (\$/MMB)} + 0.985$$

The Penner equation is as follows:[63]

$$\text{Hydrogen Cost (\$/kg)} = 0.286 \text{ x NG price (\$/MMBtu)} + 0.15$$

Although natural gas prices are different in different markets, and although hydrogen producers may not pay spot market rates, the commodity futures price for industrial hydrogen provides a transparent reference point for these calculations. It is possible to estimate a range of SMR hydrogen costs for producers paying market rates for natural gas by inputting daily prices and the upper and lower bound of the 50-day moving average during 2022. All costs are based on the Henry Hub commodity futures price for industrial hydrogen.[64]

The spot price on June 16th, 2022 was $7.62 per million BTUs (MMBtu). The 50-day moving average for industrial natural gas futures (Henry Hub) has not fallen below $4.12/MMBtu this year and reached a high of $7.83/MMBtu on June 22, 2022.

At the June 16th spot price ($7.62), the formula give estimates of SMR hydrogen costs of **$2.38/kg and $3.42/kg**, respectively. At the lower bound of the 2022 50-day moving average ($4.12) these formulas give estimates of **$1.39/kg and $2.15/kg**, respectively. At the upper bound of the 50-day moving average ($7.81) the estimates are **$2.45/kg and $3.86/kg**, respectively. All costs were adjusted for inflation.[65, 66]

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[60] Office of Fossil Energy, "Hydrogen Strategy: Enabling a Low-Carbon Economy," Department of Energy, July 2020, https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf, 6.

[61] "Hydrogen Shot," Energy.gov, accessed November 22, 2021, "Natural Gas (Henry Hub) Commodity," Markets Insider, (raw data), accessed June 16, 2022, https://www.energy.gov/eere/fuelcells/hydrogen-shot.

[62] Gray, David, and Glen Tomlinson. "Hydrogen from coal." *Mitretek Technical Paper MTR* 31 (2002): 2002.

[63] S. S. Penner, "Steps toward the Hydrogen Economy," *Energy*, The Second Biennial International Workshop "Advances in Energy Studies," 31, no. 1 (January 1, 2006): 33–43, https://doi.org/10.1016/j.energy.2004.04.060.

[64] https://markets.businessinsider.com/commodities/natural-gas-price?op=1

[65] The following two formulas were used, with output converted SI units, and adjusted for inflation to 2022 dollars:

Hydrogen Cost ($/MMBtu) = 1.27 x NG price ($/MMB) + 0.985
Hydrogen Cost ($/kg) = 0.286 x NG price ($/MMBtu) + 0.15

[66] Additional discussion on the use of both formulas can be found in Bartels, Pate, and Olson, *An economic survey of hydrogen production from conventional and alternative energy sources*, International Journal of Hydrogen Energy, Volume 35, Issue 16, 2010, Pages 8371-8384, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2010.04.035.

Although not conclusive, **these formulas do indicate that the cost of SMR hydrogen – and therefore the breakeven point for renewable hydrogen – may have climbed above $2/kg.**

	SPOT PRICE (June 16, 2022) – $7.62/MMBtu	50-DAY MOVING AVG. (Low) – $4.12/MMBtu	50-DAY MOVING AVG. (High) – $7.83/MMBtu
Hydrogen Cost ($/kg) (Gray and Tomlinson)	$2.38	$1.39	$2.15
Hydrogen Cost ($/kg) (Penner)	$3.42	$2.45	$3.86

Table 6. Estimated average SMR hydrogen production costs.

SMR Hydrogen Cost Literature Survey

A recent survey of the literature found a wide range of actual reported costs for SMR both with and without CCS. The range in costs was high and the relationship to natural gas prices, although significant, was less clear than expected.

The cost range of SMR without CCS was $1.03/kg to $2.16/kg (in 2016$) according to Parkinson et al.[67] Adjusted for inflation, this range is $1.25/kg to $2.62/kg in May 2022 USD.[68]

The R^2 value – or coefficient of determination – between these costs and natural gas prices was 0.3965. This means that 39.65% of the variation in hydrogen cost in this particular data set was determined by the natural gas price. Although natural gas price is an important factor in the cost of hydrogen made using SMR, it is not the sole determinant.

Furthermore, current high natural gas prices are in part a product of domestic policy and in part a product of geopolitical events – both of which could reverse course. **Renewable hydrogen developers should not plan projects assuming SMR hydrogen costs will remain high indefinitely**. It is important to remember that after natural gas prices peaked in 2008 at over $13/MMBtu they declined sharply and entered a more than decade-long plateau in the $2-5/MMBtu range.

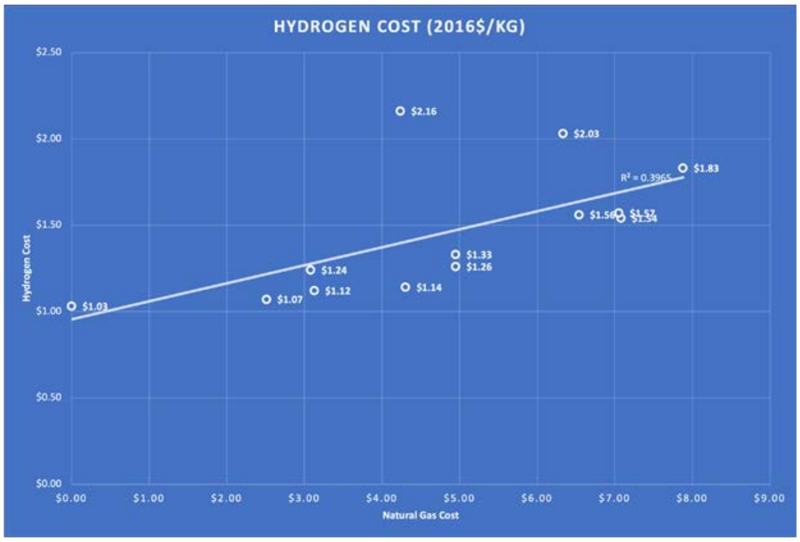

Figure 8. Hydrogen production cost via SMR ($/kg) versus natural gas cost ($/MMBtu).

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[67] B. Parkinson et al., "Levelized Cost of CO2 Mitigation from Hydrogen Production Routes," *Energy & Environmental Science* 12, no. 1 (January 16, 2019): 19–40, https://doi.org/10.1039/C8EE02079E.

[68] CPI Inflation Calculator. U.S. Bureau of Labor Statistics. https://www.bls.gov/data/inflation_calculator.htm. Accessed June 24, 2022.

Part IV – Hydrogen Production & Demand Potential

Hydrogen Demand Potential

As the renewable hydrogen economy develops, demand for hydrogen will grow. Hydrogen demand forecasts help to understand the scale of the opportunity available. Researchers at Argonne National Laboratory (ANL) and the National Renewable Energy Laboratory (NREL) have modeled future hydrogen demand.

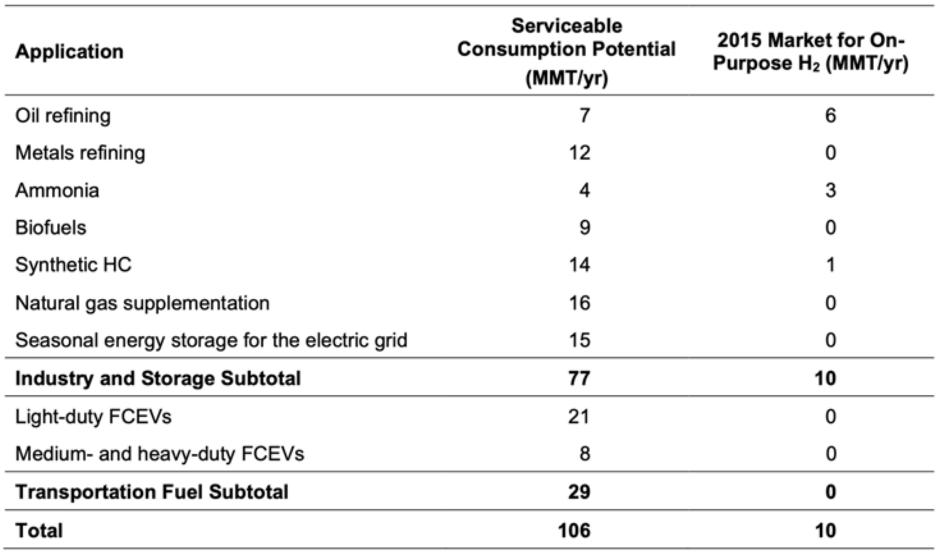
Sources of Demand

Work at ANL identifies eight major sources of hydrogen demand:[69]

- petroleum refining
- biofuels production
- ammonia plants
- synthetic fuels and chemical
- natural gas pipeline injection
- steel production
- light-duty vehicles
- heavy-duty vehicles

Hydrogen Demand by Source, U.S.

Researchers at NREL have modeled future demand of hydrogen from each of these sources, as well as aggregate hydrogen demand. They project that the "sum of the serviceable consumption potentials for hydrogen demand" is 106 million metric tons (MMT) per year, with 29 MMT/year for fuel cell vehicles, 15 MMT/year for seasonal storage for electricity, and 62 MMT/year for industrial uses.[70]



Application	Serviceable Consumption Potential (MMT/yr)	2015 Market for On-Purpose H_2 (MMT/yr)
Oil refining	7	6
Metals refining	12	0
Ammonia	4	3
Biofuels	9	0
Synthetic HC	14	1
Natural gas supplementation	16	0
Seasonal energy storage for the electric grid	15	0
Industry and Storage Subtotal	**77**	**10**
Light-duty FCEVs	21	0
Medium- and heavy-duty FCEVs	8	0
Transportation Fuel Subtotal	**29**	**0**
Total	**106**	**10**

Table 7. Serviceable consumption potential for hydrogen demand, by application.[71]

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[69] Amgad Elgowainy, Marianne Mintz, Uisung Lee, Thomas Stephens, Pingping Sun, Krishna Reddi, Yan Zhou *et al.*, *Assessment of Potential Future Demands for Hydrogen in the United States* (Argonne National Laboratory, October 2020), 2-3.

[70] Mark Ruth, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A.J. Simpson, Amgad Elgowainy *et al., The Technical and Economic Potential of the H2@Scale Concept within the United States.* (National Renewable Energy Laboratory, October 2020), 48.

[71] Ruth *et al.*, 48.

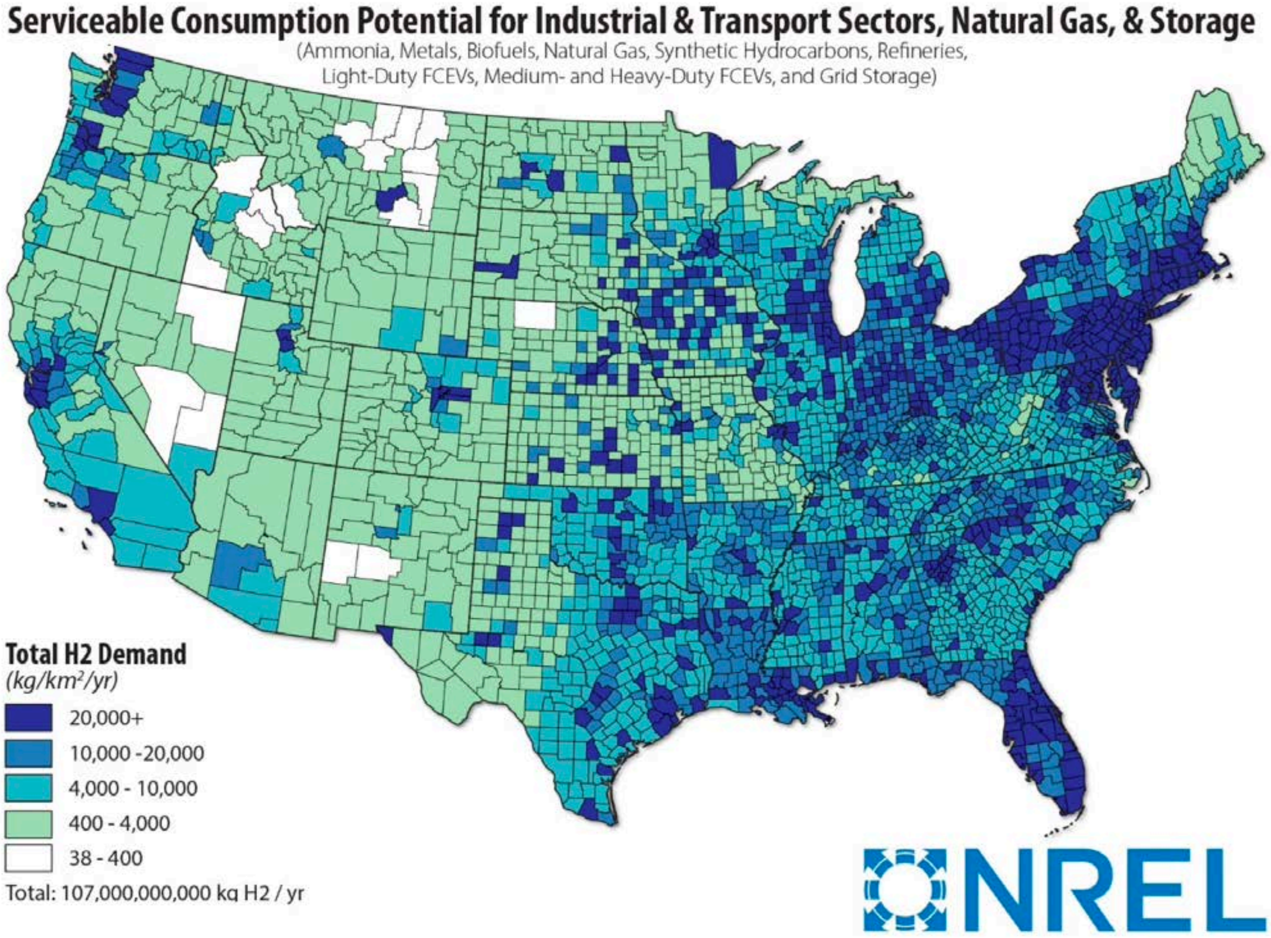

Figure 9. Total projected hydrogen demand.[72]

Aggregate Hydrogen Demand, U.S.

The NREL also produced a series of county-by-county maps of hydrogen demand. The map above shows total projected demand for hydrogen from all demand sources.

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[72] Ruth *et al.*, 52.

Hydrogen Production Potential

Net Hydrogen Production Potential, U.S.

Net production is a key consideration. Areas with higher net production potential could become net-exporters of hydrogen. The map below shows technical potential for hydrogen production using solar and wind resources minus serviceable consumption potential. Darker blue shaded counties have higher net production potential. Most of Iowa lies within the dark blue corridor with the highest net-production potential.

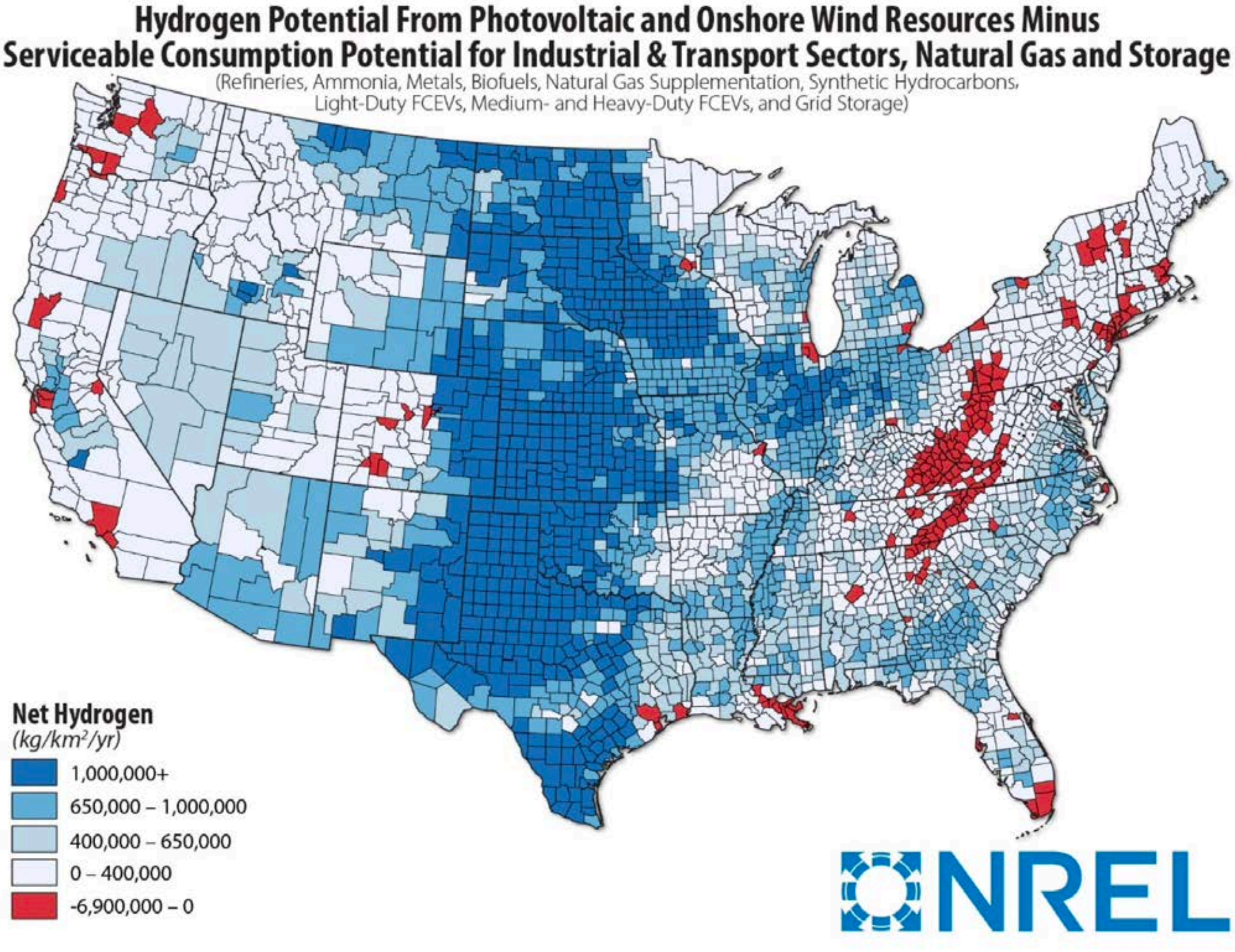

Figure 10. Net hydrogen production potential, by county. (Hydrogen production potential from solar and onshore wind minus serviceable consumption potential.)[73]

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[73] Ruth *et al.*, 56.

Hydrogen Production Potential from Wind, U.S.

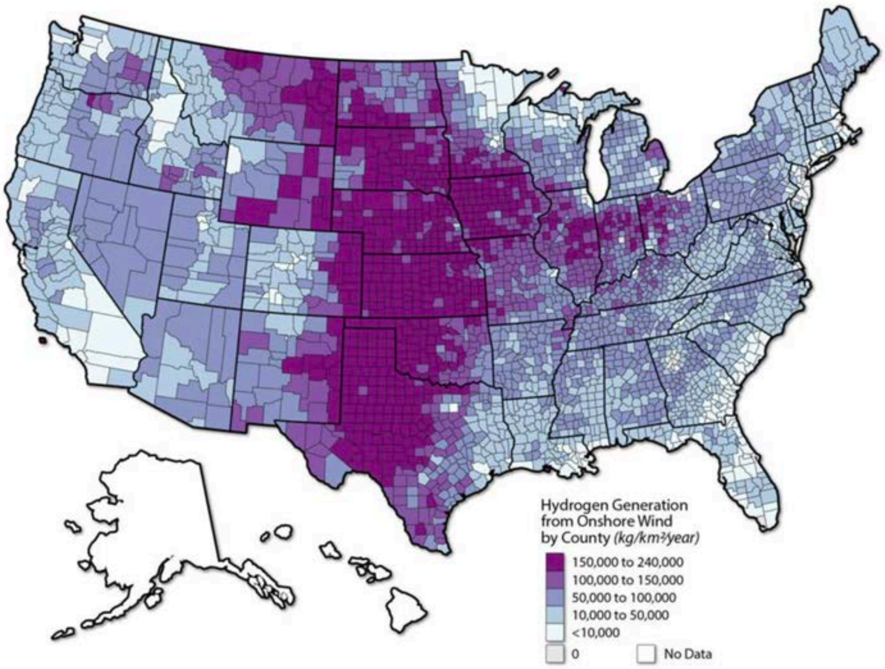

Figure 11. Hydrogen production potential from onshore wind, by county.[74]

Hydrogen Production Potential from Solar. U.S.

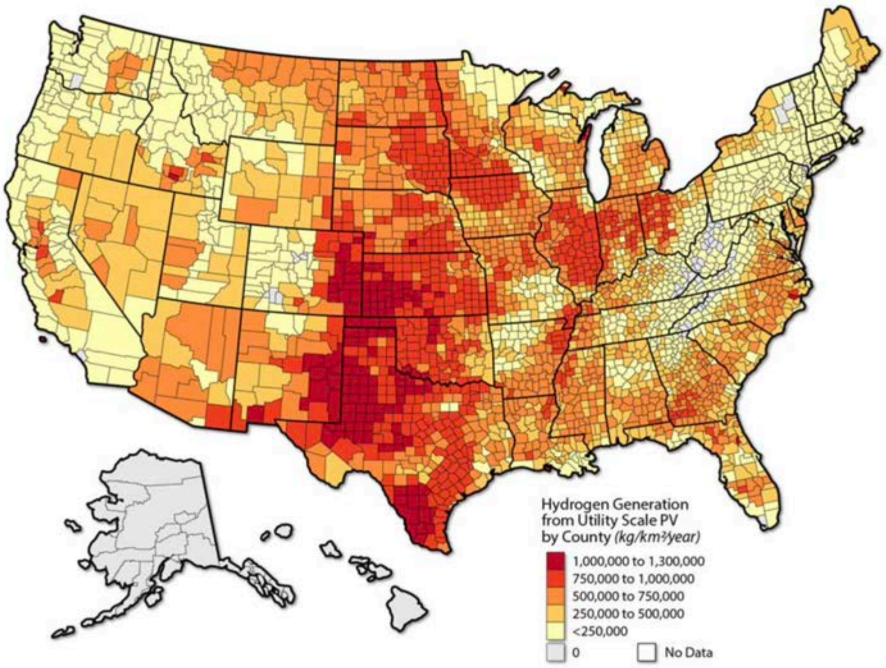

Figure 12. Hydrogen production potential from utility-scale solar, by county.[75]

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[74] Elizabeth Connelly, Michael Penev, Anelia Milbrandt, Billy Roberts, Nicholas Gilroy, Marc Melaina, *Resource Assessment for Hydrogen Production* (National Renewable Energy Laboratory, July 2020), 16.

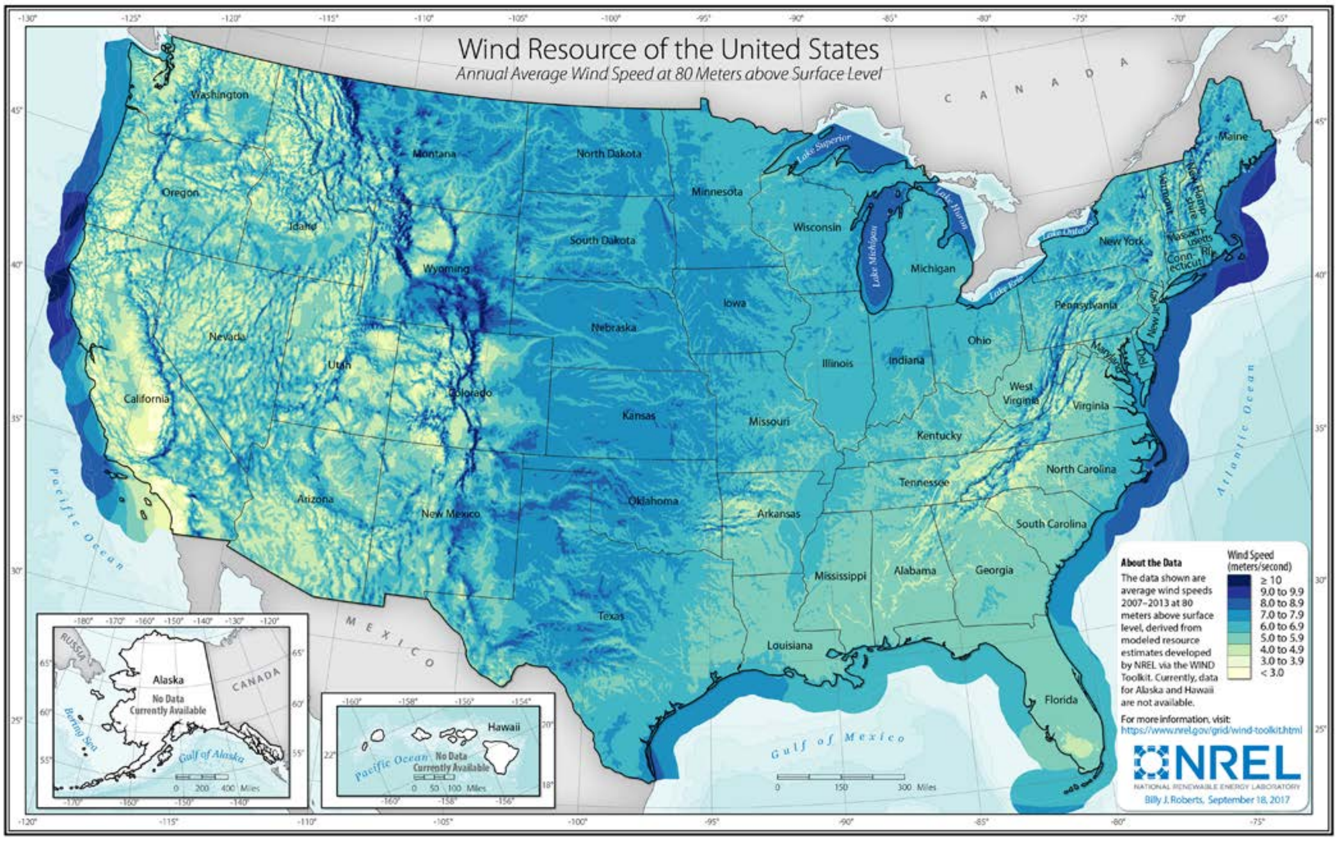
[75] Connelly *et al.*, 20.

Part V — Renewable Energy Resources & Prices

Wind Energy Resources

Wind Resource, U.S.

Iowa is part of the American "wind belt" and has excellent wind resources. Iowa generates 57.51% of its energy with wind – the highest percentage of any state in the nation – and is second only to Texas in total installed capacity with 11,660 MW.[76]



About the Data

The data shown are average wind speeds 2007–2013 at 80 meters above surface level, derived from modeled resource estimates developed by NREL via the WIND Toolkit. Currently, data for Alaska and Hawaii are not available.

For more information, visit: https://www.nrel.gov/grid/wind-toolkit.html

Billy J. Roberts, September 18, 2017

Figure 13. United States annual average wind speed at 80 meters. Source: NREL[77]

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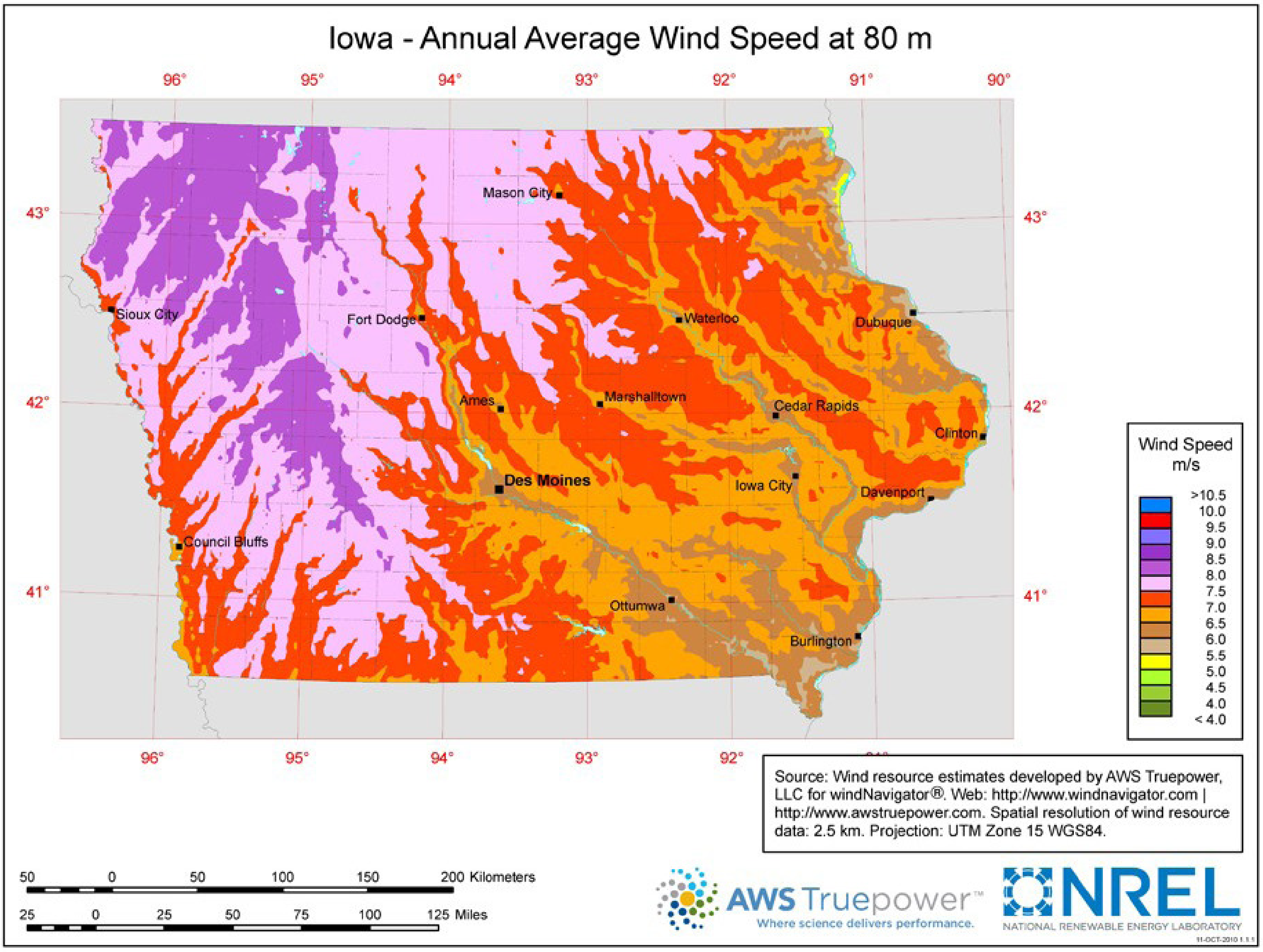
[76] "Wind Energy in Iowa," (*raw data*), WINDExchange, United States Department of Energy, accessed August 15, 2021, https://windexchange.energy.gov/states/ia.

[77] "Wind Resource of the United States: Annual Average Wind Speed at 80 Meters above Surface Level," (*map*), National Renewable Energy Laboratory, accessed August 15, 2021, https://www.nrel.gov/gis/wind-resource-maps.html.

Wind Resource, Iowa

Iowa has an excellent wind resource. Areas with annual average wind speeds of 6.5 meters per second (m/s) or higher at a height of 80 meters are considered suitable for wind development. Most of Iowa has annual average wind speeds above 6.5 m/s.[78]


Iowa - Annual Average Wind Speed at 80 m

Source: Wind resource estimates developed by AWS Truepower, LLC for windNavigator®. Web: http://www.windnavigator.com | http://www.awstruepower.com. Spatial resolution of wind resource data: 2.5 km. Projection: UTM Zone 15 WGS84.

Figure 14. Iowa annual average wind speed at 80 meters. Source: NREL[79]

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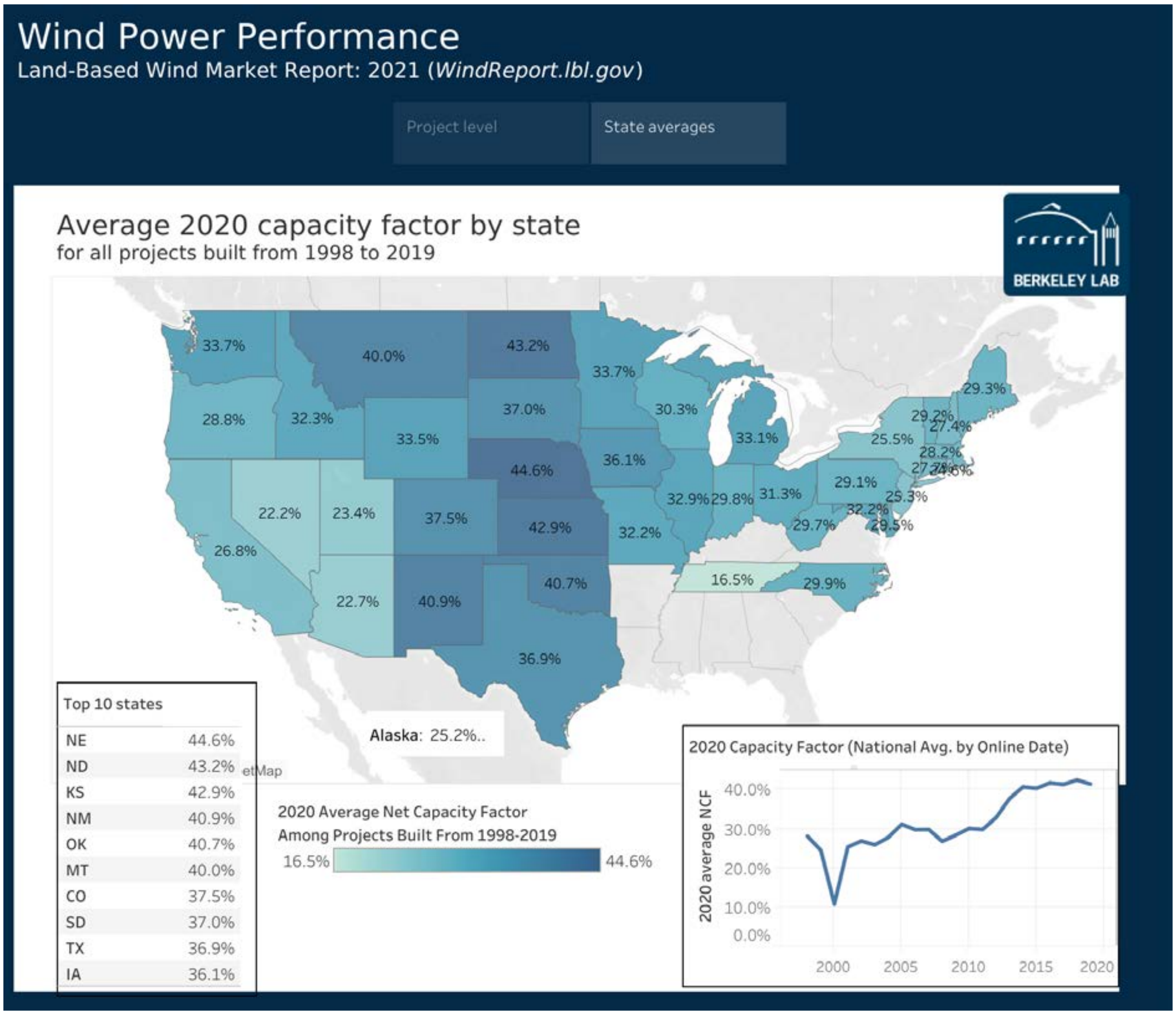
[78] "Iowa - Annual Average Wind Speed at 80 m," (*map*), WINDExchange, United States Department of Energy, accessed August 15, 2021, https://windexchange.energy.gov/maps-data/319.

[79] "Wind Energy in Iowa," WINDExchange.

Wind Capacity Factor

Capacity factor is the ratio of actual energy output to maximum energy output over time. Wind has high capacity factor compared to other renewable energy sources. A higher capacity factor is better suited to hydrogen production.[80]

Iowa's wind resource ranks in the top 10 states in terms of capacity factor.



Top 10 states

NE	44.6%
ND	43.2%
KS	42.9%
NM	40.9%
OK	40.7%
MT	40.0%
CO	37.5%
SD	37.0%
TX	36.9%
IA	36.1%

Figure 15. Wind capacity factor by state.[81]

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[80] Greg Wilson, Interview, May 12, 2020.

[81] "Wind Technologies Market Report - Wind Power Performance," (*interactive data visualization*), Electricity Markets & Policy, Lawrence Berkeley National Laboratory, accessed September 1, 2021, https://emp.lbl.gov/wind-power-performance.

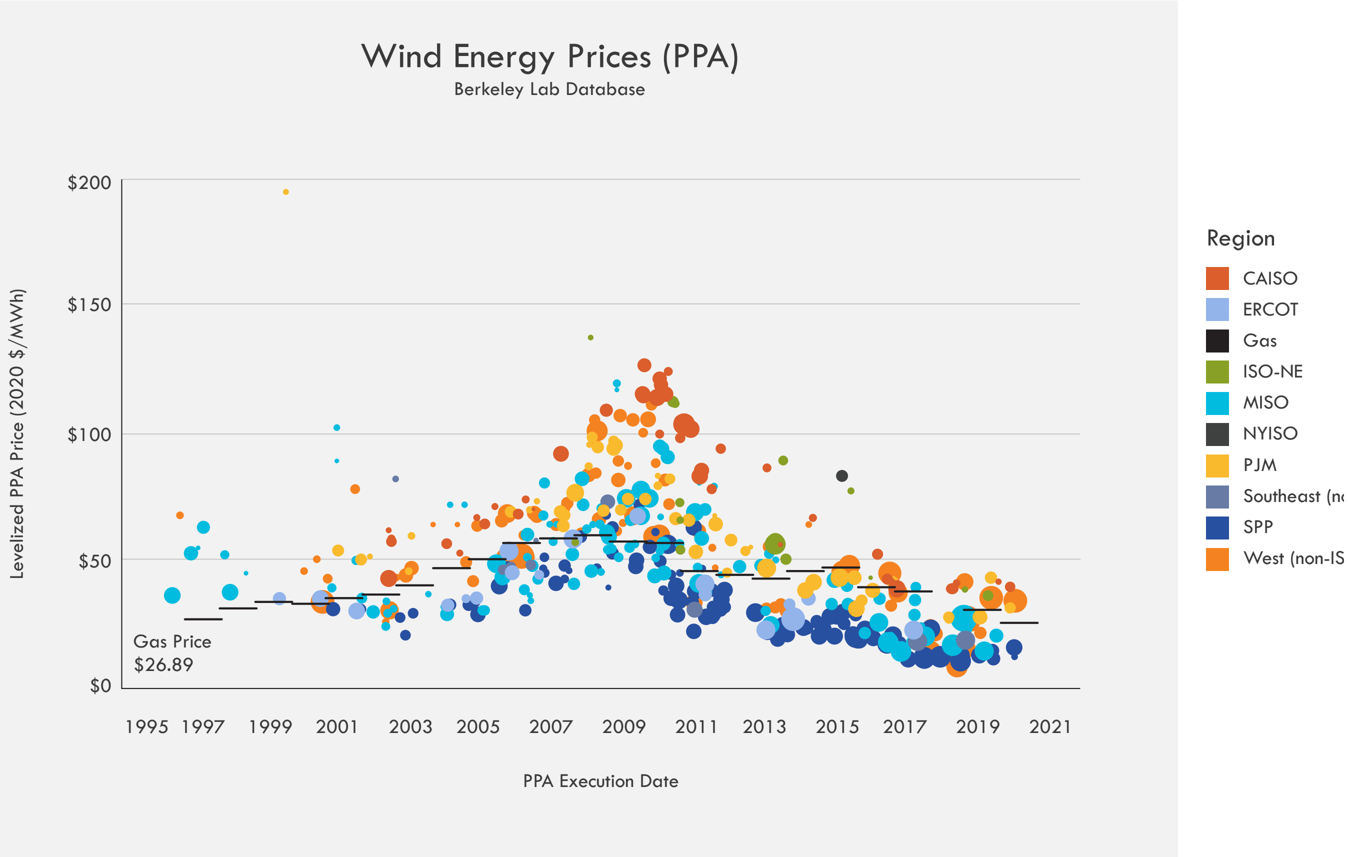

Figure 16. Wind power purchase agreement (PPA) prices by ISO, 2020.[82]

Wind Energy Prices

Iowa enjoys low wind energy prices. The two independent system operators (ISOs) that operate in Iowa, MISO and SPP, reported some of the lowest wind energy PPA prices and average market values nationwide.

Recent PPA pricing in MISO and SPP is at or below $20/MWh ($0.02/kWh) with some recent projects in the mid-teens. The average wholesale market value of wind was $11/MWh ($0.11/kWh) in MISO and $14/MWh ($0.14/kWh) in SPP as of 2020.

Wind energy prices have been generally stable since 2018, but increased slightly in 2020 and 2021.[83, 84]

Wind Pricing Data Sources

There are several ways to evaluate wind energy pricing.

- *Power purchasing agreements (PPAs)* are contracts that set pricing between wind project owners and utilities or other energy off-takers.
- *Wind market value* is a measure of wind's potential revenue when sold into the grid via either direct bidding or PPA.
- The *unsubsidized levelized cost of energy (LCOE)* for wind is a bottom-up calculation of the cost to produce wind energy over the lifetime of a wind project, minus any tax incentives or other subsidies.

All three of these metrics are tracked or estimated by the Department of Energy.

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[82] "Wind Technologies Market Report - Wind Power Purchase Agreement (PPA) Prices," (*interactive data visualization*), Electricity Markets & Policy, Lawrence Berkeley National Laboratory, accessed September 1, 2021, https://emp.lbl.gov/wind-power-purchase-agreement-ppa-prices. Adapted from data visualization.

[83] Since the first edition of this paper, new wind energy data has been released by the Department of Energy. Wholesale and PPA wind energy prices increased slightly in 2021.

[84] Ryan Wiser and Mark Bolinger *et al., Wind Energy Technology Data Update: 2020 Edition*, (Lawrence Berkeley National Laboratory, August 2020), 62, 74.

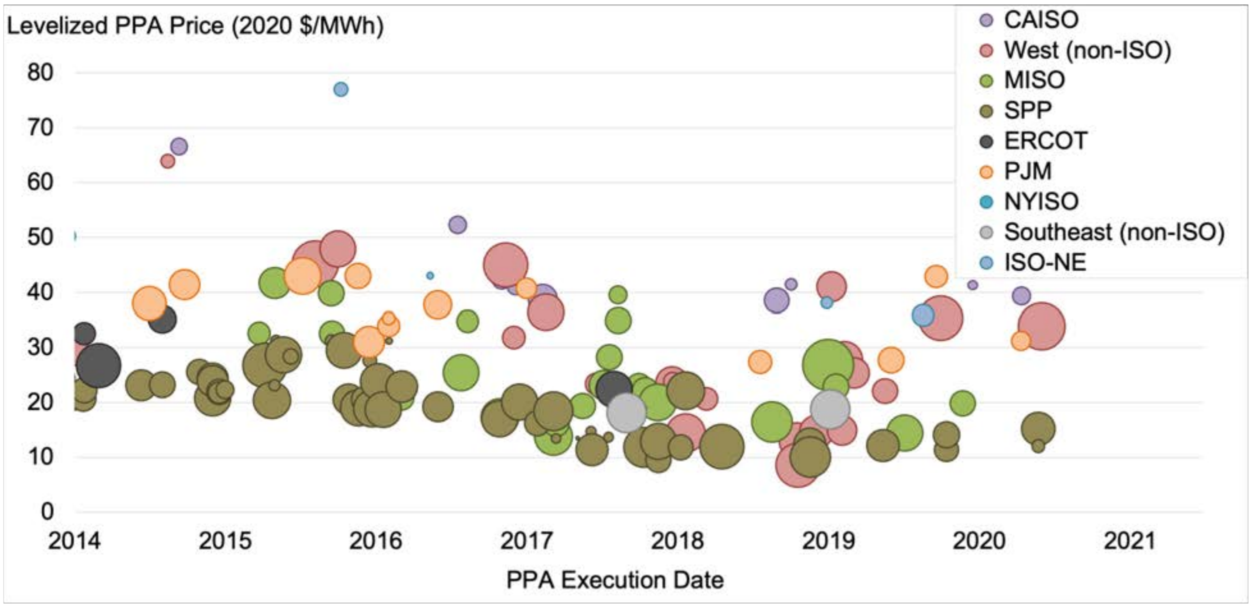

Figure 17. Levelized wind PPA prices by PPA execution date and region (recent sample). Note: size of bubble reflects contract capacity. Sources: Berkeley Lab, FERC.[85]

Wind Energy Prices in Iowa, PPA (Utility)

Power purchasing agreement (PPA) contract pricing is nonpublic information, but this data is collected and aggregated by the U.S. Department of Energy Lawrence Berkeley National Laboratory (LBNL) and National Renewable Energy Laboratory (NREL) for use in analyzing renewable energy cost trends. PPA prices for both wind and solar have been steadily declining as plant capital costs decline and project sizes increase.[86]

Iowa is covered by both MISO and SPP and these ISOs report some of the lowest wind energy prices in the U.S. Berkeley Lab reports recent PPA pricing in the Central U.S., including MISO and SPP, "**around or below $20/MWh"** (**$0.02/kWh**) with some projects in the mid-teens.[87]

Average nationwide wind PPA pricing fell to approximately $20/MWh by 2018, driven by sub-$20/MWh average PPA prices across large capacities of new wind projects in the interior region of the country. The interior region saw average PPA prices below $20/MWh as early as 2017 and PPA prices have remained low.[88]

The Berkeley Lab database contains 506 PPAs totalling 50,465 MW of wind projects that have either been built or are planned. Most of these projects have a utility as the counterparty. Of the 135 PPAs executed since 2014, levelized prices ranged from $8.6/MWh to $82.7/MWh. Recent average prices are below $20/MWh in the Central U.S., and around $30/MWh in the West and East. Berkeley Lab cites declining CapEx and OpEx, improved performance, and low interest rates as causes of the low PPA rates seen today.[89]

Raw data from Berkeley Lab shows that recent PPA prices within ISOs operating in Iowa are in the low to high teens. (Note: it cannot be discerned from this dataset exactly which state these individual projects are located in – only that they are within the reporting ISO's territory.)

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[85] Wiser and Bolinger *et al.*, 2021, 46.

[86] Greg Wilson, "Renewable H2 in Iowa," Fairfield, Iowa, October 15, 2020.

[87] Ryan Wiser and Mark Bolinger *et al., Land Based Wind Market Report: 2021 Edition*, (U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, 2021), x.

[88] Ryan Wiser and Mark Bolinger et al., *2018 Wind Technologies Market Report*, (U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy), 59-60.

[89] Wiser and Bolinger *et al.*, 2021, x, 44-46.

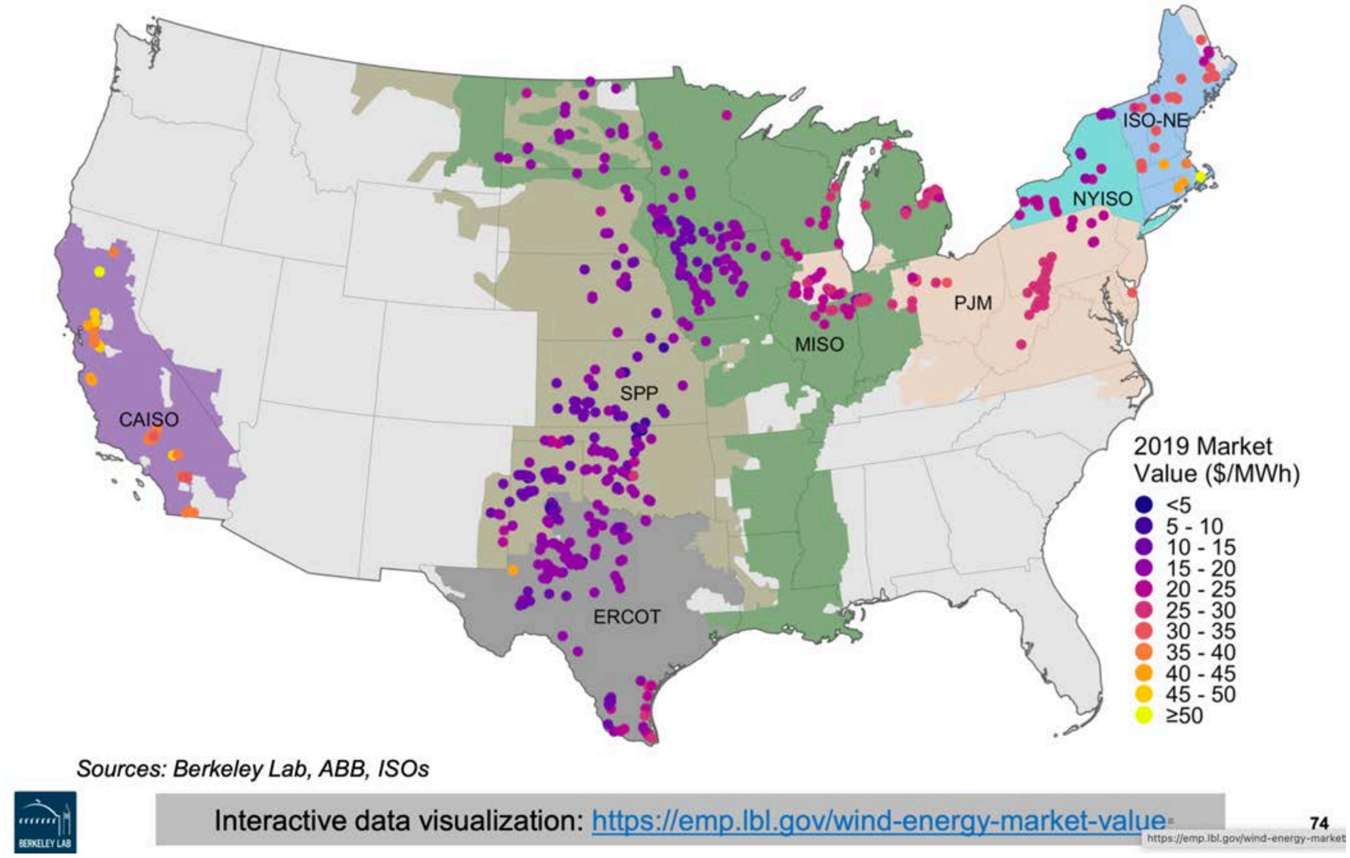

Figure 18. Levelized wind PPA prices by PPA execution date and region (recent sample). Note: size of bubble reflects contract capacity. Sources: Berkeley Lab, FERC.[90]

The most recent PPA prices ($/MWh) in MISO and SPP in the DOE's Land-Based Wing Market Report 2021 Data File, which includes anonymized actual PPA contract pricing, are as follows.[91]

For MISO, the most recent reported (2019) contract prices were (oldest to newest):

- $26.87 (1/3/2019)
- $22.82 (1/22/2019)
- $14.48 (7/8/2019)
- $19.85 (11/25/2019)

For SPP the most recent reported (2019 & 2020) contract prices were (oldest to newest):

- $12.17 (5/16/2019)
- $11.40 (10/17/2019)
- $14.11 (10/17/2019)
- $15.20 (5/27/2020)
- $12.06 (5/27/2020)

Wind Energy Prices in Iowa, PPA (Non-Utility)

In contrast to Berkeley Lab's in-house dataset, LevelTen Energy's PPA price index contains projects for which a large electric user, rather than a utility, is the counterparty. LevelTen data shows low prices that increased slightly during 2020 and 2021, with the lowest in SPP and ERCOT at around $20/MWh. MISO prices are in the low $30s in this dataset.[92]

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[90] Wiser and Bolinger *et al.*, 2021, 46.

[91] "Land-Based Wind Market Report: 2021 Edition Data File," (*raw data*), U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, accessed July 19, 2022, https://emp.lbl.gov/sites/default/files/2021_land-based_wind_market_report_public_data_file_0.xlsm.

[92] Wiser and Bolinger *et al.*, 2021, x, 46-47.

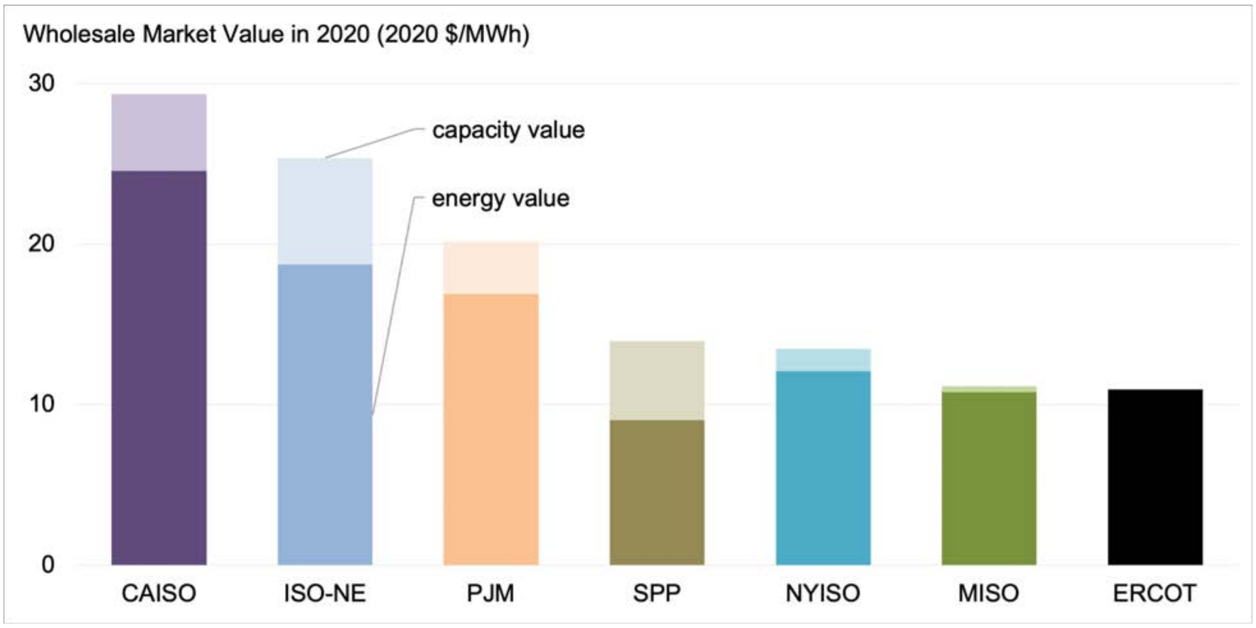

Figure 19. Wholesale market value of wind by ISO, 2020. Source: Berkeley Lab, ABB, ISOs.[93]

Wind Energy Prices in Iowa, Wholesale Wind Market Value

Iowa average wind energy wholesale market values are some of the lowest in the country, at 1.4 ¢/kWh and below. According to Berkeley Lab research, **the average grid-system market value of wind in 2020 was $11/MWh in MISO and $14/MWh in SPP**. Among specific wind projects nationwide, the range in market values from the 10th to 90th percentile was $7/MWh to $29/MWh, and the 50th percentile of wind projects was $15/MWh.[94, 95]

Wind projects sell into the wholesale electricity market either via PPAs or by bidding into the market directly. In the former, the PPA purchaser schedules wind energy into the market and pays the wind project owner the agreed price, which may or may not reflect market pricing. In the latter cases, the wind project owner is paid the market price.

Wholesale pricing is always influenced by supply-demand balances, as well as other factors including transmission system limitations. Iowa's transmission constraints contribute to low wholesale prices by causing regular, localized oversupply of wind power. Because price and cost are closely connected in regulated markets (including electricity markets in most states) that wholesale price data is a good proxy of electricity costs.

Wind's market value (i.e. the potential revenue of wind) is impacted by several factors that tend to drive the wholesale market value of wind down. Wind projects are often cited in areas with transmission line constraints, which drives down wholesale prices at the local pricing nodes where wind plants interconnect to the grid. In addition, high wind output pushes wholesale energy prices down, so when wind assets are most productive they are also least profitable per MWh produced. Finally, wind production profiles are often poorly aligned with customer load profiles.

Researchers noted that wind penetration, generation profile, transmission congestion, and curtailment can all impact the market value of wind, with generation profile and congestion being the most impactful. ISOs active in Iowa have the highest and third highest wind penetration: SPP at 31%, ERCOT at 23%, and MISO at 11%. These ISOs also have among the largest reductions in wind's market value at approximately 50% below average wholesale prices in SPP, ERCOT and MISO. In addition, MISO has the highest reduction in market value from transmission congestion.[96]

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[93] Wiser and Bolinger *et al.*, 2021, 54.

[94] Wiser and Bolinger *et al.*, 2021, xi, 51-54.

[95] Wiser and Bolinger *et al.*, 2020, 62.

[96] Wiser and Bolinger *et al.*, 2021, xi, 57.

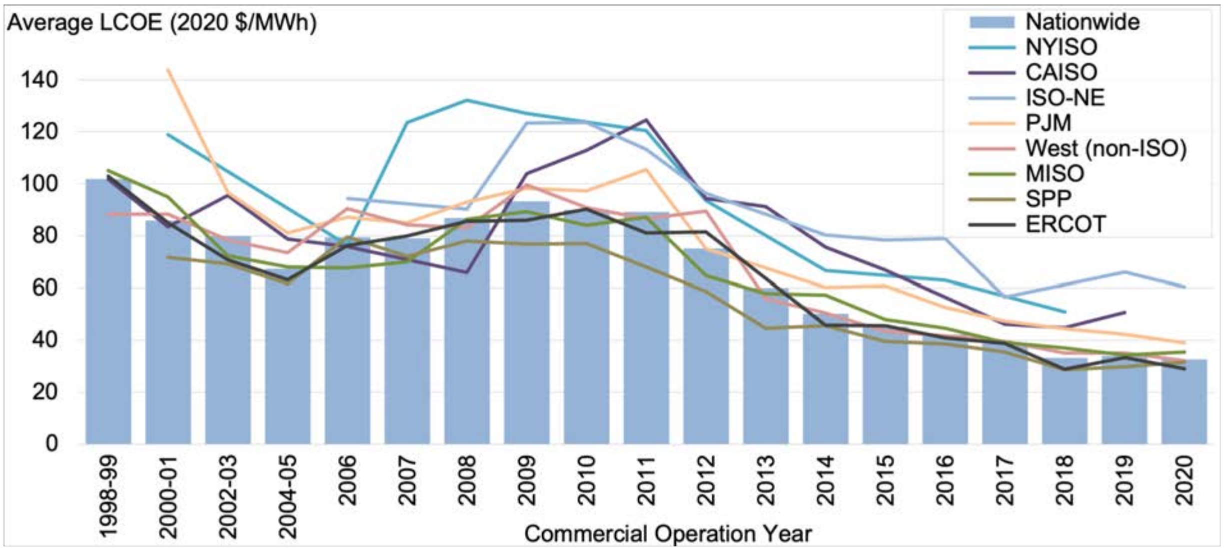

Figure 20. Average LCOE of wind by ISO and nationwide, 1998-2020. Source: Berkeley Lab

The low market value of wind in MISO and SPP, and the high impact on market value in those ISOs from transmission congestion and undesirable generation profiles, indicate that hydrogen plants cited close to wind projects may be able to able to outbid the wholesale electricity market even at the low prices required to make PEM electrolysis competitive with SMR hydrogen.

Wind Energy Prices in Iowa, Wind LCOE Levelized Cost of Wind Energy

Berkeley Lab researchers estimated the (unsubsidized) levelized cost of energy (LCOE) of wind from its components, including installed cost, capacity factor, estimated operational costs, financing costs, and project lifespan. Berkeley Lab has data on installed cost and capacity factor for 104 GW of wind – almost double the size of its PPA dataset – accounting for 85% of all wind capacity built in the U.S. between 1998 and 2020. To get the unsubsidized LCOE, the levelized costs of all subsidies and tax credits were excluded from the analysis.

The nationwide average unsubsidized levelized cost of energy (LCOE) for wind was $33/MWh in 2020. The LCOE of wind is $32/MWh in SPP and $35/MWh in MISO. Average LCOEs have been trending down since 2009 nationwide and in most ISOs. They fell rapidly until 2018, leveled off, and have remained relatively stable since then.[97]

Barriers to Integration with Wind Energy

There are three primary barriers to renewable hydrogen integration with wind power. First, the lack of a tariff specific to curtailed power limits the renewable hydrogen opportunity to certain types of projects. Second, wind farm curtailment data is nonpublic at the level of the individual wind farm. Wind farm operators know their own curtailment rates, of course, but third parties looking for potential partners and evaluating project site locations do not. Third, the wind power industry does not have existing relationships with potential off-takers or expertise in chemical handling and storage.

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[97] "Land-Based Wind Market Report: 2021 Edition Data File," (*raw data*), U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, accessed July 19, 2022, https://emp.lbl.gov/sites/default/files/2021_land-based_wind_market_report_public_data_file_0.xlsm.

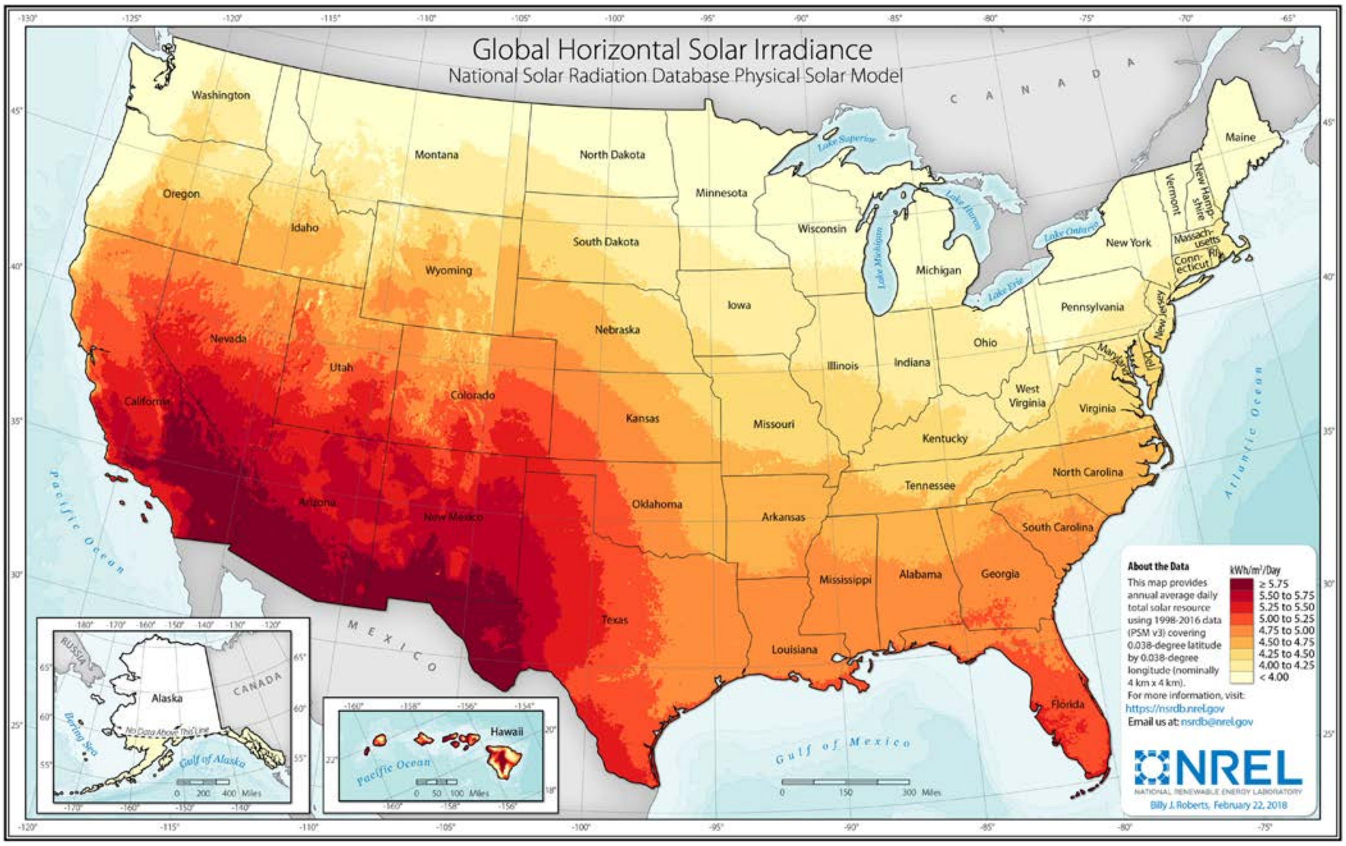

Figure 21. Annual global horizontal solar irradiance of the United States, 2018.[98]

Solar Energy Resource

Iowa has an excellent solar resource. Iowa ranks 16th for technical solar potential, putting it ahead of Florida and the Carolinas. Iowa's total solar potential is estimated to be 4 million MW – enough to meet the state's existing electricity demand 100 times over. Iowa currently has 158.7 MW of installed solar capacity and additional 1,349 MW of approved or proposed utility-scale projects.[99]

Utility-scale solar farms have the potential to perform very well in the state. Although there are not many utility-scale solar projects to co-locate a hydrogen project near at the present time, a captive solar array dedicated to renewable hydrogen production is a viable option in Iowa. In particular, solar arrays could power small-scale production of renewable hydrogen for local consumption, for example a school district's bus fleet.[100]

Barriers to Integration with Solar Energy

The barriers to renewable hydrogen integration with the solar industry are similar to the challenges with wind integration. The absence of a tariff specific to renewable hydrogen production, and the proprietary nature of curtailment data are both potential roadblocks. However, because solar energy is likely best suited to self-consumption projects like a heat and power plant or a school district's bus fleet, these barriers may be less consequential.

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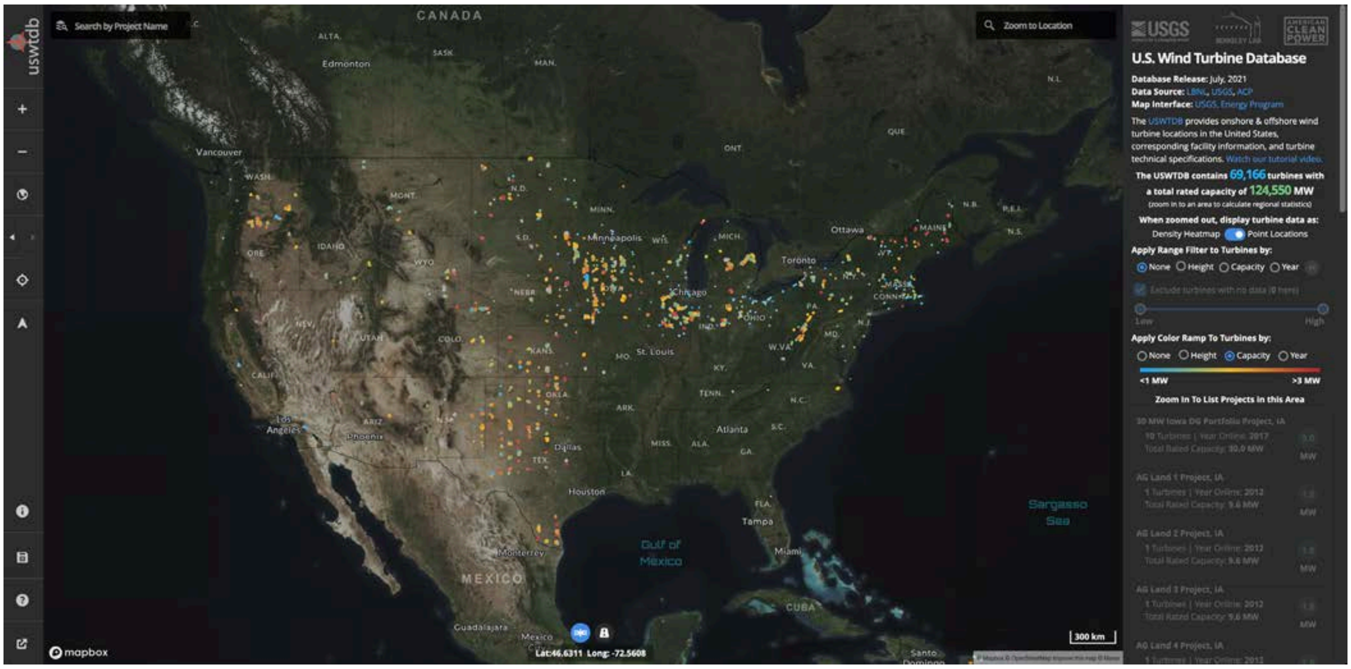
[98] "Global Horizontal Solar Irradiance: Annual average daily solar irradiance of the United States, 2018," (map), National Renewable Energy Laboratory, accessed August 15, 2021, https://www.nrel.gov/gis/solar-resource-maps.html.

[99] "Iowa Solar Energy Fact Sheet," Iowa Environmental Council (January, 2021), https://www.iaenvironment.org/webres/File/Solar%20Energy%20Fact%20Sheet%20-%202021.pdf.

[100] Greg Wilson, "Renewable H_2 in Iowa," Presentation, Fairfield, Iowa, October 15, 2020.

Part VI – Hydrogen Project Siting



U.S. Wind Turbine Database

Database Release: July, 2021
Data Source: LBNL, USGS, ACP
Map Interface: USGS, Energy Program

The USWTDB provides onshore & offshore wind turbine locations in the United States, corresponding facility information, and turbine technical specifications. Watch our tutorial video.

The USWTDB contains 69,166 turbines with a total rated capacity of 124,550 MW
(zoom in to an area to calculate regional statistics)

When zoomed out, display turbine data as:
Density Heatmap ● Point Locations

Apply Range Filter to Turbines by:
● None ○ Height ○ Capacity ○ Year

Apply Color Ramp To Turbines by:
○ None ○ Height ● Capacity ○ Year
<1 MW >3 MW

Zoom In To List Projects in this Area

Figure 22. All United States wind farms, 2021. Color coded by capacity (blue=smaller, red=larger).[101]

Wind Farms, U.S.

The ideal location for a renewable hydrogen or ammonia plant is at the interconnection point where a directly-owned wind farm with high curtailment connects to the grid. Wind farms near commercial pricing nodes with high transmission congestion are especially well suited to renewable hydrogen projects. (For projects using captive power sources – a solar or wind farm dedicated to renewable hydrogen production – location is less important and can be chosen using other criteria.)

Wind Farms, Iowa

Iowa is home to 184 wind farms. The largest wind farm owners in Iowa are MidAmerican Energy Company and NextEra Energy Resources. MidAmerican, a utility, currently owns 59 wind farms and directly uses the power produced by them. NextEra owns 16 wind farms and sells the power to utilities and municipalities via contract agreements. Alliant Energy subsidiary, Interstate Power and Light, is the off-taker for 27 wind farms, but only directly owns three of those. The remaining wind farms are owned by investors, rural electric cooperatives, or municipalities.[102]

Wind farm owners that sell power to off-takers usually do so via power purchasing agreements (PPAs). Most PPAs in the wind energy industry are structured as take-or-pay contracts. Take-or-pay contracts require that the "purchaser will pay the seller not only for wind energy actually delivered to the point of delivery but also for 'available capacity,' or energy that would have been delivered but for the curtailment."[103]

Wind farm owners that sell power to off-takers via PPAs have little incentive to capitalize on curtailed power – they are already getting paid for it. Off-takers do have a financial incentive to use curtailed power, but may have not have the ability to do so if curtailment is driven by transmission constraints. Therefore, the best candidates for renewable hydrogen pilot projects are wind farms that are directly owned.[104]

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[101] B.D. Hoen, J.E. Diffendorfer, J.T. Rand, L.A. Kramer, C.P. Garrity, and H.E. Hunt, 2018, United States Wind Turbine Database (v4.1, (July 21, 2021): U.S. Geological Survey, American Clean Power Association, and Lawrence Berkeley National Laboratory data release, https://doi.org/10.5066/F7TX3DN0.

[102] "U.S. Wind Energy Projects – Iowa," (interactive map data), Clean Grid Alliance, accessed September 1, 2021, https://cleangridalliance.org/our-work/projects?gp=iowa.

[103] "Community Wind Toolbox Chapter 13: Power Purchase Agreement," Windustry (October 20, 2007), accessed August 23, 2021, https://www.windustry.org/community_wind_toolbox_13_power_purchase_agreement.

[104] Wilson, interview, May 12, 2020.

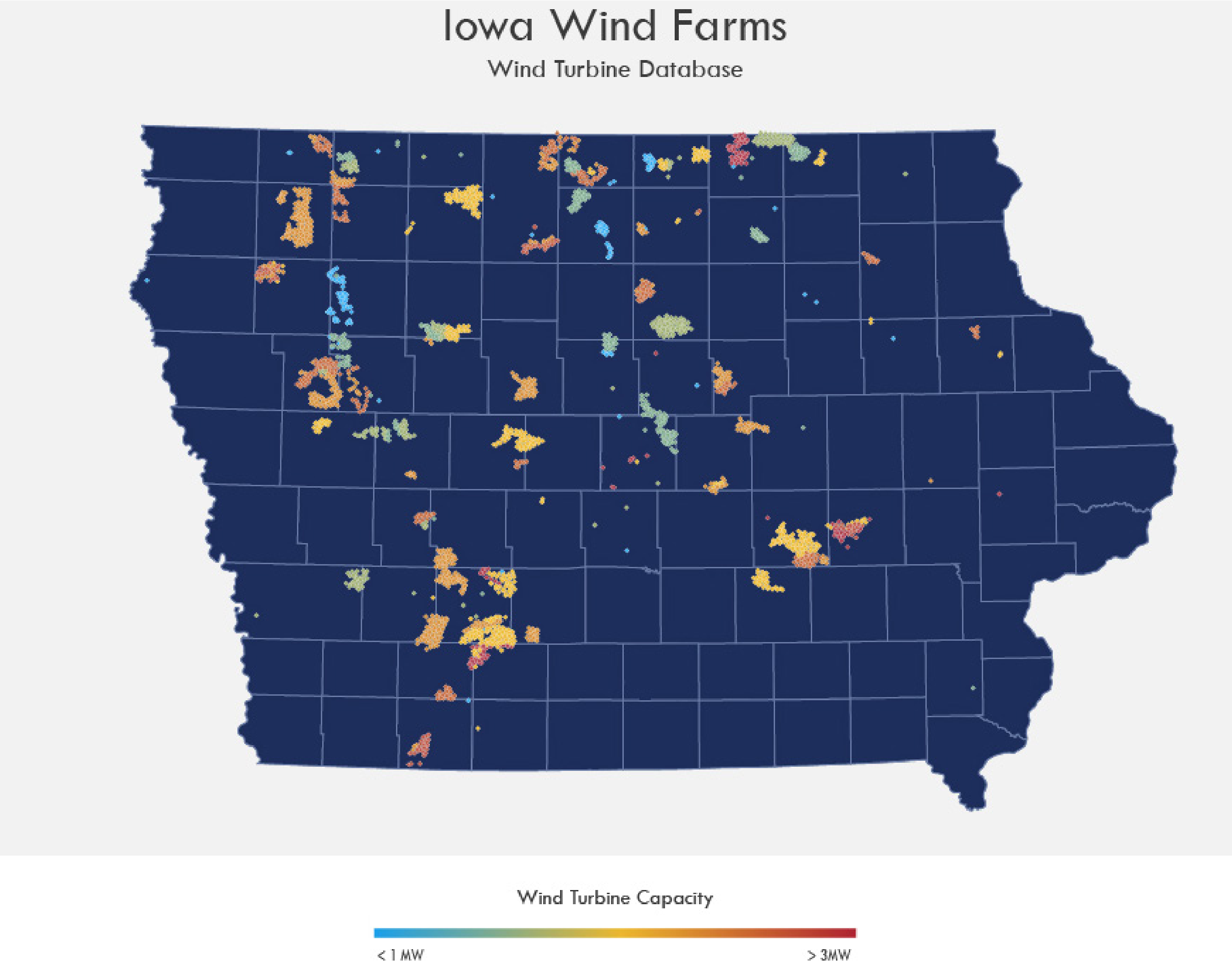

Figure 23. Iowa wind farms, 2021.[105]

Transmission Congestion & Curtailment

Iowa has significant transmission line constraints. These constraints prevent Iowa's wind farm operators from sending power to distant load centers with high demand, which in turn results in local surpluses of wind power. That surplus is *curtailed*.

Curtailment, which is "a reduction in the output of a generator from what it could otherwise produce given available resources (e.g., wind or sunlight), typically on an involuntary basis," is a normal part of wind or solar energy production.[106]

Curtailment of wind and solar energy is usually due to transmission constraints, though there are other causes, including grid stabilization requirements and excess production during times of low demand.

Curtailment data is proprietary. There is no publicly available, open-access source of curtailment data at the level of individual wind farms or solar installations. Wind farm owners are unlikely to share curtailment data publicly, though they may be willing to share this data with potential partners with appropriate non-disclosure agreements.

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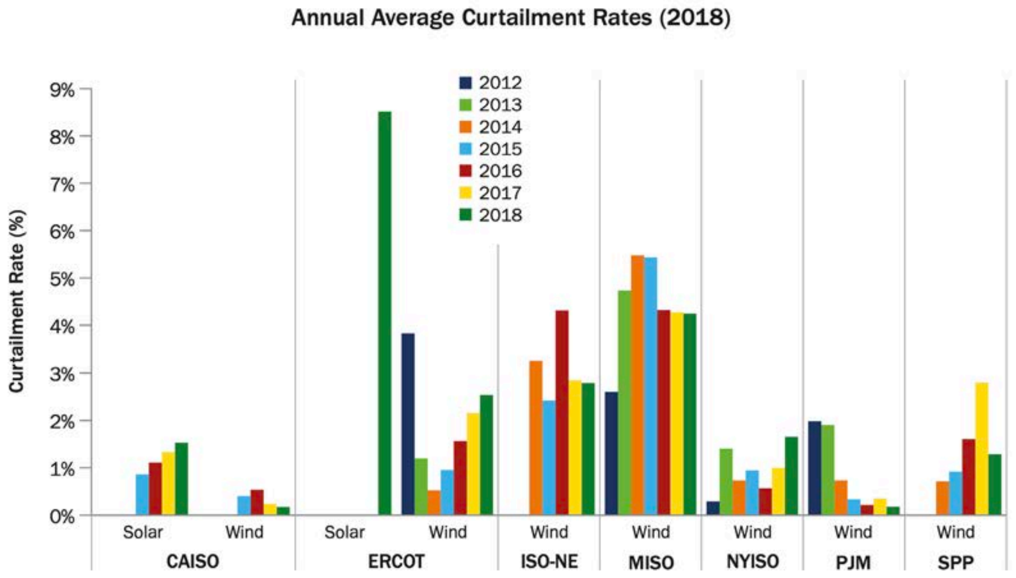
[105] Adapted from Hoen et al. United States Wind Turbine Database.

[106] Lori Bird, Jaquelin Cochran, and Xi Wang, *Wind and Solar Energy Curtailment: Experience and Practices in the United States*, (National Renewable Energy Laboratory, March 2014), 1. https://www.nrel.gov/docs/fy14osti/60983.pdf



Sources: Curtailment data collected from ISOs and reported in Wiser and Bolinger (2019) and Bolinger, Seel, and Robson (2019)
Notes: The depicted data include both "forced" (i.e., ISO-instructed) and "economic" (i.e., incentivized by prevailing LMP) curtailment. Solar curtailment data availability for ERCOT before 2016 is limited.

Figure 24. Annual average curtailment by ISO, 2018.[107]

Researchers at Iowa State University have indicated that it may be possible to estimate curtailment for individual wind farms using public data, including real-time monitoring of the MISO wholesale energy market, but there is as yet no published research on this topic.

Although fine-grained curtailment data is unavailable, ISOs do report curtailment averages. **Wind energy curtailment within MISO is particularly high. This represents an opportunity; curtailed wind power could instead be used to power renewable hydrogen production plants.**[108]

Curtailment Rates

Although curtailment data is proprietary at the level of individual wind farms, average rates of curtailment are available at the ISO level. Note that although both MISO and SPP operate in Iowa, most of Iowa is within MISO's territory.

The nationwide average wind curtailment rate was 3.4% in 2020. Wind curtailment has increased over the last five years, though efforts to reduce curtailment through the construction of additional transmission lines have been successful in some areas.[109]

Curtailment is especially high in ISOs that serve the central United States, including Iowa. MISO has the highest wind energy curtailment rate at 5%. MISO's wind curtailment rate has been above 4% since 2013 and continues to increase. SPP's curtailment rate is the third highest at 2.5% – nearly double its curtailment rate from just two years prior in 2018.

In 2020, the ISOs reported the following annual average curtailment rates:[110]

- MISO (5.0%)
- ERCOT (4.6%)
- SPP (2.5%)
- ISO-NE (1.5%)
- NYISO (1.4%)
- CAISO (0.6%)
- PJM (0.1%)

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[107] Office of Renewable Energy & Renewable Energy, *2018 Renewable Energy Grid Integration Data Book* (United States Department of Energy, February 2020), 83. https://www.nrel.gov/docs/fy20osti/74823.pdf

[108] Wilson, interview, May 12, 2020.

[109] Ryan Wiser and Mark Bolinger *et al.*, *Land Based Wind Market Report: 2021 Edition*, (U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, 2021), ix, 35.

[110] Wiser and Bolinger *et al.*, 2021, 35.

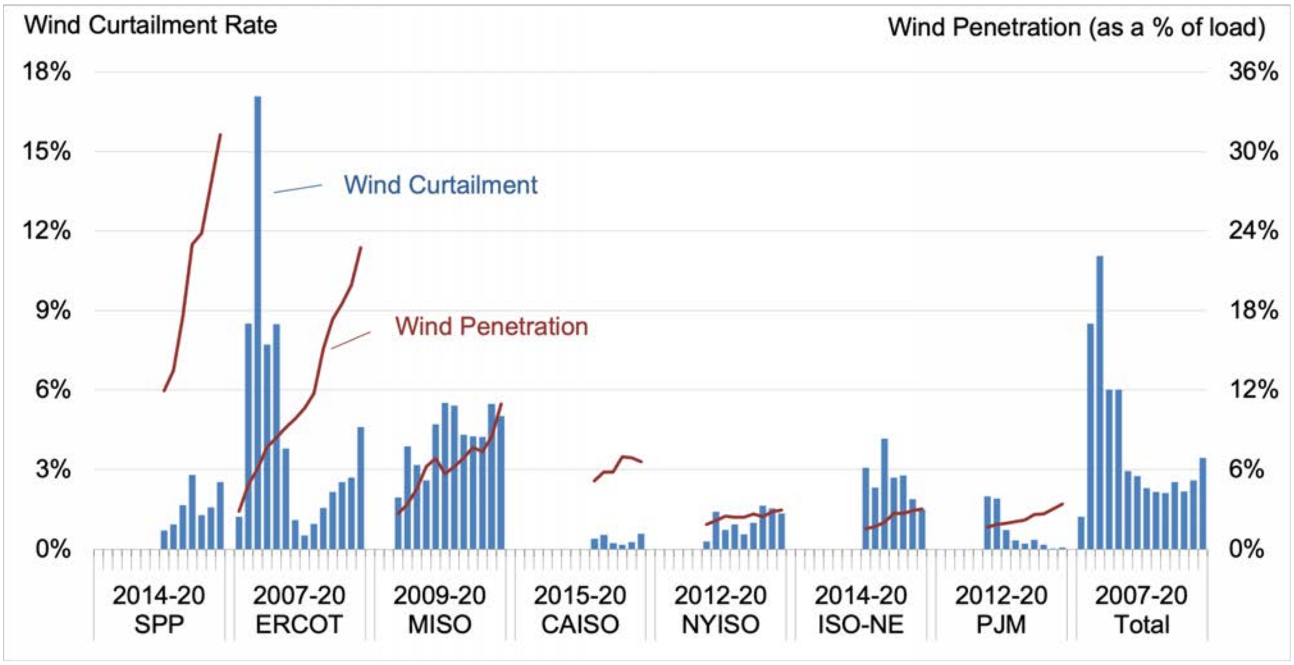

Figure 25. Annual average wind curtailment and wind penetration rates by ISO, 2020. Sources: ERCOT, MISO, CAISO, NYISO, PJM, ISO-NE, SPP.[111]

The high rate of wind curtailment within MISO and SPP indicates that wind-rich states like Iowa have an opportunity to use power that would otherwise go to waste. Excess wind energy could be used for renewable hydrogen production. Co-located renewable hydrogen projects near wind farms with the highest curtailment may be among the best choices for future projects.

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[111] Wiser and Bolinger *et al.*, 2021, 35.

Part VII – Existing Markets for Hydrogen & Ammonia

Ammonia Production and Market Size

Ammonia production represents a vast, existing market for renewable hydrogen. Hydrogen is the principle ingredient in the manufacturing of ammonia. Ammonia (NH_3) is made from hydrogen and atmospheric nitrogen using an artificial nitrogen fixing process called the Haber-Bosch process. The ammonia made from this process is critical to modern agriculture.

The global market for ammonia is currently valued at $74.61 billion and is expected to grow at a compound annual rate of 5.59% over the next five years.[112]

Approximately 88% of domestic ammonia is used for fertilizer in the form of anhydrous ammonia, urea, and other nitrogen compounds. As of 2019, ammonia was produced by 16 companies at 35 plants in 16 different state. Most ammonia is produced in Texas and Louisiana, but Iowa has several production plants.[113]

Iowa is a major agricultural state with the highest corn production in the nation by a wide margin and the second highest soybean production.[114] Iowa farmers use an average of 139 pounds of nitrogen fertilizer, including anhydrous ammonia, urea, and other fertilizers made from ammonia, per planted acre.[115] With approximately 23,619,000 acres planted – more than any other state – demand for nitrogen fertilizers in the state exceeds 1.5 million tons per year.

Brown, Blue, & Green Ammonia

The Royal Society describes three methods of ammonia production, differentiated by CO_2 emissions – the final product is identical.

- **Brown ammonia –** *Higher carbon ammonia made using a fossil fuel as the feedstock*
- **Blue ammonia –** *Low-carbon ammonia: brown ammonia but with carbon capture and storage technology applied to the manufacturing process*
- **Green ammonia –** *Zero-carbon ammonia, made using sustainable electricity, water and air.*[116]

Green ammonia can only be produced using renewable hydrogen. Currently, most hydrogen is made from natural gas using steam methane reforming. This process accounts for 90% of the CO_2 emissions from ammonia production. **Ammonia production accounts for 1.8% of all CO_2 emissions worldwide.[117]** This is an extremely high percentage for a single chemical manufacturing process. Substituting green ammonia made with renewable hydrogen for brown ammonia would significantly reduce global greenhouse gas emissions.

Iowa Agrichemical Industry

Iowa has several chemical plants or terminals involved in the transportation and production of ammonia products.

CF Industries

CF Industries operates one nitrogen plant and two terminals in Iowa. All three are connected to the NuStar ammonia pipeline and can also accept and ship product via other methods.

- **Port Neal Complex** in Sergeant Bluff, IA. Nitrogen plant producing ammonia, granular urea, urea ammonium nitrate, and diesel exhaust fluid. 2.3 million ton annual capacity.[118]

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[112] Koncept Analytics, *Global Ammonia Market (by Application & Region): Insights & Forecast with Potential Impact of COVID-19 (2021-2025), April 28, 2021*. https://www.konceptanalytics.com/report/chemicals/global-ammonia-market-by-application-region-insights-forecast-with-potential-impact-of-covid-19-2021-2025

[113] U.S. Geological Survey, *Mineral commodity summaries 2020* (United States Geological Survey, January 2020), 116-117. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf

[114] "Iowa's Rank in United States Agriculture," U.S. Department of Agriculture National Agricultural Statistics Service (July 15, 2020), https://www.nass.usda.gov/Statistics_by_State/Iowa/Publications/Rankings/IA-2020-Rankings.pdf

[115] U.S. Department of Agriculture Economic Research Service, "Fertilizer Use and Price," Table 10, (*raw data*), accessed September 1, 2021. https://www.ers.usda.gov/data-products/fertilizer-use-and-price/

[116] The Royal Society, *Ammonia: zero-carbon fertiliser, fuel and energy store, Policy briefing,* (The Royal Society, February, 2020), 12. https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/

[117] ibid., 4, 12.

[118] "Port Neal Complex," CF Industries, accessed September 15, 2021, https://www.cfindustries.com/who-we-are/locations/port-neal.

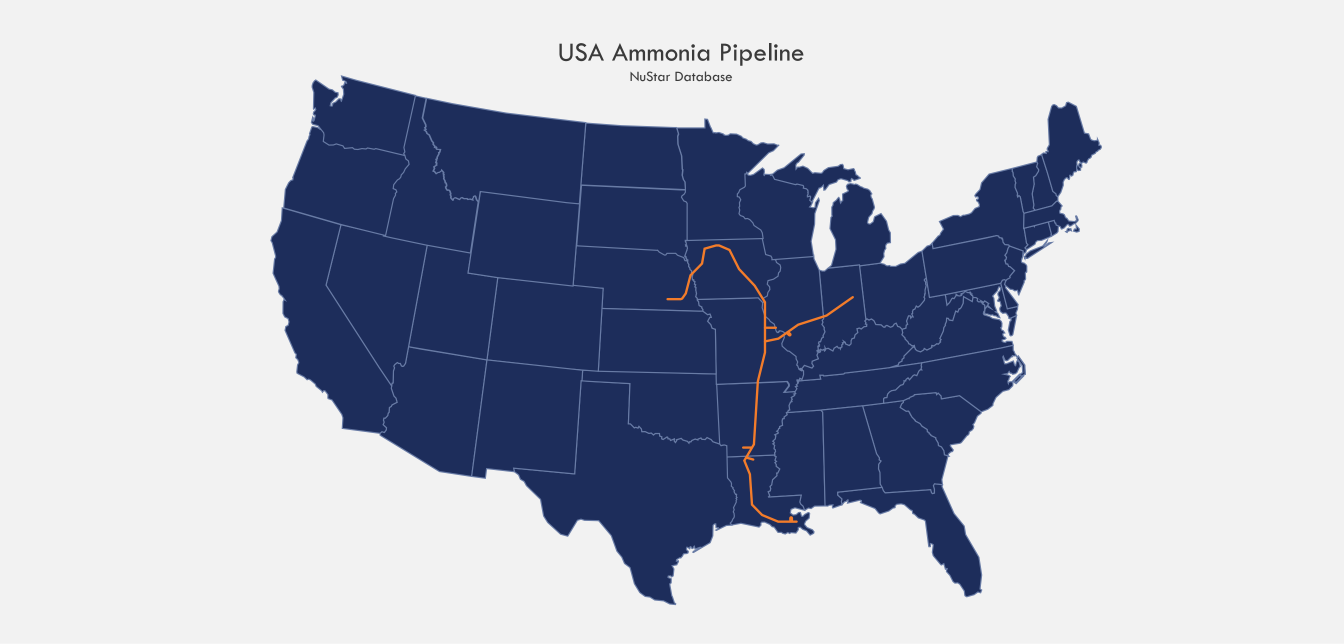

Figure 26. NuStar Ammonia Pipeline.[119]

- **Spencer Terminal** in Spencer, IA. Transshipment of ammonia delivered via pipeline and rail.[120]
- **Garner Terminal** in Garner, IA. Transshipment of ammonia and urea ammonium nitrate delivered via pipeline and rail.[121]

Iowa Fertilizer Company

Iowa Fertilizer Company (IFCo), located in Wever, IA, is the first new greenfield nitrogen plant – a plant built from scratch as opposed to an expansion of an existing plant – built in the U.S. in 30 years. IFCo is one of the largest nitrogen plants in the U.S. It produces a range of productincluding liquid ammonia, anhydrous ammonia, urea, and diesel exhaust fluid.[122]

Greenfield Nitrogen

Greenfield Nitrogen is an early-stage firm proposing a carbon-free, green ammonia plant in Garner, IA. Greenfield Nitrogen is currently in the pre-construction phase.[123]

Ammonia Pipeline Map

The NuStar Ammonia Pipeline is a 2,000-mile anhydrous ammonia pipeline originating in Louisiana in the Mississippi delta area. It is served by three marine terminals in the Mississippi delta and three anhydrous ammonia plants in Louisiana. It runs through Arkansas into Missouri where it forks, with one branch serving Illinois and Indiana, and the other serving Iowa and Nebraska.[124]

The pipeline is connected to multiple terminals owned by third-parties. Anhydrous ammonia is used as an agricultural fertilizer and as a feedstock to produce other fertilizers and chemicals. The Ammonia Pipeline transported an average of nearly 30,000 barrels per day in 2020.[125]

Although not all of the anhydrous ammonia shipped through the pipeline ends up in Iowa, the pipeline's throughput demonstrates the scale of demand for anhydrous ammonia in the Midwest.

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[119] *ibid.*, 4, adapted from map data.

[120] "Spencer Terminal," CF Industries, accessed September 15, 2021, https://www.cfindustries.com/who-we-are/locations/spencer-terminal.

[121] "Garner Terminal," CF Industries, accessed September 15, 2021, https://www.cfindustries.com/who-we-are/locations/garner-terminal.

[122] "Iowa Fertilizer Company," OCI, accessed September 15, 2021, https://www.oci.nl/operations/iowa-fertilizer-company/.

[123] "Iowa Fertilizer Company," OCI, accessed September 15, 2021, https://www.oci.nl/operations/iowa-fertilizer-company/.

[124] NuStar Energy L.P., Form 10-K 2020, San Antonio, Texas, 2021, retrieved https://investor.nustarenergy.com/static-files/de669172-5318-4a96-9593-8cf9b24960ef, 4, 9.

[125] *ibid.*, 9.

Part VIII – Future Markets for Hydrogen & Ammonia

Hydrogen can replace many of the fossil fuels we use today. It can be injected directly into the natural gas grid at up to 5-10% with no negative impact to infrastructure or safety. Projects already exist in Germany, France, and the U.K. featuring gas grid injection.[126,127]

Hydrogen has industrial uses as an essential ingredient in refineries, including refining carbon-neutral biofuels. Biodiesel production requires methanol, which can be made with renewable hydrogen. Hydrotreated vegetable oil, a carbon-neutral aviation fuel similar to biodiesel, also requires hydrogen to produce.

Hydrogen can be used to produce synthetic natural gas (SNG) via methanation. SNG is desirable for baseload power in areas with many natural gas power plants, like the Midwest. SNG production also requires carbon dioxide (CO_2), which could be provided by carbon capture at Iowa's 41 ethanol plants.

Hydrogen can be burned in modified peaking power plants. It can be transported for use in combined heat and power plants common in large facilities like universities and military bases. It can be stored on site to power fuels cells for use in grid stabilization or other energy storage applications.[128]

Ammonia and hydrogen can be mixed with coal to co-fire certain types of coal power plants at ratios of 20%. Projects are underway in Japan to convert "ultrasupercritical" coal plants to 100% ammonia fuel within the next two decades. These projects are likely to be replicated elsewhere.[129]

Hydrogen can be used in a variety of manufacturing processes. Industrial furnaces and kilns can burn hydrogen, often with little modification required. Manufacturing is Iowa's second largest industry and contributes 18.4% to the state's GDP.[130]

Hydrogen can power fuel cells in heavy transport applications, including truck and rail freight. Iowa is a crossroads state with significant cross-country truck freight traveling via I-80 and I-35. Truckers view Iowa as a desirable place to stop for fuel due to its convenient distance from major cities, including Chicago, St. Louis, Kansas City, Minneapolis, and Milwaukee.[131]

Freight Transportation in Iowa

Iowa is a transportation hub. Interstate 80 and Interstate 35 meet in Des Moines. The busiest freight rail line in the U.S. crosses through the state. Iowa has eight commercial and 100 publicly-owned general aviation airports. In addition, Iowa is bordered by the Missouri and Mississippi rivers, both of which are navigable.[132]

	2012		2020		2030		2040	
	Tons (millions)	Value ($ millions)	Tons (millions)	Value ($ millions)	Tons (millions)	Value ($ millions)	Tons (millions)	Value ($ millions)
Total	**1018.1**	**$563,313**	**1181.3**	**$656,952**	**1279.7**	**$740,262**	**1361.3**	**$838,457**
Within Iowa	243.2	$95,335	277.2	$108,407	297.2	$116,511	310.7	$124,380
From Iowa	397.3	$241,115	480.0	$286,210	537.1	$333,513	592.7	$392,457
To Iowa	377.6	$226,863	424.2	$262,335	445.4	$290,237	457.9	$321,619

Table 8. Commodity flows in Iowa, 2012-2040.[133]

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[126] Méziane Boudellal, *Power-to-Gas: Renewable Hydrogen Economy for the Energy Transition* (Berlin, Boston: De Gruyter, 2018), https://doi.org/10.1515/9783110559811, 110-111.

[127] Greg Wilson, "Renewable H$_2$ in Iowa: Technology Overview, Development & Partnering Opportunities," Fairfield, Iowa, June 16, 2020.

[128] Wilson, interview, May 12, 2020.

[129] Sonal Patel, "JERA Planning to Shift Coal Power Fleet to 100% Ammonia," POWER Magazine, November 20, 2020, accessed September 13, 2021. https://www.powermag.com/jera-planning-to-shift-coal-power-fleet-to-100-ammonia/

[130] Center for Industrial Research and Service (CIRAS), *Manufacturing in Iowa*, (Iowa State University, January 2018), 3-4. https://www.ciras.iastate.edu/files/publications/Manufacturing_In_Iowa_2018.pdf

[131] Bob Rafferty, (Transportation Industry Expert), interviewed by Eric Johnson via Zoom, August 30, 2021.

[132] *Iowa State Freight Plan*, Iowa Department of Transportation, (2017, amended 2021), retrieved https://iowadot.gov/iowainmotion/Specialized-System-plans/2017-State-Freight-Plan, 82.

[133] *Iowa State Freight Plan*, 63, Table 5.1.

Freight movement in Iowa (including freight transportation into Iowa, within Iowa, and from Iowa via all transportation modes) was 1.1 billion tons in 2012, the most recent year data was available. This figure is expected to grow 35.6% by 2040.[134]

"Commodity movement in the state is dominated by agriculture-related products," according to the Iowa Department of Transportation (Iowa DOT).[135] Cereal grains are the number one commodity by both tonnage and value, and are forecast to remain in the top position by tonnage in 2040. Machinery is expected to move from the number two to number one commodity by value in 2040.

Freight transport is likely to begin shifting to renewable fuel sources during the coming decade. Given the large amount of freight movement in Iowa, heavy transport – particularly by truck and rail – is a possible source of future hydrogen demand.

Truck Freight

The Iowa DOT states that "the overwhelming majority (80 percent) of freight tonnage in Iowa is moved by truck."[136] As of today, it is too early to tell if long-distance trucking will move to electrification or a renewable fuel like biodiesel, hydrogen, or ammonia.[137] If the trucking industry does move to renewable hydrogen or green ammonia as a fuel source, Iowa is well positioned to provide fuel via the state's large truck stops on I-80 and I-35.

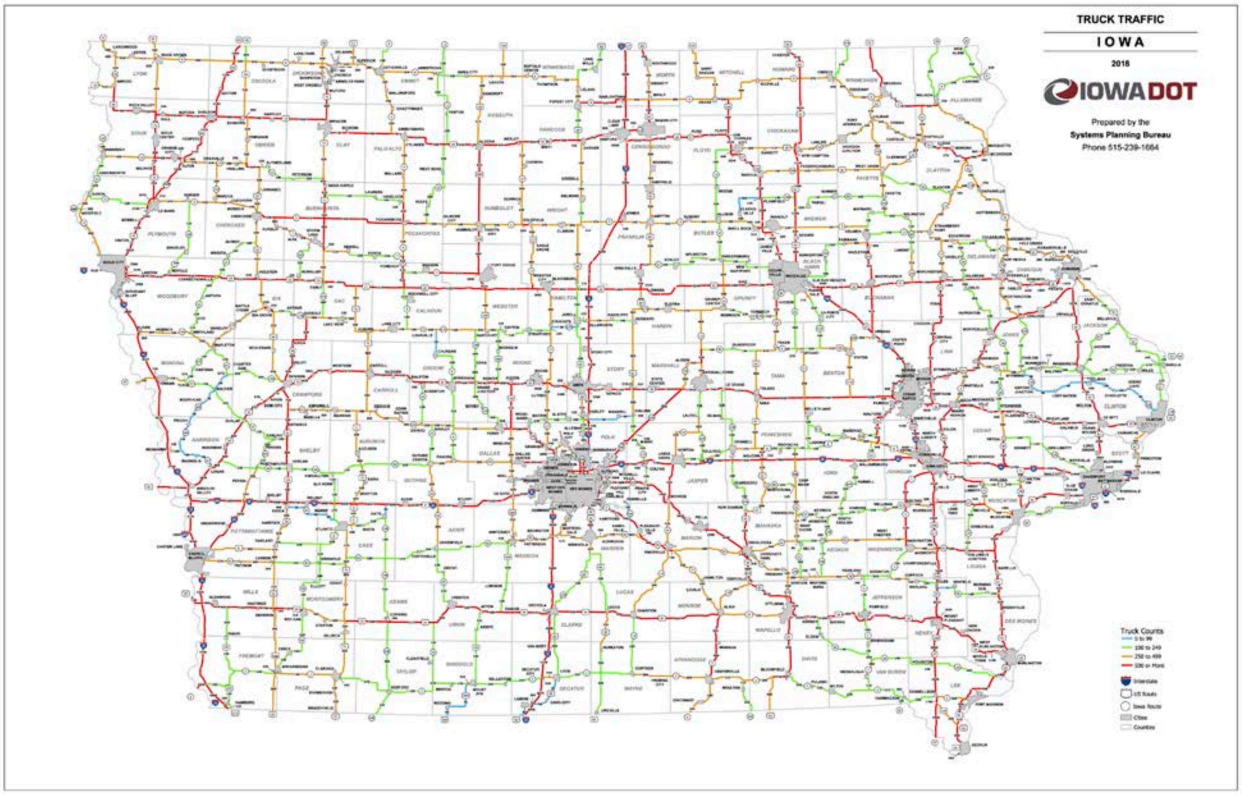

Figure 27. Iowa truck traffic density, 2018.[138]

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[134] *Iowa State Freight Plan*, 62.

[135] *Iowa State Freight Plan*, 70.

[136] *Iowa State Freight Plan*, 116.

[137] Wilson, interview, May 12, 2020.

[138] "Truck Traffic, 2018," (map), Iowa Department of Transportation, accessed September 1, 2021, https://iowadot.gov/maps/msp/pdf/TruckTrafficMap.pdf.

Rail Freight

The busiest rail freight route in the nation crosses through Iowa east to west. From 1985 to 2014 (the most recent year for which there is data) Iowa's rail operating miles, net ton-miles, and revenue per ton have all increased. Spending on maintenance and improvements has also increased. These signs point toward continuing growth of Iowa's rail industry. "Operating revenues and overall net ton-miles of the railroads are an indicator of the condition and performance of the rail system," according to the Iowa DOT.[139]

Electrification of freight rail is unlikely in the U.S. due to the massive infrastructure overhaul required. Renewable fuels derived from hydrogen are a more probable clean energy source for freight trains. Trains can be powered by carbon-free biodiesel with little or no modification, internal combustion engines designed to burn hydrogen or ammonia, or hydrogen fuel cells.[140] Hydrogen fuel cell locomotives are currently in the developmental stage in California.[141]

Barriers to Integration with Heavy Transport

There are two major obstacles to the adoption of hydrogen in heavy truck transport: the lack of hydrogen refueling infrastructure and hydrogen vehicle availability. It is likely that either hydrogen vehicle manufacturers or fleet operators will have to pay to install a significant number of hydrogen fueling stations before adoption of heavy transport vehicles becomes widespread.

The same problems exist for rail freight, though it may be easier to overcome in the more vertically integrated rail industry.

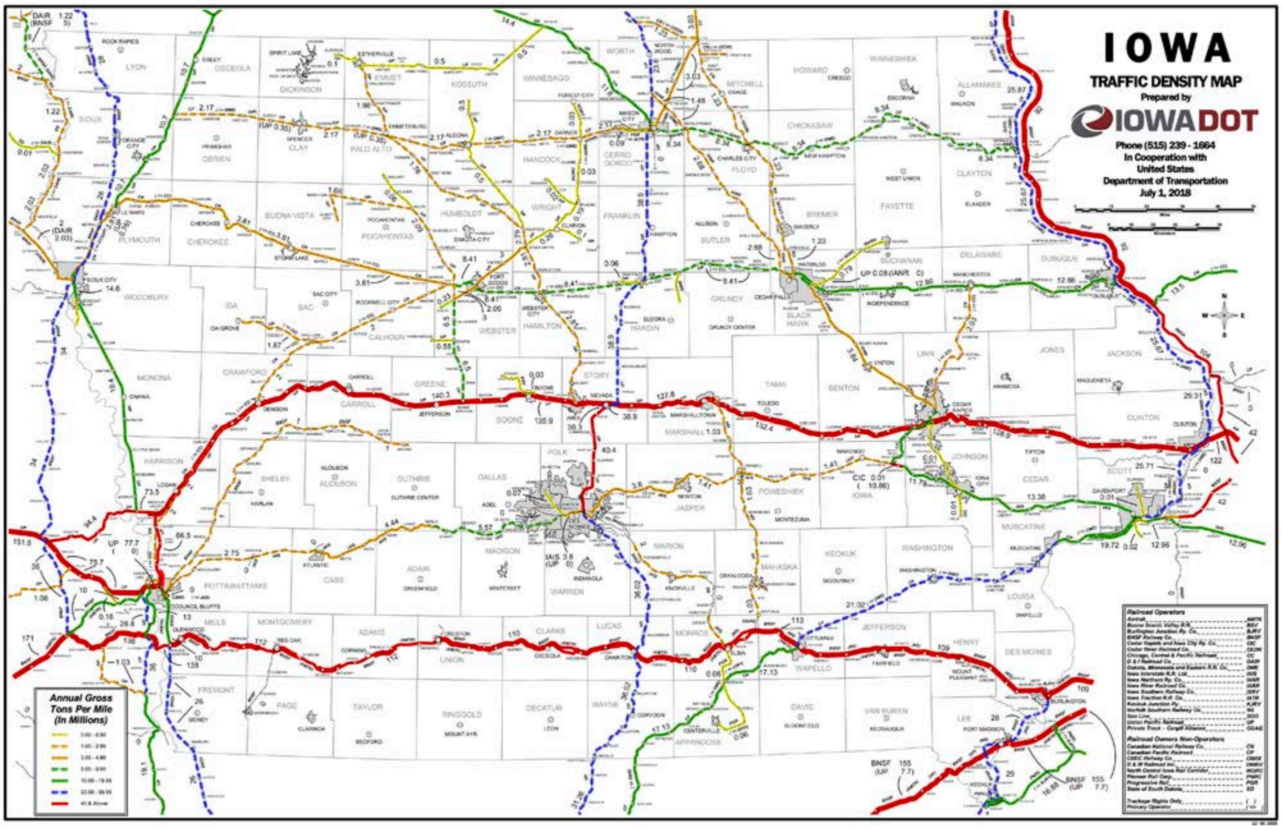

Figure 28. Iowa rail freight tonnage, 2018. [142]

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139 *Iowa State Freight Plan*, 130-131.

140 Wilson, interview, May 12, 2020.

141 Sierra Northern, "California Energy Commission awards Sierra Northern Railway Team nearly $4,000,000 to build and test Hydrogen Switcher Locomotive," (*news release*), Sierra Northern, March 18, 2021, accessed September 15, 2021, http://sierranorthern.com/news/articles/california-energy-commission-awards-sierra-northern-railway-team-nearly-4-000-000-to-build-and-test-hydrogen-switcher-locomotive/.

142 "Traffic Density, 2018," (map), Iowa Department of Transportation, accessed September 1, 2021, https://iowadot.gov/iowarail/railroads/maps/Density.pdf.

Bus Systems

School Bus Fleets

Iowa has 327 school districts as of 2020. Those school districts drove a cumulative total of over 41 million bus miles (30,892,197 route miles and 10,319,041 non-route miles) transporting an average of 249,663 students per year.[143]

Several projects in Europe have already demonstrated the viability of powering bus fleets with renewable hydrogen. For example, Aberdeen H_2 is currently powering 6 hydrogen fuel cell buses in Aberdeen, Scotland using a 1 MW electrolyzer. London's 3Emotion project has a fleet of 20 hydrogen fuel cell buses. Additional hydrogen buses are operating in Cologne and Wuppertal, Germany.[144]

Mass Transit

There are several transit systems in the state with significant ridership that could use renewable hydrogen-powered buses. There is already appetite for clean energy in public transportation in Iowa.[145] CyRide in Ames currently has 12 hybrid-electric buses in its fleet.[146]

Total annual public transportation ridership in Iowa was 23,828,108 in 2019, the most recent year of data. Annual revenue miles were 29,876,531.[147]

Barriers to Integration with Bus Fleets

As self-contained systems, public transport systems and school bus fleets do not have the same barriers as heavy transport. Project funding and competition from electric vehicles (EVs) are likely the most significant barriers. Initial purchase price – including hydrogen fuel cell buses, a refueling station or stations, and a hydrogen production facility – far exceeds the cost of a similar number of diesel or EV buses. Although such projects can be competitive over the long term, up front funding can be a challenge. Competition from EV buses may also dampen enthusiasm for hydrogen fuel cell buses.

Biofuels

Renewable hydrogen is a necessary part of the refining process for producing fully renewable biodiesel and similar fuels.

Traditionally, biodiesel is produced using a process called transesterification, which requires methanol. Most methanol is sourced from fossil fuels, but it can also be produced using renewable hydrogen and captured carbon dioxide.

TOP FIVE TRANSIT SYSTEMS	RIDERSHIP	REVENUE MILES
Ames (CyRide)	6,121,023	1,324,351
Des Moines (DART)	4,395,395	5,767,440
University of Iowa (Cambus)	3,474,572	749,902
Iowa City	1,583,166	1,029,923
Cedar Rapids	1,333,692	1,402,958

Table 9. Annual ridership and revenue miles of Iowa's largest public transit systems.[148]

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143 "Transportation Publications and Data, 2019–2020 Annual Transportation Data for Iowa Public Schools," (*raw data*), Iowa Department of Education, accessed September 15, 2021, https://educateiowa.gov/pk-12/school-transportation/transportation-publications-and-data.

144 "Jive," Joint Initiative for hydrogen Vehicles across Europe, (*interactive map data*), accessed September 15, 2021, https://www.fuelcellbuses.eu/projects/jive.

145 Samuel Hiscocks, Garrett Pedersen, Justin Meade, Hector Torres-Cacho, (Freight Planning Coordinator, Iowa DOT, and colleagues), interviewed by Eric Johnson via Zoom, September 8, 2021.

146 "Active Fleet," (*raw data*), CyRide, accessed September 15, 2021, https://www.cyride.com/about-us/fleet-information/active-fleet.

147 "STA Fund Allocation (Estimate), Allocation Year 2022," (*raw data*), Iowa Department of Transportation, accessed September 15, 2021, https://iowadot.gov/transit/pdf/STAFundAllocationforFY2022.pdf.

148 *ibid.*

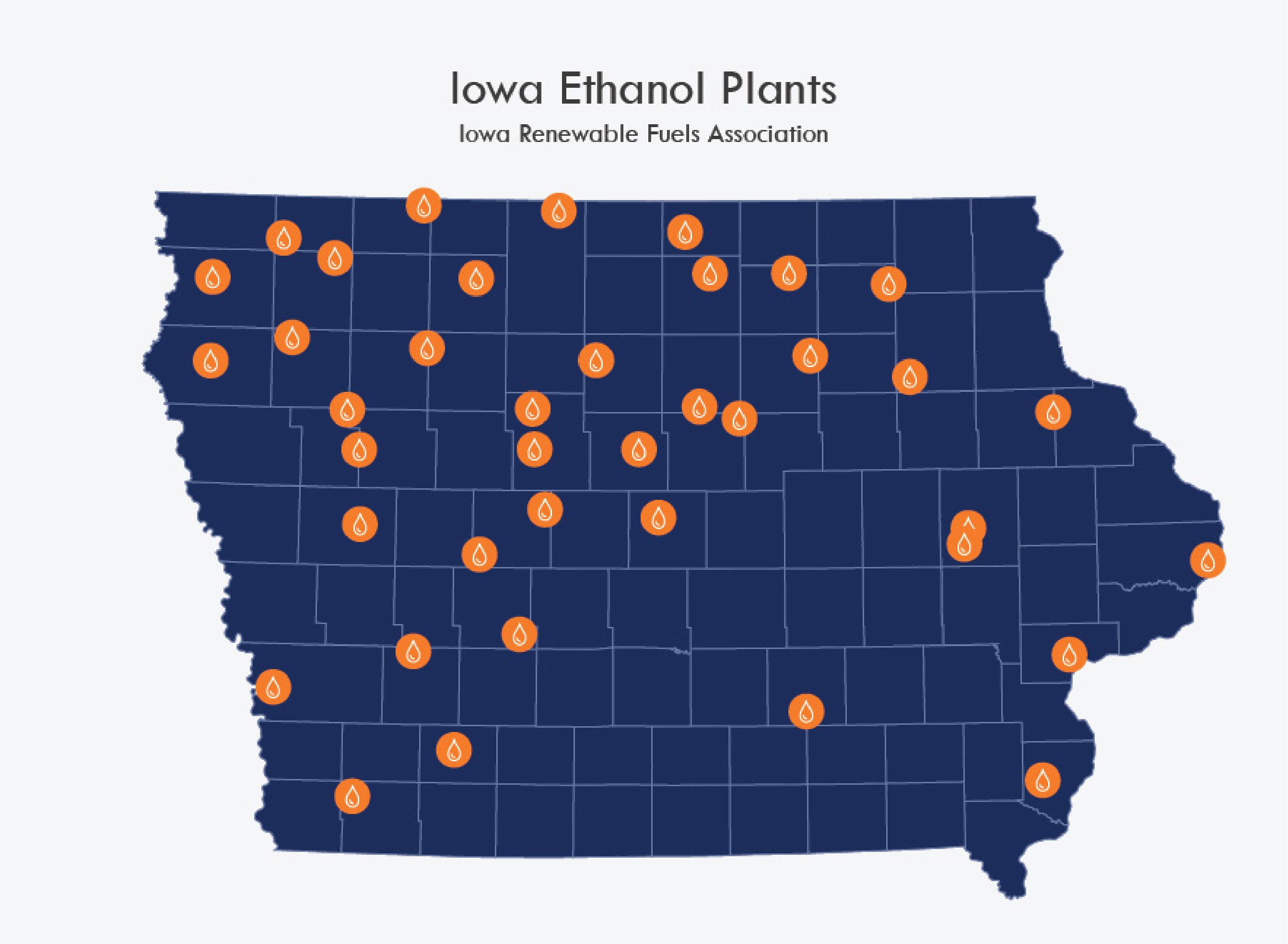

Figure 29. Iowa ethanol biorefineries.[149]

An alternative process for producing a biodiesel variant called hydrotreated vegetable oil (HVO) uses hydrocracking or hydrogenation – both of which require hydrogen as a feedstock. HVO is gaining ground in Europe as a carbon-neutral aviation fuel.[150]

Although demand for gasoline is expected to decline due to electrification of light duty vehicles, demand for renewable diesel is expected to increase.[151] Renewable diesel demand will also be driven by California's Low Carbon Fuel Standard, particularly if it is replicated by other states.[152]

Synthetic natural gas (SNG), also called renewable natural gas, is another renewable fuel that requires a renewable hydrogen source. In addition, it requires captured carbon dioxide – which can be provided by Iowa's 41 ethanol plants.

Ethanol Plants, Iowa

Iowa has 41 active ethanol plants producing 4,466,000,000 gallons of conventional ethanol and 34,000,000 gallons of cellulosic ethanol every year.[153]

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[149] *ibid.* Adapted from Iowa Renewable Fuels Association raw data and map.

[150] Camilla Naschert, "Biofuel's thirst for green hydrogen opens new market for utilities," S&P Global Market Intelligence, Feb 10, 2021, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/biofuel-s-thirst-for-green-hydrogen-opens-new-market-for-utilities-62406439

[151] Greg Wilson, email to author, September 3, 2021.

[152] "Low Carbon Fuel Standard," California Air Resource Board, accessed September 10, 2021, https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard

[153] "Iowa Ethanol Biorefineries," (*raw data & map*), Iowa Renewable Fuels Association, accessed September 10, 2021. https://iowarfa.org/ethanol-center/ethanol-biorefineries/

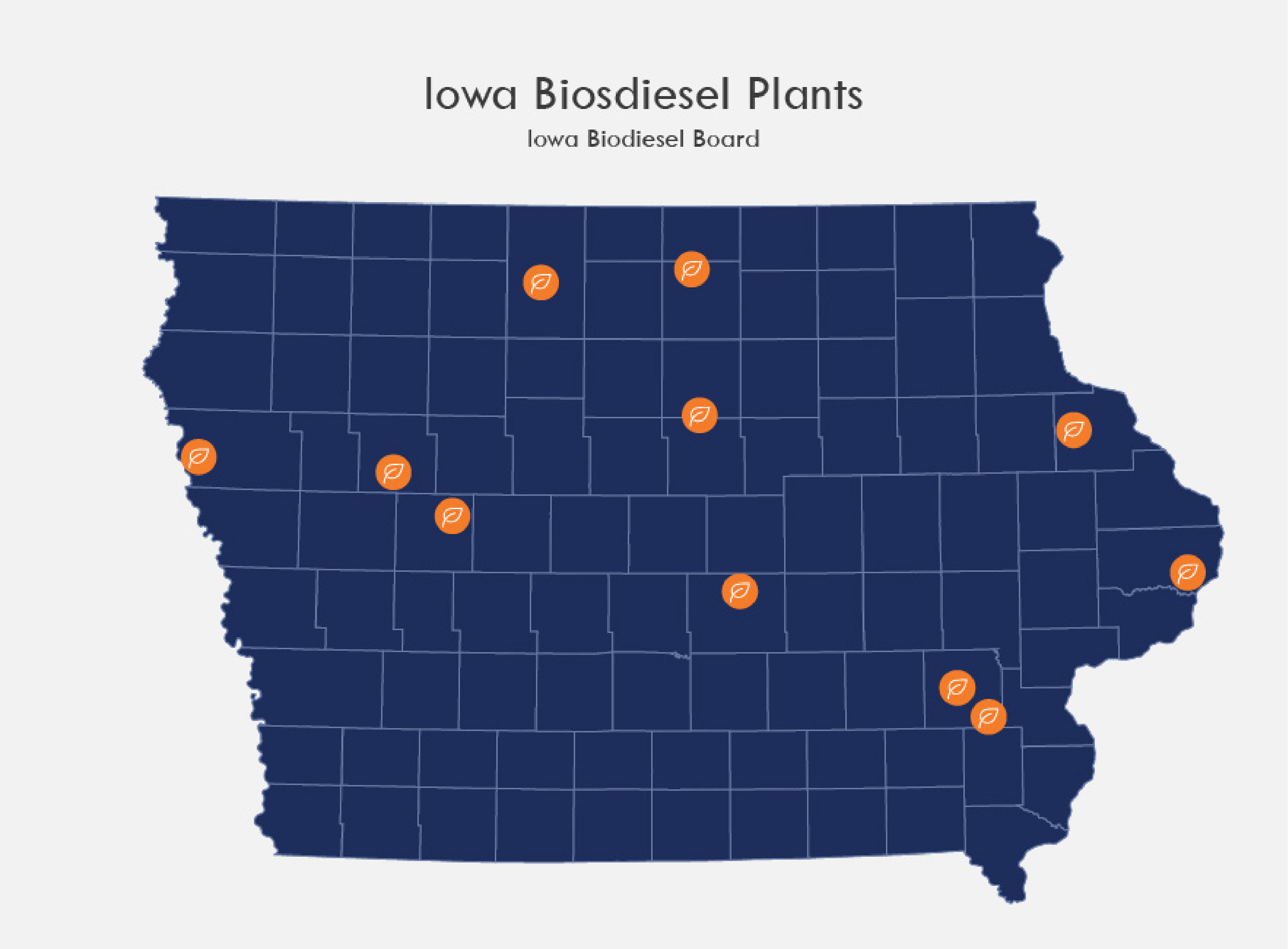

Figure 30. Iowa biodiesel plants [154]

Biodiesel Plants, Iowa

Iowa has 11 biodiesel plants producing 391,000,000 gallons of fuel every year.[155]

Barriers to Integration with Biofuels

The principle barriers to integration with biodiesel production are the availability of renewable methanol made with hydrogen, and the price of that renewable methanol. The principle barrier to integration with HVO production is lack of demand for HVO. Interest is growing in Europe, but at this time HVO does not have high demand anywhere.

Hydrogen is not used in the production of ethanol, using either the wet-mill process or dry-mill process. However, ethanol and hydrogen may potentially become interrelated. Carbon dioxide from the fermentation stage of ethanol production could be captured and used to make renewable methanol for biodiesel production. Biomass waste from ethanol production could be used as a feedstock to make renewable hydrogen using pyrolysis or thermolysis in a process unrelated to electrolysis (and therefore beyond the scope of this paper).

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[154] *ibid.* Adapted from Iowa Biodiesel Board raw data and map.

[155] "Plant Locations," (raw data and map), Iowa Biodiesel Board, accessed September 10, 2021. https://www.iowabiodiesel.org/iowa-biodiesel/plant-locations

Part IX – Federal Renewable Hydrogen Policy

Inflation Reduction Act

On Tuesday, August 16, 2022, President Biden signed the Inflation Reduction Act into law.[156] The Inflation Reduction Act (IRA) contains many renewable energy and climate change-related provisions.[157]

In addition to extending the Investment Tax Credit (ITC) and Production Tax Credit (PTC) for 10 years, applying the ITC and PTC to standalone battery energy storage systems in addition to wind and solar, providing new incentives for electric vehicles, subsidizing the nuclear power industry, and more, the IRA also ushers in a new clean hydrogen credit.

Clean Hydrogen Credit

The IRA creates a technology-neutral 10-year production credit for clean hydrogen under Section 45V of the Act. Projects must be placed in service before 2033 to qualify.

Because the credit is not tied to a particular technology, both renewable (green) hydrogen facilities and SMR with CCS (blue) hydrogen facilities can qualify if they meet carbon intensity standards.

The credit is available in four tiers, based on lifecycle carbon intensity, measured in kg of CO_2 equivalent (CO_2e) per kg of H_2. The maximum carbon intensity allowable to claim a credit is 4 kg CO_2e / kg H_2. The GREET model developed by Argonne National Laboratory[158] will be used to determine well-to-gate lifecycle greenhouse gas emissions.

The base credit is \$0.60/kg H_2 produced. The four tiers are as follows:

- <0.45 kg CO_2e / kg H_2 – 100% percent of \$0.60 credit = \$0.60/kg H_2
- 0.45¬–1.5 kg CO_2e / kg H_2 – 33.4% percent of \$0.60 credit = \$0.20/kg H_2
- 1.5–2.5 kg CO_2e / kg H_2 – 25% percent of \$0.60 credit = \$0.15/kg H_2
- 2.5–4 kg CO_2e / kg H_2 – 20% percent of \$0.60 credit = \$0.12/kg H_2

The credit available to each of these tiers is multiplied by five if labor requirements are met, or if construction begins prior to the "Act Beginning Construction Deadline". Under these circumstances, the base credit becomes \$3.00/kg H_2.

The labor requirements include a prevailing wage requirement and an apprenticeship hours requirement. The Act Beginning Construction Deadline is no later than 60 days after the Secretary of Labor issues labor requirement guidance.

The prevailing wage requirement states that laborers and mechanics (including subcontractors) involved in the construction, alterations, or repair of the facility must be paid at least prevailing wages for similar work in the area. Prevailing wages will be determined by the Secretary of Labor.

The apprenticeship requirement states that apprenticeship hours must be at least 10% of total hours for projects begun before January 1st, 2023; at least 12.5% for projects begun during 2023; and at least 15% for projects begun after January 1st, 2024.

If these requirements are met, and the 5x multiplier is applied, the four credit tiers are as follows:

- <0.45 kg CO_2e / kg H_2 – 100% percent of \$3.00 credit = \$3.00/kg H_2
- 0.45¬–1.5 kg CO_2e / kg H_2 – 33.4% percent of \$3.00 credit = \$1.00/kg H_2
- 1.5–2.5 kg CO_2e / kg H_2 – 25% percent of \$3.00 credit = \$0.75/kg H_2
- 2.5–4 kg CO_2e / kg H_2 – 20% percent of \$3.00 credit = \$0.60/kg H_2

A \$3.00/kg credit will make many renewable hydrogen projects cost-competitive with traditional SMR hydrogen. In

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[156] The White House, "Bill Signed: H.R. 5376," The White House, August 16, 2022, https://www.whitehouse.gov/briefing-room/legislation/2022/08/16/bill-signed-h-r-5376/.

[157] "H.R.5376 - 117th Congress (2021-2022): Inflation Reduction Act of 2022," legislation, August 15, 2022, 2021/2022, http://www.congress.gov/.

[158] "GREET Model," Argonne National Laboratory, accessed August 18, 2022, https://greet.es.anl.gov/.

some cases, renewable hydrogen production will be cheaper than SMR.

Renewable hydrogen production costs in Iowa – already projected to be cost-competitive with SMR – may very well end up significantly below typical SMR costs.

The Infrastructure Investment and Jobs Act

On November 15, 2021, after several months of back-and-forth amendments in Congress, the Infrastructure Investment and Jobs Act was signed into law by President Biden.[159] It contains a number of provisions that will affect the hydrogen industry.[160] Some of the key provisions of the Infrastructure Act are as follows:[161]

- Authorizes $9.5 billion in spending for clean hydrogen, including
    - $8 billion for development of large-scale Regional Clean Hydrogen Hubs,
    - $1 billion for Clean Hydrogen Electrolysis Research and Development,
    - $500 million for Clean Hydrogen Manufacturing and Recycling.
- Directs federal government to develop national hydrogen roadmap and strategy.
- Defines clean hydrogen.

Regional Clean Hydrogen Hubs

The Infrastructure Act calls for the creation of four regional clean hydrogen hubs, defined as "a network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity."

These will have feedstock diversity, with at least one each using renewable energy, nuclear energy, and fossil fuels. They will also have end-use diversity, with at least one each providing for electric power generation, industrial applications, residential & commercial heating, and transportation. Finally, they will be located in diverse geographic areas.

The Secretary of Energy has until May 14, 2022 (180 days) to begin soliciting proposals and one year from the solicitation date to select four hubs. The Department of Energy has $8 billion available for this project, which can be spent on grants to the hydrogen hubs.

The location of the regional clean hydrogen hubs is of particular interest to Iowans. The employment and economic impact of hosting a hub will be substantial. The four states chosen as hydrogen hub locations will reap rewards far in excess of their share of the $8 billion funding made available by the Infrastructure Act. As demonstrated in the economic and employment analysis, European research indicates that every billion euros of investment in renewable hydrogen is expected to create 10,000 jobs along the supply chain. If the U.S. sees a similar economic impact from hydrogen investment, a hydrogen hub in Iowa could yield thousands of new jobs in the state.

Clean Hydrogen Research and Development

The Infrastructure Act sets a budget of $1 billion for clean hydrogen research and development funding. This R&D program is meant to:

- establish technology cost goals;
- encourage production of clean hydrogen from diverse energy sources;
- encourage use of clean hydrogen in a variety of

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[159] "Executive Order on Implementation of the Infrastructure Investment and Jobs Act," The White House, November 15, 2021, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/11/15/executive-order-on-implementation-of-the-infrastructure-investment-and-jobs-act/.

[160] The Infrastructure Act does not include any hydrogen tax credits or similar incentives. Those were included in the proposed Build Back Better Act, a budget reconciliation bill, which contained provisions meant to be complementary to those in the Infrastructure Act. As of the publication of this report, the Build Back Better Act has not passed and appears unlikely to pass. Hydrogen tax incentives have not been proposed separately from Build Back Better at this time.

[161] Section 40311 through Section 40315 of the Infrastructure Investment and Jobs Act, H.R. 3684, 117th Cong. (2021).

settings, including residential, commercial, and industrial;
- improve safety and efficiency of both delivery and storage;
- study vehicle, locomotive, marine, and airplane applications;
- promote domestic clean hydrogen equipment manufacturing;
- encourage use of clean hydrogen for transportation, including light vehicles, heavy transport, rail, and maritime.

The Infrastructure Act does not enumerate specific research projects. The Secretary of Energy is expected to work with industry and other stakeholders to flesh out the details of the R&D program.[162]

Clean Hydrogen Electrolysis Research and Development

The Infrastructure Act also sets a budget of $1 billion to support hydrogen production using electrolyzers. This money will be spent on research, development, demonstration, commercialization, and deployment. The goal of the program is to produce hydrogen for $2/kg or less by 2026.

The Secretary of Energy is directed to fund demonstration projects and to offer grants to eligible entities. Eligibility will be determined by the Secretary. Demonstration projects are supposed to produce clean hydrogen via electrolysis while validating commercial feasibility. Grants will be awarded on a competitive basis and should "provide the greatest progress toward achieving the goal of the program" which is sub-$2/kg hydrogen.

At the time of this report's publication the exact grant criteria are unknown. However, organizations with renewable hydrogen pilot projects currently in the planning phase should watch this program closely to see if they can take advantage of this funding source.

Clean Hydrogen Manufacturing and Recycling

The Infrastructure Act also established $500 million in grant funding for clean hydrogen raw materials and equipment manufacturing & production, as well as reuse & recycling.

Hydrogen producers are more likely to receive these grants if they:

- increase efficiency and cost-effectiveness in manufacturing;
- support domestic supply chains;
- incorporate nonhazardous alternative materials for components and devices;
- partner with tribal organizations;
- are located in economically distressed areas of the major natural gas-producing regions of the United States.

Clean Hydrogen Definition

In addition to providing funding for various renewable hydrogen program, the Infrastructure Act creates a minimum statutory definition of clean hydrogen and sets a timetable to establish a more precise standard.

- The bill sets a maximum carbon intensity of 2 kilograms of carbon dioxide per kilogram of hydrogen to be considered clean hydrogen.
- The Secretary of Energy has 180 days to define clean hydrogen more precisely.
- The Secretary has to include the EPA, industry, and other stakeholders in this process.
- The Secretary must revisit the definition in 5 years to determine if it should be revised.
- Hydrogen from any source can be considered clean if it meets this standard.

A carbon intensity of 2 kg CO_2 per 1 kg of H_2 (or 2:1) is approximately 1/5 of the carbon intensity of hydrogen

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[162] Peter Connors and Matthew Neuringer, "Key Hydrogen Provisions of the Bi-Partisan Infrastructure Plan," Orrick Herrington & Sutcliffe LLP (August 13, 2021), accessed November 15, 2021, https://www.orrick.com/en/Insights/2021/08/Key-Hydrogen-Provisions-of-the-Bi-Partisan-Infrastructure-Plan.

produced from natural gas using steam methane reforming (SMR). Hydrogen made with SMR has a carbon intensity of approximately 9.3 kg CO_2 per 1 kg H_2.[163]

A 2:1 carbon intensity may be achievable using fossil fuels with carbon capture and sequestration (CCS) – known as 'blue hydrogen.' A 2:1 carbon intensity is easily achievable with renewable hydrogen made using electrolyzers powered by wind or solar energy.

Because the 2:1 ratio set by the Infrastructure Act is a maximum carbon intensity, the Federal government could impose a stricter standard either now or in the future. The initial 180 day window presents an opportunity for private industry and other stakeholders to work with the government in setting the initial standard.[164]

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[163] Robert Rapier, "Estimating The Carbon Footprint Of Hydrogen Production," Forbes (June 6, 2020), accessed November 15, 2021, https://www.forbes.com/sites/rrapier/2020/06/06/estimating-the-carbon-footprint-of-hydrogen-production/. Note: This calculation is based on real-world numbers from Praxair, a major producer of hydrogen.

[164] The Inflation Reduction Act sets different – and stricter – standards for clean hydrogen.

Part X – Geopolitics and Renewables: The Ukraine War and Europe's Renewable Hydrogen Push

The war in Ukraine has brought renewable energy and energy independence front and center in national security discussions. Renewable hydrogen figures prominently in these discussions, particularly in Europe.

Europe's Energy Dependence

Europe is heavily dependent on Russian oil and gas imports. Russia is the principle importer of energy to Europe, providing 39.2% of the EU's natural gas supply and 24.8% of the EU's crude oil supply as of 2021.[168]

Europe is a net energy importer, with 57.5% of European Union energy coming from imports as of 2020. Every EU member state and almost every European nation is a net energy importer. Primary energy production has declined in Europe since 2010. France produces the greatest share of its own energy, due in large part to its nuclear program.[169]

Europe's reliance on Russian gas is not only a security liability; it is also seen by many Europeans a form of complicity with Russia's war. Germany alone pays Russia over 200 million euros per day for natural gas.[170]

Planned Closures and 'Fossil Backsliding'

Prior to the February invasion, EU member states had given themselves aggressive decarbonization targets. For example, in 2020, Germany finalized plans to phase out all coal power by 2038. (Germany currently gets around 35.4% of its power from coal.)[171]

With the indefinite suspension of the Nord Stream 2 pipeline,[172] and now Russia cutting gas exports to Europe by 60%,[173] Europe – and especially Germany – will have to look elsewhere to make up for the energy shortfall.

European nations have addressed the energy shortfall in several ways, including gasoline subsidies in Germany, increased coal-burning at existing power plants in the Netherlands and Italy, and reactivating decommissioned coal plants in Germany and Austria. Germany has authorized the construction of 12 new liquified natural gas (LNG) terminals. In addition, the Group of 7 is weighing several proposals, including oil import price caps and a reversal of a ban on public investment in overseas fossil fuel projects.[174]

There has been some handwringing about this "fossil backsliding" among European nations, but it is viewed as a geopolitical necessity in European capitals.[175]

Nuclear Renaissance

Nuclear energy has both proponents and detractors in Europe, with some nations planning to denuclearize and others to expand their nuclear programs.

The 2011 Fukushima nuclear disaster in Japan sparked a wave of a nuclear closures and anti-nuclear sentiment worldwide. All 17 of Germany's nuclear reactors that were operational when Fukushima occurred were scheduled to be shut down by the end of 2022.[176] Three of the last six were shut down at the end of 2021 and the final three were scheduled to be shut down at the end of this year (2022).[177]

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[168] Eurostat, "EU Imports of Energy Products - Recent Developments," accessed June 28, 2022, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=EU_imports_of_energy_products_-_recent_developments.

[169] Eurostat, "Energy Production and Imports," accessed June 28, 2022, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_production_and_imports.

[170] Katrin Bennhold, "The End of the (Pipe)Line? Germany Scrambles to Wean Itself Off Russian Gas," *The New York Times*, April 6, 2022, sec. World, https://www.nytimes.com/2022/04/06/world/europe/germany-gas-russia-ukraine.html.

[171] "Germany Agrees Plan to Phase out Coal Power by 2038," *BBC News*, January 16, 2020, sec. Europe, https://www.bbc.com/news/world-europe-51133534.

[172] Charles Riley Horowitz Julia, "Germany Halts Nord Stream 2 and Russia Responds with a Stark Warning | CNN Business," CNN, February 22, 2022, https://www.cnn.com/2022/02/22/business/nord-stream-2-germany-russia/index.html.

[173] Stanley Reed and Melissa Eddy, "Russia Crimps Gas Flows Just as Europe Races to Stock Up for Winter," *The New York Times*, June 23, 2022, sec. Business, https://www.nytimes.com/2022/06/23/business/europe-natural-gas-russia.html.

[174] Katrin Bennhold and Jim Tankersley, "Ukraine War's Latest Victim? The Fight Against Climate Change.," *The New York Times*, June 26, 2022, sec. World, https://www.nytimes.com/2022/06/26/world/europe/g7-summit-ukraine-war-climate-change.html.

[175] *ibid*.

[176] Judy Dempsey and Jack Ewing, "Germany, in Reversal, Will Close Nuclear Plants by 2022," *The New York Times*, May 30, 2011, sec. World, https://www.nytimes.com/2011/05/31/world/europe/31germany.html.

[177] "The History behind Germany's Nuclear Phase-Out," Clean Energy Wire, September 25, 2014, https://www.cleanenergywire.org/factsheets/history-behind-germanys-nuclear-phase-out.

On the other hand, just weeks before Russia's invasion of Ukraine, France announced it would add 14 new nuclear reactors to its existing portfolio of 56 reactors, which produce around 70% of the nation's electricity. France is also planning to build 50 offshore wind farms and increase its solar capacity tenfold by 2030.[178]

In a bid to appease pro-nuclear countries like France, as well as natural gas-dependent countries like Germany, the European Commission classified some nuclear plants and natural gas investments as "transitional" green investments in early February. The reclassification was intended to reduce carbon emissions in the short term while allowing more time for renewable energy development.[179]

In the months after the Ukraine invasion, many European countries moved to expand their nuclear programs. Belgium reversed its decision to phase out nuclear energy. The Netherlands, which currently has one reactor, now plans to build two more. The UK has plans to build up to eight more nuclear plants. Additional projects are planned in Eastern Europe.[180]

REPowerEU and the Long Term Renewable Energy Outlook in Europe

On March 8, 2022, the European Commission unveiled the REPowerEU program. REPowerEU is a crash plan to wean Europe from Russian energy exports by 2030 if not sooner. Some analysts believe it could accelerate adoption of green hydrogen in Europe by 10 years.[181]

REPowerEU calls for a number of measures aimed both at easing the immediate energy crisis and enhancing European energy independence. These include retail energy price controls, natural gas stockpiling, diversifying natural gas supplies, building liquified natural gas (LNG) import facilities, increasing biomethane production, increasing renewable hydrogen production and imports, building more renewable energy assets, and increasing building energy efficiency.[182]

European Commission President Ursula von der Leyen said:

> *"We must become independent from Russian oil, coal and gas. We simply cannot rely on a supplier who explicitly threatens us. We need to act now to mitigate the impact of rising energy prices, diversify our gas supply for next winter and accelerate the clean energy transition. The quicker we switch to renewables and hydrogen, combined with more energy efficiency, the quicker we will be truly independent and master our energy system."* [183]

In terms of renewable hydrogen, plan specifics include the creation of a Hydrogen Accelerator program to "develop infrastructure, storage facilities and ports, and replace demand for Russian gas with additional 10 mt of imported renewable hydrogen from diverse sources and additional 5 mt of domestic renewable hydrogen."[184]

To put this goal in perspective, global hydrogen demand in 2020 was approximately 90 million tons (mt).[185] An additional 15 mt by 2030 represents 16.7% of global production – all from renewable sources.

The potential impact of Europe's accelerating move towards renewable hydrogen is hard to overstate. Energy research firm Rystad Energy stated that the Ukraine war has "turbocharged the [renewable hydrogen] sector". In fact, according to Rystad, green hydrogen is now cheaper than blue hydrogen in some European markets. In the Iberian

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[178] Liz Alderman, "France Announces Major Nuclear Power Buildup," *The New York Times*, February 10, 2022, sec. World, https://www.nytimes.com/2022/02/10/world/europe/france-macron-nuclear-power.html.

[179] Monika Pronczuk, "Europe Labels Nuclear and Natural Gas as Sustainable Investments.," *The New York Times*, February 2, 2022, sec. Business, https://www.nytimes.com/2022/02/02/business/energy-environment/europe-green-taxonomy.html.

[180] Liz Alderman and Stanley Reed, "Nuclear Power Could Help Europe Cut Its Russia Ties, but Not for Years," *The New York Times*, April 26, 2022, sec. Business, https://www.nytimes.com/2022/04/26/business/russia-nuclear-power-europe.html.

[181] "Climate Change: EU Unveils Plan to End Reliance on Russian Gas," BBC News, March 8, 2022, sec. *Science & Environment*, https://www.bbc.com/news/science-environment-60664799.

[182] "Joint European Action for More Affordable, Secure Energy," Text, European Commission - European Commission, accessed June 28, 2022, https://ec.europa.eu/commission/presscorner/detail/en/ip_22_1511.

[183] *ibid*.

[184] "Factsheet - REPowerEU," Text, European Commission - European Commission, accessed June 28, 2022, https://ec.europa.eu/commission/presscorner/detail/en/fs_22_1513.

[185] "Hydrogen – Analysis," IEA, accessed June 28, 2022, https://www.iea.org/reports/hydrogen.

Peninsula green hydrogen can be produced at prices as low as \$4/kg, while prices for blue and gray hydrogen have risen from around \$8/kg to \$12-14/kg "in a matter of days" in some areas due to higher natural gas feedstock costs.[186]

Hydrogen Diplomacy

Germany and Japan are leading the way in "hydrogen diplomacy" – developing bilateral trade agreements with potential renewable hydrogen suppliers.[187]

While fossil fuel diplomacy was largely tethered to geography and geology, hydrogen diplomacy will primarily rest on preexisting international relationships, according to IRENA. Geography will still play a role – technical solar and wind potential, adequate space, and inexpensive water supplies are important to renewable hydrogen production – but importing states may be able to pick and choose among exporters based on other factors. These could include strong relationships, equity concerns, and resilience to climate impacts, among other factors.[188]

Japan, China, Europe, and the United States will be key players in hydrogen diplomacy. Japan was one of the earliest adopters of renewable hydrogen with the first national hydrogen strategy published in 2017. China and the United States, the number one and two producer and consumer of hydrogen, respectively, both have substantial renewable hydrogen development programs. The European Union, India, and South Korea are also early adopters with aggressive development timelines.[189]

As of August 2021, \$65 billion in government investment and \$160 billion in private investment have been allocated for renewable hydrogen projects worldwide through 2030, with the majority of those investments in France, Germany, and Japan.[190]

In addition to 'turbocharging' the renewable hydrogen production industry, the war in Ukraine may also accelerate international trade in renewable hydrogen. Europe is expected to be a major hydrogen importer in the future.

IRENA anticipates that one-third of green hydrogen will be traded across borders in 2050, with half being shipped via pipeline and half by ship. This is roughly comparable to natural gas today, 24% of which is traded internationally with a nearly even split between pipeline and ship.[191]

Hydrogen may rewrite security alliances in much the same way that the United States shale boom allowed for a partial disengagement from Middle East politics.

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[186] Cheap, Secure, and Renewable – Europe Bets on Green Hydrogen to Fix Energy Woes," accessed July 6, 2022, https://www.rystadenergy.com/newsevents/news/press-releases/cheap-secure-and-renewable-europe-bets-on-green-hydrogen-to-fix-energy-woes/.

[187] IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*, International Renewable Energy Agency, Abu Dhabi, (2022): 79.

[188] *ibid.*, 80-81.

[189] *ibid.*, 39-40.

[190] *ibid.*, 41-42.

[191] *ibid.*, 37.

Part XI — Obstacles & Opportunities

Potential Challenges

There are obstacles to developing a renewable hydrogen industry in Iowa. The ultimate barrier to renewable hydrogen adoption is the dearth of existing projects. There are nearly no large-scale projects in the U.S. to draw lessons and data from. Businesses interested in renewable hydrogen production are therefore faced with many unknowns.

Development decisions – from selecting an electrolyzer to identifying off-takers – must be undertaken without the benefit of well-established industry practices. New relationships have to be formed between businesses in previously unrelated industries. Information on the quantity of curtailed wind power is proprietary. The use of curtailed wind to power electrolysis has not yet been commercially attempted in the U.S. and current utility tariffs are not suited to this approach.

Technical Challenges

Polymer electrolyte membrane (PEM) is a well-understood technology and PEM electrolyzers are commercially available from multiple manufactures. Existing projects, many of which are overseas, demonstrate the viability of renewable hydrogen production using PEM.

Nevertheless, renewable hydrogen is at a developmental stage where essentially every project is bespoke. Each new project may face unique technical challenges depending on its particular mix of power source, electrolyzer stack, storage duration and volume, end-use for the hydrogen, transportation requirements, and off-taker requirements.

These obstacles are not insurmountable, but they do exceed the technical challenges in a typical wind or solar installation.

Legal & Regulatory Challenges

The formation of state policy that proposes a flexible ratemaking mechanism could provide a pathway for the adoption of low-carbon energy generation resources including renewable hydrogen. Purchasing power at market rates may not be economically viable for hydrogen production unless some free (curtailed) power is also used. As demonstrated in the techno-economic analysis, wholesale electricity prices in Iowa are at or near the threshold for $2/kg hydrogen production.

Under current tariffs, wind energy – even if it is currently curtailed – has to be sold at rates that may be too expensive to be economical in a renewable hydrogen plant. Without a new flexible rate policy, renewable hydrogen production will be limited to plants with power purchasing agreements in place, or vertically integrated operations in which the hydrogen producer owns the solar array or wind farm powering the hydrogen plant.

Business & Financial Challenges

Troy Van Beek, CEO of Ideal Energy, stated that there are two primary business-related barriers to hydrogen projects in Iowa: "Number one is the cost of electricity. Number two is that it's too new; no one wants to be the guinea pig."[165]

Additional barriers related to business and finance include:

- **Disparate industries.** Potential players within the renewable hydrogen industry are isolated from one another. For example, wind farm owners are unfamiliar with the agrichemical industry and do not have existing relationships with potential off-takers. Bringing power producers and off-takers together is essential.
- **Market uncertainty.** There is a large existing market for hydrogen, but until the first company successfully starts making renewable hydrogen in Iowa and selling it, the dynamics of that market will remain unknown to producers.
- **Perception of risk.** Because renewable hydrogen production at scale has not been done before in Iowa, the risk profile of a renewable hydrogen project may appear worse than it actually is.
- **Due diligence.** There are few commercial-scale renewable hydrogen projects in the U.S. This makes it very difficult to perform due diligence.
- **Lack of experts.** Renewable hydrogen is a relatively small field. Many U.S. experts are within academia or government labs. Renewable hydrogen experts in the private sector are few in number and in high demand.
- **Lender & investor uncertainty.** It may be difficult to acquire capital for hydrogen projects, because there are so few commercial-scale projects to draw comparisons to.

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[165] Troy Van Beek (CEO of Ideal Energy), interviewed by author via phone, November 15, 2021.

A Path Forward – How Iowa Can Capitalize on the Renewable Hydrogen Opportunity

To build a renewable hydrogen industry in Iowa, the state needs to build a solid foundation of industry knowledge, make legislative and regulatory changes, and develop a focused approach to the upcoming federal programs.

Build Industry Knowledge

Research. This research paper is intended to offer an in-depth look at the overall renewable hydrogen opportunity in Iowa. However, much more information is needed. Data on curtailed wind is proprietary; wind farm operators could potentially be encouraged or incentivized to share that data. Additional technical reports on specific hydrogen stacks and hydrogen plant designs will help move the industry. Finally, pilot project results will go a long way to inform the industry and attract businesses.

Demonstration Project. Operational pilot projects are the key to building institutional knowledge. Once one or more projects are operational, other project developers will have a blueprint for renewable hydrogen production.

Networking. Developing relationships between potential hydrogen producers (e.g. wind farm owners) and potential off-takers (e.g. the agrichemical industry) will hasten the development of Iowa's first hydrogen projects. In addition, lenders, legislators, regulatory bodies like the Iowa Utilities Board, and other stakeholders should be brought into the conversation.

Education & Awareness. It is necessary to show businesses that are not currently in the hydrogen industry that there is opportunity in renewable hydrogen. Ideal Energy hopes that this report will contribute, but additional outreach efforts are necessary to open lines of communication between potential partners and other stakeholders.

The major utilities and wind farm owners in Iowa – MidAmerican Energy, Alliant Energy, and NextEra – are all studying the renewable hydrogen opportunity. In fact, NextEra subsidiary Florida Power & Light is building a renewable hydrogen pilot project at its Okeechobee, Florida plant.[166]

However, many other potential stakeholders may not be aware of renewable hydrogen, including other wind farm operators, public transit authorities, school districts, and agrichemical companies

Legislative & Regulatory Changes

Energy stakeholders should work with legislators in the formation of state policy that proposes a flexible ratemaking mechanism that could provide a pathway for the adoption of low-carbon energy generation resources including renewable hydrogen. A new flexible rate policy is needed to sell curtailed power back into the grid for use in hydrogen production plants.

Governor Kim Reynolds' Carbon Sequestration Task Force had discussions that focused on proposing a state policy and establishment of a flexible ratemaking mechanism designed to support the increased development of low carbon energy resources including renewable hydrogen production. This policy could allow wind farm owners to sell excess power that is currently being curtailed to renewable hydrogen plants at rates lower than allowed by current tariffs.

Such a policy could benefit wind farm owners by making it possible to monetize curtailed power.[167] It would also benefit renewable hydrogen plant owners by allowing them to easily purchase power from their utilities rather than by entering into power purchasing agreements with wind farm owners.

This policy would dramatically improve the viability of standalone renewable hydrogen projects. Without such a policy, a renewable hydrogen plant would have to be vertically integrated with a power source, like a wind farm, or have a PPA in place with a wind farm owner in order to be viable.

Apply to Become a Renewable Hydrogen Hub

Iowa will greatly benefit if it is chosen as one of the four renewable hydrogen hubs. In addition to the $8 billion dollars of funding that is at stake, the impact on gross state product and employment will be substantial for the states selected. **Stakeholders within Iowa should begin to work together now to develop a strong application.**

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[166] Christian Roselund, "Why NextEra's Green Hydrogen Pilot Is a Big Deal," RMI, August 5, 2020, https://rmi.org/why-nexteras-green-hydrogen-investment-is-a-big-deal/.

[167] Note: This will not solve all curtailment issues, some of which are due to grid congestion. To use power that is curtailed due to congestion, hydrogen plants would have to be built in close physical proximity to wind farms.

Conclusion

Conclusion

Iowa is extremely well-positioned to capitalize on the growing renewable hydrogen economy. With ample wind and solar resources, inexpensive wind power, and access to both existing and future markets for hydrogen and ammonia, Iowa has the potential to become a strategic hub of the hydrogen economy.

"Energy transition" – the global changeover from fossil fuels to a renewable, carbon-free energy economy – will involve trillions of dollars of wealth creation. Iowa businesses, investors, and other stakeholders are in a unique position to lead the way.

Change Log

Edition 2 – August 2022

- Wind price data was updated using 2021 DOE & LBL sources with 2020 data (previously 2020 DOE & LBL sources with 2018/2019 data were used).
- Discussion of rising natural gas prices was included.
- A section was added providing a) several formulas used to estimate SMR hydrogen production costs from natural gas feedstock costs, and b) a literature survey of actual SMR hydrogen costs over the past 15+ years.
- A discussion of renewable hydrogen in a geopolitical context was added, specifically vis-à-vis European energy independence and security concerns in the wake of the Russian invasion of Ukraine.

Edition 1 – January 2022

- Original version.

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