OKLAHOMA

Hydrogen Production, Infrastructure, & Production Task Force Report & Roadmap

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Executive Summary

The Hydrogen Production, Transportation, and Infrastructure Task Force (OK H2 Task Force) was established by Senate Bill 1021 to research, collaborate, and submit this report on the viability of growing the production, use, supply chain, and infrastructure for a hydrogen economy within the state and for energy export.

Industries, investors, research institutions and policymakers will need to work together to develop and unlock the full value of the hydrogen economy for Oklahoma. Oklahoma's dependable and economical natural gas supplies, extensive natural gas pipeline networks, vast water supplies, low cost of electricity, and substantial renewable energy generation provide a strong foundation for the production and delivery of hydrogen for Oklahoma's benefit and for export to support other states and international economies focusing on low-carbon fuels.

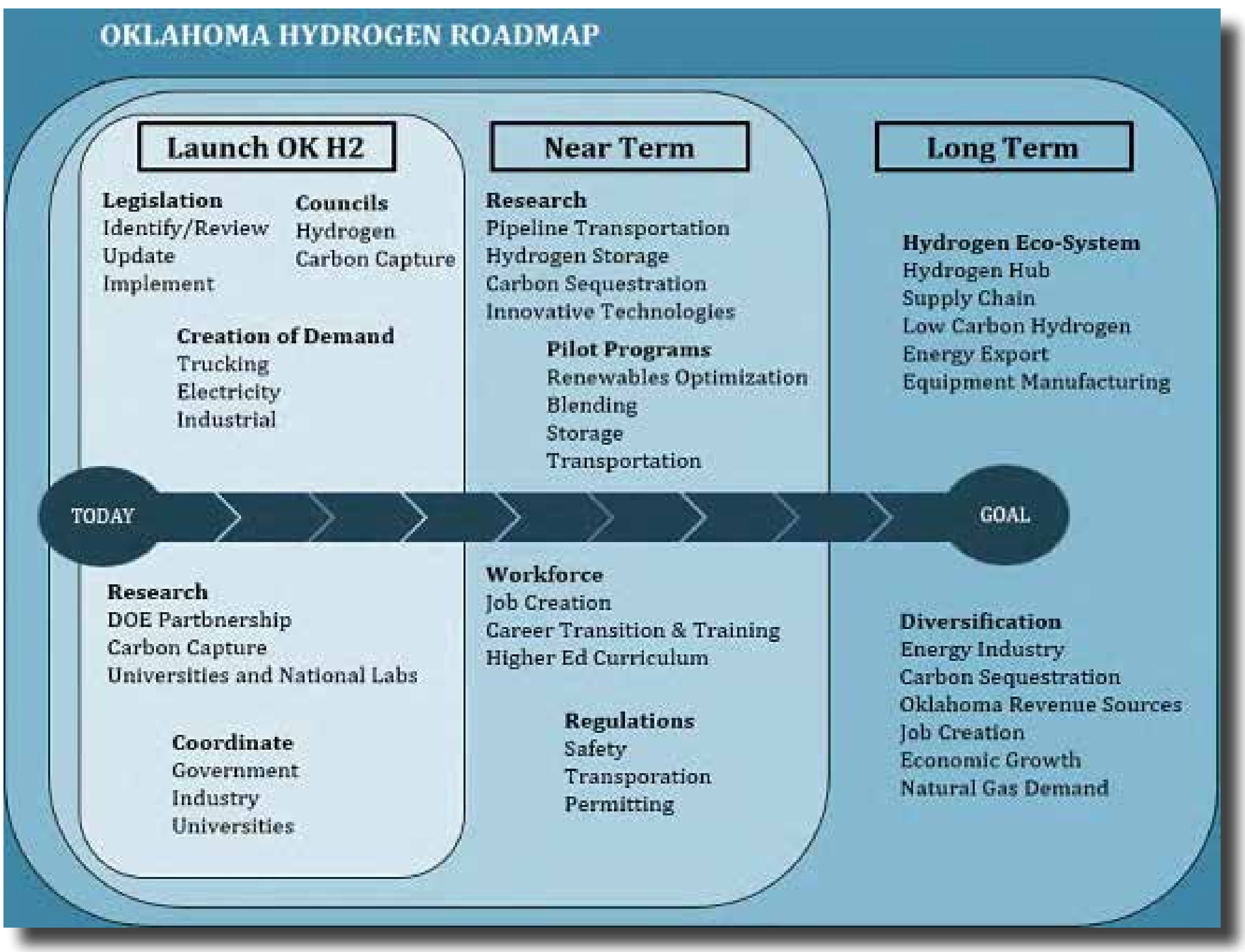
The job creation and financial impact associated with the development of the Oklahoma hydrogen economy could add over 6,000 jobs and provide impacts ranging from approximately $1.5 billion to $2.5 billion for the state of Oklahoma.

Oklahoma's pioneering culture, robust university research resources and business friendly tax and incentive structures complement our state's geographically advantageous location to support the nation's demand for low-carbon hydrogen fuel. Oklahoma is already home to state-of-the-art hydrogen production facilities, hydrogen related equipment manufacturers, and long-standing carbon sequestration facilities. The hydrogen industrial entities operating today provide a solid foundation for leveraging our growing renewable energy production and expansive water supplies to produce zero carbon hydrogen. Oklahoma contains some of the nation's largest natural reserves of hydrogen in the form of hydrocarbon fuels, notably natural gas. Additionally, Oklahoma is endowed with abundant geologic pore space available for storage of fuels, which may include hydrogen fuel, but also carbon capture and storage. With these resources, Oklahoma can be a national leader in at-scale hydrogen production and distribution. Additionally, the science and regulatory experience from the history of unconventional oil and gas production can be harnessed to minimize risks arising in a hydrogen economy.

The OK H2 Task Force focused on low carbon or no carbon Hydrogen. There is no bias against any emerging hydrogen production method, but there are two (2) leading categories of produced hydrogen; blue and green. Blue hydrogen is derived from natural gas sourced hydrogen utilizing steam methane reforming (the leading method of hydrogen production globally today) combined with carbon capture and sequestration. Green hydrogen is generally associated with the use of renewable energy and water using electrolyzing technologies to produce hydrogen. The idea that H2 produced from renewable resources could also be stored and later converted to electricity, enabling the low cost and carbon free energy produced from wind and solar resources to become dispatchable, a concept that seems to have merit here in Oklahoma and is addressed further within. The various methods of hydrogen production and the various methods of referencing by color type are discussed in detail within the report.

Near to mid-term commercialization opportunities for hydrogen produced in Oklahoma lies in the industrial and transportation sectors. Utilizing hydrogen as a transportation fuel may be the first and most cost competitive sector for this developing low carbon energy solution. Fuel cell vehicles (FCEVs) have extended range, quicker fueling times, can carry heavier payloads and offer a fuel economy close to 70 miles per gallon equivalent. The potential for heavy- duty FCEV trucking is an attractive new alternative for goods movements along national trucking corridors as well as for local and regional product deliveries on Oklahoma's interstate crossroads and material handling vehicles. Adopting hydrogen as a heavy-duty transportation fuel can also reduce the risks associated with the potential detrimental economic impacts associated with the US EPA air quality non-attainment classifications for our major metropolitan areas.

The OK H2 Task Force recommendations include continued focus on growing a hydrogen energy economy here in Oklahoma, assuring hydrogen fuel is included within existing regulations and legislation similar to compressed natural gas (CNG) and electric vehicles (EV), readying our infrastructure and supporting policies to champion FCEV heavy-duty transportation, fuel production and as a back-up power generation asset, aligning our state's business and manufacturing friendly taxes and incentives to attract companies that reflect that full value chain within the hydrogen sector, and continue to investigate opportunities to collaborate with neighboring states and federal agencies to grow a competitive hydrogen economy.



Section 1. Introduction

Justification for report State Law

Senate Bill 1021, signed into law April 20, 2021, established the Hydrogen Production, Transportation, and Infrastructure Task Force (OK H2 Task Force) to research and report on the viability of hydrogen production and use within the state and for export. Specific areas of focus include availability of water resources and cost competitive power necessary to produce hydrogen, incentives, and taxation necessary to encourage the development of hydrogen technology, infrastructure and transportation, and the development of a state-wide roadmap for a hydrogen economy which includes, among other things, infrastructure, production, distribution, transportation, and off-taker market uses. Furthermore, the OK H2 Task Force is charged to investigate the viability of utilizing the existing pipeline infrastructure to move hydrogen, existing and potential needs of the pipeline industry to integrate hydrogen, and potentially necessary pipeline safety standards for distribution of hydrogen fuel.

This document fulfills the reporting obligations under SB 1021, Section H, by publishing findings and recommendations of the OK H2 Task Force, including fiscal impact statements for all recommendations by December 1, 2021.

Oklahoma's Hydrogen Potential

Oklahoma's extensive interstate, intrastate and local distribution pipeline systems provide a state-wide platform that could leverage the state's vast and dependable natural gas resources (natural gas is a feed stock product to produce hydrogen which will be discussed later in this report). Oklahoma's natural gas infrastructure also provides a low cost and dependable transportation mechanism for hydrogen produced from our state's extensive renewable energy power generation facilities (ranked third in the US) which can be coupled with our abundant water resources (hydrogen produced via electrolysis will be discussed later in this report).

As the global economy shifts to low-carbon forms of energy, Oklahoma is uniquely positioned to fulfill the long-term supply of hydrogen to the US and abroad by optimizing the many strategic resources available today and in the future. To complement Oklahoma's dependable, around the clock natural gas supplies to produce hydrogen, the Department of Energy's National Renewable Energy Laboratory (NREL) recently completed research discloses our nation's potential for hydrogen production from renewable energy sources like wind and solar, and Oklahoma holds an advantageous geographic position for hydrogen production from renewable energy (see Renewable Energy section below). Oklahoma produces 68% more energy than is needed within the state, the balance of which is exported (https://www.eia.gov/beta/states/overview).

Oklahoma's midcontinent location is not only strategic from an interstate transportation perspective but is at the intersection of economical and plentiful renewable energy, extensive water supplies and manufacturers of the parts and pieces needed to produce hydrogen from our abundant resources. In the decades to come, as we expand our state's renewable electricity production and leverage our water resources (e.g.: electrolysis), hydrogen production can utilize off-peak renewable energy which could provide not only additional energy resources for export but also a dependable mechanism for balancing our electricity grid during conditions of renewable energy oversupply (storing wind and solar is difficult while hydrogen storage serves as a potential solution).

The Oklahoma Department of Transportation has developed the Hydrogen Application Project, an interactive web-based tool which displays our state's resources and infrastructure to support stakeholder's interests in the hydrogen economy. The Hydrogen Application Project mapping includes a useful list of "layers" that display data sets like high volume truck corridors, airports, water ways and ports, rivers, lakes, and groundwater basins, existing fueling stations for heavy and medium duty trucks, CNG and EV charging stations, potential phase one and phase two hydrogen fueling station locations (which will be discussed below), and many other useful data. The Hydrogen Application Project can be found at the link listed below: https://okdot.maps.arcgis.com/apps/webappviewer/index.html?id=0198757b53f84ee49dbbeb74374c31a8

In Summary, Oklahoma's inherent advantages include, but are not limited to:

- Extensive pipeline infrastructure
- Highly skilled oil and gas and renewable energy workforces
- Lowest-cost electricity
- One of the nation's most business-friendly environments
- Substantial renewable energy production (3rd largest US renewable energy producing state and growing)
- Access to abundant clean water and alternative water sources

- Carbon and H2-ready pore space and geology for Carbon Capture, Utilization and Sequestration as well as H2 storage.
- Underground energy storage
- The inland most seaport in the US via Tulsa's Port of Catoosa.
- Cluster of companies currently engaged in the hydrogen economy supply chain (e.g.: equipment manufacturing)
- Low-cost of living and high quality of life

Industries, investors, and policymakers can work together in the developing hydrogen economy. To unlock hydrogen's potential in Oklahoma, the following should be considered:

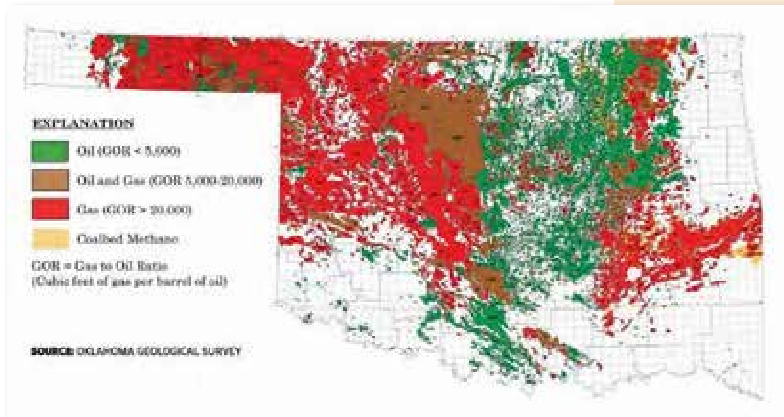
- Kickstarting markets with the needed incentives and support
- Create public incentives to bridge barriers to the initial market launch
- Support infrastructure development
- Expand the use of hydrogen across sectors and achieve economies of scale
- Include hydrogen-based options in government procurement
- Support research, development, demonstration, and deployment of innovative hydrogen technologies
- Harmonize technical codes and safety standards
- Support outreach and workforce development
- Review energy sector regulations to ensure they account for hydrogen
- Set dependable, technology-neutral low-carbon goals (e.g.: "Oklahoma Hydrogen Production Goal" concept)

(Road Map to a U.S. Hydrogen Economy. The Fuel Cell and Hydrogen Energy Association: 2019. http://www.fchea.org/us-hydrogen-study page 21)

Section 2. Opportunities and Challenges for Oklahoma

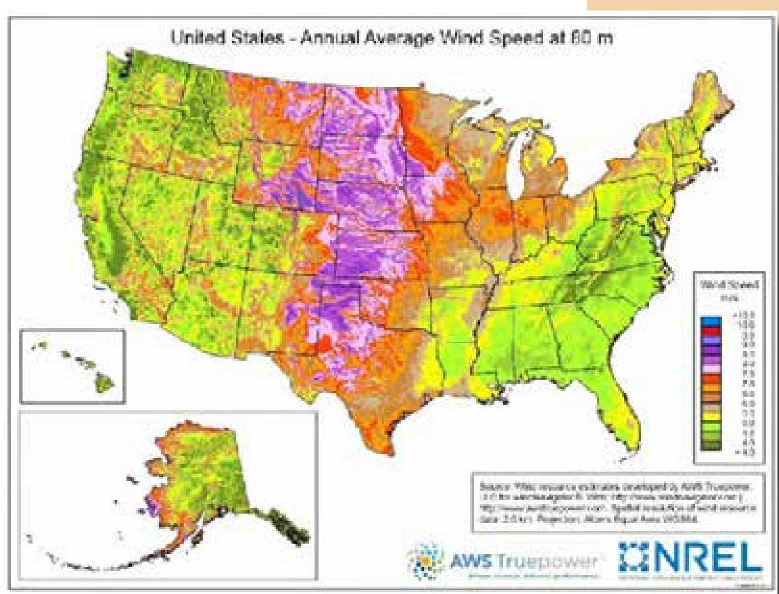
Hydrogen makes sense in Oklahoma

Our state's fossil fuel exploration and production companies have provided our local and national economies with dependable and affordable fuel and feedstock supplies for over a century. Natural gas is currently the primary feedstock to produce hydrogen and will continue to be the primary source for hydrogen production well into the future with an anticipated 75% of the US' 2050 hydrogen supplies sourced via steam methane reforming. (US DOE FE Hydrogen Strategy July 2020 page 1 and IEA Energy Technical Perspective 2020 graphic page 141)



The graphic to the right captures Oklahoma's extensive fossil fuel resources, and the associated extensive storage and sequestration potential within depleted reservoirs and other geological formations. Oklahoma has a diverse geology with some of the world's deepest sedimentary basins and salt formations, all possible targets for hydrogen or CO2 storage, see Appendix for Oklahoma Geological Survey Fact Sheet No. 1 and the CO2 Storage Opportunities in Oklahoma White Paper).

The production of hydrogen in Oklahoma has a long standing and resilient history which could be expanded to meet the growing demand for hydrogen as a diversified fuel source. Our state's refineries produce hydrogen; Holly Frontier in Tulsa, Wynnewood Refinery, Valero in Ardmore and Phillips in Ponca City, and Oklahoma is home to state-of-the-art fertilizer plants that produce their own hydrogen to produce nitrogen fertilizers; CF Industries facilities in Woodward and at the Tulsa's Port of Catoosa, as well as Koch Industries in Enid.



Electricity prices in Oklahoma are among the lowest in the country, making it more economically feasible for a transition to a low-carbon hydrogen energy economy.

The map to the right shows the predicted mean annual wind speeds at 80 meters above ground level. In central and western Oklahoma average annual wind speeds are shown to range from 7.0 to 9.0 meters per second (approximately 16 to 20 miles per hour).

Areas with good exposure to prevailing winds and annual average wind speeds around 6.5 meters per second (14.5 miles per hour) or greater at 80 meters above ground level are considered suitable for utility-scale wind turbines which are typically 80 to 100 meters tall but can reach up to 140 m to access even better wind resources. (Wind resources estimate by AWS Truepower LLC. Map developed by National Renewable Energy Lab. See also The Nature Conservancy wind power siting tool referenced in the Appendix)

Oklahoma's long history in the manufacturing of gas processing equipment (natural gas, natural gas liquids, industrial gases, heat exchangers, etc.) also supports our nation's hydrogen production equipment supply chain demands through the efforts of entities like Linde, Baker Hughes, Chart Industries, GasTech Engineering, American Hydrogen and others. Our state's capable hydrogen supply chain companies are currently manufacturing hydrogen equipment for installation across the US and Canada, so Oklahoma has an embedded portfolio poised and ready to supply the expanding hydrogen economy domestically and internationally.

Nationally, the federal government is focusing on investments in the creation of at least four (4) hydrogen hubs across the US through the Infrastructure Bill, many proposed Bills supporting hydrogen and carbon capture, and the National Defense Authorization Act of 2021 which also supports hydrogen fuel development. The OK H2 Task Force initiative has provided a timely forum for stakeholders and industries to discuss and align to participate in the developing national hydrogen initiatives.

Implementation Considerations

As mentioned above, a collaborative effort among key stakeholders (e.g., federal and state agencies, industry, academia, and major research institutions) is key to resolving the challenges in scaling, designing safe and reliable hydrogen infrastructure, developing a competitive and locally sourced hydrogen supplies, and creating a safe and economical method to sequester and utilize captured carbon dioxide (CO2).

To implement a viable hydrogen-based energy economy, the State will need to promulgate new statutes and regulatory rules to establish a low-carbon initiative with achievable, near term-goals applicable across industry and across the state (Oklahoma Hydrogen Production Goal concept). Maintaining achievable goals allows the market to drive out the best projects with economic, environmental, and stakeholder benefits.

Research is required to identify geologic formations that are appropriate for CO2 sequestration and hydrogen geologic storage taking into consideration the State's recent history with induced seismicity attributed to produced water disposal and, to a very small extent, hydraulic fracturing. Detailed geologic mapping of structure, petrophysical properties, faulting, and formation thickness will aid in determining the capacity of geologic formations identified for hydrogen storage and for CO2 sequestration. Described in more detail below, there are many pipelines to transport natural gas across Oklahoma and research is required to determine blending potential, re-purposing potential, and to study the potential for new pipeline infrastructure dedicated to the movement of hydrogen by pipeline. Cooperation between the oil and gas industry and academia will be key to this research effort. For each ton of hydrogen produced by steam methane reformation, 9 tons of CO_2 are produced and must be sequestered.

Additionally, training of workforce to transition to a hydrogen-based energy infrastructure will be key, and should include considerations of social motivations, risk management and mitigation, behavioral economics, and public policy.

The key technical challenges for hydrogen and related technologies are cost, durability, reliability, safety, and performance, as well as the lack of hydrogen infrastructure and lack of present commercial demand. To achieve widespread commercialization, hydrogen utilization technologies must enter larger markets and be able to compete with incumbent technologies in terms of life-cycle cost, performance, durability, and environmental impact. Non-technical barriers also need to be addressed, such as developing and harmonizing codes and standards, fostering best practices for safety, and developing a robust supply chain and workforce. https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

Hydrogen should be comparable to conventional fuels and technologies on a cost per-mile basis to be competitive as a transportation fuel. For fuel cell electric vehicles to be competitive, the total untaxed, delivered, and dispensed cost of hydrogen likely will need to be less than $4 per gallon equivalent. One kilogram of hydrogen is equivalent to one gallon of gasoline on an energy basis, according to the DOE's Alternative Fuels Data Center. https://www.oregon.gov/energy/energy-oregon/Pages/Hydrogen.aspx

Areas of focus for hydrogen cost enhancements include:

- Technology innovations to reduce costs or improve the efficiency of electrolysis through continued research, development, and deployment
- Electricity price optimization, utilizing off-peak, low-priced power for economical hydrogen production and grid balancing opportunities
- Development of a vibrant import and export marketplace for hydrogen
- Commercialization of alternative zero-carbon hydrogen production technologies, including improvements in electrolysis, pyrolysis, and other innovations and solutions to reduce overall hydrogen production costs
- Pore space suitable for CCUS or underground storage of hydrogen within depleted reservoirs and salt formations in Oklahoma
- Developing cost effective technologies to transport hydrogen in pipelines

Developing reliable production methods with sustainable capacity to provide a readily available supply of renewable hydrogen for private and industrial demand is the overarching goal. Continued research is needed to develop these novel technologies and to produce hydrogen at large scale from Oklahoma's extensive and dependable natural gas resources.

Establishment of regional hydrogen hubs will require convergent approaches across disciplines and strong partnerships across academia, national laboratories, industry, local and state governments, and communities. Oklahoma's universities, as experts in outreach to the public and private sector, research innovation engines, conduits for public-private partnerships, and education in leading edge fields will play a vital role in the creation and sustainability of regional hubs. With our strong scientific, technical, social, economic, and policy research and practice, OU, TU, and OSU can be the collaborative linchpins that aligns public and private partnerships in support of an Oklahoma-led effort to build a regional hydrogen hub and lead in this energy frontier. In Appendix is a partial and growing list of the faculty and infrastructure resources at OSU

Section 3. Production

Overview

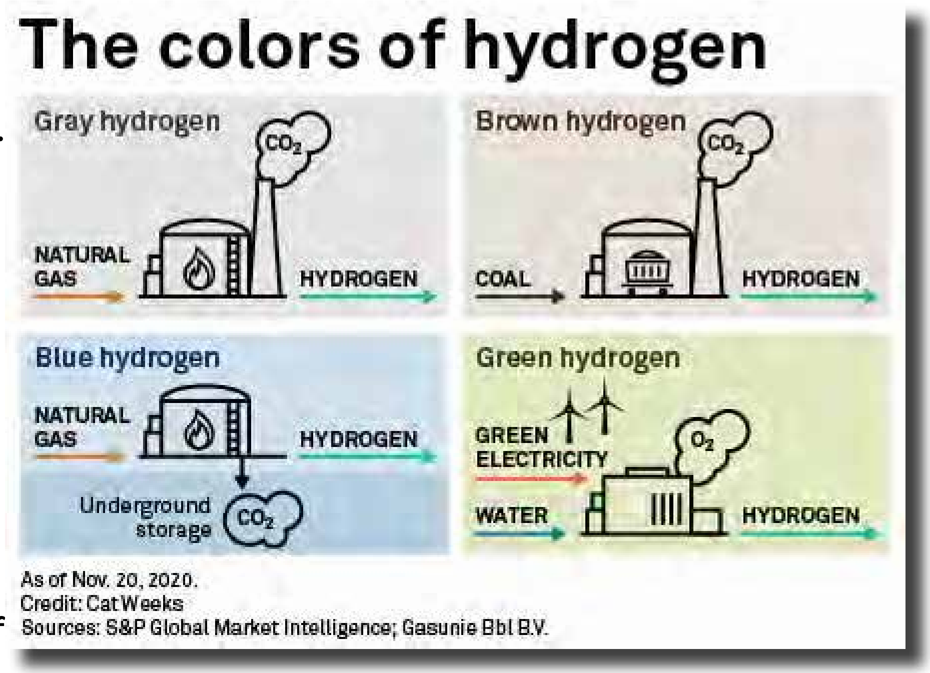
Hydrogen gas is colorless, odorless and has the highest energy content by weight of any fuel. When used in a fuel cell, hydrogen can generate electricity with only heat and water vapor as by-products. Hydrogen gas poses an overall safety risk comparable to that of methane, although specific risks may differ due to hydrogen's distinct properties. Hydrogen rises and disperses faster than methane when released into the air. (Pipeline Transportation of Hydrogen: Regulation, Research and Policy Congressional Research Service March 2, 2021) Hydrogen is the most abundant element in the universe; however, it is rarely found in its elemental form on Earth. It must be produced from a hydrogen-containing feedstock (e.g., water, biomass, fossil fuels, or waste materials) using an energy source. As mentioned above, Hydrogen has the highest energy content by weight (emphasis added) of all known fuels – 3X higher than gasoline. (DOE Hydrogen Program Plan))

The primary pathways for producing hydrogen are steam methane reforming, gasification, pyrolysis, and electrolysis (these methods for producing hydrogen will be described below in more detail below). Currently, 99% of the US hydrogen production is derived from fossil fuels and 1% from electrolysis. 95% of fossil fuel derived hydrogen produced today is from steam methane reforming while 4% is produced via gasification. Hydrogen is used within oil refineries, to produce ammonia (NH3 for fertilizer) and for methanol production. (Hydrogen Strategy Enabling a Low-Carbon Economy DOE Fossil Energy page 5)

The regulation of hydrogen production in the United States is governed by 40 CFR Part 98 Subpart P – Hydrogen Production. The Environmental Protection Agency (EPA) is the governing body for this regulation. A detailed list of regulations and oversight can be viewed in the Appendix to this report. https://www.osti.gov/servlets/purl/1773235/ There are several codes and standards related to hydrogen production that are subject to approval from state or local authorities having jurisdiction which would adopt and enforce these as regulations. Examples of these codes and standards include but are not limited to NFPA 2, NFPA 70, ASTM D03.14, Compressed Gas Association (CGA) H-5.5, American Society of Mechanical Engineers (ASME) B31, and CGA S-1.1-1.3 [7]. State and local jurisdictions may adopt these or other codes and standards, and different jurisdictions may adopt different editions (year published) of these codes and standards. These ANSI-accredited industry-consensus standards may be incorporated by reference by federal, state and local jurisdictions.

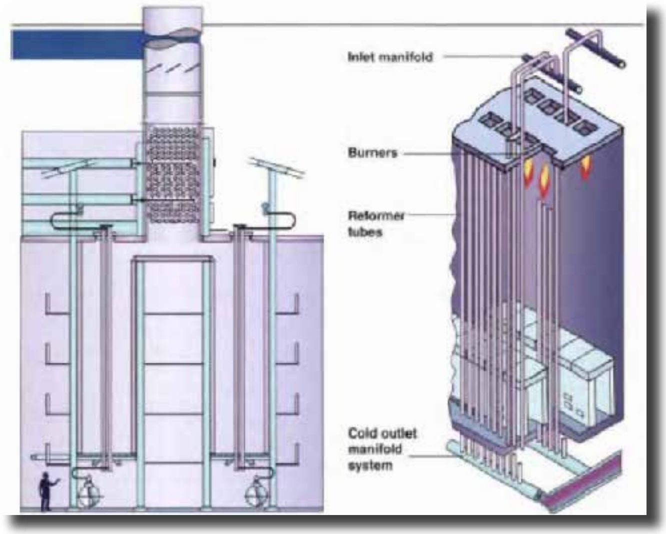
Blue and Green Hydrogen

There are numerous definitions used to identify the level of carbon intensity for specific hydrogen production techniques. For this report we will focus on 1) "blue hydrogen" which includes various technologies like Steam methane reforming (SMR) or methane pyrolysis coupled with carbon capture, use and storage, and 2) "green hydrogen" which is defined as hydrogen produced utilizing renewable energy sources, water and electrolysis. For informational purposes, the graphic below captures four (4) of the most mentioned "colors" of hydrogen.



Steam Methane Reforming (SMR) utilizes steam and a catalyst to separate methane into hydrogen and carbon dioxide: CH4 (methane) + 2 H2O (steam) CO2+ 4 H2. SMR is currently the most dependable and affordable means of producing industrial quantities of hydrogen (Graphic to right from Colorado School of Mines, Hydrogen from Natural Gas via Steam Methane Reforming January 4, 2015). SMR operators are investigating carbon capture technologies to de-carbonize their hydrogen production. The main by-product of producing hydrogen (H, H2 or H2) from natural gas and other fossil fuels is carbon dioxide (CO2 or CO2) which is in most cases vented to the atmosphere. Carbon capture will be discussed below.

Far into the foreseeable future hydrogen production will depend upon our state's fossil fuel supplies, however, managing carbon through capture and sequestration is paramount to success in our nation's low-carbon future. Oklahoma has the potential for substantial carbon storage within underground formations which require additional research, validation, and implementation. Carbon capture is key to leveraging our state's dependable and affordable natural gas resources for the production of blue hydrogen. The DOE continues to invest heavily within the low-carbon and zero-carbon energy solutions space, and it appears this activity may increase in the coming years. The DOE's Office of Fossil Energy and Carbon Management efforts will focus on the following four major R&D hydrogen areas:



1. Carbon-neutral hydrogen production using reforming and gasification technologies
2. Large-scale hydrogen transportation infrastructure
3. Large-scale onsite and geological hydrogen storage
4. Hydrogen use for electricity generation, fuels, and manufacturing

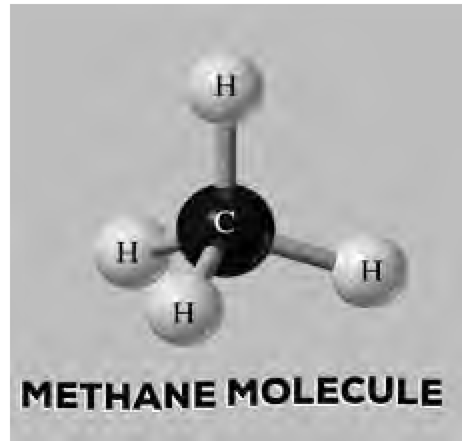
Oklahoma can play a pivotal role in the DOE's research, development, and deployment processes above. (DOE Hydrogen Strategy Enabling A Low-Carbon Economy, Office of Fossil Energy and Carbon Management)

Carbon capture will be paired with steam methane reforming, which will open beneficial markets for not only our state's natural gas supplies, but also create an additional marketplace for carbon sequestration enterprises (see Appendix for the Oklahoma Geological Survey Fact Sheet No. 1). For each ton of hydrogen produced by steam methane reformation, 9 tons of CO2 are produced and can be utilized or sequestered. The current federal tax codes provide a valuable incentive for the capture, utilization, and sequestration of CO2, however, for companies interested in this growing industry we should review and consider methods for reducing the risk associated with the timeline needed for permitting (e.g. Class VI), underground pore space use and ownership, and "pooling" for mineral owner considerations.

Gasification of coal, biomass and waste is similar to SMR regarding energy intensity and carbon dioxide emissions. An example of an operating gasifier is Basin Electric's (North) Dakota Gasification Company which utilizes approximately 16,000 tons of lignite coal and converts it into a mixture of carbon monoxide (CO), carbon dioxide (CO2) and hydrogen (H, H2 or H2). (https://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/great-plains)

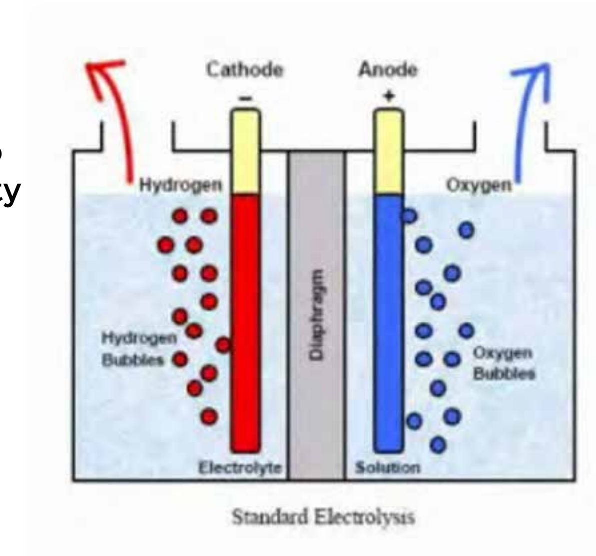
Oklahoma does not currently host gasification technology, however, should an entity show interest in deploying this type of technology in the state, carbon capture solutions similar to steam methane reforming should be considered.

Pyrolysis is the thermal decomposition of methane within a reactor containing a catalyst and heat. One of the benefits of methane pyrolysis is the production of hydrogen and solid carbon (carbon black), a process that is potentially a CO2 free source of hydrogen. (Carbon2Chem Project, Methane Pyrolysis for CO2-Free H2 Production, July 23, 2020) Alternatively, the production of hydrogen with the dissociation of the hydrogen atoms from the carbon atom in methane can be achieved with catalytic technologies at relatively high temperatures through the use of molten metal or molten salt reactors (https://www.chemistryworld.com/news/molten-metal-enables-climate-friendly-hydrogen-production/3008299.article) but the process results in cross contaminated, "dirty", solid carbon and catalyst byproducts with uncertain market value . Another promising technique is catalytic vapor deposition (OU-CoMoCAT process) using a continuous rotary reactor that produces hydrogen and carbon nanotubes from methane or other hydrocarbons.



Utilizing Oklahoma's natural gas supplies in cooperation with our research institutions is necessary for the emerging pyrolysis technologies that are moving through the research, development, and deployment cycle. Additionally, rules and regulations associated with the permitting process for emerging technologies like pyrolysis will be instrumental for the implementation process, and the expansion of collaboration with the DOE's Fossil efforts mentioned above could provide meaningful engagement for our research institutions and workforce plans. Oklahoma passed an advanced recycling legislation in 2021 which included pyrolytic conversion as an acceptable technology.

Electrolysis utilizes electricity to split water (H2O) into its constituent elements oxygen (O2) and hydrogen (H2) and is the most common technological area of focus for advancement due to readily available and affordable renewable electricity (wind and solar) in areas with robust water supplies and demand for hydrogen. Electrolysis requires clean water from de-mineralization or reverse osmosis systems, but the supply sources of raw water can be diverse and include fresh water, effluent, and production water. Innovative research is concentrated on efficiency enhancements to the electrolysis process. Hydrogen production from electrolysis is currently more expensive than steam methane reforming, but less expensive than methane pyrolysis. Zero-carbon electrolysis is intermittent due to the nature of renewable electricity supplies like wind and solar, however, nuclear power is potentially a low-carbon source for hydrogen. Electrolyzers could provide an advantage for electric grid balancing as this technology can create demand for electricity during off-peak conditions and shifts the energy potential to on-peak generation using hydrogen as the fuel source. Electrolysis provides an advantage

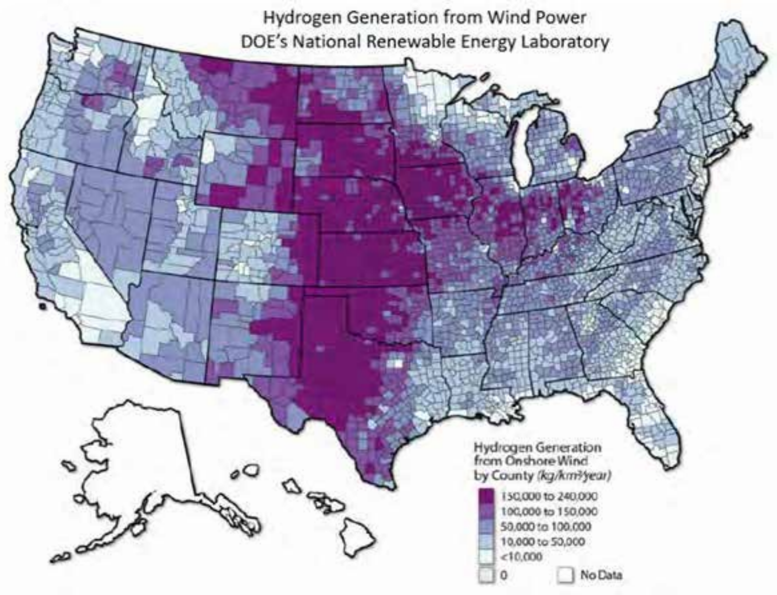


Standard Electrolysis

for on-site or distributed applications compared to other hydrogen production methods as electrolysis can be applied in a modular fashion to meet the existing and future growth needs for industrial quality hydrogen (electrolyzers can produce 99.99% pure hydrogen with oxygen as the vent gas or captured and utilized as an enriched for combustion).

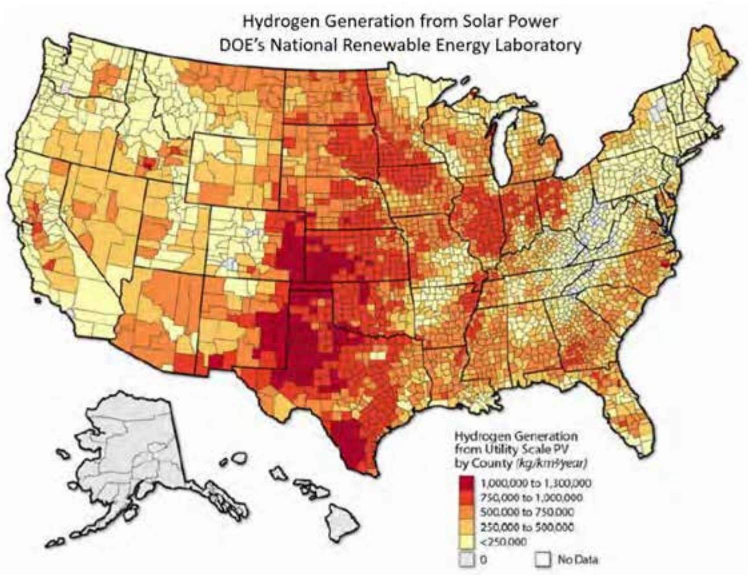
Though electrolysis is a tried-and-true technology, the Department of Energy through their research laboratories and collaborations with research institutions have committed to driving the production costs down to encourage the economic uses for green hydrogen. (https://www.energy.gov/eere/fuelcells/hydrogen-shot-summit) Within our state, identifying opportunities to fully utilize our existing and expanding renewable electricity supplies, access to water and transportation infrastructure will be key to the deployment of electrolysis in both remote areas and for on-site hydrogen generation at the source of demand.

Renewable Energy



Continued development of renewable energy production, along with Oklahoma's access to plentiful fresh water for use with electrolysis technologies, will provide opportunities to produce green hydrogen that will complement the state's reliable SMR produced hydrogen. The DOE's National Renewable Energy Laboratory (NREL) recently completed research discloses our nation's potential hydrogen production from renewable energy sources like wind and solar. NREL's H2@ Scale "Texas and Beyond" initiatives are conducting additional research for affordable hydrogen production methods, transportation, storage and determining the long-term demand potential for hydrogen as an energy carrier to increase revenue opportunities in multiple energy sectors. (https://www.nrel.gov/docs/fy20osti/77198.pdf page 16 and 20)

Oklahoma continues to maintain its position in the top 3 states for wind production across the US. The purple and blue NREL map depicts our state's potential for hydrogen production from current and future wind generation resources, and the map to the right depicts solar photovoltaic sources of electricity. The continued development of solar and wind resources, opportunistically combined with our state's water resources and natural gas transportation infrastructure could provide a springboard for green hydrogen production which complements our SMR based dependable hydrogen production from natural gas and other fossil fuels.



Renewable energy is of course dependent upon sunshine and wind, the accurate predictions for high power generation days is invaluable. The University of Oklahoma is home to one of the most prestigious weather forecasting research centers in the world. The University of Oklahoma is leading a National Science Foundation AI Institute for Research on Trustworthy Artificial Intelligence "AI" in Weather, Climate, and Coastal Oceanography that is being hailed as a "historic milestone in environmental science." Accurately predicting opportunities for green hydrogen production would provide investors an advantage in operational excellence and profitability. The collaboration between our major universities' research centers provides stakeholders in the hydrogen economy advantages in transitioning innovations to commercialization.

(https://www.ou.edu/web/news_events/articles/news_2020/ou-receives-20-million-grant-to-lead-inaugural-national-science-foundation-artificial-intelligence-institute)

Water resources

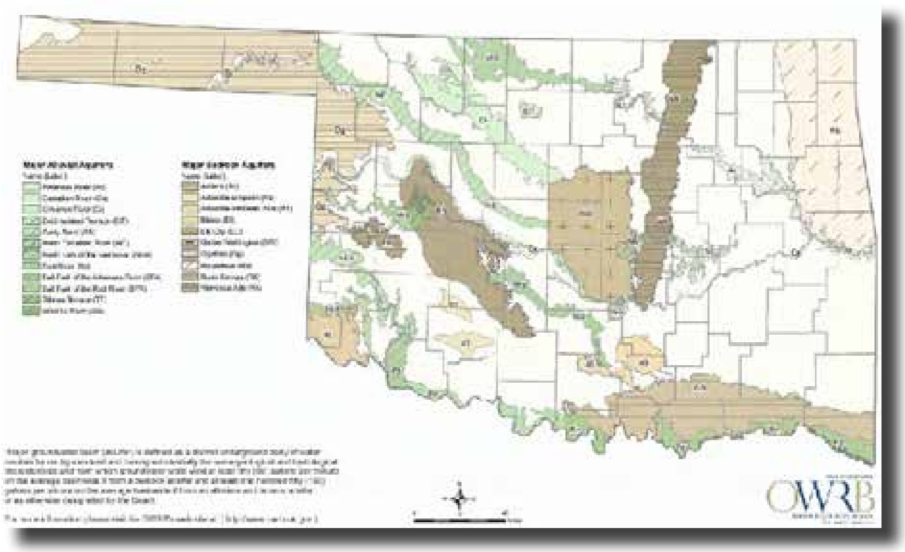
The Oklahoma Comprehensive Water Plan (OCWP) serves as the overarching long-term water resources management strategy and the definitive resource regarding current and future availability of fresh water and water quality across Oklahoma. This information can serve to assess the potential for locating hydrogen production facilities in our state. The Oklahoma Water Resources Board (OWRB) is currently updating supply and demand forecasts by 82 basin regions as part of the 2025 OCWP update.

In addition, a major policy recommendation from the 2012 OCWP, and resulting Oklahoma Water For 2060 Act, calls for the development of non-traditional sources of water, including reuse of traditional wastewater streams and other marginal waters as a way to add to Oklahoma's water supply budget. Today, as an inaugural member of the EPA-led 2020 Water Reuse Action Plan, state and local leaders remain hyper-focused upon developing these resources. H2 from electrolyzers is one of those opportunities.

Generally, surface water is more abundant toward the central, eastern, northeastern, and southeastern areas of the state, as annual precipitation increases dramatically from the western side of the state toward the east. Interestingly, the 98th Meridian travels roughly parallel to Interstate Highway 35 and separates to Eastern more water rich areas of the U.S. from the Western where areas are typically arid and with less water.

The state's major aquifer systems are illustrated below. Bedrock aquifers are deep groundwater resources, distinguished from alluvial aquifers that are typically shallower and directly connected to surface water systems.

Water Supply



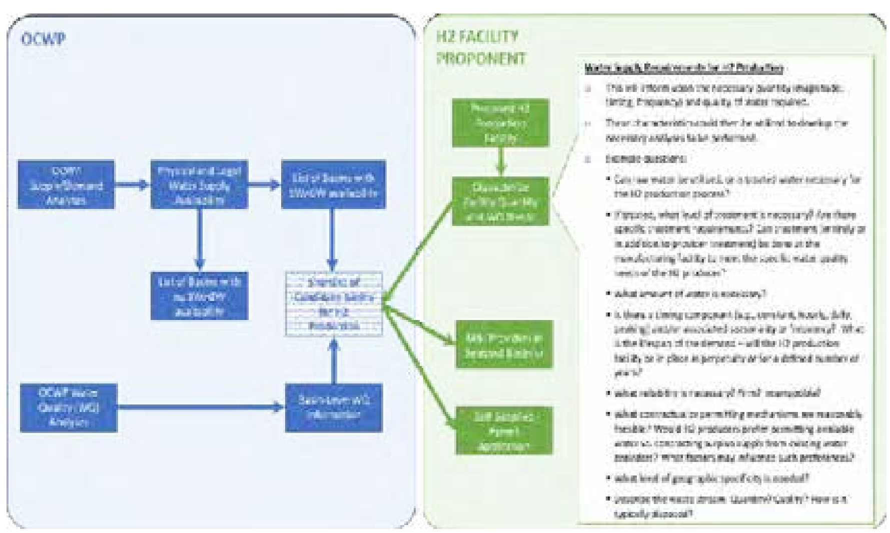
The state's water resources include 23 major groundwater aquifers and numerous surface water systems. The OCWP forecasts the physical and permit water availability of groundwater and surface water throughout the state. Water availability projections are made from current conditions through a 50-year planning horizon in decadal increments, reflecting forecasted changes in water use over time. The OWRB has completed detailed studies to characterize many of the state's major groundwater aquifers.

Under Oklahoma law, surface water is owned by the state, whereas groundwater is a private property right. OWRB administers permits for all water resources across the state, except surface water in the northeast corner of the state (basins 80 and 81 of 82 basins statewide) where the Grand River Dam Authority administers surface water use.

Water Quality

The OWRB conducts stream sampling on more than 100 river and stream sites each year and has collected water quality samples from over 750 wells, allowing for long-term assessment of beneficial uses and water quality trends.

Innovative Water Solutions



With substantial public support, the OCWP recommended the state research and build a framework for appropriate and safe uses of Oklahoma's various non-potable sources of water. Supporting these water conservation and development goals, the Water for 2060 Act (HB 3055) was passed in 2012 as part of a Joint Legislative Committee recommendation.

Assessing Water Supply for Hydrogen Production

Highly treated municipal wastewater is perhaps the most readily available water source throughout the state, both from a water quantity and spatially distributed perspective. Marginal quality water could also be a suitable source water for hydrogen production. The information available from the OCWP can be directly utilized to assess areas across Oklahoma with suitable water supply and water quality for future hydrogen production. This includes water produced from oil and gas production, which could provide a beneficial re-use through technological solutions for processing production water.

The role of natural gas

Natural gas is anticipated to continue to serve as the foundational supply chain source for hydrogen production, extending well into the future (US DOE FE Hydrogen Strategy July 2020 page 1 and IEA Energy Technical Perspective 2020 graphic page 141). With Oklahoma's extensive supply of affordable natural gas, our research institutions should be engaged in the research, development and deployment of novel technologies which convert natural gas to hydrogen economically with minimal environmental impacts, striving for co-production of solid carbon forms which can be used beneficially for building products, or other industrial applications. The cost of H2 cost can be offset by the value and market volume of carbonaceous by-products. Potential to utilize catalytic methods to produce graphene or carbon nanotubes (CNTs) which can be used in large-scale applications. Example applications are environmental remediation, wastewater purification (adsorption and catalysis), reinforced cement for, carbon electrodes (batteries, fuel cells), polymer composites, and road pavement.

Availability of cost competitive power for hydrogen production

As mentioned above, the cost of Oklahoma's electricity is consistently the lowest in the United States. As the hydrogen economy grows in the state, there are many factors to consider. There are many areas with available power and transmission, however, it will be a matter of timing to ensure peak load is covered. If build out is required, there must be consideration of cost recovery, ratepayer protection, transmission planning in coordination with Southwest Power Pool (SPP), and financing up front construction costs in lieu of ratepayer risk (https://www.eia.gov/electricity/state/).

On-site hydrogen production concepts

It is plausible that green hydrogen power plants could develop into energy parks or hydrogen hubs, with offtake users located nearby to the hydrogen source for uses such in heavy duty trucking, steel manufacturing, commercial bus fleets, personal auto fuels, fertilizer plants, industrial heat and steam production, use in household appliances through blending in the natural gas pipeline infrastructure.

Hydrogen production complements renewable energy (off peak "storage")

There is potential for collaboration between renewable energy development companies and hydrogen production companies to develop regional production hubs that maximize the associated investments for both parties. Off peak power production could be directed to the production of hydrogen which could be stored and utilized at a later date when energy demand is higher or injected into the natural gas pipeline infrastructure for use over the course of many days.

Safety issues

Safety must be a primary concern and should be studied as it relates to production and transportation, which is discussed below.

Section 4. Transportation & Distribution Infrastructure

Overview

Oklahoma's central location in the continental United States, extensive natural gas pipeline infrastructure, and the confluence of major interstate routes make the state a major link in the nation's network of trade and commerce and serves as a natural hub for interstate truck traffic. In 2015, 817 million tons of freight were transported in Oklahoma, with 512 million tons moving through the state with an origin and destination outside of Oklahoma. Through traffic accounts for 63% of total freight tonnage and 83% of total freight value in Oklahoma. With 79 million tons of inbound traffic versus 100 million tons of outbound traffic, Oklahoma is a net exporter state. 90% of all freight traffic in Oklahoma is domestic, as defined by the U.S. Department of Commerce as produced within the nation's borders. https://oklahoma.gov/odot/programs-and-projects/transportation-programs/odot-freight-transportation-plan.html.

In general, most freight transported through Oklahoma is being moved from Texas northeast toward the Great Lakes area and the northeastern seaboard, or from California and the western United States to the east coast or northeast.

Freight traffic by mode of transportation (ODOT, 2017)

Coal and nonmetallic minerals (i.e., limestone, granite, stone, sand, gravel, potash, phosphate, and other fertilizer miners) represent the largest volumes of commodities transported by tonnage. Chemical products (i.e., unrefined petroleum such as crude oil and natural gas) are the largest commodity by value.

In 2015, 473 million tons were transported by truck, 338 million tons were transported by rail and 6 million tons were transported by waterway. Air traffic represents a relatively small amount of the total freight movement in Oklahoma but fills a niche by providing business travelers access to more remote areas of the state.

Transportation recommendations on safety issues

Create research center(s) at Oklahoma colleges or universities to document and research hydrogen transportation issues, including fuel stations, corridors, economic incentives, storage technology and safety. The U.S. Department of Transportation (DOT) has oversight over many of these applications through various relevant administrations within DOT. This includes pipelines, whether repurposed or new installations, as well as transportation via roads, railroads, and waterways. https://www.osti.gov/servlets/purl/1773235/

It is also recommended to develop and implement a state hydrogen safety education campaign in conjunction with industry partners that focuses on dispelling myths, sharing knowledge from other states and countries, explaining storage requirements and technology, and highlighting Hazmat procedures and tools already in place.

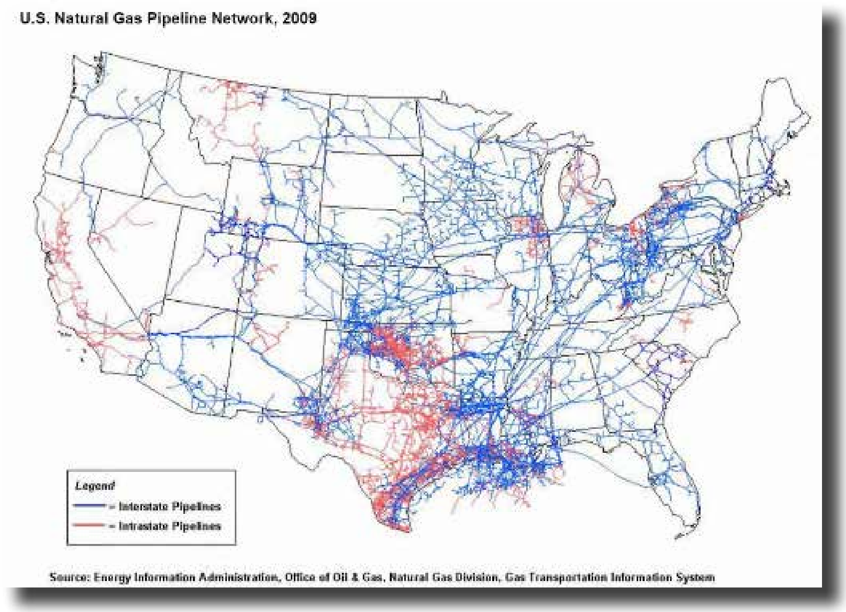
Regulatory overview

A short summary of the various regulatory organizations and their associated jurisdictions is as follows: The Oklahoma Corporation Commission (OCC), Oklahoma Department of Environmental Quality (ODEQ), Water Resource Board (WRB), Oklahoma Department of Transportation (ODOT), Oklahoma Department of Public Safety (DPS), Oklahoma Department of Wildlife Conservation (ODWC) provide regulatory oversite for organizations that will be involved in the growing hydrogen economy. These regulatory issues may involve federal regulators as many of the early projects may involve federal funding which would necessitate a NEPA analysis to determine and study environmental impacts. This will have an obvious effect on the timing of any commencement of construction on any projects. The following provides a snapshot of the various organizations and their areas of focus:

- Distribution Pipeline - OCC, ODEQ
- Distribution Trucking - OCC, ODOT, DPS
- Distribution Blending - OCC, ODEQ
- Storage - OCC, ODEQ

Opportunities to leverage existing pipeline infrastructure (interstate, intrastate and local distribution company pipelines)

Oklahoma is advantageously positioned with extensive and dependable natural gas pipeline infrastructure to serve in-state markets and for the delivery of energy to major market centers. There are numerous Department of Energy studies underway (with Oklahoma companies engaged in the research projects), that are analyzing the safe levels of blending hydrogen into the existing natural gas systems. As the map discloses to the right, Oklahoma could deliver hydrogen via the natural gas pipeline network to locations across the USA as pipeline capacity allows.



Pipeline operators engaging in discussions and studies, supplying data, and working with ODOT and OCC to create map overlays of viable pipelines for blending of hydrogen or for proposed dedicated construction could provide a valuable tool to aid in the determination of both production facilities and end users' locations associated with the hydrogen economy in Oklahoma.

Pipeline Crossings of Highways and Public Right-of-Way

A myriad of public and private utilities cross Oklahoma highways, including fuel transmission, electrical, telecommunications, water, and sewer lines. Most of the highway crossings are facilitated via an underground bore to pass underneath the roadway, while some select utilities pass over highways via a dedicated bridge or an attachment on a roadway bridge. As per state law, only public utilities are permitted to be buried inside of public rights-of-way. Private utilities, such as pipelines for transmission of petroleum products, may be buried parallel to highways, outside of public right-of-way through a private easement.

Hydrogen pipelines could be placed parallel to highways, outside of public right-of-way and would be allowed to cross highways through ODOT's permitting process, detailed below.

Most volatile petroleum products have specific regulations, such as minimum easement width, depth, cathodic protection, signage, and excavation restrictions that would prevent them from being located inside state right-of-way even if they were designated as public utilities. Not only is ODOT unable to place such restrictions on public rights-of-way, but the agency also cannot indemnify the facility owners from liability in the event of a pipeline failure. Highway rights-of-way regularly undergo maintenance and construction that includes excavation by heavy machinery, which is not conducive for buried high-pressure pipeline due to risks to the traveling public and to workers.

While hydrogen pipelines would not be permitted to be located inside public right-of-way, crossings of any type of utility are allowed if they meet specific criteria outlined by ODOT based on U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) regulations. Primarily, these regulations require such pipelines to be encased, sealed, and vented in accordance with certain standards and buried at a minimum of 48 inches below subgrade and not less than 30 inches below the bottoms of ditches. Proper markers are required to be attached to vents and/or right-of-way fencing at intervals of no more than 1,000 ft. and be plainly visible to workers, first responders and the public.

Steel pipelines may be installed without encasement if the pipe material meets certain standards, employs anti-corrosion countermeasures, and is buried at least 48 inches below the flow line of drainage ditches or other drainage structures.

Requests for pipeline crossing permits on highways may be made by contacting the appropriate ODOT Field District office and requesting approval of the District Engineer. Central office experts in ODOT's Right-of-Way and Utilities Division are available to assist with consultation and review. Requests for crossings of city streets or county roads must be made to the appropriate local officials (Oklahoma Department of Transportation. OP-UT 6-5 of the ODOT Right-of-Way and Utilities Policy & Procedure Manual).

Rail Transportation

Oklahoma has 1,987 miles of railroad currently in operation by Class I operators BNSF Railway, Union Pacific Railroad and Kansas City Southern, as well as 1,132 miles of railroads used by Class III short-line operators. The State of Oklahoma, through ODOT, owns and maintains 152 miles of railroad, of which 126 miles are operated through lease agreements with short-line operators.

High volume freight rail routes in Oklahoma:

- North-south: BNSF Railway along I-35 and US-77 corridor between Kansas, Oklahoma City and Texas
- East-west: BNSF along US-412/US-64 corridor between Tulsa and the Woodward/Alva area in northwestern Oklahoma
- North-south: Union Pacific Railroad between I-40 near Checotah, Tulsa and Kansas
- North-south: Union Pacific along US-54 between Texas and Kansas and BNSF along US-287 between and Texas and Colorado in the Panhandle

Since 2005, Oklahoma has had no intermodal rail terminals, which are facilitates that can transfer containers from one mode of transport to another. The nearest intermodal facilities are located in Dallas, Kansas City and Memphis.

Railroad-related concerns and mobility issues can be attributed to several factors. Inadequate track and a rail yard's physical capacity can produce railroad bottlenecks, as can the crossing of two or more tracks. Rail bottlenecks in turn, impact rail velocity. Deficient structures such as bridges can introduce speed restrictions that affect freight mobility.

These factors not only affect the mobility of rail freight but can also have an impact on highway traffic. Slow or stopped trains can interfere with motor vehicle traffic at grade crossings. Even fast-moving trains in high frequency railroad corridors can create bottlenecks for motor vehicles.

The Oklahoma State Freight Transportation Plan includes a list of 16 locations with railroad mobility issues, including limitations on standard 286,000 lb. freight cars, lack of capacity and missing connections; however, the rail network is extensive and can be improved to facilitate distribution of hydrogen in the state.

Hydrogen as a Fuel Source for Trains

According to the Oklahoma Railroad Association and the Association of American Railroads, Canadian Pacific, one of AAR's member railroads, is planning to test a hydrogen powered locomotive. There are other opportunities for Oklahoma's rail infrastructure to adopt hydrogen as a fuel source and we should encourage additional pilot programs and research activities.

Transportation of Hydrogen by Rail

Feedback on hydrogen transport has been received from the Oklahoma Railroad Association and the Association of American Railroads that indicates no liquid hydrogen is currently being transported by train in the United States; however, hydrogen is a commodity authorized by regulation for rail transport if tendered in a USDOT approved tank car. While moving hydrogen by tank car is more hazardous than liquefied natural gas, the rail associations are not aware of industry or regulatory opposition to transportation by rail if the market demand exists. As a matter of fact, the association is receptive to the hydrogen transportation market once it opens to Oklahoma, given all safety precautions are applied.

Due to the cold storage of hydrogen in liquified form, a special insulated tank car is required to transport hydrogen by rail, and very few of these railroad cars are in operation nationwide. Both ORA and AAR note that the tank cars currently used to transport liquefied natural gas, which would be similar to what would be required for hydrogen, are more expensive than traditional tank cars and are currently estimated at around $750,000 each.

Title 49 of the Code of Federal Regulations, Part 174 details PHMSA requirements as they pertain to the transportation of hazardous materials by rail. https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-C/part-174

Waterway Transportation

Opened in 1971, the 445-mile McClellan-Kerr Arkansas River Navigation System (MKARNS) in eastern Oklahoma extends from the Tulsa Port of Catoosa southeast through Arkansas to the Mississippi River and the Gulf of Mexico.i The MKARNS links Oklahoma to a 12-state service area with various domestic ports on the U.S. inland waterways system and foreign ports by way of New Orleans and the Gulf Intracoastal Waterway. This system can be used as a viable tool in the U.S. for international hydrogen with some improvements to the MKARNS over time.

The MKARNS is designated Marine Highway 40 by the U.S. Department of Transportation and is the nation's most westerly inland freight water and provides an ice-free shipping channel year-round. The navigation system supports 11,000 jobs and provides a national and international outlet for Oklahoma and regional commodities and products.

Oklahoma has two public ports – the Tulsa Port of Catoosa and the Port of Muskogee – and other private ports on the MKARNS, including Oakley's Port 33 near Inola, C.G.B. Wagoner, Frontier Terminal and Georgia Pacific near Muskogee-Fort Gibson, C.G.B. Webbers Falls, and the Port of Keota. These ports process more than 6 million tons of cargo annually with a $1.6 billion economic impact in Oklahoma. https://oklahoma.gov/odot/programs-and-projects/waterways/mkarns-50th-anniversary.html

(USDOT, 2021)

General Freight Issues

According to the U.S. Army Corps of Engineers Tulsa District, there is a backlog of maintenance projects on the McClellan-Kerr Arkansas River Navigation System (MKARNS) in eastern Oklahoma. Critical backlog projects to address infrastructure with an estimated 50% chance of failure within a 5-year period include deteriorated gate mechanisms at the Robert S. Kerr, Mayo, Webbers Falls and Graham locks and dams.

Additionally, the McClellan-Kerr Arkansas River Navigation System has a 9 ft. controlling navigation depth, compared to a 12 ft. depth on most other inland waterways which allow heavier loads and larger barges. U.S. Congress authorized a 12 ft. depth on the MKARNS in 2005, but no funding has been appropriated to USACE for the necessary dredging. Waterway industry stakeholders and port operators are actively seeking funds to remedy this deficiency.

Transportation of Hydrogen by Waterway

Feedback has been received from Oklahoma's port operators that acknowledge the potential for hydrogen to be a prosperous commodity, however, strong concerns regarding safety were expressed by all Port representatives. Oklahoma's port operators expressed strong concerns regarding safety of hydrogen transport and storage, given that the common perception of hydrogen is that it is highly explosive. While the Ports feel certain that strict safety protocols and precautions exist, they implore hydrogen industry leaders to educate ports and industrial locations about the real risks, issues and challenges associated with production and storage of the gas, as well as the modern safeguards that are in place to mitigate the risks.

The Tulsa Port of Catoosa has one industry now that produces and maintains pressurized tank trailers and storage as part of their services. The Port Authority has requested that future hydrogen tenants provide areas of impact and safety information for review and approval by its board of directors before allowing large quantities for storage.

CF Industries, located at the Tulsa Port of Catoosa, is the closest thing Oklahoma currently has to an existing hydrogen production and shipping operation with their production and transportation of anhydrous ammonia (NH_3). BayoTech and Linde both have a strong presence at the Port of Catoosa and are already in the Hydrogen production or technology business. Both companies have offered to help with making Oklahoma a Hydrogen-producing state.

Title 49 of the Code of Federal Regulations, Part 176 details PHMSA requirements as they pertain to transportation of hazardous materials by waterborne vessel. https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-C/part-176?toc=1

The U.S. Coast Guard sets and enforces national standards for waterway transportation. Title 33 of the Code of Federal Regulations, Parts 154, 155 and 156 detail USCG regulations for prevention of pollution for vessels carrying hazardous materials. https://www.ecfr.gov/current/title-33/chapter-I/subchapter-O

Title 46 of the Code of Federal Regulations, Parts 38, 150, 151, 153 and 154 detail USCG regulations as they pertain to shipping of hydrogen and similar materials by water. https://www.ecfr.gov/current/title-46

Transporting by barge is the most economical, safe, and environmentally friendly way of shipping bulk and oversized cargo, therefore, the transport of hydrogen products seems like a logical next step towards sustainable growth on the MKARNS. It is the position of ODOT Waterways, that the production, distribution, and export of hydrogen products via the MKARNS would open doors to new business opportunities and economic growth. Furthermore, Oklahoma Ports and industries along the waterways will likely embrace the addition of this commodity if their concerns regarding safety are appropriately addressed.

Oklahoma's ports and the MKARNS are an underutilized resource and provide the state with an incredible connection to international markets. The Oklahoma Department of Transportation is heavily involved in promotion of waterborne transportation of freight and coordination of transportation projects that will enhance the ability of the state's ports and the MKARNS to recruit more industries to the area.

Heavy-Duty Trucking: Hydrogen Fueling Stations and Corridors

The Fixing America's Surface Transportation (FAST) Act of 2015 provides for the designation of alternative fuel corridors for electric vehicle (EV) charging, hydrogen, propane, and natural gas by the Federal Highway Administration (FHWA). Corridor designations must identify near-and long-term need for, and location of alternative fueling infrastructure at strategic locations along major national highways to improve mobility of passenger and commercial vehicles that employ these technologies across the United States. https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/

State or local agencies can nominate alternative fuel corridors for designation by FHWA. An eligible corridor is defined as a segment of the National Highway System (NHS), which includes all interstates and other major highway and turnpike routes in Oklahoma. Additionally, to encourage the creation of a national network of alternative fuel infrastructure, a corridor may also include feeder routes/roads that connect to that NHS segment. Both corridors within a single state and multistate corridors are eligible, with the goal of connecting communities, cities, and regions to develop a national network of alternative fuel facilities.

Routes can be nominated as "Pending" when a smaller number of fuel stations are in operation, or stations are planned but not yet built along a particular corridor. Once a corridor has been built out with an adequate number of public fuel stations within a specificized range, the corridor can be nominated as "Ready" and become eligible for special highway signage.

Designation of Alternative Fuel Corridors are prioritized by FHWA based on the following factors.

Alternative Fuel Facilities
- Number of existing alternative fuel facilities on corridor
- Number of additional planned/projected alternative fuel facilities on corridor
- Distance between existing and planned/projected alternative fuel facilities on corridor
- Visibility, convenience, and accessibility to the users on the corridor
- Explanation of successfully developing new alternative fuel facilities along the corridor based on past activity/success

Corridor Scale/Impact
- Connections to other segments of the NHS to create and develop a national network of alternative fuel infrastructure
- Whether the corridor connects to one or more major metropolitan areas and/or multiple States (multiple States that submit a joint application must identify a lead applicant as the primary point of contact)
- Whether the corridor connects to one or more major intermodal facilities (i.e., freight, transit, etc.)

Emission Reductions
Estimated reductions in greenhouse gas and/or criteria pollutant emissions along the corridor, or in the area, due to existing and projected alternative fuel facilities are factors considered. In a November 2021 report developed by the Association of Central Oklahoma Governments (ACOG), it was determined that a non-attainment designation for the Central Oklahoma region could result in $9 to $15 billion in lost economic opportunity between 2022 and 2050. It is assumed here that a similar economic impact would be applicable for the Northeastern Oklahoma region over a similar time frame if that region was designated non-attainment. A non-attainment designation brings additional federal regulatory requirements for transportation projects, emissions reductions for facilities, and other economic impacts (see Appendix for reference document on non-attainment cost).

Development of Team, Degree of Collaboration, and Support
As we move forward with the hydrogen economy, a team should be formed to focus on collaboration and formation of partnerships regarding alternative fuel vehicles and infrastructure with both public and private sector entities should include:

- State and local officials (nomination must include support from the transportation agency or agencies with jurisdiction over the proposed corridor such as the State, local government, Indian tribe, and/or Federal land management agency)
- Other Federal agencies
- U.S. Department of Energy's (DOE) Clean Cities Program, as well as its associated network of coalitions and stakeholders)
- Representatives of energy utilities; electric, fuel cell electric, propane, and natural gas vehicle industries; equipment manufacturers; fuel suppliers; Original Equipment Manufacturers (OEM); public or private fleets; auto dealerships; energy marketers; utilities/energy companies; alternative fuel and clean air advocacy organizations; local and regional planning entities; freight and shipping industry; clean technology firms; hospitality industry; highway rest stop vendors; industrial gas and hydrogen manufacturers

- Demonstrated interest and support (i.e., support demonstrated through past
- work in the area on alternative fuels, support from local elected officials, public support, stakeholder support, development of incentives, etc.)
- Whether the proposed corridor is an existing electric vehicle charging, hydrogen fueling, propane fueling, or natural gas corridor been designated by a State or group of States.

Optional Information and Considerations

Consideration of Clean Cities coalition locations and existing alternative fuel markets, an FHWA infrastructure coverage criterion for each alternative fuel technology table, and other important data points are captured in the attached Appendix.

Existing Alternative Fuel Infrastructure

CNG vehicles

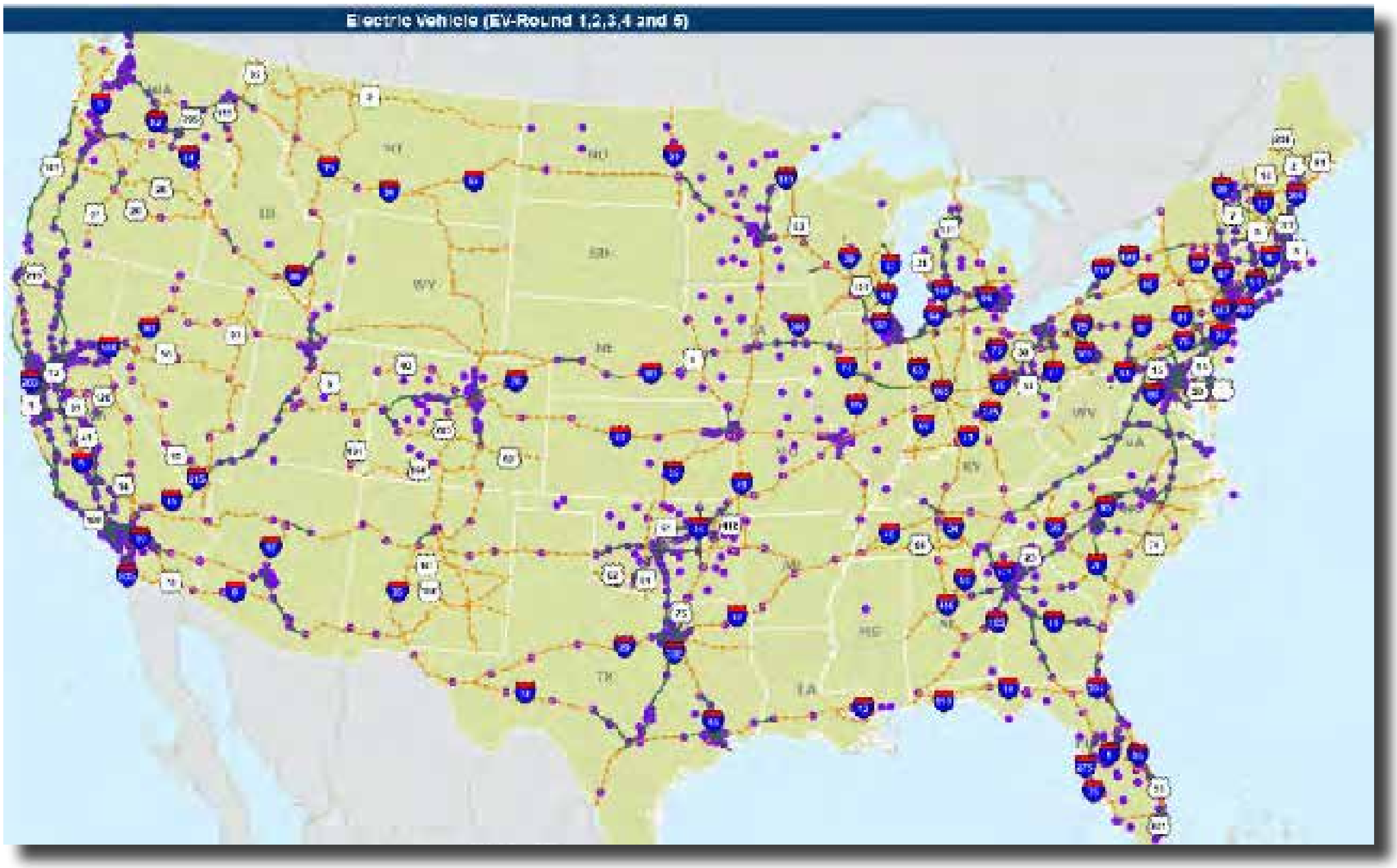
Oklahoma is a national leader in the production and use of natural gas products and features nearly 100 Compressed Natural Gas fueling stations open to the public. The Federal Highway Administration has designated CNG-Ready corridors that include all Oklahoma interstates and significant segments of US-412, US-81, US-69 and SH-351/ Muskogee Turnpike. Segments of US-69, US-75 and SH-51 are designated as CNG-Pending.

Map of designated CNG-Ready (solid lines) and CNG-Pending (dashed lines) corridors in the continental U.S. (USDOT, 2021)

Electric Vehicles

There are 157 Level 3 (fast charging) Electric Vehicle (EV) stations and 112 Level 2 (slow charging)EV stations in Oklahoma. With charging infrastructure in place, FHWA-designated EV-Ready corridors include much of I-35, I-40, I-44, US-75 and SH-51. Major highways including US-81, US-62, US-69 and US-412 are designated EV-Pending.

Currently, more than 4,000 EVs are registered with the Oklahoma Tax Commission, including 2,200 Battery Electric Vehicles and 2,000 Plug-in Hybrid Vehicles according to information from the Oklahoma Tax Commission.



Map of EV-Ready (solid lines) and EV-Pending (dashed lines) in the continental U.S. (USDOT, 2021)

Hydrogen Fueling Infrastructure

For a corridor to be designated Hydrogen-Ready, public hydrogen fueling stations must be spaced no more than 100 miles apart along the corridor. Hydrogen-Pending corridors may have hydrogen fueling stations spaced more than 100 miles apart or hydrogen stations planned for construction. The only Hydrogen-Ready corridors designated by FHWA in the United States are in California, specifically in Southern California and the San Francisco Bay area.

Official data from the U.S. Department of Energy's Alternative Fuels Data Center (AFDC) indicates that there are 48 public hydrogen stations located in California and one in Hawaii. AFDC also notes other North American stations are located in British Columbia, Ontario and Quebec. https://afdc.energy.gov/fuels/0

Love's Travel Stops and Country Stores, of Oklahoma, estimates that about 15 public hydrogen fueling stations are planned along the East Coast and notes that other private hydrogen fueling stations have been built for use by commercial and public transit fleets in the United States.

Hydrogen-Pending routes have been designated in nearly 20 states, including Colorado, Missouri and Texas; which indicates that stations are planned in these areas.

There are currently no public hydrogen fueling stations or known hydrogen-powered vehicles operating on public roads in Oklahoma. It is known that businesses such as Amazon are using hydrogen-powered equipment manufactured by Plug Power for industrial use. This includes powering forklifts with hydrogen through on-site fueling stations for warehouse operations.

Designated Hydrogen-Ready (solid lines) and Hydrogen-Pending (dashed lines) corridors in the continental U.S. (USDOT, 2021)

Alternative Fuel Corridor Recommendations for Hydrogen in Oklahoma

Oklahoma's rich alternative fuel production and corridor development places the state in a favorable position for hydrogen production and corridor application. The state's central location adds emphasis to its viability for such corridors due to the amount of commercial traffic. The following Oklahoma highway corridors with high traffic volumes, especially commercial truck traffic, and interstate connection to major cities and hubs are identified as candidates for future application to FHWA to be designated as hydrogen corridors.

An extensive list of both proposed Phase I Corridors and Phase II Corridors are listed in detail within the attached Appendix.

It's critical to recognize that surface transportation facilities are the first step in accommodating a hydrogen industry while a network of pipelines is being identified for use or construction. Additionally, these infrastructures will continue to serve as "last-mile" delivery means for public travel and industrial applications.

Storage

The regulation of a hydrogen storage system is dependent on the purpose of the storage system and whether the hydrogen is stored in gaseous or liquid form. The U.S. Department of Labor Occupational Safety and Health Administration (OSHA) regulates hydrogen storage through 29 CFR Part 1910 Subpart H – Hazardous Materials. This CFR provides the safety requirements of the structural components and operations of gaseous and liquid hydrogen in terms of storage as well as delivery [8]. Note that there are scope limitations defined for hydrogen storage in this CFR, such as minimum quantity, which depend on whether the hydrogen is gaseous or liquefied. Additional information on regulatory agencies is included in the Appendix. https://www.osti.gov/servlets/purl/1773235/

Hydrogen can be stored as a compressed hydrogen gas in high-pressure tanks, as cryogenic liquid hydrogen in insulated tanks, as a compound within other materials, or on the surface of other materials. Liquid hydrogen has a higher energy density per volume than hydrogen gas but is costly to produce due to the energy needed for cooling.

Geologic storage, beyond salt caverns, needs to be paired with a responsible evaluation of the ancillary risks to the environment, such as possible groundwater contamination, emissions that violate the carbon-neutral goal, and induced seismology. It is also important to note that wellbore integrity solutions need to be developed in tandem with geologic storage as an essential element for a comprehensive understanding of hydrogen underground storage.

Carbon Sequestration

Hydrogen production from natural gas must be coupled with a carbon capture strategy to meet net-zero carbon emission metrics. Carbon capture and sequestration activities can provide a platform for valuable tax incentives and credits, as well as public and private investments, making hydrogen production not only clean but competitive. New pending legislation surrounding enhancements to the 45(Q) suite of incentives makes the commercial viability of CCUS much more attractive. Oklahoma has a competitive advantage over neighboring states in its many developed and undeveloped geological targets for such a "blue" hydrogen model (see Appendix for DOE's National Renewable Energy Laboratory document disclosing Oklahoma's 211 billion tons of theoretical sequestration capacity). Additionally, subsurface storage of hydrogen fuel will require injection into western Oklahoma's underground salt formations, or newly identified reservoir targets as mentioned above. Carbon capture use and storage, along with hydrogen underground storage, require a comprehensive strategy for geological site investigation, engineering, and monitoring by the Oklahoma Geological Survey. Oklahoma Geological Survey currently provides the Oklahoma Corporation Commission with information from the state seismic network which mitigates hazards related to Class-II well injection. Future carbon capture and hydrogen storage efforts confront similar risks, which can be similarly mitigated with coordination between the Oklahoma Geological Survey the corporation commission and the Department of Environmental Quality (Oklahoma Geological Survey, 2021, Geological Carbon Management in Oklahoma, OGS Fact Sheet No.1, https://www.ou.edu/ogs/publications/factsheets).

Safety issues

Research must be performed to determine which geologic formations are appropriate for CO2 sequestration given the State's recent history with induced seismicity attributed to produced water disposal. Detailed geologic mapping of structure, faulting, and formation thickness will aid in determining the capacity of any geologic formation to hold or adsorb CO2. Cooperation between the Oil and Gas industry and Academia will be key to this research effort. Additionally, a joint study on safety impacts on pipelines to burner tip customers if hydrogen is blended into the pipeline system with natural gas. This should include electric generation and gas utility distribution.

<u>Truck Size and Weight Issues</u>
A network of federal and state laws governs size and weight regulations for commercial trucks, which are enforced by the USDOT Federal Motor Carrier Safety Administration (FMCSA) at the federal level and the Oklahoma Department of Public Safety (DPS) at the state level. Carriers seeking to transport an oversize or overweight (OS/OW) load that exceeds these regulations either within or through Oklahoma are required to obtain a permit and specific route from DPS.ii Other DPS requirements, such as the use of escort vehicles and warning placards, may also apply.

Federal law allows loads of up to 80,000 lb. Gross Vehicle Weight (GVW) on the interstate system. It's important to note that the maximum GVW originally set in 1956 Federal-Aid Highway Act that created the interstate network had a lower weight of 73,000 lbs., which was then increased in 1974 after much of the system had been constructed. https://ops.fhwa.dot.gov/freight/policy/rpt_congress/truck_sw_laws/app_a.htm#ex49

All Oklahoma highways are open to legally loaded trucks (80,000 lbs. GVW on interstates and 90,000 GVW on non-interstate routes); however, certain routes may be restricted, and certain bridges may be load posted with specific weight limits. The Oklahoma Department of Transportation has input into the designated weight limits based on infrastructure capabilities and long-term health.

A provision of the Fixing America's Surface Transportation (FAST) Act of 2015 states that vehicles with engines fueled primarily by natural gas may exceed any vehicle weight limit (up to a maximum gross vehicle weight of 82,000 pounds) under 23 U.S.C 127 by an amount that is equal to the difference between the weight of the vehicle attributable to the natural gas tank and fueling system carried by that vehicle and the weight of a comparable diesel tank and fueling system. A similar provision was made in state law in 2016 to mirror federal exemptions for natural gas vehicles.

The result is that vehicles powered by compressed or liquefied natural gas may exceed state GVW limits by up to 2,000 lbs. on public roadways – both interstate and non-interstate routes. These statutes are specific to natural gas and would have to be amended to extend the weight exemptions hydrogen-powered trucks.

No federal regulations exist for truck heights, but Oklahoma imposes a legal height of 14 ft. for trucks on the highway and turnpike systems and 13.5 ft. on local roads. Trucks with taller loads are required to obtain a permit and an approved route from DPS to avoid bridge clearance issues. https://www.oscn.net/applications/oscn/DeliverDocument.asp?CiteID=436865

The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 imposed a national freeze on routes that are allowed to carry Longer Combination Vehicles (LCVs), which are tractor-trailer combinations greater than 60 ft. in length. Oklahoma is one of the few states that permitted LCVs prior to this change and was grandfathered. Doubles with 29 ft. trailers may use any route on the National Highway System in Oklahoma, including interstates. Doubles with trailers that exceed 29 ft. in length are limited to interstate highways and 45 individual Oklahoma highway segments, which are listed in Title 23 of the Code of Federal Regulations, Part 658, Appendix C. According to Oklahoma law, no combination of trucks and trailers operating on public roads may exceed a total 70 ft. https://ops.fhwa.dot.gov/Freight/policy/rpt_congress/truck_sw_laws/index.htm

Hazardous Materials Routes

Motor carriers transporting hazardous materials, including hydrogen, are subject to state and federal regulations for permitting and routing of truck loads.

The FMCSA maintains the National Hazardous Materials Route Registry (NHMRR), which includes Hazmat route designated at the request of states. The NHMRR designations for Oklahoma were made in 1997 and include the following details:

- All shipments of hazardous materials should remain on interstate routes as much as possible while avoiding the centers of large metropolitan areas during times of the day when congested and also avoiding construction zones if they are able.
- Oklahoma City
  - I-40 between I-44 and I-35 in downtown Oklahoma City is banned from Hazmat transportation. I-44 and I-240 are designated as the bypass for this section of I-40.
- Tulsa
  - I-244 (West and North legs of the Inner Dispersal Loop) should be used for Hazmat transportation through downtown Tulsa

As far as additional safety concerns for commercial truck transportation, it is important to note that US-69 in eastern Oklahoma is used extensively by the U.S. Department of Defense for transportation of explosive materials to and from the McAlester Army Ammunition Plant in Pittsburg County in southeastern Oklahoma. https://www.fmcsa.dot.gov/regulations/hazardous-materials/national-hazardous-materials-route-registry-%E2%80%93-oklahoma

Transportation of Hazardous Materials by Truck

Federal and state regulations exist for commercial trucks and the drivers operating them in the transportation of hazardous materials. A Commercial Driver License (CDL) issued by DPS with the following endorsements may be required to transport materials like hydrogen:

- “H” Endorsement: Hazardous Materials
- “N” Endorsement: Tank Vehicle
- “X” Endorsement: Combination of Hazardous Materials and Tank Vehicle

Additionally, a background check through the Transportation Security Administration (TSA) is required for the issuance of an Oklahoma CDL. https://oklahoma.gov/dps/obtain-an-oklahoma-commercial-driver-license/cdl-license-endorsements-or-restrictions.html

As per The Oklahoma Motor Carrier Safety and Hazardous Materials Transportation Act, drivers and/or workers involved in an accident or incident during the transportation, loading or unloading of hazardous materials must immediately notify DPS, which will produce a report that is sent to USDOT. Those involved in an accident or incident may also be required to notify USDOT as well. https://www.oscn.net/applications/oscn/DeliverDocument.asp?CiteID=82814

The USDOT Pipeline and Hazardous Material Safety Administration (PHMSA) sets and enforces national standards for the storage and transportation of hazardous materials. Title 49 of the Code of Federal Regulations, Parts 171, 172, 177, 178 and 180 detail these requirements as they pertain to the transportation of hydrogen and similar materials on publicroadways.https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-C

The USDOT Federal Motor Carrier Safety Administration (FMCSA) sets national standards for licensing and testing of truck drivers and permitting of hazardous loads. Title 49 of the Code of Federal Regulations, Parts 356, 389 and 397 detail these as they pertain to the transportation of hydrogen and similar materials. https://www.ecfr.gov/current/title-49/subtitle-B/chapter-III

Rail Safety Considerations

The Oklahoma Railroad Association (ORA) and the American Association of Railroads (AAR) provided comments about rail transportation of hydrogen, including safety issues and concerns.

Due to the cold storage of hydrogen in liquified form, a special insulated tank car is required to transport hydrogen by rail, and very few of these railroad scars are in operation nationwide. ORA and AAR note that the tank cars currently used to transport liquefied natural gas, which would be similar to what would be required for hydrogen, are more expensive than traditional tank cars and are currently estimated at around $750,000 each.

Title 49 of the Code of Federal Regulations, Part 174 details PHMSA requirements as they pertain to the transportation of hazardous materials by rail. https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-C/part-174

Waterway

Oklahoma's port operators expressed strong concerns regarding safety of hydrogen transport and storage, given that the common perception of hydrogen is that it is highly explosive. While the Ports feel certain that strict safety protocols and precautions exist, they implore hydrogen industry leaders to educate ports and industrial locations about the real risks, issues and challenges associated with production and storage of the gas, as well as the modern safeguards that are in place to mitigate the risks.

The Tulsa Port of Catoosa has one industry now that produces and maintains pressurized tank trailers and storage as part of their services and has petitioned the port multiple times for permission to place outdoor storage tanks of hydrogen. Additionally, a past opportunity involved a welding gas supplier who wanted to produce hydrogen at a location to dispense to the public. The Port, however, was not in favor of allowing it (in large quantities) until the company provided a safety plan that demonstrated the area of impact.

CF Industries, located at the Tulsa Port of Catoosa, is the closest thing Oklahoma currently has to an existing hydrogen production and shipping operation with their production and transportation of anhydrous ammonia (NH_3).

Title 49 of the Code of Federal Regulations, Part 176 details PHMSA requirements as they pertain to transportation of hazardous materials by waterborne vessel. https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-C/part-176?toc=128

The U.S. Coast Guard sets and enforces national standards for waterway transportation. Title 33 of the Code of Federal Regulations, Parts 154, 155 and 156 detail USCG regulations for prevention of pollution for vessels carrying hazardous materials. Title 46 of the Code of Federal Regulations, Parts 38, 150, 151, 153 and 154 detail USCG regulations as they pertain to shipping of hydrogen and similar materials by water. https://www.ecfr.gov/current/title-33/chapter-I/subchapter-O

https://www.ecfr.gov/current/title-46

Air

Feedback has been received from the Oklahoma Aeronautics Commission that indicates hydrogen is not currently being transported by air and is unlikely to anytime in the near future without significant advances in technology and safety measures.

According to OAC, many in the industry believe it will be a very long path forward to get the Federal Avigation Administration to certify the technology and orient the public to be comfortable with widespread use of hydrogen fuel aircraft. Timeframes such as 2040 and 2050 have been tossed around as dates for widespread use of hydrogen in aircraft, and even then, there is considerable uncertainty as to what vehicles it will be used in at that time.

Title 49 of the Code of Federal Regulations, Part 175 details PHMSA requirements as they pertain to transportation of hazardous materials by aircraft. https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-C/part-175

The Federal Aviation Administration sets and enforces national standards for aircraft, including design, operation and fueling. Title 14 of the Code of Federal Regulations, Parts 23, 25, 27, 29 and 33 deal with aircraft requirements for fuel sources, which includes hydrogen power. https://www.ecfr.gov/current/title-14/chapter-I

Oklahoma Opportunities

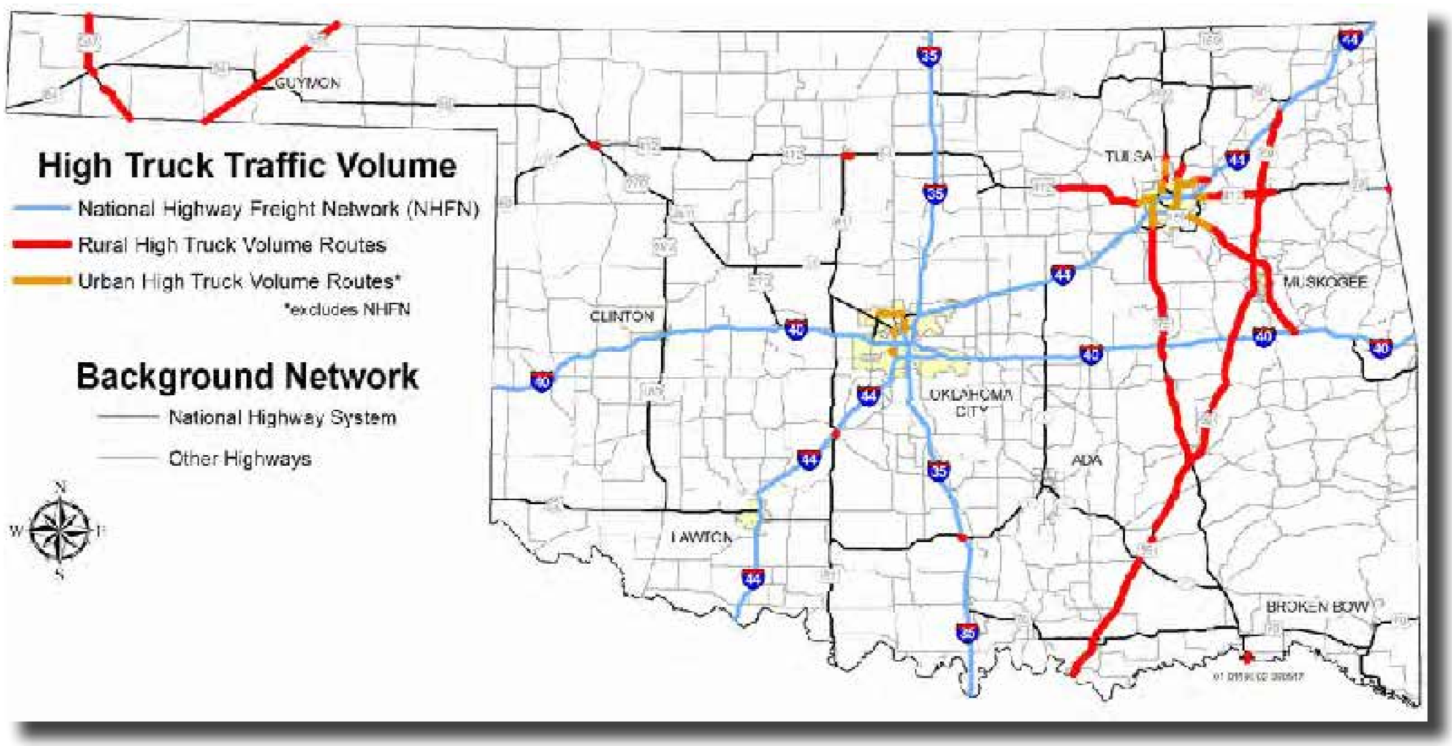
Filling stations using delivered hydrogen via heavy trucks is possible under current guidelines. Implementing clear regulator authority similar to those recently developed in the Oklahoma Drive Act of 2021 for Electric Vehicles would be appropriate and recommended.

- Potential for joint venture projects with power producers for onsite production and use
- Safety studies and legislative review would need to be analyzed for appropriate updating

Highway Transportation

Oklahoma's central location and major highway corridors make the state an important link in the region and nation's network of trade and commerce, especially for interstate commercial truck traffic. Oklahoma's highway system includes more than 30,000 lane miles or more than 12,000 centerline miles of interstates, U.S. highways and state highways maintained by ODOT and nearly 625 centerline miles of tolled interstates and highways maintained by OTA. The highway system is the 17th largest in the nation by centerline miles, ahead of states like Florida and just behind California.

Major cross-country interstate routes like I-35, I-40 and I-44 facilitate transportation of freight from coast to coast and from Texas and Mexico north to the Great Lakes states and the Northeast.



High commercial truck volume corridors in Oklahoma (ODOT, 2017) Commercial Truck Traffic

Major routes for freight traffic include Oklahoma's interstates – I-35, I-44, I-40, I-240, I-235, I-244 and I-444 (Inner Dispersal Loop in Tulsa) – which are part of the National Highway Freight Network. Urban High Truck Traffic Volume routes include several major non-interstate turnpikes and non-tolled freeways, including the John Kilpatrick Turnpike (proposed future I-240) in Oklahoma County and US-64/SH-51/Broken Arrow Expressway in Tulsa County. Rural High Truck Traffic Volume routes include:

- US-69 from the Texas state line near Colbert to I-44/Will Rogers Turnpike at Big Cabin
- US-75 between the Kansas state line and I-40 in Henryetta
- SH-375/Indian Nation Turnpike between I-40 in Henryetta and US-69 in McAlester
- SH-351/Muskogee Turnpike between Broken Arrow and I-40
- US-412 between Tulsa and US-69
- US-412/Cimarron Turnpike between Tulsa and Hallett
- The junction of US-412 and US-270 in Woodward
- The junction of US-412 and US-81 in Enid

- US-81 in Chickasha
- US-54 between the Texas state line and the Kansas state line in the Panhandle
- US-287 between the Texas state line and the Colorado state line in the Panhandle

Oklahoma has a strong transportation presence and can compete well on a national level due to its central location, expansive transportation network and recent infrastructure investments making it a viable hub for transportation and distribution of hydrogen in the nation. Oklahoma is also well-positioned with existing alternate fuel corridors with high volumes of commercial truck traffic that can work as a blueprint for future Hydrogen corridors.

Pipeline Transportation

An extensive pipeline network is needed as the ultimate goal if Oklahoma is to become a major hydrogen producing state. This will allow Oklahoma to not only produce hydrogen for use in the state and the U.S. but also to export internationally. However, surface transportation by truck, rail and waterway will be a key component initially and also after pipelines are fully implemented for "last mile" delivery, etc. Oklahoma must also continue to develop modern rules and procedures to facilitate surface transportation of hydrogen in the near and long-term.

What is most needed for Oklahoma to become a successful hydrogen production, distribution and transportation center is public-private partnerships that can bring about interest from hydrogen producers, pipeline owners and fuel station owners who will add hydrogen to their portfolios.

Transportation Recommendations

Based on thorough research and available data, the Transportation Cabinet makes the following recommendations to capitalize on state resources in a strategic manner to help make Oklahoma a hydrogen producing state.

Research and Development (1-2 years)

- Create a research center at an Oklahoma college or university to research hydrogen transportation issues, including fuel stations, corridors, economic incentives, pipelines, and storage technology, and to pursue federal grant funding opportunities.

Safety Education (1-2 years)

- Develop and implement a statewide hydrogen safety education campaign in conjunction with industry partners that focuses on dispelling myths, sharing knowledge from other states and countries, explaining storage requirements and technology and highlighting Hazmat procedures and tools already in place. This should be aimed at businesses and the public alike to help familiarize Oklahomans of the benefits of hydrogen and the related industry job creation in the communities.

Legislative and Regulatory Updates (2-3 years)

- Identify and support necessary updates to Oklahoma state statutes and administrative rules to remove any remaining barriers and prepare the way for a hydrogen program, including alternative fuel incentives applicability to hydrogen
- Support action on agreed-upon national standards for hydrogen fueling stations (i.e. 350 bar vs. 700 bar) or other variances that could create a barrier to a speedy implementation or additional unnecessary costs to fuel station operators or the industry.
- Support authorizing legislation for state incentives for addition of hydrogen fueling stations and subsequent application for designation of hydrogen corridors
- Support federal and state legislation to standardize reasonable truck weight exemptions for alternative fuel vehicles and extending these exemptions to hydrogen powered trucks, considering engineering recommendations for infrastructure.

Hydrogen Fueling Stations (2-5 years)

- Develop partnerships with commercial fueling station owners to add hydrogen to the footprint of their stations on major corridors.
- Fuel stations must be in place before corridors can apply for Federal Highway Administration designation as alternative fuel corridors.
- Incentives for fuel station build-outs must consider the cost differential in the more expensive hydrogen pumps vs. other alternate fuel pumps such as EV or CNG.
- Incentives should also require a longer time period before a hydrogen car can be resold by the first buyer. Early suggestions are no less than 2-3 year ownership. This will allow the hydrogen industry the longevity to become better established and dispel uncertainties in hydrogen vehicle ownership.

Alternative Fuel Corridor Designation

- Develop and seek Federal Highway Administration approval of Phase I Corridors (1-5 years) in partnership with substate planning districts
- Develop and seek FHWA approval of Phase II Corridors (5-10 years) in partnership with substate planning districts

Resource Development

- Use the below interactive GIS tool, which was developed as a living map to provide a platform for continued hydrogen research and planning programs across multiple agencies and organizations https://okdot.maps.arcgis.com/apps/webappviewer/index.html?id=0198757b53f84ee49dbbeb74374c31a8
- The Oklahoma Department of Transportation website contains the GIS mapping link above and the Transportation Cabinet report to the Hydrogen Production, Transportation, and Infrastructure Task Force: https://oklahoma.gov/odot/about/boards-and-task-forces/hydrogen-task-force.html

Section 5: Market Uses

Hydrogen is currently utilized within many industries and has a myriad of applications developing around the globe. Uses for hydrogen include, but are not limited to:

- Chemical and industrial purposes (e.g., ammonia production, petroleum processing, microchip manufacturing, and other industrial applications).
- Heaters, boilers, and similar heating appliances
- Residential, commercial, and industrial heating systems
- Blending into natural gas supply value chain
- Production of electricity via fuel cell and combustion systems
- Used within combustion turbines or internal combustion engines for power generation
- Power generation via fuel cells for primary and auxiliary power systems. Fuel cells are adaptable to scale and can be used in a variety of applications including utility-sized power plants, various forms of surface transportation vehicles, back-up generators, and many additional applications

(https://www.osti.gov/servlets/purl/1773235)(https://www.oregon.gov/energy/energy-oregon/Pages/Hydrogen.aspx)

A promising early application for hydrogen fuel is in the transportation sector. Fuel cell vehicles (FCV) utilize hydrogen to produce electricity to drive electric motors (similar to an electric vehicle that relies upon batteries to store electricity), have the benefits of extended range, quick refueling and impressive fuel economy which is close to 70 miles per gallon equivalent (https://www.epa.gov/greenvehicles/hydrogen-fuel-cell-vehicles). Oklahoma's strategic location for long haul trucking as disclosed above provides an opportunity for our state to participate in the hydrogen fueled transportation sectors.

	Transportation Applications	Chemicals and Industrial Applications	Stationary and Power Generation Applications	Integrated/Hybrid Energy Systems
Existing Growing Demands	• Material-Handling Equipment • Buses • Light-Duty Vehicles	• Oil Refining • Ammonia • Methanol	• Distrubuted Generation: Primary and Backup Power	• Renewable Grid Integration (with storage and other ancillary services)
Emerging Future Demands	• Medium-and Heavy-Duty Vehicles • Rail • Maritime • Aviation • Contruction Equipment	• Steel and Cement Manufacturing • Industrial Heat • Bio/Synthetic Fuels	• Reversible Fuel Cells • Hydrogen Combustion • Long-Duration Energy Storage	• Nuclear/Hydrogen Hybrids • Gas/Coal/Hydrogen Hybrids with CCUS • Hydrogen Blending

Figure 1. Existing and emerging demands for hydrogen

The Department of Energy National Renewable Energy Laboratory's report "The Technical and Economic Potential of H2@Scale Concepts within the United States" dated October 2020 discloses the scope and scale for diverse hydrogen markets from current consumption levels of 10 million metric tons per year up to a theoretical 106 million metric tons per year (not taking into consideration the economics of matching supply and demand), with a reasonable potential between 22 and 41 million metric tons per year (taking into account regional economics and current technologies the market is on the lower end of the range). Transportation is the largest new hydrogen opportunity with a 27% potential market. (https://www.nrel.gov/docs/fy21osti/77610.pdf)

Petroleum refineries are the largest consumers of hydrogen in the US (10 Million Metric Tons per year), growing approximately 27% from 2017 through 2050. (H2@Scale Demand Analysis Report Argonne Lab page xii 7.5 vs 5.9 MMT)

Nitrogen fertilizers (Ammonia/NH3) require substantial quantities of H2 (in 2018 9.8MMT of fertilizer was produced domestically and 3.8MMT was imported). It is important to note that ammonia is also a viable "carrier" of hydrogen as it is a stable product and can be moved efficiently via truck, pipeline, and by ship. Ammonia production domestically is estimated to increase 25% from 2017 to 2024, with an additional 15% growth through 2050. (Argonne National Labs Assessment of Future Potential Demands for Hydrogen in the United States page pages 25 and 28)

Global hydrogen development strategies have focused on deployment of "clusters" with large-scale hydrogen off takers. The specific clusters include port areas for fuel bunkering, port logistics like drayage and marine vehicles, and heavy transportation vehicles. Additionally, industrial centers that are home to refineries, power generation, fertilizer and steel production are areas of focus, as are export hubs in resource rich areas. (Hydrogen Insight Report 2021 Hydrogen Council, McKinsey and Company page vii)

Sustainability initiatives and Environmental, Social and Governance (ESG) reporting activities have raised awareness for the management of greenhouse gas footprints and life cycle impacts to produce energy, goods and services, transportation, and manufacturing. Natural gas is the most efficient and dependable solution to produce industrial heat, steam, and electricity generation at this time, however, the trend in environmental impact reduction commitments by large corporations may provide an opportunity for blending low-carbon hydrogen into the natural gas pipeline networks as a method of reducing overall emission impacts. Companies interested in renewable natural gas (methane produced from animal manure and landfills) for sustainability reasons may be interested in purchasing low-carbon hydrogen for their industrial heat, steam, and power generation. One of the most economical methods of transporting hydrogen is by pipeline, thus blending at the source of hydrogen production into the state's natural gas pipeline network could provide a safe, dependable, and cost-effective means of transportation to the point of consumption.

A near term and long-term use for hydrogen as a fuel source showing promise is in the heavy-duty trucking sector which not only move products within our state, but most of the tonnage transported by heavy duty trucking moves through Oklahoma. As we have seen with other previous alternative transportation, the infrastructure for refueling will be required before stakeholders procure trucks that can use hydrogen as a fuel. The benefits associated with hydrogen as a trucking fuel include longer range than batteries, exhaust is water and heat, and refueling time is similar to diesel refueling. Oklahoma has strategic transportation corridors that would provide advantageous refueling infrastructure locations to service the next generation of heavy-duty trucks.

Several models of unmanned aerial vehicles (UAVs or "drones"), currently utilize fuel cells for power while others use batteries. Fuel cells provide the drones with longer flight times and quick refueling compared to traditional battery-operated drones.
Oklahoma's UAV stakeholders could be engaged in research, development, and

deployment of novel technologies in the expanding UAV sector utilizing hydrogen to extend range and airtime. (Fuel Cell and Hydrogen Energy Association fact sheet Materials Handling and Fuel Cells https://www.fchea.org/transportation)

Ports have been a focal point and high priority target globally for the development of hydrogen for use as a low-carbon fuel source. Tulsa's Port of Catoosa could be our state's focal point for a hydrogen "cluster" and region for building critical mass in the developing hydrogen economy. The Tulsa Port is not only home to a global leader in hydrogen production, but also home to many industrials and manufacturers which fulfill portions of the nation's hydrogen supply chain today. We could implement varying pilot concepts for transportation (marine, drayage, forklift transportation), and form a corporation friendly environment for proof-of-concept initiatives (blending for power generation, electrolysis and pyrolysis concepts using renewable energy).

Lessons learned from previous initiatives in CNG

Oklahoma has experience in the alternative fueled vehicle sector and we learned lessons over the years. The following captures some of the lessons learned which can be considered for initiatives associated with growing our hydrogen economy:

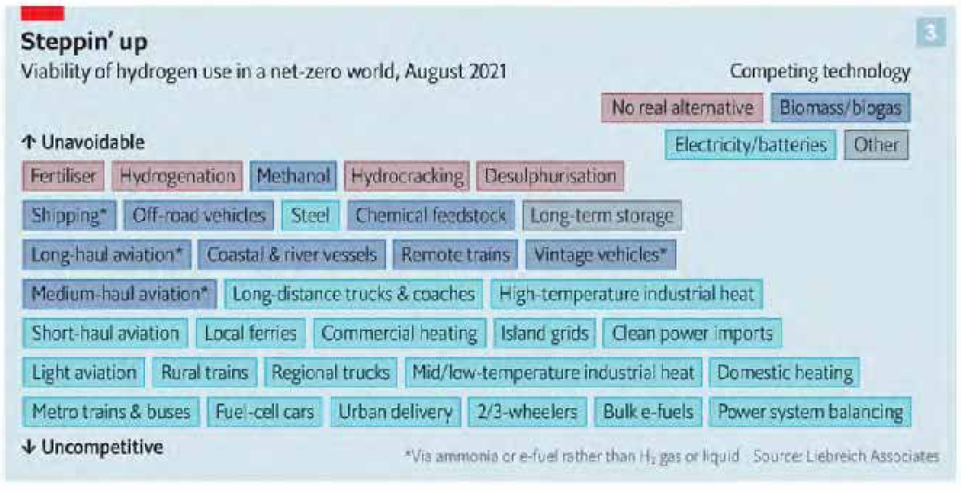
- Ownership of hydrogen-powered cars should be 2-3 years for incentives to be applicable
- Large local fleet vehicles should be the focus area as the infrastructure will provide economies of scale and possibly provide public refueling stations
- Hydrogen fueling station infrastructure for both public and private applications should be incentivized
- Collaboration with other states that are implementing hydrogen programs, transport, storage and fueling infrastructure.
- Define and publish a goal for inclusion in the State Energy plan to kickstart through state vehicle purchases
    - Include appropriate fleet planning steps for long term success
- Incentives at a utility level are useful, easy to manage, and result in numerous vehicle purchases

Section 6: Economic Opportunities

Overview

Oklahoma's long legacy in energy positions the state to not only be a producer but a consumer of hydrogen. Adding Hydrogen to our ever-expanding energy portfolio is a strategic investment both from the public and private investment point of interest.

The Hydrogen sector has many cross-cutting applications that Oklahoma is positioned to take advantage of. Our abundant amount of natural gas, wind generation and likely growth in the solar industry provide a path toward a vibrant energy-focused industry in Oklahoma.



The challenges that lie ahead are rooted in supply and demand. If hydrogen is readily available through the natural resources in Oklahoma, then it is only a viable economy if there are end users who need the products. Moving forward, it is demand that will drive the hydrogen economy not policy makers. Our job is to catalyze and support private industry to participate, innovate, thrive, and create opportunities for the coming markets. In that sense Oklahoma understands that both production operations and end users must evolve simultaneously for the economy to prove worthy of the immense amount of investment needed to stand up operations.

Hydrogen fuel has the potential to be used in a myriad of ways, including to decarbonize natural gas distribution systems, industrial processes, thermal power generation, heavy and long-distance transportation, aviation, aerospace, deep space, defense and more. A litany of industries are looking to hydrogen as a new clean energy solution. In fact, the entire world is talking about decarbonization, and hydrogen is an important part of that process. With it brings a heavy lift in making the transition, yet the shift is well underway. Demand, research and technology innovation, and federal investment will drive down any arguments regarding scale and cost which is why the transition is well underway.

While the most obvious benefits of a hydrogen economy lie in the energy sector there are other industries which this economy can have an enormous impact on. Aviation and large watercraft such as ferries and barges may very well play a large role in the hydrogen infrastructure even though the application of hydrogen to these industries is ongoing. Planes using hydrogen fuel cells could give battery-electric alternatives and provide a competitive edge. ZeroAvia, a startup backed by British Airways and Jeff Bezos, Amazon's billionaire founder, completed the first fuel-cell-powered flight in a commercial-sized aircraft in Britain a year ago. Ferry operators in Norway and on America's west coast are now experimenting with short-haul ferries powered by hydrogen fuel cells.

Airbus is pushing forward and sees hydrogen as a viable solution and are wagering their support for the transition. In September, it confirmed a plan to power planes using hydrogen by 2035 stating hydrogen has an energy density three times that of kerosene and is made for aviation.

Many of the world's big heavy haul truck makers, including Volvo and Daimler, are racing against startups like Nikola and Hyzon to bring hydrogen-fueled heavy haul trucks to market on the basis that the weight and recharging time of batteries means they are not able to be used. When large trucks with heavy loads need to travel farther than 120 miles batteries become unrealistic and are unable to serve the demand of the industry. As the shift to hydrogen begins to take place, we might see a transitional approach in heavy haul trucking using retrofit hybrid (diesel Hydrogen) engines. Lower costs of a retrofit option of $50K vs $300K for a 100% hydrogen engine will help to bridge the transition as heavy haulers with long haul fueling infrastructure that isn't built out yet. As older trucks are removed from fleets, we will begin to see full conversions hitting the road.

Cummins, known for its conventional diesel engines, is betting big on hydrogen, having acquired firms making electrolyzers, fuel cells and hydrogen tanks. Tom Linebarger, Cummins chief executive, says he is highly confident that hydrogen will be "even money" with diesel on total cost of ownership by 2030. Customers, he says, are worried about the reliability of vehicles with batteries. Fuel-cell vehicles are a solution as using hydrogen removes the dependency of the grid.

Job creation Workforce development

With the emergence of a new industry in the state the need for qualified workers will be immense. The ability for a geographic region to train workers and create jobs in both quality and quantity will likely be a determining factor in the success or failure in the creation of a new industry cluster. Should state leaders decide to invest heavily in a hydrogen economy it will be well positioned to create a workforce in this area because of the nature and circumstances that surround existing industries.

Currently the largest employment sector in Oklahoma is energy, and technicians are the job most in demand. In 2020, there were 79,825 active jobs reported in the energy sector. That number is expected to decrease by nearly 10,000 jobs by 2025. The demand decrease for jobs can be attributed to afew key drivers; 1) the worlds movement to decarbonization creates a dynamic shift in the Energy Sector. Experts are projecting a gradual decline in demand over the next 10 years, and 2) the advent of automation as it will be the defining lead for workforce in the energy sector as new technology delivers efficiencies. However, moving toward automation doesn't mean displacement of workers. Automation complements laborers and challenges workforce to become more skilled in an advancing technological industry all the while increasing quality and production. This thrust will be felt across all industry sectors and will not be specific to energy. The opportunity to upskill existing workers will lead to a stronger more technological economy. Strong preferences for professionals and technologists including engineers, software developers, analysts, cyber security, and other highly technical skill sets will be part of a growing demand.

Put simply, if one employment sector is expected to decrease then the best way to utilize workers in need of a job is to transition into a similar position. Considering the hydrogen energy similarities with existing energy jobs, workers could be retrained and reskilled at a faster pace than workers from other industries.

The shifting nature of work will require investments that build upon existing workforce to reskill and upskill with the intent to transition people into high growth occupations. Oklahoma employers have relied heavily on the Career Tech system to train and qualify our workforce, especially in the energy industry. For years energy could be found under manufacturing and other STEM field. However, in preparation for the future transition of the industry a new cluster was developed, and in 2020 the Oklahoma Career Tech system added energy as the 17th career cluster to their system. Oklahoma's Career and Technology Education (https://www.okcareertech.org/) provides leadership, resources and technical assistance using the instructional framework which links what students learn in school with the knowledge and skills they need for success on the job. All of this will set the stage for Oklahoma to thrive with the emergence of a Hydrogen Economy.

Hydrogen is set to make a return to the mainstream as the international community seeks to respond to the world's energy and climate challenges, particularly considering the targets set by the 2015 Paris Climate Agreement and recent climate activism around the world. The term 'Hydrogen Economy' refers to the vision of using hydrogen as a clean, low-carbon energy resource to meet the world's energy needs, replacing traditional fossil fuels and forming a substantial part of a clean energy portfolio. The international hydrogen market could be worth up to $2.5 trillion by 2050, meeting 18 percent of global energy demand, providing 30 million jobs around the world.

There are several reasons hydrogen is receiving serious consideration as an alternative energy source after years of being pushed to the side. In addition to a global desire for more environmentally friendly fuel sources, improvements in hydrogen technologies, increasing government support for climate-friendly fuel diversification (e.g., in countries such as Japan, Korea and Germany) and changes in global energy policy, in emission standards and in the global technology landscape with renewables that require grid-scale storage for system stability all help to support the argument for developing the hydrogen economy. It is also generally recognized that hydrogen has the potential to decarbonize a range of industries.

Oklahoma recommendations

A few opportunities and recommendations rise to the top of the list when considering the above information.

- Business Recruitment defining Hydrogen production as a manufacturing facility will be in line with how Oklahoma defines oil and gas refineries.
- Develop incentives for established energy companies to build capabilities in carbon capture vertical (from sequestration to equipment manufacturing and services).
- Diversify economic base, expanding Oklahoma's energy portfolio.
- Creating policy that supports the appropriate development of this new economy.
- Create an environment that incentivizes investment in alternative fuels.
- Develop metrics around the impacts of alternative energy sources, including hydrogen and CCUS
- Develop regional and national partnerships that allow Oklahoma's unique resources to compliment other states and industries

Additionally, investments in R&D funding for advancing technologies in the Hydrogen economy are needed and the production and deployment for emerging hydrogen-based industries is where Oklahoma should focus. For any technology to be adopted, it must meet three criteria: it must be technically feasible; it must be affordable; and people must be willing to adopt it. We need to create policies that support the appropriate development of this new economy.

Create an energy innovation and alternative fuels fund for R & D tech development. Investing in a national research center driven by public private partnerships can create a technology transfer pipeline which will attract thought leaders in alternative fuels.

Federal Infrastructure Bill opportunities leverage Oklahoma's long-standing history of exporting energy can continue with the delivery of dependable hydrogen supplies from an advantageous midcontinent foundation. Oklahoma maintains a business-friendly economy which should also be leveraged to bring hydrogen demand closer to the supply as a national environmental strategy.

Section 7: Fiscal Impact Statement and Recommendations

Fiscal Impact Statements

Calculation of the direct impacts utilized the National Renewable Energy Laboratory (NREL) report “The Technical and Economic Potential of the H2@Scale Concept within the United States” dated October 2020, which estimates the anticipated growth in hydrogen production as well as cost estimates from Enapter, a private company engaged the manufacture of equipment for the hydrogen market. Costs and direct impacts from various NREL scenarios estimating total hydrogen production from 22 MMT of hydrogen to 41 MMT of hydrogen were calculated and it assumes cost of electricity of approximately 3.5 cents per kWh.

If Oklahoma were to capture 3% of the new growth in the hydrogen market, a market roughly equivalent to the size of the existing refining capacity in the state of the total US market, then Oklahoma would produce 0.66 million metric tons (MMT) of hydrogen when total contiguous production equaled 22MMT and would produce 1.23MMT if the total market size were 41MMT. This baseline scenario would require an estimated $1.072 billion in new CAPEX in the state ranging up to $1.998 billion in new CAPEX in the high production category.

Using similar industries’ composition of CAPEX, approximately 16% of this investment ($171.5 million in the low baseline scenario to $319.6 billion in the high baseline scenario) would include new construction activities, which increases an additional 18% to approximately 34% of the total when engineering, installation and contract work is included. Machinery and equipment account for nearly two-thirds of the total CAPEX totaling $675.3 million in the low baseline scenario and up to $1.258 billion in the high baseline scenario.

If Oklahoma captured greater proportions of the total hydrogen market (up to 25% of the market is illustrated in the tables captured in the Appendix), then the required CAPEX to produce the hydrogen would be much greater between $8.932 billion and $16.646 billion in total CAPEX.

IMPACT TYPE	EMPLOYMENT	LABOR INCOME	VALUE ADDED	OUTPUT
DIRECT EFFECT	1,626	$ 11,485,600	$ 405,370,000	$ 1,450,000,000
INDIRECT EFFECT	2,884	$ 219,176,000	$ 370,742,000	$ 837,166,000
INDUCED EFFECT	1,876	$ 7,933,700	$ 141,910,000	$ 257,000,000
TOTAL EFFECT	6,385	$ 413,367,000	$ 918,022,000	$ 2,544,000,000

OPEX, or operational expenditures, occur annually and would include the cost to produce the hydrogen. These costs include electricity, labor/maintenance, and water expenses. These expenses would total $1.393 billion in the low baseline scenario and $2.597 billion in the high baseline scenario where Oklahoma is capturing only 3% of the market. Electricity is the largest expense for a hydrogen facility’s production costs (and thus Oklahoma’s low electricity rates provide a benefit for hydrogen producers).

Given that the above are costs of production, an economic impact can be estimated. Assuming only a 4% profit margin, total sales of hydrogen would be $1.450 billion. This is expected to directly employ over 1,600 people with indirect impact from supplier industries employing an additional 2,884 people. Given that jobs in similar industries pay very good wages, the induced impacts, or the impacts from households directly employed by the hydrogen industry, would create an additional 1,876 jobs resulting in total employment impacts of 6,386 new jobs in Oklahoma.

Recommendations

- Develop legislation, or potentially an Executive Order, for an annual update on hydrogen economy developments, progress, and challenges for delivery to the Governor, President Pro Temp, and the Speaker of the House.
- Align existing legislation related to CNG, EV and other alternative transportation fuels by including hydrogen.
- Creating policies that support the appropriate development of this new economy, including streamlining permitting for hydrogen production and use
- Determine Oklahoma's carbon sequestration potential storage capacity, de-risk the timeline for Class VI permitting, and provide processes for all stakeholders involved in sequestration to provide a pathway for implementation

Section 8: Conclusion, Action Items, and Roadmap

Industries, investors, research institutions, and policymakers working together and collaborating to unlock the full value of the hydrogen economy for Oklahoma is key to our success. Oklahoma's diverse resources (fossil, renewable and water), combined with its existing infrastructure (roadways, corridors, pipelines, rail, and waterways) intersect to provide a strong platform from which to produce low-cost hydrogen supporting our state's economy and environment through both in-state applications and for export across the US.

Legislators, regulators and permitting agencies should review and augment as necessary existing rules and laws to provide transparent pathways for developers and investors interested in the Oklahoma hydrogen economy. Our focus on a business-friendly environment for hydrogen stakeholders will complement activities involving the federal funding for hydrogen hub infrastructure activities.

Policymakers should consider the creation of a hydrogen collaborative of interested stakeholders and solidify a required annual reporting of progress, developments, and updates to executive leadership at the Capitol. Hydrogen will likely develop in a measured fashion, and it is important to maintain momentum as first movers may hold an overall advantage in the decades to come.

Oklahoma is home for numerous hydrogen industrial companies which can be leveraged and grow this industry into the critical mass necessary for a resilient economy. Initially focusing on heavy-duty trucking to provide the base demand for hydrogen fuel will lead to expansion into other market segments such as blending H2 into a natural gas-powered turbine for power generation.

Continued expansion of our state's focus on research and development, in collaboration with corporate interests in business development and innovation commercialization, will aid in the attraction of industry participants in the full hydrogen supply chain vertical (manufacturing of equipment, logistics and storage, transportation of hydrogen, production and renewable energy). The opportunities to collaborate and participate in federal programs investigating the pathway to removing or reducing hurdles associated with the hydrogen economy provides Oklahoma the platform to engage at a national level.

Hydrogen production intersects two of Oklahoma's largest energy sectors, natural gas, and renewable energy, which depends upon our natural resources (water), skilled workforce, and will support growing industries of interest to Oklahoma's economy (heavy trucking, aerospace, drones, and innovative technology development). We have the opportunity to focus on developing Oklahoma's hydrogen economy as a first mover in the midcontinent. The report provides a roadmap for stakeholders to utilize and engage in activities to implement a hydrogen economy in Oklahoma.

Action Items and Roadmap

The Task Force Chair, Co-Chairs and members engaged a diverse group of stakeholders in meetings and subcommittee sessions to compile the following list of priority action items for the State of Oklahoma to kick off the hydrogen economy which will diversify and complement our energy portfolio, create jobs and for economic expansion. The following list captures near term and long-term initiatives for consideration and implementation:

<u>Oklahoma Hydrogen Business Council</u>

- Leverage the Oklahoma Energy Initiative for funding and governance opportunities for H2, Carbon Capture, and other low carbon and advanced technologies.
- Create and assemble a purpose driven initiative and team to continue the development of the Oklahoma hydrogen economy through legislation, executive order, or other processes.
- Development of a detailed hydrogen roadmap that includes an economic development strategy to advance the hydrogen economy in Oklahoma by expanding upon market opportunities identified by the OK H2 Business Council.
- Host and encourage summit meeting(s), public/private partnerships, innovative technologies in hydrogen, blending initiatives, green and blue hydrogen production promotion, other areas of focus that strategically support the hydrogen economy including storage infrastructure, permitting, and an annual reporting mechanism for executive leadership.
- Identify goal(s) for in-state hydrogen production and work with electric utilities in Oklahoma to include hydrogen into integrated resource planning and electricity rate structures.

<u>Legislation and regulatory efficiency</u>

- Identify and support necessary changes or new Oklahoma legislation and regulations for the hydrogen economy to remove barriers, streamline construction review, codes/standards and permitting for hydrogen production and fueling facilities.
- Add hydrogen to existing legislation (i.e., CNG, EV charging stations), create policies and a business environment that incentivizes investment in hydrogen, and develop and adopt safety protocols for the transportation and use of hydrogen. This can also consider amending the Oklahoma Energy Initiative to include hydrogen advancement and promotion: https://casetext.com/statute/oklahoma-statutes/title-17-corporation-commission/chapter-23-oklahoma-energy-initiative-act/section-8022-oklahoma-energy-initiative-duties

<u>Development of end-users to build diverse demand</u>

Identify appropriate opportunities to incentivize the development of innovative uses for hydrogen that include, but not limited to:

- Heavy to medium sized vehicles
- Industrial applications
- Storage (gaseous, liquified, optimizing surplus renewable energy via hydrogen storage)
- Port transportation (boats, drayage trucks)
- Material handling (forklifts)
- Power generation utilizing fuel cell and combustion turbines

Carbon Capture Council

Create and assemble a purpose driven initiative and team to develop the necessary resources and research to promote Oklahoma's carbon capture and sequestration assets, expertise and develop seminars to showcase university and industry expertise. The carbon capture council should also focus on de-risking the carbon capture, transportation and sequestration permitting timeline to assure business enterprises have a transparent process to follow to attain success.

Partnership for Department of Energy Research and Initiatives

Develop and implement a collaborative group to include other state agencies, federal laboratories, universities and key stakeholders to secure Department of Energy grants and funding focused on the development of strategic hydrogen hubs.

Regulatory Overview

Determine existing regulatory processes and oversight associated with hydrogen and update, modify, or create as appropriate. Consider existing regulatory and permitting processes and streamline to encourage business development and timely processes. Review state and federal regulations that apply to hydrogen and determine areas of concern that require solutions.

Pilot Programs

- Develop and promote the implementation of pilot programs to build out the foundational infrastructure necessary to kick start the hydrogen economy in Oklahoma.
- Create a collaborative partnership with our major research universities and private enterprises to develop, deploy and commercialize novel technological solutions in the hydrogen sector. This can include, as an example, transportation solutions which focus on pilot trucking programs and build out of fueling stations and associated hydrogen fuel supplies for heavy to medium duty road vehicles, material handling equipment, airport, and port vehicles.

Workforce

- Define and develop the necessary skills training to support workforce transitions into the hydrogen economy.
- Consider incentives similar to those provided for automotive and aerospace engineers to facilitate recruiting of key industry participants.
- Align with Department of Commerce, the Oklahoma Manufacturing Alliance, technical colleges and universities, federal agencies, and others to assure curriculum and training for hydrogen industry jobs are optimized.

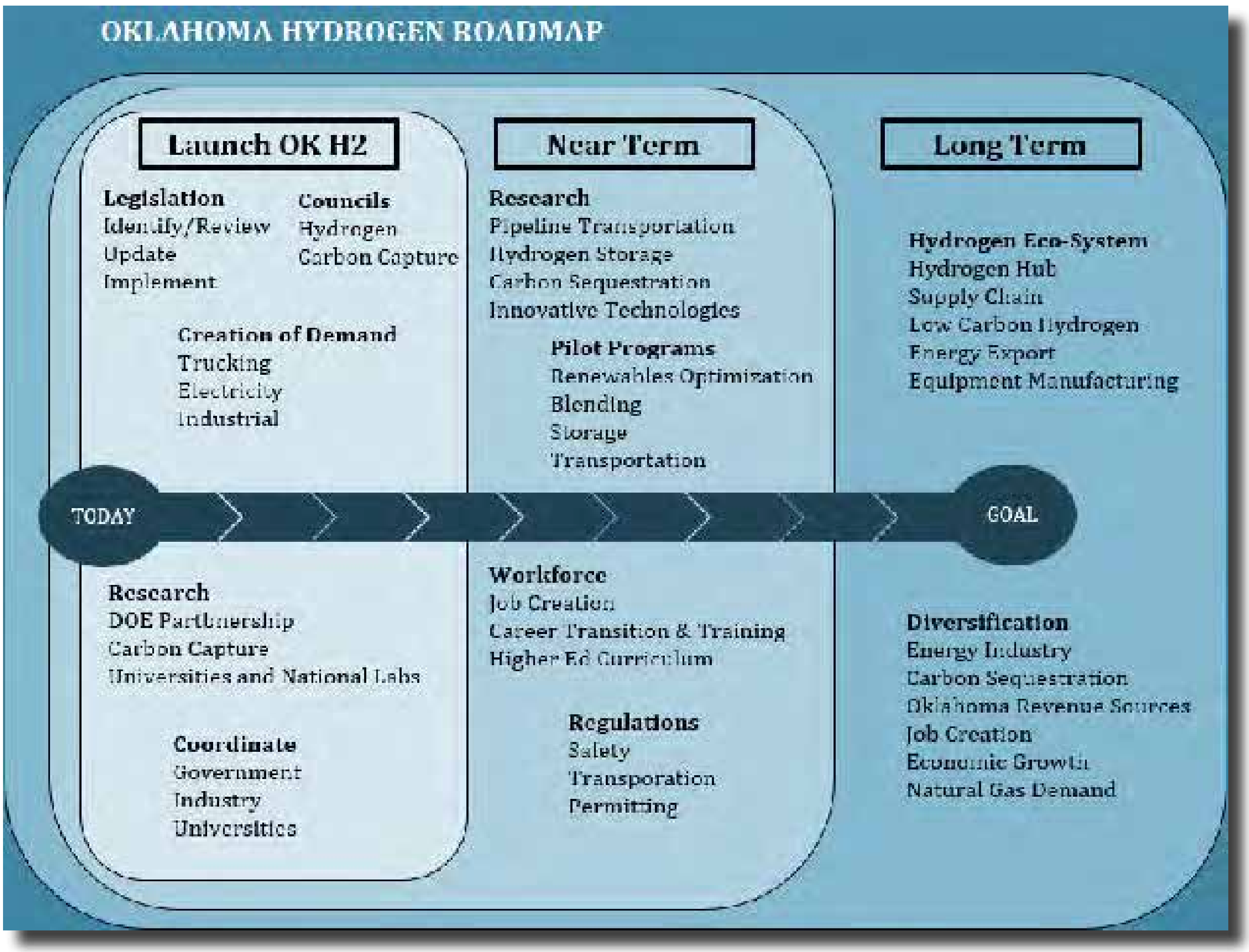
Transportation, Research, and Innovation

- Develop, research, and deploy, through the creation of research centers of excellence and private enterprise partners, solutions for efficient transportation, production, and storage of hydrogen.
- Leverage our major universities' expertise in the energy and geology research to develop, deploy, and commercialize technological solutions that promote and support the profitable implementation of a hydrogen economy for the state.

- Position Oklahoma's pipeline infrastructure network as a crossroads for national hydrogen distribution and support the development of dedicated hydrogen pipelines.

Safety
- Create a council for the identification of existing safety protocols that apply to all aspects of hydrogen production, transportation, storage and use, and any gaps in safety protocols that require solutions.
- Develop safety standards and training to assure hydrogen industry participants' performance is focused on safety.

The above opportunities are vast and broad, with inherent challenges and complicated timelines. The roadmap to success will unfold as we progress through the process of initiating a completely new industry within the State of Oklahoma, and the following is intended to provide a foundation for conversation and collaboration and is not intended to be the pre-set course for this journey.



APPENDIX

Oklahoma Hydrogen Task Force Subcommittee Stakeholder Comments

<u>CF Industries</u>
Dear Secretary Ken Wagner,

On behalf of CF Industries, I wanted to share the following recommendations with respect to the draft "Hydrogen Production, Transportation and Infrastructure Task Force Report" that is being prepared by the task force pursuant to Senate Bill 1021.

At CF Industries, our mission is to provide clean energy to feed and fuel the world sustainably. With our employees focused on safe and reliable operations, environmental stewardship, and disciplined capital and corporate management, we are on a path to decarbonize our ammonia production network—the world's largest—to enable decarbonized hydrogen and nitrogen products for energy, fertilizer, emissions abatement, and other industrial activities. Headquartered in Deerfield, Illinois, CF owns and operates five world-class and highly efficient manufacturing complexes in the United States, including two facilities in Oklahoma in Woodward and Verdigris. CF also operates an extensive storage, transportation, and distribution network in North America.

Since its founding, CF has been at the forefront of addressing one of the defining issues of the 20th century: feeding a growing and hungry planet. The ammonia that CF manufactures is the building block for nitrogen fertilizer products essential to global food production. By increasing crop yields, CF's products also reduce the amount of land needed to feed the world, helping prevent the destruction of carbon-sequestering forests. In the 21st century, CF has a critical role in addressing the existential issue of climate change. We have already announced projects to produce both green and blue ammonia in the United States. The decarbonized ammonia that we will produce can offer a cost-effective way to speed the global shift to a hydrogen economy and help to decarbonize other sectors. Moreover, CF has committed to achieving net-zero carbon emissions by 2050, with an interim goal of reducing our operational emissions intensity by 25 percent per ton by 2030 from a 2015 baseline.

We welcome the task force's work to promote actions to promote the development of low- and zero-carbon hydrogen production and supply and suggest the following actions might be considered as part of the recommendations for the task force report:

- Seek and obtain primacy from the Environmental Protection Agency (EPA) to issue Class VI well permits for permanent CO2 sequestration. The draft report notes the need to "de-risk the timeline for Class VI permitting." One of the most effective ways for the state to do so is to seek and obtain primacy from the EPA to issue Class VI permits directly. That would empower the state to issue permits as quickly as possible, and thus facilitate the development of carbon, capture and sequestration (CCS) projects.
- Explore and emphasize industrial decarbonization as a hydrogen end use. While we agree that heavy-duty trucking presents a promising end-use opportunity as outlined in the draft report, there are other opportunities for the use of

hydrogen, including power generation or in maritime that could also be mentioned. As well, the Task Force should explore and emphasize the importance of hydrogen's industrial end uses across the state. Oklahoma's industrial sector, which already includes the energy-intensive crude oil and natural gas industries as well several hydrogen-intensive ammonia production facilities. These account for nearly two-fifths of the state's end-use energy consumption. Hydrogen can play an important role in helping these facilities achieve decarbonization objectives.

- Develop state policies to facilitate a clean hydrogen economy. The Task Force should explore state-based policies—including grants, loans, tax credits, and other incentives—to facilitate clean hydrogen development across the entire value chain. The Task Force should seek input from a diverse group of stakeholders on policy concepts unique to Oklahoma that would accelerate clean hydrogen project deployment, including both CCS and hydrogen produced from renewable sources.

<u>GasTech Engineering</u>

The Gas Technology Engineering team foresees many opportunities in hydrogen production, storage, and delivery. These opportunities include: Hydrogen production, with associated carbon capture, using Oklahoma's abundant natural gas supply (blue hydrogen), and Hydrogen production via electrolysis driven by energy from Oklahoma's wind farms (green hydrogen). Gas Tech welcomes the expanded market diversity to improve the company's sustainability, create more high paying jobs, positively affect the environment, and make GasTech more resilient for future generations. - Ron D. Key, P.E. Chief Technology Officer GasTech Engineering LLC

<u>NuIonic Technologies</u>

Microwave Catalytic Reforming –Natural Gas as feedstock, but without the emissions
In a paradigm shift away from conventional steam rerforming reforming processes and post-combustion CCUS, Nu:ionic Technologies (www.nuionic.com), has a new take on hydrogen production. Their process uses catalytic microwave reforming of natural gas to generate hydrogen, and largely eliminates the greenhouse gas emissions associated with conventional steam methane reforming for the production of low carbon hydrogen. The company's hydrogen technology reduces natural gas consumption for hydrogen production by 30% and the reformer reactor size is reduced by up to 30 times in volume, due to elimination of the fired heating equipment. The remaining CO2 is readily capturable for a net reduction in GHG emissions of 95%. The company is part of a number of start-ups working to reduce the cost of low carbon hydrogen, and they aim to launch commercial hydrogen generation units in early 2023. For more information, contact Jan Boshoff at 918-257-2350, jan.boshoff@nuionic.com

<u>Enel North America, Inc.</u>

1. Production/Consumption Tax Benefit for Clean Hydrogen – Enel supports the final report adopting a specific recommendation to set up a tax benefit framework that incentivizes consumers of hydrogen to transition to clean hydrogen usage, creating demand in the state. The consumer benefit rewards local industries for transitioning to clean hydrogen, but also would be an attractive draw for out-of-state companies who are trying to meet their ESG's to consider business-friendly Oklahoma. Additionally, a technology-neutral production incentive for clean hydrogen, modeled after the program proposed in federal legislation, would help ensure that there is supply

available to meet increased demand for clean hydrogen. If proposed and adopted, any such incentive should have an appropriate sunset date and program caps in order to ensure that, while we are intentionally growing this industry, the State has certainty for budgetary planning purposes. While all states would see the benefit from the federal incentive program, any state support will ensure Oklahoma is the premiere spot for clean hydrogen investment in the region, and a prime candidate for a federal clean hydrogen hub.

2. Clean Hydrogen Goal – Enel supports the creation of a clean hydrogen goal. While not being a mandate, a goal provides companies with another layer of support in attracting purchasers/users of clean hydrogen. Additionally, a goal would signal to the federal government that we are ready to support clean hydrogen and a hydrogen hub.

<u>American Hydrogen</u>

Oklahoma Hydrogen Task Force

Blue and Green Hydrogen Market Dynamics

- Though blue and green pathways produce the same resulting hydrogen, the cost and end-use applications of these production methods are vastly different.
- Oklahoma's burgeoning wind industry gives credence to a green hydrogen economy, though the costs associated with the electrolysis process still remain uncompetitive with traditional fossil fuels.
- Building regional demand will require cheap and reliable access to hydrogen supply, access that can only happen today as a product of gray or blue hydrogen production.
- Investment in demand side infrastructure (i.e., fueling stations, fuel cells, burners) can only be assured after these supplies are established.
- Hydrogen production projects in greenfield markets typically assume a phased development approach in which smaller amounts of generation are brought to market.

This minimizes commercial risk and gives projects the ability to scale with demand.

Ongoing Stakeholder Engagement

- Any aspirations Oklahoma has of becoming a hydrogen hub will require an alignment of regulatory guidance/frameworks, economic and environmental interests, and public/private partnerships.
- The biggest takeaway from our participation on the Oklahoma Hydrogen Task Force was the opportunity to network with other stakeholders working in the hydrogen economy.

<u>EDP Renewables, NA</u>
Secretary Wagner,

As I conveyed to you last week, we have appreciated the work of the task force to give industry an opportunity to help define a path for Oklahoma's use and development of hydrogen technology. EDP Renewables has a dedicated hydrogen business unit which is now actively working in the US, and they have reviewed the draft report. While we know our comments may not be timely for inclusion in the final report on which you're working, we want to offer some thoughts related to action items you could take, in the event it helps to inform your next steps.

Suggestions:

- Adopt an H2 strategy for OK, with clear targets and a roadmap to promote green H2 economy (long term visibility on the policy tools and regulatory framework is key to attract private investment)
- Take advantage of the abundant renewable resources and existing infrastructure to set goals of electrolytic H2 capacity to be achieved in a 10-yr timeframe
- Create funding instruments to support the development of the entire value chain (electrolyzers capex, logistics, consumption of H2, adaptation of industrial processes to incorporate H2, heavy-duty and other special purpose vehicles acquisition cost, etc)
- Define favorable rate structures for electrolyzers to help bridge the cost competitiveness gap
- Take advantage of the flexibility of electrolyzers and allow for sector coupling and their provision of grid services
- Ensure coordination with Fed level policies and neighboring States initiatives

Please let us know if you have questions or would like to set up a call to discuss further.

Thank you.

<u>The Nature Conservancy</u>
The Oklahoma chapter of The Nature Conservancy has developed and deployed a wind power siting tool for use by wind power developers and purchasers. The tool, Site Wind Right, also shows significant portions of Oklahoma are suitable for wind development.

Hydrogen Items for consideration of Statewide Hydrogen Taskforce – Economic Opportunities, Taxation, and Incentives & Market Uses Subcommittee

US DOE Alternative Fuel Data Center
Hydrogen Production & Distribution
Research & Development
Benefits & Considerations
Hydrogen Stations
Vehicles – Availability & Emissions
Hydrogen Laws & Incentives

Air Quality and Emissions Reductions

Lifecycle Emissions

According to the US Department of Energy, "hydrogen, when used in a fuel cell to provide electricity, is a zero tailpipe emissions alternative fuel produced from diverse energy sources."

Lifecycle emissions from hydrogen productions, distribution, and use as a transportation fuel should also be considered when evaluating overall public health and environmental benefits for Oklahomans.

Non-attainment designation

In 2017, all of Oklahoma's metropolitan areas were designated in-attainment or unclassifiable; otherwise not violating Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS) for ozone pollution.

A non-attainment designation brings additional federal regulatory requirements for transportation projects, emissions reductions for facilities, and other economic impacts.

In a November 2021 report developed by the Association of Central Oklahoma Governments (ACOG), it was determined that a non-attainment designation for the Central Oklahoma region could result in $9 to $15 billion in economic costs to the Central Oklahoma region between 2022 and 2050.

It is reasonable to say that these economic costs would be comparable to other Oklahoma metropolitan areas in the event they were designated non-attainment.

Mobile sources of emissions, especially on-road emissions sources, make up the majority of the OKC and Tulsa metropolitan areas' ozone causing pollution (NOx and VOC's). Accelerating the adoption of hydrogen fuel cell vehicle technologies along with other alternative fuels and electrification is critical in keeping Oklahoma's metropolitan areas in-attainment of EPA air quality standards and improving air quality for all Oklahomans.

OGS Fact Sheet No. 1
Geological Carbon Management in Oklahoma

The Oklahoma Geological Survey
November, 2021

1. Introduction

In response to an increasing frequency of requests to the Oklahoma Geological Survey (OGS), a group of OGS staff prepared this fact sheet on *geological carbon management* (GCM), an umbrella term for using the subsurface to mitigate carbon emissions. The focus is primarily on *geological carbon sequestration*, one type of *carbon sequestration*. Carbon sequestration encompasses a still wider range of approaches, such as managing ecosystems to enhance CO_2 sequestration in soils, plants, and the oceans[1]. We focus here on issues surrounding geological site selection and monitoring, leaving out many topics in the politics, economics, and social science of GCM, as well as questions surrounding the sources and transport of carbon dioxide (CO_2) and methane (CH_4)[2-5].

2. Carbon capture & storage: definitions & goals

Carbon capture, and storage (CCS) involves injecting CO_2 into geological formations. CCS is a form of *geostorage*, the latter a term that encompasses the subsurface storage of any fuel such as natural gas or hydrogen (H_2). CCS contributes to "net-zero" goals (an economy that contributes no CO_2 to the atmosphere) by mitigating and offsetting industrial CO_2 emissions from power plants, fertilizer production, gas processing, and cement manufacturing, amongst many others. CCS also offsets emissions from sectors where CO_2 emissions are geographically distributed and therefore more difficult to mitigate, such as aviation and agriculture. CCS also can sequester CO_2 collected by *direct air capture* (DAC).

Carbon capture utilization and storage (CCUS) is a subset of CCS where CO_2 is used for industrial purposes. A common use in Oklahoma is *enhanced oil recovery* (EOR), wherein CO_2 is used to stimulate oil and gas production, leaving an estimated 90-95% of used CO_2 trapped in the subsurface[6]. CCUS also describes the conversion of stored CO_2 into various fuels, industrial minerals, polymers, agricultural applications, and many others. A special case of considerable interest for Oklahoma is the pairing of CCS with of "blue" H_2 production from natural gas[7].

One unit of measure of atmospheric CO_2 is parts per million (ppm). CO_2 is currently at >400 ppm, up from ~350 ppm in 1990, and a longer-term <300 ppm during the rise of industrial civilization[8-10]. In contrast with ppm, most GCM uses units of metric tons, equivalent to ~1.1 US tons. The use of tonnage results from the measurable weight of carbon that makes up >80% of most hydrocarbon fuels[11]. Setting aside CH_4 emissions, the carbon bonds with oxygen, resulting in ~3.1 tons of atmospheric CO_2 for every ton of carbon. Current estimates of global CO_2 emissions are >30 billion tons (Gt) of CO_2 per year, with Oklahoma contributing >46 million tons (Mt) per year[12]. GCM will likely include a geographically distributed range of sizes and storage durations to contribute to net zero, and today there are already 27 CCS focus sites worldwide targeting 36 Mt of storage with dozens more in the pipeline[13].

3. Carbon capture & storage: principles

CO_2 is typically injected as a supercritical fluid brine where it might be *trapped* in one of the following ways (Fig. 1).

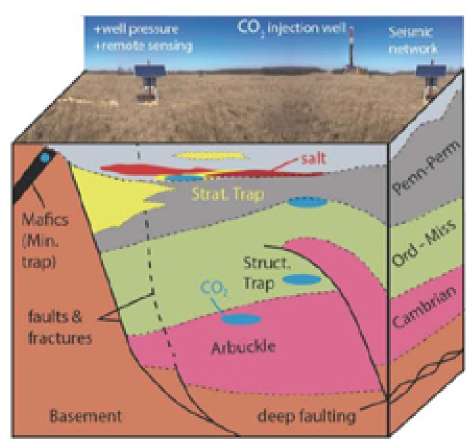


Figure 1. Schematic of carbon management targets in Oklahoma.

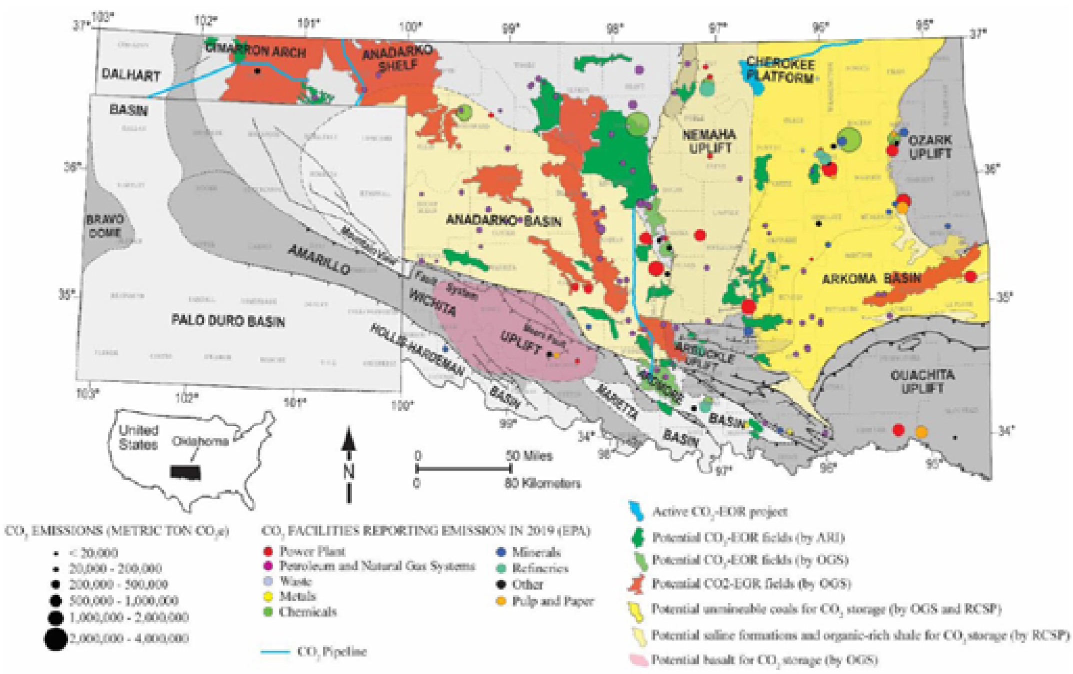


Figure 2. Geological provinces and prominent carbon emissions and facilities [12,22-27]. Major CO_2 emissions are illustrated for the year 2019 along with known CO_2 pipelines, geological provinces, and some major oil and gas fields.

CO_2 brine might be structurally or stratigraphically trapped against an overlying impermeable layer, residually in the natural pore space, or dissolved into surrounding natural pore water (solubility trapping)[14]. Mineral trapping can also occur when CO_2 reacts to form a carbon-rich solid[15-17]. Such mineralization is enhanced in magnesium-iron rich, "mafic" rocks, and has an advantage that the CO_2 cannot easily escape once solidified.

As a brine, CO_2 is similar to many injected fluids, such as liquid petroleum gas, residual oil, and even water with low total dissolved solids. These fluids are less dense than the background "connate" fluids. In contrast, other injected fluids such as produced-water or bio-oil are denser than the connate fluids. The buoyancy of injected CO_2 means that a reservoir must have sufficient storage capacity, injectivity *and* a reservoir seal that will hold the lower density fluid that can migrate upward along higher permeability pathways including faults, fractures, or compromised well completions. At depths greater than 2625 ft (800 m) the density of the CO_2 is high enough to allow efficient pore filling and to decrease the buoyancy difference compared with connate fluids[14]. In most cases CCS targets *saline aquifers*, the porous formations that reside below *underground sources of drinking water* (USDWs)[12]. Studies of unconventional oil and gas reservoirs also find that through pore-scale adsorption and absorption processes the geological targets for hydraulic-fracturing production of oil and gas may also be targets for CCS[18].

The simplest estimate of reservoir storage capacity multiplies the thickness and area of a potential reservoir by its porosity, along with an efficiency factor that ranges from 0.0 to 1.0, typically set at 0.1-0.2 to account for the fraction of the reservoir that is available for storage[19, 20]. Despite simplifying many obstacles to CO_2 invasion, such as pore-throat barriers, pore-closing mineralizing chemical reactions, and a wide range of flow instabilities, such simple estimates can be quite useful for initial mapping of storage potential over large areas.

4. Storage estimates for GCM in Oklahoma

Oklahoma was an early adopter of GCM[2], with CCUS efforts stemming back to 1982. Today, for example, CO_2 is being captured from emissions streams at fertilizer plants in Enid, OK, and Coffeyville, KS[21]. That CO_2 is piped to oil fields in Southern Oklahoma and Osage County where it is used, and largely captured, during EOR. The map of Oklahoma[12, 22-27] (Fig. 2) illustrates the complex geological landscape of Oklahoma including uplifts (such as the Arbuckle Uplift and Wichita Uplift) exposing Ordovician, Cambrian, and pre-Cambrian rocks at the surface versus deep sedimentary basins (such as the Anadarko Basin and Arkoma Basin) that have Permian rocks at the surface. The generalized cross-section (Fig. 3) shows that the sedimentary rocks in the Anadarko Basin can be more than 40,000 ft thick, while the sedimentary sequence is less than 10,000 ft thick to the north and northeast of Oklahoma City.

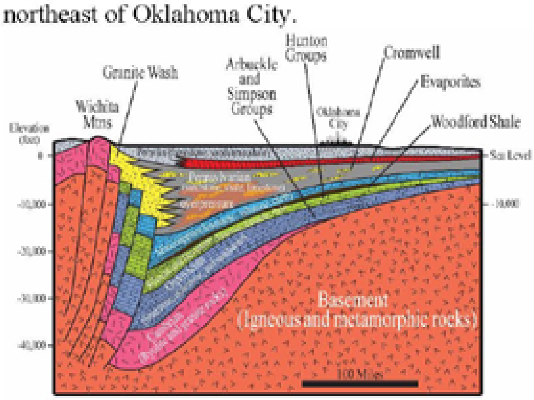


Figure 3. Generalized cross-section of the Anadarko Basin on the left or south-southwest to the Anadarko Shelf on the right or north-northwest[26]. Mafic zones are locally distributed in the basement and lower Cambrian sections.

Because of the *heterogeneity of Oklahoma's geology*, there is an abundance of viable target formations for variable carbon sequestration and use approaches. By way of example, the OGS has compiled preliminary effective porosity data for the Cromwell, Hunton, Simpson, Arbuckle Groups — note that *group* is a term for numerous geological formations of a certain age range and character — as well as some igneous mafic units one might target for mineral trapping (Table 1). These values were used to estimate the land area that would be required to store 10 Mt CO_2 assuming mean thickness and porosity, a relatively high efficiency factor of 0.50, and a density difference of 515 kilograms per cubic meter[28].

The "CO_2 areas" shown in Table 1 indicate that the Arbuckle Group and Mafic units can store 10 Mt CO_2 with the smallest footprints owing mostly to their great thickness. The Cromwell, Hunton, and Simpson Groups also have tremendous storage capacities throughout Oklahoma considering that there are tens of thousands of acres available in each of several counties. For example, there are more than 65,000 acres in Haskell County where these formations reside in the subsurface at suitable conditions. There may be countless other viable CCUS targets in Oklahoma and capacity for storing a combined total of many hundreds of Mt, if not Gt, of CO_2.

Table 1 Estimates of land area needed for subsurface storage of 10 Mt CO_2 in promising target zones in Oklahoma. Note porosity values use a variety of methods, and are here presented only as qualitative estimates.

	Zone (# sites studied)	*variable (units)*	mean thickness, h (ft)	mean porosity, ϕ (%)	CO_2 area, A (acres)
Geological Zone	Cromwell (7)		58	9.9	5491
	Hunton Group (1)		160	16.0	1230
	Simpson Group (7)		147	10.7	2002
	Arbuckle (2)		432	7.1	1026
	Mafic or Precambrian (2)		1080	3.0	972

mean value from OGS geological studies

calculated footprint required for storage of 10 Mt CO_2

5. Mitigating Hazards of Leakage & Seismicity

As with all geostorage efforts, CCS has risks, with widely discussed hazards of leakage to the surface along vertical pathways such as fractures, faults, or the wellbores themselves, as well as leakage laterally into surrounding geological formations[29]. Additionally, any form of geostorage risks causing a possible increased frequency of earthquakes, a.k.a. induced seismicity[30].

Leakage is widely discussed in terms of some acceptable rate, such as 0.01% of stored CO_2 per year[20], though it is expected to vary over time as a function of wellbore integrity, injection rate, and trapping mechanisms. Leakage is primarily mitigated through site characterization focusing on caprock integrity and seal quality. Borehole engineering also can mediate leakage through the use, for example, of polymers that stabilize cements that otherwise dissolve with introduction of carbonic acids[31]. Once captured, regional and site-specific well-pressure monitoring can detect leakage, as has been shown by both computational modelling and active field experiments[32,33].

The other widely considered hazard is an increase in earthquake activity as has occurred from produced-water injection over the last decade[30]. For example, 18 earthquakes of magnitude (M) 3 or greater occurred between 2006 and 2011 at the Texas Cogdell oil field following the injection of CO_2 and other gases[34,35]. This example, along with a myriad of case studies over the last decade, illustrates that seismic risk will depend on hydromechanical properties of the injection reservoir, state of stress, injection rates and pressures, and net total volumes of injected fluid.

Underground injection (UIC) of produced wastewater in Oklahoma illustrates that good site selection and careful project design can also lower seismic risk to acceptably low levels[30]. In these instances, seismicity can occur from pumping at moderate rates over years, or very high rates over a matter of hours as is the case with hydraulic fracturing. Based on such mitigation efforts, as well as the mapping of faults in the subsurface via geological and geophysical investigation, a common explanation for the earthquake activity is that the input of water causes pressure changes that push the fault to failure[36]. Pairing that scientific observation and deduction with regulatory action can then stem the effects of induced seismicity and borehole leakage.

Currently, the Oklahoma Corporation Commission (OCC) works to mitigate seismicity during wastewater disposal and hydraulic fracturing. OCC implemented injection reductions in 2016 across a broad swath of the state that have, in part, led to a reduction in the number of earthquakes of magnitude 3 or greater. For example, over 900 earthquakes M3 or greater occurred in 2015, but this number fell to 45 by 2020. In addition, after larger events (M4.0 or greater), OCC often implemented rapid mitigation measures including shutting-in wells closest to the earthquake epicenter, the earthquake's surface point of origin, with gradual reductions stepping away from the epicenter. OGS has provided the OCC with direct scientific observations of the subsurface geology and associated seismic behavior of activated faults via the OGS-maintained state-wide seismometer network[37]. Through this OGS-supported research, the regulatory actions reduced the probability of aftershocks in the affected areas[34]. Such efforts provide a glimpse of existing risk-based approaches that could be evaluated for possible future implementation during future GCM in Oklahoma.

6. Plain Language Summary Statement

Oklahoma's diverse and heterogeneous geology offers numerous opportunities for geological carbon management, from carbon-dioxide injection accompanying oil and gas production, to storage of emissions resulting from hydrogen production, to long-term and large volume sequestration of carbon dioxide Experience to date suggests that geological and geophysical investigations can help mitigate many of the leakage and earthquake hazards that can accompany such subsurface, geological carbon management.

7. Acknowledgements

OGS thanks Holly Buck (State University of New York at Buffalo), Tim Filley (University of Oklahoma), Franek Hasiuk (Kansas Geological Survey), Seyyed Hosseini (Bureau of Economic Geology, UT Austin), and Camelia Knapp (Oklahoma State University) for technical reviews. This effort was self-funded by the OGS, a state agency based at the University of Oklahoma.

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Web Site for .pdf download of OGS fact sheets: https://www.ou.edu/ogs/publications/factsheets

Contact: ogs@ou.edu

8. References

1. Farrelly, D.J., et al., 2013. Carbon sequestration and the role of biological carbon mitigation: a review. *Renewable and sustainable energy rev., 21*, pp.712-727.
2. Abramson, E., et al., 2020, Great Plains Institute whitepaper on regional infrastructure for midcentury decarbonization; Note numerous other resources on the Great Plains Institute website: https://www.betterenergy.org.
3. de Coninck, H. and Benson, S.M., 2014. Carbon dioxide capture and storage: issues and prospects. *Ann. Rev. of environment and resources, 39*, 243-270.
4. The CDR Primer: https://cdrprimer.org
5. Walter, J.I., et al., 2020, Convergence Accelerator Workshop on Atmospheric Carbon Reduction: https://ou.edu/ogs/workshops/nsf-convergence-accelerator-workshop---carbon-reduction
6. Melzer, L.S., 2012. Carbon dioxide enhanced oil recovery (CO2 EOR): Factors involved in adding carbon capture, utilization and storage (CCUS) to

enhanced oil recovery. *Center for Climate and Energy Solutions*, pp.1-17.
7. Oklahoma Hydrogen Task Force: https://ee.ok.gov/resource/hydrogen-task-force/
8. NOAA: https://www.esrl.noaa.gov/gmd/obop/mlo/
9. IEA: https://www.iea.org/reports/global-energy-review-2021/co2-emissions
10. Keeling, R.F. and Graven, H.D., 2021. Insights from Time Series of Atmospheric Carbon Dioxide and Related Tracers. *Ann. Rev. of Environment and Resources*, *46*, 85-110.
11. Jarvie, D.M., 1991. AAPG Special Volume on total organic carbon (TOC) analysis: Chapter 11: Geochemical methods and exploration.
12. See https://www.epa.gov for numerous tools for tracking emissions and conducting conversions
13. See the CCS Institute for numerous fact sheets & additional resources: https://www.globalccsinstitute.com/resources/global-status-report/
14. Friedmann, S.J., 2007. Geological carbon dioxide sequestration. Elements, 3(3): 179-184.
15. Matter, J.M. and Kelemen, P.B., 2009. Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation. *Nature Geoscience*, *2*(12), pp.837-841.
16. McGrail, B.P., et al., 2006. Potential for carbon dioxide sequestration in flood basalts. *Journal of Geophysical Research: Solid Earth, 111*(B12).
17. Hills CD, et al., 2020, Mineralization Technology for Carbon Capture, Utilization, and Storage, *Frontiers of Energy Research,* v. 8, doi: 10.3389/fenrg.2020.00142
18. Fakher, S. and Imqam, A., 2020. A review of carbon dioxide adsorption to unconventional shale rocks methodology, measurement, and calculation. *SN Applied Sciences*, *2*(1), pp.1-14.
19. Aminu, M.D., et al., 2017. A review of developments in carbon dioxide storage. Applied Energy, 208: 1389-1419.
20. See https://netl.doe.gov/coal/carbon-storage/strategic-program-support/best-practices-manuals for the Department of Energy, National Energy Technology Laboratory Best Practices documents
21. Liu, Hanming et al., 2018, Overview of CCS Facilities Globally, 14th Greenhouse Gas Control Technologies Conference, Melbourne.
22. Dutton, S. P., 1984, Fan-delta Granite wash of the Texas panhandle: Oklahoma City Geological Society, 1–144.
23. Campbell, J. A., et al., 1988, Habitat of petroleum in Permian rocks of the midcontinent region, in W. A. Morgan and J. A. Babcock, eds., SEPM Special Publication 1, 13–35.
24. McConnell, D. A., et al., 1990, Morphology of the frontal fault zone, southwest Oklahoma: Implications for deformation and deposition in the Wichita uplift and Anadarko Basin: Geology, 18, 634–637.
25. Northcutt, R. A., and J. A. Campbell, 1995, Geologic provinces of Oklahoma: Oklahoma Geological Survey OpenFile Report 5-95.
26. Johnson, K. S., and K. V. Luza, 2008, Earth sciences and mineral resources of Oklahoma: Oklahoma Geological Survey, Educational Publication 9, 22.
27. LoCricchio, E., 2012, Granite wash play overview, Anadarko basin: Stratigraphic framework and controls on Pennsylvanian Granite wash production, Anadarko Basin, Texas and Oklahoma: AAPG Annual Convention and Exhibition, 1–17.
28. Kimbrel, E.H., et al., 2015. Experimental characterization of nonwetting phase trapping and implications for geologic CO2 sequestration. *International Journal of Greenhouse Gas Control, 42*, pp.1-15.
29. McGrail, B.P., et al., 2006. Potential for carbon dioxide sequestration in flood basalts. *Journal of Geophysical Research: Solid Earth, 111*(B12).
30. White, J.A. and Foxall, W., 2016. Assessing induced seismicity risk at CO_2 storage projects: Recent progress and remaining challenges. Intern. Journ. of Greenhouse Gas Control, 49: 413-424.
31. Tavassoli, S., et al., 2018. An experimental and numerical study of wellbore leakage mitigation using pH-triggered polymer gelant. *Fuel, 217*.
32. Hovorka, S.D., et al., 2011. Monitoring a large volume CO2 injection: Year two results from SECARB project at Denbury's Cranfield, Mississippi, USA. *Energy Procedia, 4*, 3478-3485.
33. Sun, A.Y. and Nicot, J.P., 2012. Inversion of pressure anomaly data for detecting leakage at geologic carbon sequestration sites. *Advances in Water Res., 44*, 20-29.
34. Walter, J.I., et al., 2018. Natural and induced seismicity in the Texas and Oklahoma Panhandles. *Seismological Res. Letters, 89*, 2437-2446.
35. Gan, W. and Frohlich, C., 2013. Gas injection may have triggered earthquakes in the Cogdell oil field, Texas. Proc. Nat. Ac. Sci., 110, 18786-18791.
36. Goebel, T., et al., 2019, Aftershock deficiency of induced earthquake sequences during rapid mitigation efforts in Oklahoma, Earth Planet. Sci. Let., 522, 135-143
37. Walter, J. I., P. et al., 2020, The Oklahoma Geological Survey Statewide Seismic Network, *Seismological Research Letters, 91*(2A): 611–621, https://doi.org/10.1785/0220190211.

CO2 Storage Opportunities in Oklahoma

White Paper

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Introduction

The Boone Pickens School of Geology and the Petroleum Engineering and Technology program in the School of Chemical Engineering at Oklahoma State University maintain a strong presence in CO2 storage research and has led and participated in programs covering much of the southeastern United States. This research includes regional characterization of storage objectives, exploration well drilling and characterization, field testing, microfluidic analysis, and characterization and evaluation of offshore storage objectives in the Gulf of Mexico and Atlantic regions. Current research includes characterization of candidate CO2 sinks in Oklahoma as part of the SECARB-USA initiative, which is led by the Southeastern Regional Carbon Sequestration Partnership, which is managed by the Southern States Energy Board and sponsored by the National Energy Technology Laboratory of the U.S. Department of Energy.

Anthropogenic CO2 emissions in Oklahoma during 2018 have been estimated by the U.S. Environmental Protection agency to be 99.6 million metric tons (Mt), and since 1990 annual emissions from the state have ranged between 91.3 and 113.5 Mt. Assessments of the CO2 storage resource available in the state have been made by the Southwestern Regional Carbon Sequestration Partnership and the National Energy Technology Laboratory ranging between 211 and 340 billion metric tons (Gt), indicating large capacity for CO2 storage in the state. This capacity is in a broad range of formations ranging in age from Cambrian through Permian and includes saline formations (sandstone, limestone, and dolomite), mature oil and gas reservoirs, and unconventional oil and gas reservoirs (shale and coal). Oklahoma hosts pipeline infrastructure that transports CO2 to mature oil fields for CO2-enhanced oil recovery operations from anthropogenic sources, including fertilizer plants in Enid, Oklahoma and Coffeeville, Kansas. Other potential CO2 sources include power plants and refineries. Direct air CO2 capture also is being developed in Oklahoma. CO2-enhanced oil recovery is being performed or has been performed in three parts of the state: Camrick Field in the Panhandle region, Burbank Field in eastern Oklahoma, and the Sho-Vel-Tum and Golden Trend fields in south-central Oklahoma.

Storage Objectives

The major priority regions for geologic CO2 storage in Oklahoma include the Cherokee Platform in the northeastern part of the state, the Arkoma Basin in the east-central part, and the Anadarko Basin in the western part. Additional opportunities exist in smaller basins, including the Ardmore and Marietta basins in south-central Oklahoma and the Hollis Basin in southwestern Oklahoma. In these basins, candidate storage objectives exist between depths of 2,500 ft and 20,000 ft, and of these, commercial potential is greatest in formations shallower than 12,000 ft.

The deepest objective for saline formation storage is Cambrian-Ordovician carbonate of the Arbuckle Group, although induced seismicity associated with disposal of produced water from oil and gas operations, particularly within faulted regions, is a known risk. Risk of induced seismicity decreases substantially upsection, and significant prospects exist for saline formation storage and CO2-enhanced oil recovery in Ordovician sandstone of the Simpson Group and Silurian-Devonian carbonate of the Hunton Group. Similar objectives exist in Mississippian limestone, and numerous stacked objectives exist in Pennsylvanian-age sandstone, particularly in the Cherokee Platform and the Anadarko Basin. Reservoir-quality sandstone units are distributed throughout the Pennsylvanian section, and it is common for oil and gas wells to penetrate multiple zones suitable for storage in the Ordovician-Pennsylvanian section. Permian carbonate and sandstone units also include potential targets for CO2 storage and are proven targets for for produced water disposal in the Anadarko Basin. Unconventional storage targets in the region include organic-rich Woodford Shale and Caney Shale in the Anadarko Basin and Cherokee Platform and coal seams in the Cherokee Platform. In these reservoirs, potential exists for CO2-enhanced oil recovery from mature shale reservoirs and coalbed methane reservoirs.

Reservoir Integrity and Groundwater Protection

The construction of preexisting wellbores is an important consideration for geologic CO2 storage in the Pennsylvanian-Permian section because hundreds of thousands of legacy wells have been drilled through this section, and the integrity of well casing and cement is variable. Another important factor in geologic CO2 storage is the integrity of reservoir seals, and numerous shale units ranging in age from Ordovician through Permian are proven seals, and the widespread Permian salt in the Anadarko Basin is also an important regional seal. Faults are the major factors affecting seal integrity. Faults tend to lose displacement upward in section and commonly terminate within the sedimentary cover. Large structural panels lacking known faults have been identified in the Anadarko Basin and Cherokee Platform, and these areas are considered priority objectives for CO2 storage in saline formations. CO2-enhanced oil recovery can be performed safely in faulted regions provided that positions of injection and production wells are planned carefully to prevent migration of fluids up faults.

Protection of underground sources of drinking water (USDW), which are formations containing water with total dissolved solids (TDS) content <10,000 mg/l, is an imperative of Underground Injection Control (UIC) regulatory programs. Analyses of subsurface water samples from 7,056 wells indicate that protected water is uncommon at depths below 2,500 ft, although some geologic structures locally have conducted fresh water to reservoir depth and thus are not considered as storage targets. The typical case for Oklahoma is the presence of hypersaline to ultrasaline formation water (80,000-300,000 mg/l TDS) at depth >2,500 ft, and so the vast majority of the subsurface contains unprotected formation water where underground injection activities are viable.

Injectivity

Data from active UIC wells demonstrate that Oklahoma's subsurface formations commonly have high injectivity; that is, the ability to inject large volume of fluid at low pressure. Injection rates are typically on the order of 100s to 1,000s of barrels per day in a spectrum of Ordovician-Permian injection targets. Wellhead injection pressures are typically very low, and a database of 2,577 single-zone injection wells indicates that many wells are underpressured and accept fluid by simple gravity feed or with pump pressures <500 psig. Indeed, ~95% of the wells injecting water in Oklahoma employ surface pumping pressures <2,000 psig, which is exceptionally low and is favorable for widespread commercial deployment of geologic CO2 storage technology.

Summary Statement

Oklahoma has exceptional potential for widespread commercial deployment of geologic CO2 storage technology, and CO2-enhanced oil recovery operations have been active for many years. The principal risks in the region are induced seismicity, leakage of fluids along faults, and leakage along preexisting wellbores, and all of these risks are manageable and can be minimized by utilizing the risk assessment and mitigation strategies that are commonly used when implementing UIC programs. Oklahoma has abundant candidate CO2 sinks with stacked storage potential throughout most of the state, and nearly every possibility for subsurface CO2 storage is in play (e.g., saline formations, mature oil and gas reservoirs, unconventional shale and coal reservoirs). Saline storage potential is greatest in strata lacking faults, and several major prospect areas have been identified. USDW intervals tend to be shallow in Oklahoma and are protected by abundant reservoir seals. Experience from underground injection indicates that reservoir intervals in Oklahoma commonly have high injectivity, which is favorable for widespread commercial deployment. In addition, numerous CO2 sources exist in the state, including power plants, fertilizer plants, and refineries, and the state has budding CO2 pipeline infrastructure.

Water Supply for Hydrogen Production

Prepared by the Oklahoma Water Resources Board

The Oklahoma Comprehensive Water Plan (OCWP) serves as the state's overarching long-term water resources management strategy and the definitive resource for information regarding current and future water supply availability and water quality across Oklahoma's many diverse regions. The most recent update to the OCWP was completed in 2012, and the Oklahoma Water Resources Board (OWRB) is now developing the next update, scheduled for completion in 2025. This information, along with information delivered by the OWRB, including interactive maps, aquifer yield studies, water rights databases, water well drilling logs, and guidance by staff can serve to assess the potential for locating hydrogen production facilities in Oklahoma.

Innovative Water Solutions –Water for 2060 Act

The 2012 OCWP process of technical investigation and robust public engagement resulted in a heightened awareness for the need to increase and diversify our water resource portfolio at the state and local levels. With substantial public support, the OCWP recommended the State research and build a framework for appropriate and safe uses of Oklahoma's various non-potable sources of water. Supporting these water conservation and development goals, the Water for 2060 Act (HB 3055) was passed in 2012 as part of a Joint Legislative Committee recommendation. The Act set a goal of holding freshwater consumption volumes flat through the year 2060, while growing Oklahoma's economy, through development of non-traditional water sources such as slightly brackish water resources or highly quality reclaimed municipal wastewater. The OWRB, ODEQ, and others continue to work in cooperation with the State Legislature to develop a new statutes and rules that promote the use and development of these untapped water resources.

The 2012 OCWP Recommendations in conjunction with Water for 2060 initiatives have been the drivers for multiple pieces of marginal water reuse legislation and studies:

- SB 1043: ODEQ Reuse Framework – authorities and resulting rule development for non-potable reuse and indirect potable reuse
- SB 1219 & HB 1485: Aquifer Storage and Recovery Framework – authorities and resulting rule development to store water for reuse and ASR pilot programs
- HB 3405 & SB 998: Authorized completion of marginal quality water wells (up to 10,000 ppm TDS) and beneficial use of marginal water
- SB 1875: Oil and Gas Produced Water Recycling Act resolving ownership and responsibilities to encourage development of produced water reuse.
- OCWP Marginal Quality Water Issues and Recommendations: Statewide overview of known and potential marginal water sources in Oklahoma with recommendations for further development.
- Brackish water resources: While a formal study has yet to begin, a brief workgroup of interested professionals in industry, consulting geologists, academia, state, and federal agencies met to discuss the viability of a pilot to find and delineate substantial brackish resources in Oklahoma. Two zones of

interest were identified for potential pilots in the western Garber-Wellington and Vamoosa-Ada aquifers.

Water Supply

Oklahoma is home to an abundant range of water resources and processes for approving new water uses are well-established. The state's water resources include 23 major groundwater aquifers and numerous surface water systems (federal, state, and local reservoir storage, as well as streams, and rivers). The availability of groundwater and surface water supplies is characterized in two separate respects:

- Physical availability, referred to as "wet water" availability, and
- Permit availability, also referred to as "legal" availability.

Physical availability accounts for the amount of water physically present in an aquifer, lake, or reservoir, or the rate of flow in a stream or river. Permit availability pertains to the maximum amount of water that could be made available for withdrawals considering long-term average annual rainfall and subtractions of domestic and permitted use under water rights issued in accordance with Oklahoma water law. Both aspects are crucial to meeting water needs of the state's current and future communities, industries, and agriculture. For example, water flowing in a stream cannot be diverted for beneficial use unless the user has a permit for that use. Conversely, a permit for water use does not guarantee that the water will physically be present for diversion and use.

The OCWP forecasts the physical and permit water availability of groundwater and surface water in each of 82 OCWP Basins defined across the state (Figure 1). Each Basin represents a watershed area that has a long-term flow record from an established flow gage. Underlying aquifers are analyzed using the same 82 Basin delineations (and as such, many aquifer boundaries cross surface water Basin boundaries). Water availability projections are made from current conditions through a 50-year planning horizon in decadal increments, reflecting forecasted changes in water use ("demands") in each Basin over time.

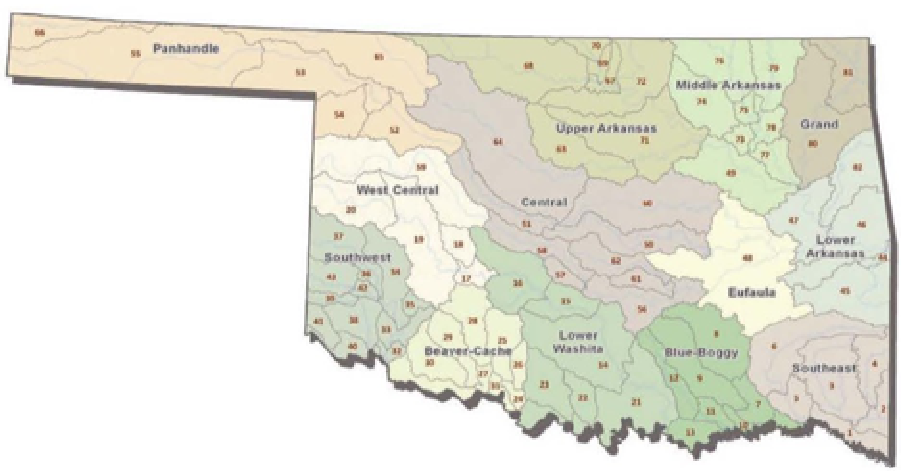


Figure 1: *OCWP Planning Basins and Planning Regions*

The state's surface water systems are illustrated in Figure 2. Generally, surface water is more abundant toward the central, eastern, and southeastern areas of the state, as annual precipitation increases dramatically from the western side of the state toward the east.

***Figure 2**: Oklahoma's Surface Water Systems*

The state's major aquifer systems are illustrated in Figure 3. Bedrock aquifers are deep groundwater resources, distinguished from alluvial aquifers that are typically shallower and directly connected to surface water systems.

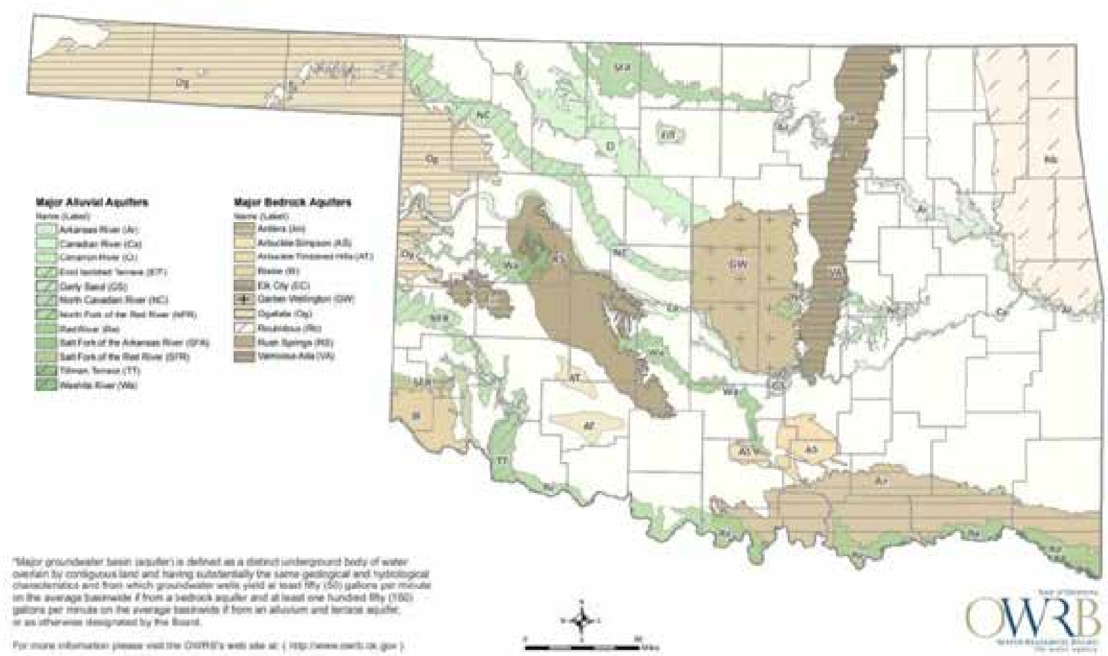


***Figure 3**: Oklahoma's Major Groundwater Aquifers*

OWRB has completed detailed studies to characterize many of the state's major groundwater aquifers. The following aquifers have been studied in detail since the completion of the 2012 OCWP update:

- Arbuckle Simpson
- Garber-Wellington
- Rush Springs
- Salt Fork of Red River Alluvial and Terrace (A&T)
- Washita River A&T Reach I
- Enid Isolated Terrace
- North Canadian River A&T Reach I & II
- North Fork of the Red River A&T
- Canadian River A&T Reach I & II

Under Oklahoma law, surface water is owned by the state, whereas groundwater is a private property right. OWRB administers permits for all water resources across the state, except surface water in the northeast corner of the state (Basins 80 and 81) where the Grand River Dam Authority administers surface water use. OWRB permits surface water using a prior appropriation system, commonly referred to as "first in time, first in right" – meaning that users who put surface water to beneficial use have priority over those who initiated use later. This system is common throughout western states, and serves as an effective tool for managing supplies, particularly in times of drought.

Groundwater permits are established by dedicating land overlying an aquifer to a well permit. Per Oklahoma statute, OWRB permits water based on the results of a detailed study of the aquifer's maximum annual yield (MAY). Permits are issued based on the equal proportionate share of the MAY, which is expressed as the amount of water that can be pumped from a permitted well (in acre-feet per year, where one acre-foot is equal to 325,851 gallons) divided by the area of land dedicated to that permit (in acres). For aquifers where a MAY has not yet been established by OWRB, an interim value of 2.0 acre-feet per year per acre (AFY/ac) is used for permitting. Recently, Senate Bill 1294 provides for a phased implementation of the MAY, where the MAY limitation is not triggered until aquifer development exceeds a defined threshold. This allows for a more gradual adjustment to well permit limitations for groundwater users, particularly those that were implemented prior to establishment of the MAY.

The 2012 OCWP update evaluated water supply availability for each of the 82 Basins in decadal increments through 2060 and summarized that information by aggregating Basins into 13 Watershed Planning Regional Reports (see https://www.owrb.ok.gov/ocwp/2012OCWP.php#regionalreports). The OCWP 2012 assessments of projected statewide physical water availability and permit availability are available at https://www.owrb.ok.gov/supply/ocwp/pdf_ocwp/WaterPlanUpdate/OCWP_PhysicalWaterSupplyAvailabilityReport.pdf and https://www.owrb.ok.gov/supply/ocwp/pdf_ocwp/WaterPlanUpdate/OCWPWaterSupplyPermitAvailability.pdf, respectively.

Water Quality

River and stream water quality monitoring data collected by OWRB are important indicators for determining compliance with water quality standards, tracking general water quality trends, and identifying pollution problems. Through the Beneficial Use Monitoring Program (BUMP), stream sampling is conducted on more than 100 river and stream sites each year. Data collected include a variety of chemical, biological, and physical parameters, allowing for long-term assessment of beneficial uses and water quality trends.

In 2012, as part of a OCWP priority recommendations package, the Oklahoma Legislature and Governor appropriated funding to initiate Oklahoma's first holistic, long-term, aquifer-based Groundwater Monitoring and Assessment Program (GMAP). The state's extensive GMAP water quality monitoring program includes some 750 wells across 21 different aquifers.

Together, these data provide important information for existing and potential future users of groundwater and surface water across the state. Trending analyses were conducted for key surface water quality parameters in each of the state's 82 Basins in the 2012 OCWP update, documented in the 13 Watershed Planning Regional Reports (see link above). Similar efforts are underway for the 2025 OCWP update; it is anticipated that groundwater quality information will also be summarized and documented in the 2025 OCWP.

Assessing Water Supply for Hydrogen Production

The information available from the OCWP can be directly utilized to assess areas across Oklahoma with suitable water supply and water quality for future hydrogen production. The flowchart shown in Figure 4 depicts how OCWP information can be applied in this context.

Figure 4 depicts two phases of evaluations representing increasing levels of detail in assessing water supply for hydrogen production. The left half, shaded in blue, shows information development that occurs in the development of the OCWP. The right half, shaded green, shows how OCWP information can be further leveraged to site a specific proposed hydrogen production facility.

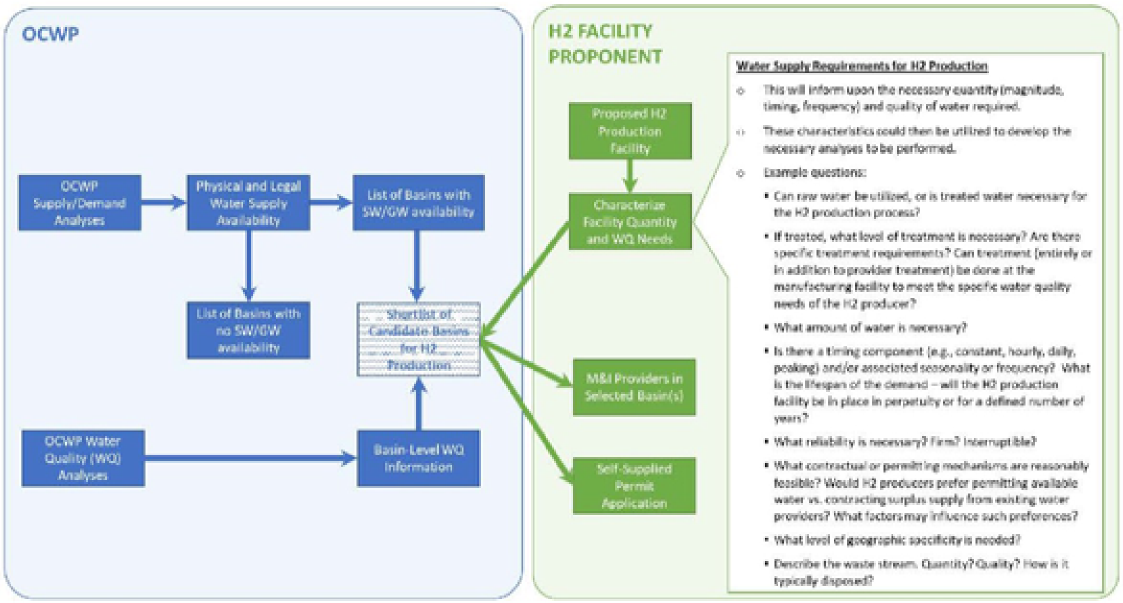


Figure 4: *Workflow for Hydrogen Production Water Supply Availability Assessments*

The upper left portion of Figure 4 depicts how water supply and demand analyses are prepared in the OCWP, yielding a Basin-by-Basin assessment of physical and legal (permit) water supply availability. This information can be used to screen out Basins that are anticipated to have limited water supply availability. For purposes of assessing potential hydrogen production locations, it is recommended that the 50-year projection of supply availability (rather than current or interim-year conditions) be used to gauge long-term availability for new industries such as hydrogen production facilities.

On a parallel path, OCWP water quality analyses also yield basin-level information that can be used to assess viability for hydrogen production. Water quality data can be considered for suitability for hydrogen production needs in Basins with suitable water supply availability, recognizing that some type of water treatment may be needed for virtually any source of supply to achieve the water quality standards necessary for hydrogen production. Together, OCWP Basin-level outputs regarding water supply availability and water quality can be used to prioritize a list of candidate Basins best-suited for potential hydrogen production facilities.

Local analyses would then need to be undertaken to assess specific siting for a specific proposed hydrogen production facility. As shown in the right half of Figure 4, this would begin with characterization of facility-specific water quantity and water quality needs. Examples of the types of questions that might support this characterization are shown in Figure 4 under the heading "Water Supply Requirements for H2 Production."

The facility-specific water needs can be compared to the prioritized list of Basins from OCWP analyses to further refine the list of candidate Basins for siting the facility. From there, detailed assessments of local water supply opportunities would follow, including the potential to obtain water from a public water supply system (i.e., a municipal or rural water system) or for facility-specific permitting ("self-supplied") for groundwater and/or surface water diversions.

Highly treated municipal wastewater is perhaps the most readily available water source throughout the state, both from a water quantity and spatially distributed perspective. This resource would likely meet pretreatment levels desired for hydrogen production with little or no change in current discharge requirements.

Another notable resource, the state has many known sources of marginal quality groundwater with trace amounts of arsenic, nitrates, etc. that although require substantial treatment for drinking water could be suitable as source water at a hydrogen production facility.

OCWP information resources from the 2012 OCWP Update can be utilized to support these analyses while the 2025 OCWP update is being prepared, then updated with 2025 OCWP data when available. OWRB could prepare GIS summary maps of groundwater and surface water availability, including maps for physical availability and permit availability. These maps could then be overlaid on maps of hydrogen distribution infrastructure and other planning considerations to further identify, characterize, and prioritize candidate areas for locating hydrogen production facilities in the state.

Transportation & Distribution Infrastructure Reference Materials

Hydrogen Fueling Stations and Corridors

Optional Information and Considerations

- Consideration of Clean Cities coalition locations/existing alternative fuel markets
- Whether the corridor or segments of the corridor are in in ozone, carbon monoxide, or particulate matter nonattainment or maintenance areas
- Goals for greenhouse gas and/or criteria pollutant emission reductions
- Available State and/or local alternative fuel vehicle incentives/programs
- Current and future demand for alternative fuel facilities based on current and predicted usage patterns (passenger, freight, and other commercial vehicles). The analysis of future demand/alternative fuel facilities should include description of how the corridor will be extended and/or how distances between stations will be shortened (i.e., gaps closed)
- Other alternative fuels included under the Energy Policy Act of 2005 but not included in Section 1413, or vehicle technologies such as Truck Stop Electrification used along corridor that contribute to greenhouse gas or criteria air pollutant emission reductions
- Availability of alternative fuel vehicle support services in the vicinity/region (e.g. maintenance and repair shops, first responders, safety officials, towing and road-side rescue services, etc.)
- Potential of designation to serve as a national case to document lessons learned/best practices

FHWA's infrastructure coverage criteria for each alternative fuel technology are presented in the table below.

Fuel/ Technology	Corridor-Ready[a] NHS Segment has...	Corridor-Pending[b] NHS Segment has...
EV Charging[c]	Public DC Fast Charging no greater than 50 miles between one station/site and the next on corridor, and no greater than 5 miles off the highway. Additionally, each DC Fast Charging site should have both J1772 combo (CCS) and CHAdeMO connectors.	Public DC Fast Charging stations separated by more than 50 miles. Location of station/site- no greater than 5 miles off the highway.
Hydrogen[d]	Public hydrogen stations no greater than 100 miles between one station and the next on the corridor, and no greater than 5 miles off the highway.	Public hydrogen stations separated by more than 100 miles. Location of station- no greater than 5 miles off the highway.
Propane[e]	Public, primary propane stations no greater than 150 miles between one station and the next on the corridor, and no greater than 5 miles off the highway.	Public, primary propane stations separated by more than 150 miles. Location of station- no greater than 5 miles off the highway.
CNG	Public fast fill, 3,600 psi CNG stations no greater than 150 miles between one station and the next on the corridor, and no greater than 5 miles off the highway.	Public, fast fill, 3,600 psi CNG stations separated by more than 150 miles. Location of station- no greater than 5 miles off the highway.
LNG	Public LNG stations no greater than 200 miles between one station and the next on the corridor, and no greater than 5 miles off the highway.	Public LNG stations separated by more than 200 miles. Location of station- 5 miles or less off the highway.

Notes

1. A corridor-ready corridor is defined as having a minimum of 2 stations. Final classifications will be made on a case-by-case basis.
2. If a corridor is being designated as corridor-pending and currently has no alternative fuel facilities located on it, then a strategy or plan and timeline for infrastructure build-out should be submitted.
3. Electric vehicle designations will only consider corridors with DC Fast Charge infrastructure and both connector types. Tesla charging stations are considered a proprietary network and do not meet the designation criteria of being publicly accessible. Therefore, these stations are not eligible for inclusion.
4. If a hydrogen refueling station currently used for non-road transportation purposes is being used to support the nomination process, then the station must be compliant with SAE J2601 standards, and meet all of the criteria outlined in this document for a hydrogen corridor including being publicly accessible.
5. For propane stations, only "primary" stations (i.e., those stations that are staffed during regular business hours, do not require drivers to call ahead in order to fuel, accept credit cards or fleet cards as a payment type, and are able to fuel vehicles at a rate of 12 gallons per minute or faster, or at a rate similar to filling a gasoline vehicle, as designated by the U.S. Department of Energy's Alternative Fuel Station Locator) would be considered when determining infrastructure coverage along a nominated corridor.

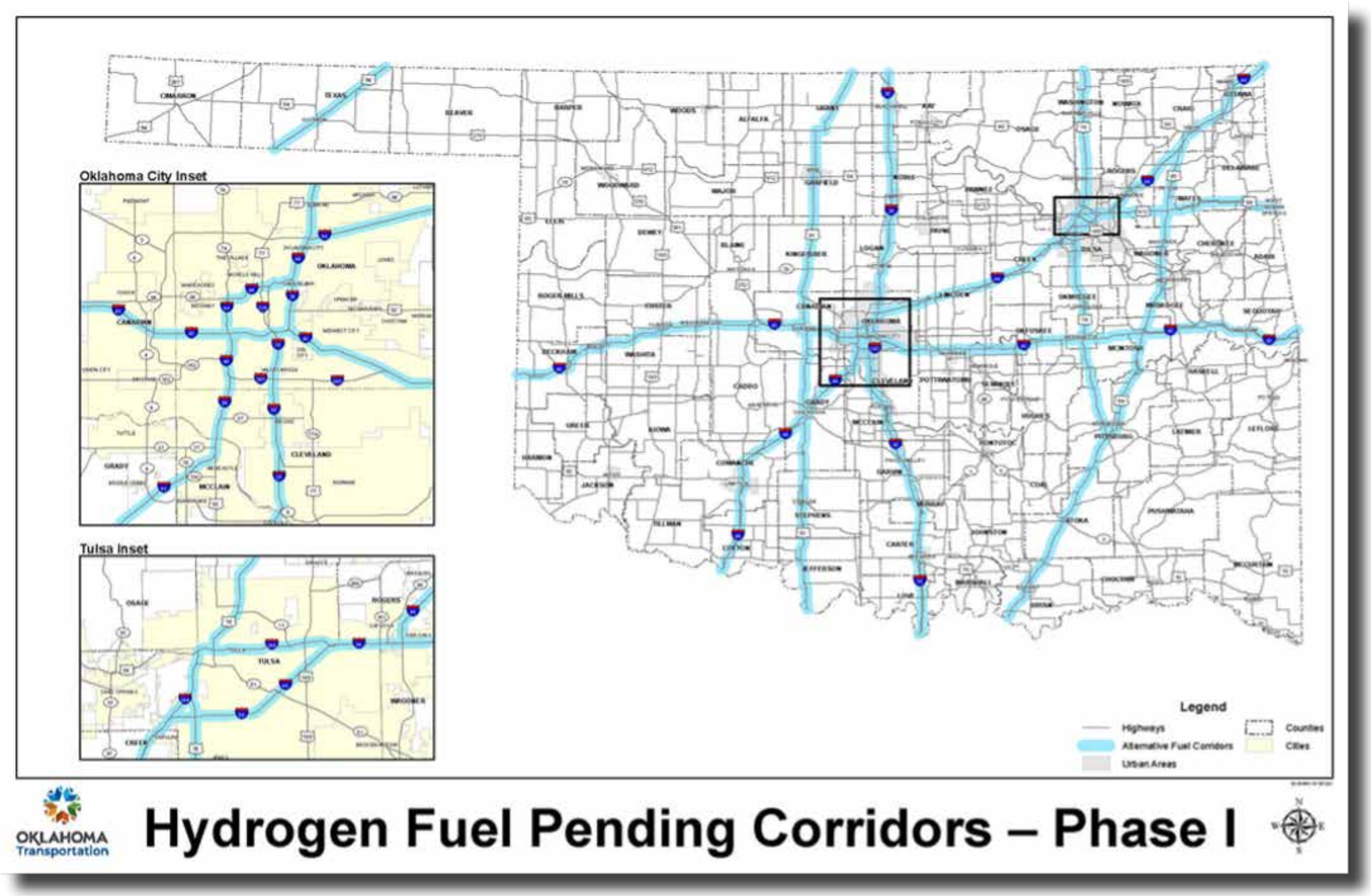
Reference: Section 1413 of the Fixing America's Surface Transportation Act - Designation of Alternative Fuel Corridors
https://www.gpo.gov/fdsys/pkg/PLAW-114publ94/html/PLAW-114publ94.htm

Reference: 81 FR 47852 (July 22, 2016)
https://www.federalregister.gov/documents/2016/07/22/2016-17132/fixing-americas-surface-transportation-act-designation-of-alternative-fuel-corridors

Reference: U.S. Department of Transportation, Federal Highway Administration. "2020 Round 5- Request for Nominations, Fixing America's Surface Transportation Act Designation of Alternative Fuel Corridors" https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/resources/rfn5.cfm

Alternative Fuel Corridor Recommendations for Hydrogen in Oklahoma

Phase I Corridors
Round 1 fuel station proposed locations highlighted in Blue
Round 2 fuel station proposed locations highlighted in Green



I-35: 236 miles from Texas state line to Kansas state line
Thackerville (1 mile)
Ardmore (29 miles)
Pauls Valley (74 miles)
Purcell (92 miles)
Oklahoma City (128 miles)
Guthrie (161 miles)
Perry (194 miles)
Tonkawa (222 miles)

I-40: 331 miles from Texas to Arkansas
Erick (3 miles)
Elk City (40 miles)
Weatherford (75 miles)
El Reno (120 miles)
Oklahoma City (148 miles)
Shawnee (188 miles)

Okemah (228 miles)
Henryetta (249 miles)
Checotah (278 miles)
Webbers Falls (302 miles)
Sallisaw (323 miles)

I-44: 328 miles from Texas to Missouri
Lawton (38 miles)
Chickasha (87 miles)
Oklahoma City (130 miles)
Stroud (188 miles)
Tulsa (238 miles)
Claremore (268 miles)
Big Cabin (301 miles)
Miami (337 miles)

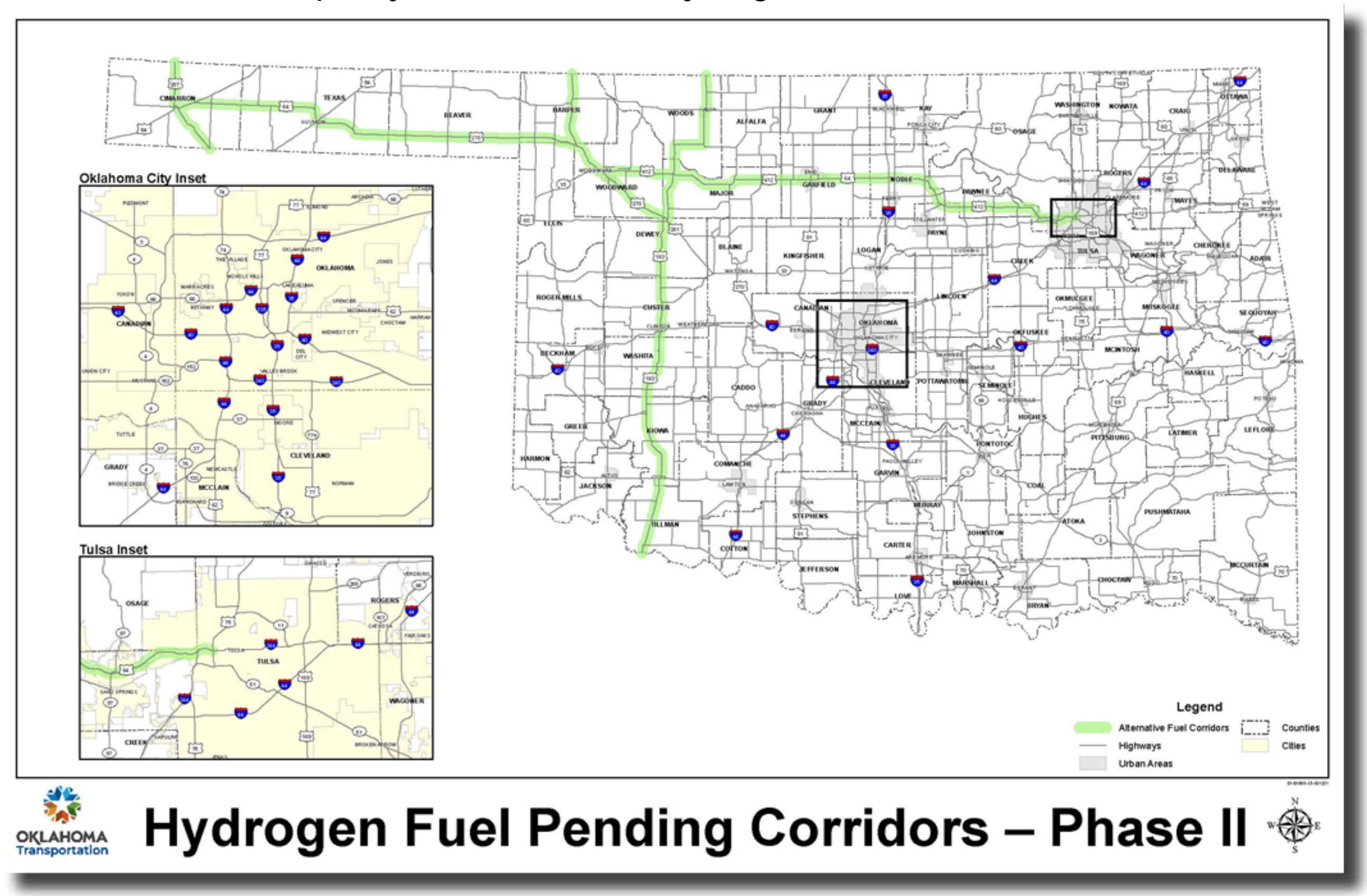
US-69: 254 miles from Texas to Kansas
Durant (20 miles)
Atoka (53 miles)
McAlester (98 miles)
Muskogee (162 miles)
Pryor (203 miles)
Big Cabin (220 miles)

US-75/SH-375/Indian Nation Turnpike: 154 miles from McAlester, Okla. to Kansas
McAlester (1 mile)
Henryetta (36 miles)
Okmulgee (55 miles)
Tulsa (94 miles)
Bartlesville (139 miles)

US-81: 226 miles from Texas to Kansas
Terral (1 mile)
Waurika (21 miles)
Duncan (46 miles)
Chickasha (86 miles)
El Reno (121 miles)
Kingfisher (145 miles)
Enid (184 miles)
Pond Creek (207 miles)
Renfrow (227 miles)

US-412: 88 miles from Arkansas state line to Tulsa
West Siloam Springs (1 miles)
Chouteau (45 miles)
Catoosa (72 miles)
Tulsa (88 miles)

US-54: 60 miles from Texas to Kansas
Guymon (22 miles)
Note: If hydrogen fueling stations are available in Texas or Kansas within 100 miles of this area, US-54 can still qualify as an Oklahoma hydrogen corridor



Phase II Corridors
All proposed fuel station locations included in Round 2, highlighted in Green

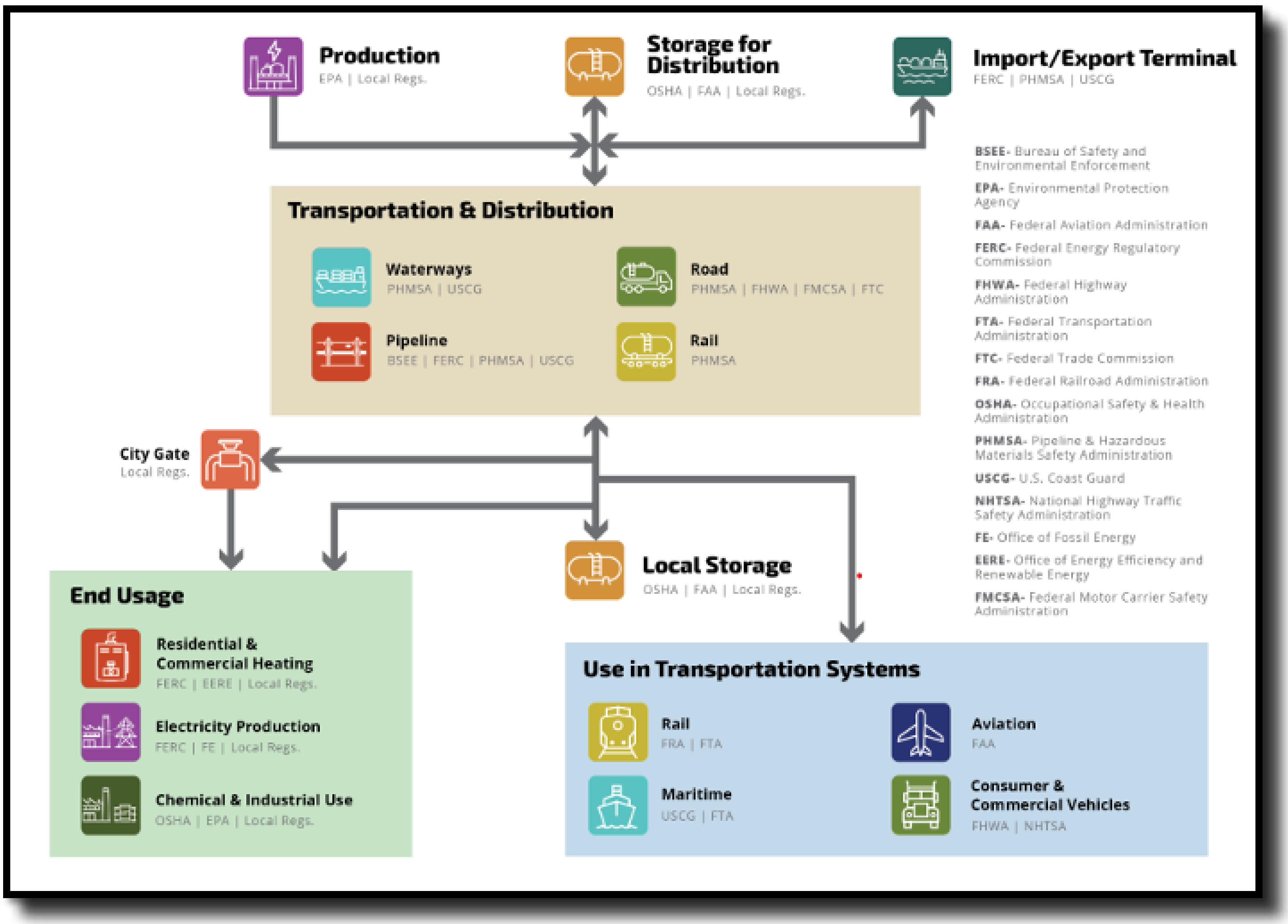
US-412: 420 miles from Tulsa to New Mexico
Tulsa (88 mile)
Morrison (150 miles)
Enid (206 miles)
Woodward (293 miles)
Elmwood (362 miles)
Guymon (419 miles)
Boise City (481 miles)

US-183/US-281: 219 miles from Texas to Kansas via Seiling-Woodward-Buffalo; 213 miles via Seiling-Waynoka-Alva
Frederick (13 miles)
Snyder (30 miles)
Hobart (60 miles)

Cordell (80 miles)
Clinton (96 miles)
Seiling (142 miles)
Woodward (via US-183) (176 miles)
Buffalo (via US-183) (211 miles)
Waynoka (via US-281) (173 miles)
Alva (via US-281) (200 miles)

US-287: 41 miles from Texas to Colorado
Boise City (25 miles)

Hydrogen Regulatory Map



This table is specifically applicable to federal regulating entities for the hydrogen supply value chain. The table also notes which regulations currently have hydrogen directly listed (green), regulations that cover general flammable or otherwise hazardous gases or liquids that should indirectly cover hydrogen (olive green), and regulations that specific to some other material (such as natural gas) that will need to be modified to include hydrogen (orange). Note that this readiness is based on a current (as of March 2021) assessment by the authors and is subject to regulatory interpretation and changes in the future. (https://www.osti.gov/servlets/purl/1773235/)

For hydrogen production facilities and storage systems, hydrogen regulations currently exist for emissions reporting and safety. Hydrogen specific regulations also exist for the distribution of hydrogen through tanker trucks, rail, and waterways, as well as hydrogen used as a fuel source for consumer/commercial road vehicles. However, other entities currently regulate similar materials (e.g., natural gas) and hydrogen will fall under that entity's authority with additional or modified regulations. The use of hydrogen or natural gas/hydrogen blends for electricity production and heating systems are subject to similar oversight as current natural gas systems. Rail, maritime, and aviation transportation using hydrogen as a fuel source will be regulated similar to current natural gas regulations.

Overview of Regulation and Oversight of Hydrogen Systems

System	Oversight	Reference	Summary	H_2 Ready?
Production	EPA	40 CFR Part 98	Defines source categories and emissions thresholds for a hydrogen production facility	Yes - production of gaseous hydrogen is specifically regulated through reporting thresholds
Storage	OSHA	29 CFR Part 1910	Dictates the safety of the structural components and operations of gaseous and liquid hydrogen storage and delivery	Yes - specifies requirements for and quantities for gaseous hydrogen storage
	FAA	14 CFR Part 420	Dictates the separation distance requirements for storage of liquid hydrogen and any incompatible energetic liquids	Yes - provides criteria for liquid hydrogen storage separation distances
Transportation by Pipeline	BSEE	43 USC Part 29	Manage compliance programs governing oil, gas, and mineral operations on the OCS	No - requirements for facilities and operations specifically for development and production of oil and gas
	FERC	18 CFR Part 153	Regulation of the siting, routing, and overall construction of the pipeline system, as well as the distribution and interstate and intrastate sale of natural gas	No - authorizes construction, operation, and modification for import and export facilities for natural gas only
		18 CFR Part 284	Filing requirements of the siting, construction, and operation of facilities used for the import or export of natural gas	
	PHMSA	49 CFR Part 192	Prescribes minimum safety requirements for pipeline facilities and the transportation of gas, including pipeline facilities and the transportation of gas within the limits of the outer continental shelf	Yes - sets requirements for natural gas transported via pipeline but other flammable gases are included in scope and definition
		49 CFR Part 193	Prescribes safety standards used for LNG facilities that are used to transport gas via pipeline	
		49 CFR Part 195	Prescribes safety standards for pipeline facilities that transport hazardous liquids	
	USCG	33 CFR Part 154	Regulations for facilities transferring hazardous materials back and forth from a vessel to a facility	Yes - sets requirements for transferring bulk hazardous materials in a vessel
Transportation by Road	PHMSA	49 CFR Part 172	Lists and classifies hazardous materials for transportation, and prescribes requirements for papers, markings, labeling, and vehicle placarding	Yes - prescribes transportation and packaging requirements for hazardous materials on public highways
		49 CFR Part 173	Provides requirements for preparing hazardous materials for shipment, and inspection, testing, and other requirements for transportation containers	
		49 CFR Part 177	Provides additional requirements when transporting hazardous materials via public highways	
		49 CFR Part 178	Prescribes specifications for packaging and containers used for transportation of hazardous materials	
		49 CFR Part 180	Provides qualification requirements for inspecting and maintaining packages and	

System	Oversight	Reference	Summary	H_2 Ready?
			containers used to transport hazardous materials	
	FMCSA	49 CFR Part 356	Motor carrier routing requirements	Yes - general safety and routing requirements for hazardous materials
		49 CFR Part 389	General motor carrier safety regulations	
		49 CFR Part 397	Transportation of hazardous materials	
	FHWA	23 CFR Part 924	Regulates highway safety which includes bridges, tunnels, and other associated elements	Yes - nothing is specified for transportation of hazardous materials
	FTC	16 CFR Part 306	Describes the certification and posting of automotive fuel ratings in commerce	Yes - specifies labeling requirements including all alternative fuels
Transportation by Rail	PHMSA	49 USC 5117	Gives the authority to authorize a variance that is still at the same safety level, special permit is required to use an alternative fuel that does not have a safety standard	Yes - specifies all requirements for transporting hazardous materials including tank car design, inspection, preparation, and testing
		49 CFR Part 172	Lists and classifies hazardous materials for transportation and prescribes the requirements for papers, markings, labeling, and vehicle placarding	
		49 CFR Part 173	Provides requirements for preparing hazardous materials for shipment as well inspection, testing, and other requirements for containers, including usage instructions for DOT-113A60W tank cars	
		49 CFR Part 174	Provides additional requirements for transportation of hazardous materials in or on rail cars	
		49 CFR Part 178	Prescribes specifications for packaging and containers used for transportation of hazardous materials	
		49 CFR Part 179	Provides construction requirements for DOT-113A60W tank cars	
		49 CFR Part 180	Provides qualification requirements for inspecting and maintaining containers used to transport hazardous materials, including DOT-113A60W tank cars	
Transportation by Waterways	PHMSA	49 CFR Part 172	Lists and classifies hazardous materials for transportation and prescribes the requirements for papers, markings, labeling, and vehicle placarding	Yes - specifies all requirements for transporting hazardous materials including package inspection, preparation, and testing
		49 CFR Part 173	Provides requirements for preparing hazardous materials for shipment, as well inspection, testing, and other requirements for containers	
		49 CFR Part 176	Requirements for transportation by vessel	

System	Oversight	Reference	Summary	H_2 Ready?
		49 CFR Part 178	Prescribes specifications for packaging and containers used for transportation of hazardous materials	
		49 CFR Part 180	Provides qualification requirements for inspecting and maintaining containers used to transport hazardous materials	
	USCG	33 CFR Part 154	Regulations for transferring hazardous materials back and forth from a vessel to a facility	Yes - specifies requirements for bulk hazardous materials transported via vessel
		33 CFR Part 156	Transfer of oil or hazardous material on the navigable waters or contiguous zone of the U.S.	
		46 CFR Part 38	Requirements for transportation of liquified or compressed flammable gases	
		46 CFR Part 150	Describes incompatibility of hazardous materials and rules for transporting these materials aboard tanks that are loaded and discharged while on the vessel	
		46 CFR Part 151	Regulations for non-self-propelled ships carrying bulk cargo	
		46 CFR Part 153	Regulations for self-propelled ships carrying bulk cargo	
		46 CFR Part 154	Regulations for self-propelled vessels that contain bulk liquified gases as cargo, cargo residue, or vapor	
Import/ Export Terminals	FERC	18 CFR Part 153	Establishes filing requirements to obtain authorization for the siting, construction, operation, place of entry for imports or place of exit for exports	No - requirements specifically for natural gas import and export terminals
	PHMSA	49 CFR Part 192	Prescribes minimum safety requirements for pipeline facilities and the transportation of gas, including pipeline facilities and the transportation of gas within the limits of the outer continental shelf	Yes - sets requirements for natural gas transported via pipeline but other flammable gases are included in scope and definition
		49 CFR Part 193	Prescribes safety standards used for LNG facilities that are used to transport gas via pipeline	
		49 CFR Part 195	Prescribes safety standards for pipeline facilities that transport hazardous liquids	
	USCG	33 CFR Part 154	Regulations for self-propelled vessels that contain bulk liquified gases as cargo, cargo residue, or vapor	Yes - sets requirements for transfer of hazardous liquids and materials on navigable waters
		33 CFR Part 156	Transfer of oil or hazardous materials on the navigable waters or contiguous zone of the U.S.	
Electricity Production	FERC	18 CFR Part 292	Sets requirements for a small power production or cogeneration facility	Yes – fuel cells included in definition of electrical generation equipment

System	Oversight	Reference	Summary	H_2 Ready?
	FE	10 CFR Part 503	Prohibits any new baseload powerplant without the ability to use coal or another alternative fuel as a primary energy source	Yes – alternative fuels do not explicitly include hydrogen, but note that fuels obtained from alternative fuel sources would be included
		10 CFR Part 504	May prohibit existing powerplants from using petroleum or natural gas as a primary energy source	
Residential & Commercial Heating	FERC	18 CFR Part 284	Provides regulation of energy sales and distribution of natural gas	No – these requirements are specifically for natural gas
	EERE	10 CFR Part 431	Provides regulation of commercial heaters, hot water boilers, and similar heating appliances	No - testing requirements for natural gas and oil-fired furnaces, boilers, etc. Definition of gas specific to natural gas and propane.
Chemical and Industrial Use	OSHA	29 CFR Part 1910	Dictates the safety of the structural components and operations of gaseous and liquid hydrogen in terms of storage as well as delivery	Yes - specifies requirements for and quantities for gaseous hydrogen storage
	EPA	40 CFR Part 98	Requires reporting of greenhouse gas emission due to combustion or use of products in a process	Yes - production of gaseous hydrogen is specifically regulated through reporting thresholds
Auxiliary Power and Alternative Power Supply	FHWA	49 CFR Part 390	Regulates additional equipment on commercial vehicles to ensure it does not reduce the overall safety of the vehicle	Yes - requirements are set to ensure that the safety of a commercial vehicles even with additional equipment
	FRA	49 CFR Part 229	Regulations for electrical systems, generators, protection from hazardous gases from exhaust and batteries, and crashworthiness for locomotives	No - Exhaust gases specific to combustion and battery venting are addressed, but not fuel cells
	USCG	46 CFR Part 111	Regulations for power supply systems on ships	No - specifically for boiler, diesel, gas turbine, or steam turbine; does not include alternatives
	FAA	14 CFR Part 23 Subpart E	Requirements for electrical generating systems including auxiliary and backup power for normal category airplanes	Yes – not specific to fuel used
		14 CFR Part 25 Subpart E	Requirements for electrical generating systems including auxiliary and backup power for transport category airplanes	
		14 CFR Part 27 Subpart E	Requirements for electrical generating systems including auxiliary and backup power for normal category rotorcraft	
		14 CFR Part 29 Subpart E	Requirements for electrical generating systems including auxiliary and backup power for transport category rotorcraft	
Use in Consumer/ Commercial Vehicles	NHTSA	49 CFR 571	Provides Federal Motor Vehicle Safety Standards for motor vehicles and motor vehicle equipment	Yes - requirements are specific for CNG vehicles, but have been used for hydrogen vehicles
	FHWA	23 CFR Part 924	Regulates highway safety which includes bridges, tunnels, and other associated elements	Yes - nothing is specific for transportation of hazardous materials

System	Oversight	Reference	Summary	H_2 Ready?
Use in Rail	FRA	49 CFR Part 229	Locomotive safety design and crashworthiness requirements	Yes - includes requirements for alternative designs which would likely be part of alternative fueled locomotives
		49 CFR Part 238	Safety requirements for passenger locomotives	
	FTA	49 CFR Part 659	Provides guidance for rail fixed guideway systems and the oversight of safety, including hazard management and safety and security plans and review	Yes - general requirements for safety and security assessments, not fuel-specific
		49 CFR Part 674	Mandates state safety oversight of fixed guideway public transportation systems	
Use in Maritime	USCG	46 CFR Parts 24–196	Regulation of vessel construction for both passenger and cargo applications as well as general fuel requirements based on the flash point of the fuel	Yes – these requirements include specific requirements for vessels based on the fuel properties the vessel uses
	FTA	49 USC Chapter 53	Requirements for National Public Transportation Safety Plan for public transportation that receives federal funding	Yes – alternative fuels are noted, but hydrogen is not specifically mentioned
Use in Aviation	FAA	14 CFR Part 23	Provides requirements and airworthiness standards for normal category airplanes	Yes - there are requirements to analyze flammable gases, but hydrogen is not specifically listed
		14 CFR Part 25	Provides requirements and airworthiness standards for transport category airplanes	
		14 CFR Part 26	Provides requirements and airworthiness standards for transport category airplanes	
		14 CFR Part 27	Provides requirements and airworthiness standards for normal category rotorcraft	
		14 CFR Part 29	Provides requirements and airworthiness standards for transport category rotorcraft	
		14 CFR Part 33	Provides requirements and airworthiness standards for aircraft engines	

(https://www.osti.gov/servlets/purl/1773235/)

Carbon dioxide sequestration potential by state https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf page 110 and 111

CO_2 Stationary Source Emissions and CO_2 Storage Resource Estimates Summary*

State/ Province	CO_2 Emissions		Oil and Natural Gas Reservoirs Storage Resource (Billion Metric Tons)			Unmineable Coal Storage Resource (Billion Metric Tons)			Saline Formation Storage Resource (Billion Metric Tons)			Total Storage Resource (Billion Metric Tons)		
	Million Metric Tons Per Year	Number of Sources	Low Estimate	Medium Estimate	High Estimate	Low Estimate	Medium Estimate	High Estimate	Low Estimate	Medium Estimate	High Estimate	Low Estimate	Medium Estimate	High Estimate
Alabama	91	134	0.06	.09	0.12	1.92	2.98	4.37	120.22	307.34	689.67	122.20	310.41	694.16
Alaska	18	63				8.64	13.44	19.75				8.64	13.44	19.75
Alberta	137	182	0.60	1.49	3.57	0.03	0.03	0.03	38.17	76.74	140.30	38.80	78.26	143.90
Arizona	57	67	0.00	0.00	0.01	0.00	0.00	0.00	0.11	0.42	1.14	0.11	0.42	1.15
Arkansas	44	120	0.11	0.18	0.25	1.58	2.46	3.61	4.38	21.20	59.84	6.07	23.84	63.70
British Columbia	17	71	0.00	0.00	0.00				0.88	1.87	3.58	0.88	1.87	3.58
California	106	374	3.56	4.85	6.63				30.33	147.55	417.07	33.89	152.40	423.70
Canadian Federal Offshore									0.96	4.65	13.15	0.96	4.65	13.15
Colorado	49	142	1.31	2.35	2.66	0.49	0.65	0.86	33.48	131.11	353.82	35.28	134.11	357.34
Connecticut	8	47												
Delaware	9	18							0.04	0.04	0.04	0.04	0.04	0.04
District of Columbia	0	6												
Florida	120	142	0.02	0.03	0.05	1.26	1.95	2.85	101.37	246.45	552.05	102.65	248.43	554.95
Georgia	69	120				0.01	0.02	0.03	145.33	148.70	159.02	145.34	148.72	159.05
Hawaii	8	23												
Idaho	3	39							0.04	0.15	0.39	0.04	0.15	0.39
Illinois	120	231	0.10	0.20	0.34	1.45	2.38	2.87	19.68	80.75	213.07	21.23	83.33	216.28
Indiana	149	180	0.02	0.04	0.07	0.09	0.14	0.17	38.14	66.67	128.52	38.25	66.85	128.76
Iowa	68	143				0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01
Kansas	42	116	1.25	1.25	1.25	0.00	0.00	0.01	9.63	34.40	85.08	10.88	35.65	86.34
Kentucky	99	122	1.05	1.75	3.21	0.14	0.18	0.20	14.72	46.43	110.20	15.91	48.36	113.61
Louisiana	126	282	3.12	5.70	8.29	8.30	12.89	18.91	151.36	734.55	2075.23	162.78	753.14	2102.43
Maine	4	28										0.00	0.00	0.00
Manitoba	2	11	0.01	0.03	0.07				6.95	13.14	22.53	6.96	13.17	22.60
Maryland	24	52	0.00	0.00	0.00	0.00	0.00	0.00	1.86	1.88	1.93	1.86	1.88	1.93
Massachusetts	15	76										0.00	0.00	0.00
Michigan	87	208	0.17	0.26	0.32	0.00	0.00	0.00	31.55	45.56	66.20	31.72	45.82	66.52
Minnesota	46	130							0.00	0.00	0.00	0.00	0.00	0.00
Mississippi	34	91	0.28	0.45	0.62	5.44	8.46	12.45	139.02	459.15	1172.03	144.74	468.06	1185.10
Missouri	95	104	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.10	0.29	0.02	0.11	0.30
Montana	21	31	0.15	0.38	0.90	0.33	0.33	0.33	98.21	335.74	856.92	98.69	336.45	858.15
Nebraska	37	72	0.01	0.03	0.07	0.00	0.00	0.00	23.65	54.47	111.91	23.66	54.50	111.98

* States/Provinces with a "zero" value represent estimates of minimal CO_2 storage resource, while States/Provinces with a blank represent areas that have not yet been assessed by the RCSPs. Medium = p50. (*ATLAS V*1.1 DATA)

State/ Province	CO_2 Emissions		Oil and Natural Gas Reservoirs Storage Resource			Unmineable Coal Storage Resource			Saline Formation Storage Resource			Total Storage Resource		
	Million Metric Tons Per Year	Number of Sources	Billion Metric Tons			Billion Metric Tons			Billion Metric Tons			Billion Metric Tons		
			Low Estimate	Medium Estimate	High Estimate	Low Estimate	Medium Estimate	High Estimate	Low Estimate	Medium Estimate	High Estimate	Low Estimate	Medium Estimate	High Estimate
Nevada	18	37												
New Brunswick	0	0												
New Hampshire	4	16												
New Jersey	22	96							0.00	0.00	0.00	0.00	0.00	0.00
New Mexico	37	84	9.71	9.71	9.71	0.08	0.16	0.30	32.97	129.29	349.08	42.76	139.16	359.09
New York	43	203	0.05	0.08	0.15				4.37	4.37	4.37	4.42	4.45	4.52
Newfoundland & Labrador	0	0												
North Carolina	62	99							1.34	6.51	18.39	1.34	6.51	18.39
North Dakota	39	48	0.37	0.91	2.19	0.54	0.54	0.54	71.94	136.50	234.71	72.85	137.95	237.44
Northwest Territories	0	0												
Nova Scotia	0	0												
Ohio	126	231	0.65	1.08	1.97	0.12	0.12	0.12	9.91	9.91	9.91	10.68	11.11	12.00
Oklahoma	67	151	3.48	4.40	4.40	0.00	0.00	0.01	19.64	76.87	207.24	23.12	81.27	211.65
Ontario	0	0							0.01	0.01	0.01	0.01	0.01	0.01
Oregon	9	47							6.81	33.15	93.70	6.81	33.15	93.70
Pennsylvania	132	281	0.80	1.34	2.45	0.27	0.27	0.27	17.34	17.34	17.34	18.41	18.95	20.06
Puerto Rico	17	23												
Quebec	0	0												
Rhode Island	4	12												
Saskatchewan	24	41	0.38	0.96	2.31				149.72	285.22	492.63	150.10	286.18	494.94
South Carolina	41	77							30.10	31.07	34.18	30.10	31.07	34.18
South Dakota	9	33	0.00	0.00	0.01				3.70	7.04	12.15	3.70	7.04	12.16
Tennessee	50	90	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.85	4.63	0.50	1.85	4.63
Texas	376	677	133.72	137.60	141.48	14.02	21.80	32.03	331.62	1505.79	4199.74	479.36	1665.19	4373.25
U.S. Federal Offshore	5	87	17.18	17.18	17.18	1.69	2.63	3.86	472.06	2277.24	6432.96	490.93	2297.05	6454.00
Utah	38	73	1.31	2.39	2.66	0.03	0.07	0.12	22.61	88.65	239.35	23.95	91.11	242.13
Vermont	0	6												
Virginia	35	111	0.00	0.01	0.01	0.16	0.37	0.69	0.27	0.86	2.21	0.43	1.24	2.91
Washington	17	74				0.59	0.92	1.35	36.03	175.26	495.39	36.62	176.18	496.74
West Virginia	71	84	5.93	9.84	18.05	0.37	0.37	0.37	11.19	11.19	11.19	17.49	21.40	29.61
Wisconsin	54	134							0.00	0.00	0.00	0.00	0.00	0.00
Wyoming	66	118	0.23	0.59	1.41	6.55	6.64	6.78	146.34	570.92	1539.56	153.12	578.15	1547.75
North America Total	3,071	6,358	186	205	232	54	80	113	2,379	8,328	21,633	2,618	8,613	21,978

* States/Provinces with a "zero" value represent estimates of minimal CO_2 storage resource, while States/Provinces with a blank represent areas that have not yet been assessed by the RCSPs. Medium = p50. (*ATLAS V1.1* DATA)

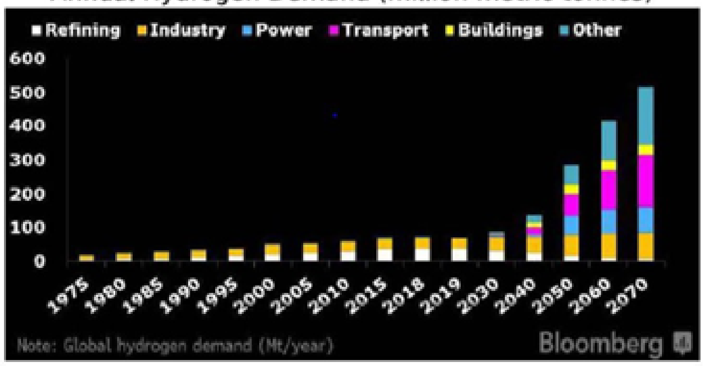
Hydrogen

February 2021

Hydrogen Investment

- Hydrogen revolution may provide a **$2.5 trillion** investment opportunity through 2050 for utilities, equipment makers, and others looking to curb emsiion intensity
  - Annual demand could reach 5% (Bloomberg)

Annual Hydrogen Demand (million metric tonnes)

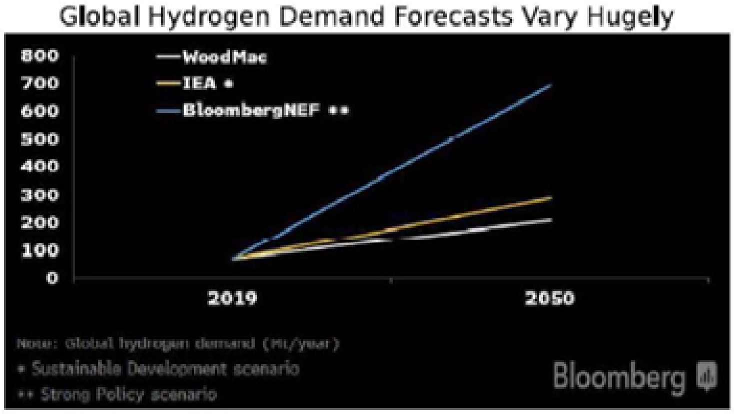


  - Hydrogen to hit 7% of energy use by middle of decade (Woods/Mckensie)
- **Hydrogen Investments Look set to Skyrocket.**
  - During 2018-2020, investments averaged about $1.5 billion/yr, according to Bloomberg data.
    - Investment in hydrogen forecast to increase to $38 billion/yr in the period 2019-2040. The majority of this investment will go toward investments in ramping production of hydrogen, while future spending on distribution may account for only 12-16% of that figure through 2070
- Hydrogen Surge likely would be from a low base
  - The next 5 years' expected surge in global hydrogen investment would be from a small base
  - Key drivers will likely be supportive government policies, decarbonization efforts by the companies themselves, the declining cost of the technology amid economies of scale and the learning curve.
  - Wind and solar generation and electrified transport look set to continue to dominate green investments this decade, but the share of hydrogen and carbon capture and store (CCS) could increase by mid-2020s from the 2018—20 level of about 0.4% each.

Large variation in growth trajectory on policy

- Uncertainty on future carbon prices, government subsidies, economies of scale and the learning curve means there is a huge variation in forecasts for hydrogen investment and consumer growth.

Global Hydrogen Demand Forecasts Vary Hugely



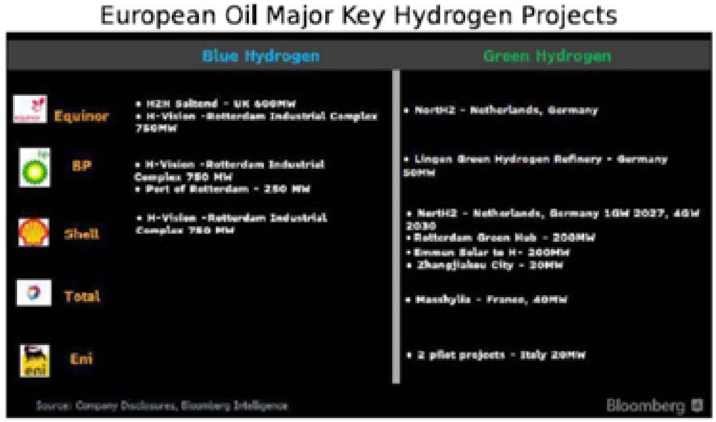
- WoodMac estimates that a cumulative $1 trillion of capital investments will be needed by 2050, while the IEA's projections imply about $2.5 trillion during that period.
  - Similarly, there is also a wide variation in projections for hydrogen demand in 2050, with Bloomberg significantly more bullish than WoodMac and the IEA.
  - Hydrogen certainly offers growth opportunities to utilities (Orsted, RWE, Snam), manufacturers (NEL, Plug Power, Alstom), refiners, transport, metals and mining (Anglo American, ThyssenKrupp) and other companies seeking to curb emission intensity (Linde, Equinor).

Industry Leaders

- Plug Power and recently listed Enapter have the attention of investors as far as pure play hydrogen goes. Plug Power is currently the industry leader by market value.
- NEL, ITM Power and McPhy Energy are among the largest listed companies focused on producing electrolyzers, while Ballard Power, Bloom Energy, FuelCell Energy and Ceres Power target fuel cells.

- Utilities (mainly in Europe at this time) are set to use fossil free electricity to generate hydrogen
  - So far utilities are leading there oil and gas peers by more than 50% in hydrogen production.
- Big Oil is taking the iniative in making "blue" hydrogen (from natural gas via carbon-capture technology).

European Oil Major Key Hydrogen Projects



	Blue Hydrogen	Green Hydrogen
Equinor	• H2H Saltend - UK 600MW • H-Vision -Rotterdam Industrial Complex 750MW	• NortH2 - Netherlands, Germany
BP	• H-Vision -Rotterdam Industrial Complex 750 MW • Port of Rotterdam - 250 MW	• Lingen Green Hydrogen Refinery - Germany 50MW
Shell	• H-Vision -Rotterdam Industrial Complex 750 MW	• NortH2 - Netherlands, Germany 1GW 2027, 4GW 2030 • Rotterdam Green Hub - 200MW • Emmun Solar to H - 200MW • Zhangjiakou City - 20MW
Total		• Masshylia - France, 40MW
Eni		• 2 pilot projects - Italy 20MW

Source: Company Disclosures, Bloomberg Intelligence

Bloomberg

California

- The California Alternative Energy and Advanced Transportation Financing authority (CAEATFA) provides a sale and use tax exclusion for qualified manufacturers of advanced transportation products, components, or systems that reduce pollution and energy use and promote economic development.
- Annually, the California Air Resources Board (ARB) must aggregate and share the number of hydrogen vehicles that manufacturers project will be sold or leased over the next three years and the total number of hydrogen vehicle registered in the state
    - The California Energy Commission will allocate up to $20 million/yr. to fund the number of stations deemed necessary based on ARB's evaluation and reports.

Montana

- Montana Governor signed a law concerning the inclusion of renewable hydrogen for property tax purposes.
- The law includes measures:
    1. Defining relevant terms
    2. Creating a new tax classification for green hydrogen and providing tax incentives
    3. Exempting green hydrogen from the major facility siting act
    4. Revising the state energy policy to include green hydrogen
    5. Revising the use of energy development and demonstration grants for green hydrogen

South Carolina

- **Hydrogen and Fuel Cell Tax Exemption**
    - Any device, equipment, or machinery operated by hydrogen or fuel cells
    - Any device, equipment, or machinery used to generate, produce, or distribute hydrogen and designated specifically for hydrogen or fuel cell applications
    - Any device, equipment, or machinery used predominantly for manufacturing, or research and development involving hydrogen or fuel cell technologies.
- **Battery Manufacturing Tax Incentive**
    - For taxation purposes, the taxable fair market value of manufacturing machinery and equipment purchased for use at a renewable energy manufacturing facility may be reduced by 20% of the original cost. Qualified renewable energy manufacturing facilities include those manufacturing batteries for hybrid, fuel cell or other motor vehicles certified by SC Energy Office.

Utah

- **Hydrogen Fuel Production Incentive**
    - Businesses that convert natural gas to hydrogen fuel or produce natural gas solely for use in the production of hydrogen fuel for zero emission vehicles (ZEVs), may be eligible for an oil and gas severance tax credit. Each eligible applicant may receive a tax credit equal to the amount of the severance tax owed, up to $5 million per year. Entities that produce hydrogen fuel for use in ZEVs or hydrogen fueled trucks may also qualify for grant funding or loans from the Community Impact Fund.

- **S.B. 112**-Bill authorizes the Utah Inland Port Authority to establish a community enhancement program to address the impacts of development. (signed by Governor's office)
- **S.B. 154-**Bill allows for grants to an entity that creates a hydrogen energy hub for a municipal entity. (signed by Governor's office)
- **H.B. 59**-Bill extends tax credits for up to $13,500 for Class 7 and 8 EV and EV/Hydrogen trucks. Although tax credit was desired to be higher, a committee in November had approved the lower amounts on a phase out plan. Lobbyist engagement helped get this passed in session despite a "no new tax incentives" policy due to the need for a major tax restructuring in Utah yet to take place (Vetoed by Governor)
- Electric Vehicle, Alternative Fuel Infrastructure, Hydrogen-Related Bill Summaries and Outcomes. (2020 legislation)
- **S.B. 95**-Bill captures $10 million of ongoing state money and redirects it to rural counties for economic projects. Nikola seeking to develop hydrogen stations or manufacturing facilities in any of the 24 rural counties could seek local county support for a portion of these funds. (Signed by Governor's Office)
- **S.B. 50**-Bill changes the air quality standard for vehicle emissions and added qualifying electric vehicles to the Commercial Property Assessed Clean Energy Act. (Signed by Governor's Office)
- **H.B 347**-Bill modified definitions to include energy-related facilities to be a part of the infrastructure of the Utah Inland Port. The bill authorizes the inland port authority to use funds to encourage, incentivize, or require development with reduced environmental impact and to develop and implement zero-emissions logistics and modifies a provision relating to a renewable energy tariff. (Signed by Governor's office)
- **H.B. 269-**Bill creates future tax credits for Nikola or another hydrogen electrolysis system of 2 megawatts and above. The tax credit is equal to 12 cents per kilogram of hydrogen produced or used with a carry forward provision of seven years if needed (Vetoed by Governor)

Washington

- **Fuel Cell Electric Vehicle (FCEV) Tax Exemption**
  - Beginning July 1, 2022, 50% of the retail sales and state use tax of 6.5% does not apply to the sale or lease of the first 650 new FCEV passenger vehicles, light-duty trucks, and medium-duty passenger vehicles powered by fuel cells. Additionally, all used FCEV sales and leases are exempt from the tax. The FCEV exemption may not be combined with the Retail Sales and Use Tax exemption.

Plug Power (Incentive Example)

- Plug Power and Apex Clean Energy announced a 345MW wind power PPA and a development services agreement for a green hydrogen production facility.
  - The hydrogen plant, will be the first and largest wind-supplied hydrogen project in the US and the largest onshore wind-powered project across the globe
  - Once operational, the plant is anticipated to produce over 30 metric tons/day of clean liquid hydrogen, enough to fuel the equivalent of over 2,000 light commercial vehicles or over 1,000 heavy duty class 8 trucks

- Plug Power received $2.8 million in sales tax incentives related to their $55 million investment in a substation that will enable 100% renewable, reliable electricity at less than $0.035/kwh

Potential Incentive Ideas

November 2021

Federal Hydrogen Push

- The US Congress is considering two major pieces of legislation that support the Administration's infrastructure and climate goals. Within the legislation, clean hydrogen receives a generous production tax credit and billions in new research funding. If enacted, both bills would provide unprecedented support for clean hydrogen production, fundamentally changing the industry's economics.
  - The US House is proposing the first-ever production tax credit for clean hydrogen projects, reaching up to $3 for each kilogram produced. The credit's value ranges up and down depending on a project's carbon intensity and labor practices; projects that qualify would receive the tax credit for the first 10 years of production.
  - The incentive of $3/kg over 10 years is equivalent to $1.9/kg over and electrolysis facility's whole life of 20 years. With this subsidy, electrolysis projects that are to be built immediately and powered by strong wind in regions like Texas can yield hydrogen for a cost of $1.1/kg. Supposedly competitive against gray hydrogen.
  - The proposed tax credit is $1/kg over 10 years for blue hydrogen, if the carbon capture storage (CCS) facility can cut emissions by 85%. This subsidy is just enough to cover the additional cost introduced by CCS.
  - The US Senate plans to increase spending on clean hydrogen research, development, and demonstration to $1.9 billion/yr., up from $0.3 billion/yr. Most of this money would support four new regional hydrogen hubs across the country. The legislation strongly supports hydrogen produced form fossil fuels from carbon capture, which increased its support from moderate **democrats and republicans**.

Table 1: Summary of U.S. Congress's hydrogen legislation

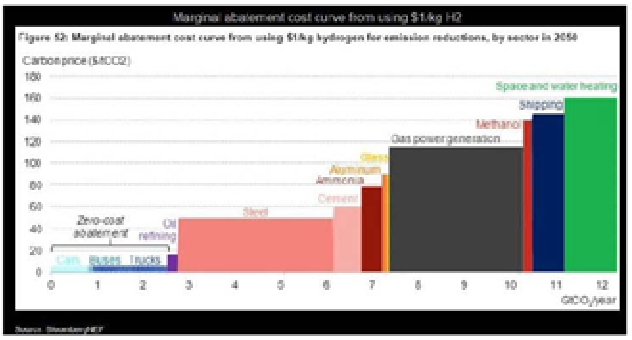
Legislation	Status	Total funding	Hydrogen provisions	Next steps	Further BNEF reading
Infrastructure bill approved by the Senate	Passed the Senate on August 10	$1 trillion	$9.5 billion for research, development and demonstration	Must pass the House with a simple majority. Vote scheduled before October.	*Senate Infrastructure Deal Has $114 Billion for Energy* (web | terminal)
House budget reconciliation bill proposal	Announced by the House Ways and Means committee on September 13	$3.5 trillion	A production tax credit worth up to $3 per kilogram for green hydrogen and $1/kg for blue	A version must be worked out and agreed upon by both House and Senate, and pass with a simple majority in both chambers	*Congressional Drafts Would Recharge U.S. Energy Policy* (web | terminal)

Source: BloombergNEF.

Proposed Incentives

- Power generation and passenger cars are a surprisingly small share of the world's emissions.
  - If both sectors were fully switched to zero-carbon power tomorrow, we'd still have eliminated only about 40 to 50% of our carbon output.
  - Another 25% comes from land use and agriculture.
  - ***The place where governments could make the biggest difference is the 20% of emissions that come from industrial activities.***
  - As a top 10 manufacturing state, keeping our air quality such that the EPA doesn't declare areas of the State a 'non-attainment' zone is in the best interest of the State.
  - Many of our larger manufacturers have already signed MOUs to get involved with the hydrogen push. (Matrix, Chart Industries, Williams, etc.)
  - Equipment manufacturers in the State have long been involved in the hydrogen game. (Gastec)
  - As we've seen in Europe, the negative externalities of rushing to zero carbon can rapidly lead to famine if not done incrementally.
- Despite several false starts, investments in hydrogen are now set to surge.

- During 2018-2020, investments averaged about $1.5 billion/year.
- This figure is forecast to increase to $38 billion per annum in 2019-2040
- $181 billion annually 2041-2070, according to the EIA.
- Most of these investments are forecast to go toward investments in ramping up the production of hydrogen, while future spending on distribution may account for only 12-16% through 2070.



- Water supply, value chain, rare metals pose the biggest challenge to the effort.

Severance Tax Credit

10-1 severance tax credit. For every 10% reduction in GHG leads to 1% credit on severance tax due, capped at 5.5% (half of the 2018 hike). A similar payroll tax credit for manufacturers or possibly explore a credit exchange program where manufacturers and energy producers work together (simultaneously addressing the 'resource curse'). Proposal to reimburse local entities structured much like the ad-valorem program.

Utah's Severance Tax Credit language

- **Hydrogen Fuel Production Incentive**
  - Businesses that convert natural gas to hydrogen fuel or produce natural gas solely for use in the production of hydrogen fuel for zero emission vehicles (ZEVs), may be eligible for an oil and gas severance tax credit. Each eligible applicant may receive a tax credit equal to the amount of the severance tax owed, up to $5 million per year. Entities that produce hydrogen fuel for use in ZEVs or hydrogen fueled trucks may also qualify for grant funding or loans from the Community Impact Fund.

Gas Processing classified as a Manufacturing industry

- Midstream companies are large stable employers in Oklahoma. The midstream industry has seen a downturn in investment due to tax law changes, ESG investing, etc. The hydrogen push will take a lot of participation from the natural gas industry in Oklahoma. The oil and gas sector has the experience, skills, and knowledge to develop and scale up production of hydrogen from natural gas as a low-carbon, low-cost source of energy. **Our goal is to compete with other states and retain jobs.**
  - In addition to gas processing. Proposal to classify all segments of the hydrogen industry as manufacturing.
  - Similar to the way petroleum refineries are classified.
  - Other ideas to spur investment in natural gas/hydrogen infrastructure.

Carbon Dioxide Capture/Sequestration Tax Deduction (Below is the Kansas incentive)

A taxpayer shall be entitled to a deduction from Kansas adjusted gross income with respect to the amortization of the amortizable costs of carbon dioxide capture, sequestration or utilization machinery and equipment based upon a period of 10 years.

- Oklahoma should potentially include language for emerging technologies in this realm
    - Oxy-Combustion, dry reforming, carbon sequestration, injecting hydrogen into natural gas streams, replacing natural gas with hydrogen, replacing coke with hydrogen coking coal.

Grid Stability Products

- Some form of sales tax exemption for products that lead to grid stability.

Energy Storage Incentive

- Hydrogen can offer large-scale, long-term storage and back-up for the intermittency and seasonal swings in the production of electricity from renewables.
    - **California** passed A.B. 2514 in 2010 which 'required' the California Public Utilities Commission (CPUC) to open a proceeding to determine appropriate targets, if any, for each load-serving entity to procure energy storage. After opening a proceeding in December 2010 to consider the matter, the CPUC adopted an energy storage procurement framework and established a statewide energy storage target of 1,325 MW by 2020, with Southern California Edison, PG&E, and San Diego Gas & Electric each responsible for a portion of the total
- Develop an energy storage cost-benefit study like have been done in Massachusetts, New York, and Nevada.
    - To provide the state with the Greatest value, incentive amounts should reflect market maturity. Therefore, depending on the amount of funds available, an incentive may be reduced over time or market penetration levels, to reflect declines in soft costs (for example, interconnection and permitting) that come with increased experience deploying systems in that state.
    - With Oklahoma owning a utility, *GRDA could be the trend setter.*

Alternative Fueling Infrastructure Tax Credit

- The current language in Oklahoma statutes excluded the Hydrogen language. The $22 mil cap is highly competitive between the EV and CNG industries. Sounds like the best bet is 3 different programs for each (EV, CNG, H2). With the cap raised and evenly distributed.
    - I.E., raising the cap to $33 million and evenly distributing amongst the EV, CNG and Hydrogen infrastructure segments.

Advanced Transportation Tax Exclusion (California language)

The California Alternative Energy and Advanced Transportation Financing Authority (CAEATFA) provides a sale and use tax exclusion for qualified manufacturers of advanced transportation products, components, or systems that reduce pollution and energy use and promote economic development. Incentives are available until December 31, 2025. For more information, including application materials, see the CAEATFA [Sales and Use Tax Exclusion Program] (http://www.treasurer.ca.gov/caeatfa/ste/index.asp) website. (Reference [California Public Resources Code] (http://www.oal.ca.gov/) 26000-26017)

Utah Natural Gas and Hydrogen Tax:

Compressed natural gas (CNG) and hydrogen are taxed at a rate of \$0.171 per gasoline gallon equivalent (GGE). Liquefied natural gas (LNG) is taxed at a rate of \$0.171 per diesel gallon equivalent (DGE). One GGE is equal to 5.660 pounds (lbs.) of CNG or 2.198 lbs. of hydrogen. One DGE is equal to 6.06 lbs. of LNG. The tax rate for natural gas and hydrogen will be annually adjusted by the State Tax Commission (Commission) not to exceed \$0.225 per GGE or DGE. The Commission will publish the adjusted fuel tax no later than 60 days prior to the effective date. For more information, see the Utah State Tax Commission [Fuel Taxes] (https://tax.utah.gov/fuel) website. (Reference [Utah Code] (http://le.utah.gov/xcode/code.html) 59-13-102 and 59-13-301)

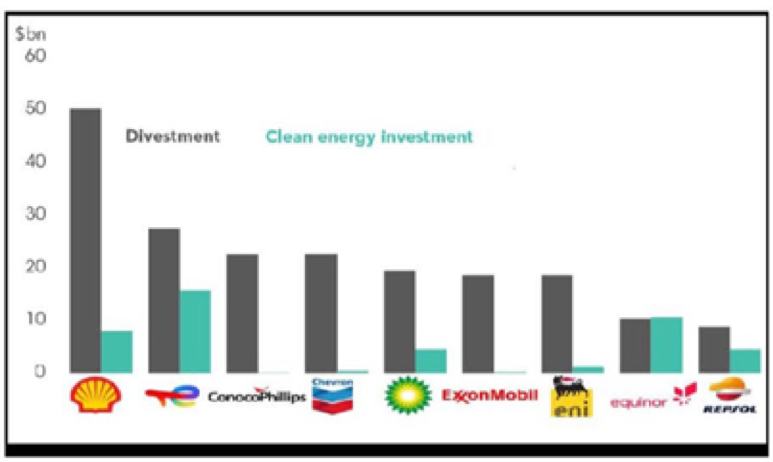
Alternative Fuel Vehicle Registration Fees-Utah:

Beginning in 2021, all-electric vehicle (EV), plug-in hybrid electric vehicle (PHEV), and hybrid electric vehicle (HEV) owners are required to pay an additional registration fee as follows:

	Registration Fee
EV	\$120
PHEV	\$52
HEV	\$20

Owners of a vehicles powered by a fuel other than motor fuel, diesel fuel, electricity, natural gas, or propane are required to pay an additional \$120 registration fee. A six-month registration option with fees at prorated amounts is also available.
(Reference [Utah Code] (https://le.utah.gov/xcode/code.html) 41-1a-1206)

Recently Announced Projects:



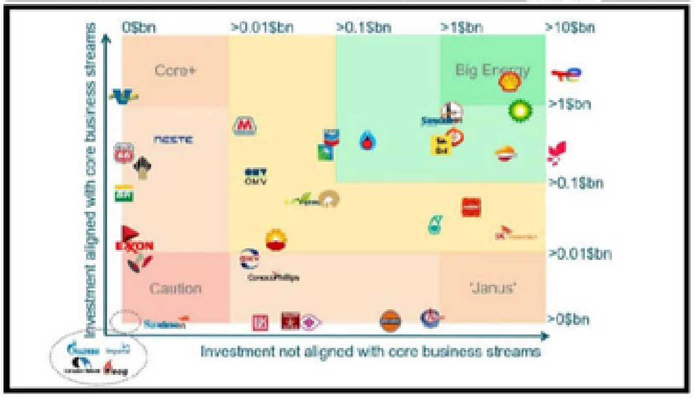
- In May 2019, Mitsubishi Hitachi Power Systems and Magnum Development announced an initiative to launch their Advanced Clean Energy Storage project in central Utah. The initiative will develop 1,000 megawatts of 100% clean energy storage, including storage of green hydrogen. The project will utilize new gas turbine technology that enables a mixture of hydrogen and natural gas to produce power with lower carbon emissions. The project aims to use 100% green hydrogen as a fuel source with the result that the turbines produce electricity with zero carbon emissions.

- A green hydrogen project was launched in California in May 2020 by the global energy company SGH2. The facility in Lancaster, California will be able to produce up to 11,000 kilograms of green hydrogen per day using a proprietary biogenic waste gasification technology, pursuant to which it gasifies plastic, paper, and other waste to produce hydrogen it describes as "greener than green" because it uses no externally sourced energy and avoids more carbon dioxide emissions than green hydrogen from renewables.
- A $10.8 million project to integrate hydrogen storage, fuel cells and fuel cell refueling property began in September 2020 through a partnership between Frontier Energy, the University of Texas, and the Department of Energy, known as H2@ Scale. The UT-Austin campus will host a project integrating commercial hydrogen production, distribution, storage, and use. The hydrogen power will power a stationary fuel cell and supply a hydrogen station with fuel for a fleet of hydrogen fuel cell vehicles.

Early Hydrogen Players:

- Oklahoma has several early entrants to the hydrogen game.
    - Matrix, Chart Industries, Gastec, Williams, ONEGAS, ONEOK
    - Oklahoma has the demand for hydrogen (fert plants, 5 refineries, several glass plants, metal foundry

Name	Ticker	Market Cap (USD)	Sector	Country	Analyst
Linde PLC	LIN US	146,195	Materials	Britain	Jason Miner
Iberdrola SA	IBE SM	82,842	Utilities	Spain	Elchin Mammadov
Air Liquide SA	AI FP	77,534	Materials	France	Jason Miner
Orsted AS	ORSTED DC	68,037	Utilities	Denmark	Elchin Mammadov
Air Products and Chemicals Inc	APD US	62,254	Materials	United States	Jason Miner
LG Chem Ltd	051910 KS	50,396	Materials	South Korea	Horace Chan
Engie SA	ENGI FP	34,638	Utilities	France	Elchin Mammadov
RWE AG	RWE GR	26,419	Utilities	Germany	Elchin Mammadov
POSCO	005490 KS	24,743	Materials	South Korea	Yi Zhu
Weichai Power Co Ltd	2338 HK	22,388	Industrials	China	Michelle Leung
Repsol SA	REP SM	19,454	Energy	Spain	Salih Yilmaz
Snam SpA	SRG IM	18,671	Utilities	Italy	Elchin Mammadov
Alstom SA	ALO FP	18,545	Industrials	France	Mustafa Okur
Plug Power Inc	PLUG US	18,010	Energy	United States	Christopher Perella
Mitsubishi Heavy Industries Lt	7011 JP	10,520	Industrials	Japan	Takeshi Kitaura
Ballard Power Systems Inc	BLDP CN	7,242	Energy	Can[illegible]	[illegible]topher Perella



Commercial Vehicles

Development of hydrogen fuel cells for passenger vehicles is 10 years behind battery-only models.

- But commercial and other uses-where EVs' lengthy downtime to recharge is a margin disadvantage—may serve as the proving ground that accelerates costs cuts and advance the technology to make it viable for automakers.
- With the mature infrastructure in Oklahoma, the demand for and infrastructure of hydrogen lessens the carrot and the stick scenario. (5 petro refineries, several fertilizer plants)
- Lithium-ion battery pack prices plunged below $200 in 2020 from $1,200 in 2010.
    - Applying a similar rate of decline to fuel cell costs could accelerate hydrogen initiatives.

Oklahoma Department of Commerce Total Economic Impacts Associated with the National Renewable Energy Laboratory report "The Technical and Economic Potential of the H2@Scale Concept within the United States" dated October 2020

Direct Economic Impact of Hydrogen Production in Oklahoma

MMT of Hydrogen Production in the Contiguous US	Percent Capture	Oklahoma Hydrogen Production MMT	Estimated CAPEX	Estimated OPEX with $.035/k
22	3%	0.66	$1,071,840,000	$1,393,392,000
22	5%	1.1	$1,786,400,000	$2,322,320,000
22	10%	2.2	$3,572,800,000	$4,644,640,000
22	20%	4.4	$7,145,600,000	$9,289,280,000
22	25%	5.5	$8,932,000,000	$11,611,600,000
41	3%	1.23	$1,997,520,000	$2,596,776,000
41	5%	2.05	$3,329,200,000	$4,327,960,000
41	10%	4.1	$6,658,400,000	$8,655,920,000
41	20%	8.2	$13,316,800,000	$17,311,840,000
41	25%	10.25	$16,646,000,000	$21,639,800,000

CAPEX Distribution based on similar industry composition

MMT of Production Contiguous US	Percent Capture	Oklahoma Hydrogen Production MMT	Real Property (requiring construction)	Machinery & Equipment	Engineering, Installation & Contract Work
22	3%	0.66	$171,494,400	$675,259,200	$192,931,200
22	5%	1.1	$285,824,000	$1,125,432,000	$321,552,000
22	10%	2.2	$571,648,000	$2,250,864,000	$643,104,000
22	20%	4.4	$1,143,296,000	$4,501,728,000	$1,286,208,000
22	25%	5.5	$1,429,120,000	$5,627,160,000	$1,607,760,000
41	3%	1.23	$319,603,200	$1,258,437,600	$359,553,600
41	5%	2.05	$532,672,000	$2,097,396,000	$599,256,000
41	10%	4.1	$1,065,344,000	$4,194,792,000	$1,198,512,000
41	20%	8.2	$2,130,688,000	$8,389,584,000	$2,397,024,000
41	25%	10.25	$2,663,360,000	$10,486,980,000	$2,996,280,000

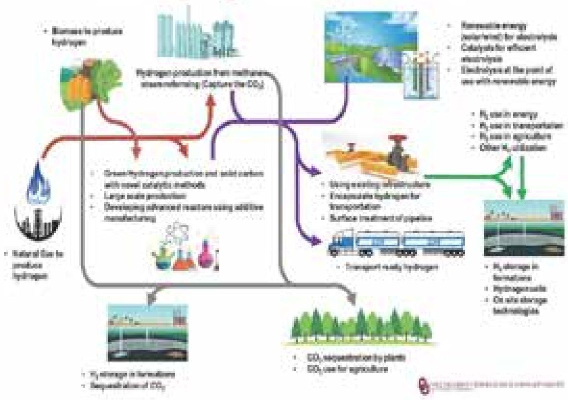
OPEX Distribution based on similar industry composition

MMT of Production Contiguous US	Percent Capture	Oklahoma Hydrogen Production MMT	electricity	Water	Labor & Maintenance
22	3%	0.66	$1,125,432,000	$130,152,000	$137,808,000
22	5%	1.1	$1,875,720,000	$216,920,000	$229,680,000
22	10%	2.2	$3,751,440,000	$433,840,000	$459,360,000
22	20%	4.4	$7,502,880,000	$867,680,000	$918,720,000
22	25%	5.5	$9,378,600,000	$1,084,600,000	$1,148,400,000
41	3%	1.23	$2,097,396,000	$242,556,000	$256,824,000
41	5%	2.05	$3,495,660,000	$404,260,000	$428,040,000
41	10%	4.1	$6,991,320,000	$808,520,000	$856,080,000
41	20%	8.2	$13,982,640,000	$1,617,040,000	$1,712,160,000
41	25%	10.25	$17,478,300,000	$2,021,300,000	$2,140,200,000

[i] ODOT Waterways/Multimodal Division, "MKARNS marks 50th anniversary" (2021) https://oklahoma.gov/odot/programs-and-projects/waterways/mkarns-50th-anniversary.html

[ii] Oklahoma Department of Public Safety, "Administrative Rules Subchapter 3 - Size and Weight Permit Load" (2021) https://oklahoma.gov/dps/administrative-rules0/size-and-weight-permits/size-and-weight-permit-load.html

Possible Hydrogen Pathways for Oklahoma



Faculty Member Name	e-mail address	Department/School	Specific area(s) of research capabilities (list all relevant areas)	Notes, including specialized tools or facilities
Timothy Filley (Hydrogen Initiative lead for The University of Oklahoma)	Filley@ou.edu	The Institute for Resilient Environmental and Energy Systems (IREES)	Filley is the Director of the OVPRP Institute for Resilient Environmental and Energy Systems. The Institute for Resilient Environmental and Energy Systems (IREES) addresses sustainability grand challenges for Oklahoma, the nation and the world. Our goal is to develop equitable solutions that help drive the transformation of the U.S. energy sector toward a net-zero carbon economy, that provide access to clean water, air, and safe built environments and do so without degrading our planetary ecosystems and climate. With this focus on challenges at the intersection of society, the environment, and energy systems, IREES works to create inclusive, collaborative and convergent research ecosystems that leverage the strengths of OU's research faculty and our public and private sector partners. Our efforts will build on and expand research programs across three key areas: Observing and predicting Earth systems; Transforming energy and infrastructure systems; Co-generating community resilience and environmental justice.	
Research Centers/Clusters/Programs at The University of Oklahoma (not exhaustive)				
		Well Construction Technology Center (WCTC)	The Well Construction Technology Center is an advanced technology research center that incorporates high pressure, high temperature fluid flow applications using both field scale and lab scale equipment for the oil industry.	
		Integrated Core Characterization Center (IC3)	The Integrated Core Characterization Center consists of the complete Amoco Rock Physics Laboratory. This lab has unparalleled industrial, commercial, and academic capabilities and offers the widest range of measurement and research opportunities in the industry. Originally established a seismic velocity measurement laboratory, it evolved into an integrated facility that provides a vast array of petrophysical, seismic, and rock mechanics capabilities.	
		Institute for Applied Surfactant Research (IASR)	The Institute for Applied Surfactant Research is a multidiscipline research facility that is composed of undergraduate students, graduate students, postdoctoral students, and researchers who conduct phase equilibrium, sand pack, and core flood studies for both environmental and crude oil recovery applications.	

		Carbon-Free H2 Production and Storage (CHEPS)	finding green and affordable ways to produce energy. The energy needs worldwide increase on a yearly basis, but current production of energy leads to greenhouse gas emissions. That is why the production of energy without harming the environment is a grant challenge for our future. In the United States, and in Oklahoma in particular, we have a lot of natural gas that can be utilized to produce hydrogen, which does not produce CO2 when it burns. However, we need to develop technologies that can take methane molecules and dissociate the hydrogen from the carbon without carbon dioxide production. We want to produce hydrogen without producing CO2 and then to develop safe and economically feasible technologies for storage and transportation of hydrogen	
		Oklahoma Water Survey	The Oklahoma Water Survey is committed to providing leadership to facilitate research that includes both academic and non-academic stakeholders throughout the Oklahoma water community to develop innovative, interdisciplinary solutions for Oklahoma's water challenges. Water-reuse strategies emphasized.	
		Mewbourne School of Petroleum and Geological Engineering	OU's Mewbourne School of Petroleum and Geological Engineering is world-renowned for its research expertise, and facilities in the areas of subsurface hydrogen storage, geothermal energy, carbon-sequestration, and fossil fuels. With new research and educational initiatives, the department is helping transform Oklahoma's energy future.	
		Samuel Roberts Noble Microscopy Laboratory (VPRP)	Imaging and analysis of materials (all types) from the atomic, nano, to the microscale. Shared-use human and equipment/physical infrastructure for nanoscale imaging and analysis. 3 Ph.D. staff researchers. Transmission electron microscopy (3) including X-ray analysis, diffraction, STEM-EDXA, etc; Scanning electron microscopy (4) including EDXA, EBSD, environmental, high-resolution, etc.; laser scanning confocal with multiphoton/FLIM/FRET, 3D image analysis; many sample preparation tools. Directed by Prof. Andrew Elwood Madden.	
		OU Water Research Center	OU has depth of expertise to study the water cycle, which will be a key element in hydrogen production, including research on produced water, ground water contamination, water modeling (drought and flood)	
AI, Machine Learning, Data Visualization and Harmonization, Signal Processing, Infrastructure Security				
David Ebert	ebert@ou.edu	Electrical & Computer Engineering, CS, DISC	Predictive analytics, visual analytics, human guided AI, trustable AI	Dr. Ebert is the director of the Data Science Institute for Societal Challenges (DISC) (https://ou.edu/disc). DISC is an interdisciplinary center that helps coordinate and foster research in data science, machine learning, and artificial intelligence, and data-enabled science across disciplines at the University of Oklahoma. DISC convenes affiliated researchers through workshops and seminars to find convergent data-driven approaches to new and unexpected research opportunities. The center is a hub that brings together experts in various research disciplines to solve societal challenges through seminars and workshops.
Justin Metcalf	jmetcalf@ou.edu	Electrical and Computer Engineering	Signal processing and machine learning	Advanced Radar Research Center (ARRC)
Amy McGovern	amcgovern@ou.edu	School of Computer Science in the Gallogly College of Engineering and in the School of Meteorology in the College of Atmospheric and Geographic Sciences	Machine learning/data mining/data science for the physical sciences; Real-world applications with a special interest in high-impact weather. STEM education.	Under the direction of lead PI Amy McGovern, the University of Oklahoma is leading a National Science Foundation AI Institute for Research on Trustworthy Artificial Intelligence "AI" in Weather, Climate, and Coastal Oceanography that is being hailed as a "historic milestone in environmental science."
Dean Hougen	hougen@ou.edu	Computer Science	artificial intelligence, including machine learning, robotics/intelligent control, and multi-agent systems; includes supervised, unsupervised, and reinforcement learning; interpretable and informative machine learning; and evolutionary computation	
Chao Lan	clan@ou.edu	Computer Science	AI/ML, anomaly detection	
Le Gruenwald	ggruenwald@ou.edu	Computer Science	machine learning, sensor and stream data mining, spatial and temporal data management, intelligent management of infrastructure, security, anomaly detection	
Ji Hwan Park	jpark@ou.edu	Computer Science	visualization, visual analytics, machine learning/deep learning, human-computer interaction, AR/VR	large-scale surrogate modeling and data analysis
Heather Bedle	Bedle, Heather <hbedle@ou.edu>	School of Geosciences	Seismic interpretation, processing, attribute analysis, machine learning, AI	computational facilities for ML, data analytics
Energy-Related Systems Engineering (Materials, Hydrogen generation, Electrolyzers, Sensing, Transportation, Renewables, Usage, CCUS)				
Dimitrios Papavassiliou	dpapav@ou.edu	Chemical, Biological and Materials Engineering	Flow and transport phenomena, interfaces, simulations, hydrogen production, porous media	Supercomputing at OU and at NSF dedicated resources (XSEDE), molecular computations, macroscopic simulations
Pejman Kazempoor	pkazempoor@ou.edu	Aerospace and Mechanical Engineering	Fuel cells, Electrolyzes, Electrochemical reactors, Hydrogen storage and transportation Process modeling and simulation, Techno-economic analysis, Life-cycle assessment, CO2 capture, Emissions reduction, Water-energy nexus, Energy storage	Leading the expansion of the hydrogen demonstration site at OU to include industrial size equipment and devices
Steven Crossley	stevencrossley@ou.edu	Chemical, Biological and Materials Engineering	Catalysis, hydrogen production, CO2 capture, hydrogen transportation, solid carbon production, upcycling of polymers	autoclave, fluidized bed and flow reactors, pyrolysis, materials characterization equipment

Iman Ghamarian	imang@ou.edu	Aerospace and Mechanical Engineering	Microstructure-property relationships, materials characterization, tribology testing, hydrogen embrittlement and fracture analysis, hydrogen-induced stress corrosion cracking analysis, additive manufacturing of metals, and machine learning	Scanning and transmission electron microscopes available at SRNML, soon to outfit with multifunctional tribometer and fatigue machine
Mrinal Saha	msaha@ou.edu	Aerospace and Mechanical Engineering	Composite manufacturing and testing, energy harvesting and storage, flexible sensor design and manufacturing, additive manufacturing	Compression molding, 3D printers, materials testing machine, Electrospinning, High temperature furnace (box and tube), ultrasonic liquid processing, atomizer, centrifuge
Ramkumar Parthasarathy	rparthasarathy@ou.edu	Aerospace and Mechanical Engineering	Spray and gas diffusion flames, emissions, turbulent multiphase flows	Chambers to study flames at atmospheric pressure, temperature and emissions measurement
Zahed Siddique	zsiddique@ou.edu	Aerospace and Mechanical Engineering	Design and development of experimental setup to test leak and emission across barriers (o-rings, seals, etc.) for oil and gas applications; high pressure and high temperature characterization of materials; rotating and reciprocating equipment for testing	High-pressure, high temperature, high rotational speed, and high torque testing equipments to test and collect leak and emission data
Hamidreza Shabgard	shabgard@ou.edu	Aerospace and Mechanical Engineering	Multiphase heat transfer, freeze and thermal desalination, thermal energy storage, heat pipes	Freeze desalination system, computational study of multiphase heat transfer
Hjalti Sigmarsson	h.sigmarsson@ou.edu	Electrical & Computer Engineering	Multi-material additive manufacturing, electromagnetic characterization of materials, custom filament mixing and extrusion	nScrypt 3Dn-300 direct digital manufacturing platform, network analysis capabilities up to 330 GHz, multiple FDM and SLA printing platforms
John Klier	klier@ou.edu	Dean of the OU Gallogly College of Engineering	Novel materials for high performance coatings and adhesives	
Li Song	lsong@ou.edu	Aerospace and Mechanical Engineering	Energy distribution and HVAC system efficiency, smart sensing, learning based control and diagnostic	IoT technology test bed in smart building setting
Binbin Weng	binbinweng@ou.edu	Electrical and Computer Engineering	Nanomaterial growth, nanophotonic engineering, and chemical sensing technology development (infrared, Raman and chemiresistive methods)	Oversees the operation of University's MREC Cleanroom facility, lead a transdisciplinary team at OU for a new methane emission monitoring solution development.
Yingtao Liu	yingtao@ou.edu	Aerospace and Mechanical Engineering	additive manufacturing, functional polymers, composites, and nanocomposites, non-destructive evaluation, experimental mechanics	metal, polymer, and composite additive manufacturing systems available. Multi-scale mechanical testing platforms. Methods and approaches to manufacture porous polymers, composites, and nanocomposites potentially for gas cleaning, filtering, storage, and host materials for catalysts.
Ngoc Bui	ngocbui21@ou.edu	Chemical, Biological and Materials Engineering & Civil Engineering	Water-Energy nexus, separation science, membrane science, interfaces, nanomaterials, resource recovery	membrane synthesis, Schlenk line, centrifuge, membrane-based separation systems, potentiostats
Michele Galizia	mgalizia@ou.edu	Chemical, Biological and Materials Engineering	membranes, separation of reaction products	membrane synthesis and characterization lab
Jeffrey Harwell	jharwell@ou.edu	Chemical, Biological and Materials Engineering	Colloid science, dispersion stability, emulsions, fluid-solid interactions, carbon capture & sequestration, reservoir chemical treatment	high pressure, high temperature core flood apparatus; rheometers; materials characterization equipment
Lance Lobban	llobban@ou.edu	Chemical, Biological and Materials Engineering	Reaction engineering, high temperature reactions, reaction mechanisms and catalysis, biomass to fuels	bench scale reactors, materials characterization equipent.
Rouzbeh Moghanloo	rouzbehgm@ou.edu	Petroleum and Geological Engineering	CCUS, TEA	MPGE lab facility, industry partners, access to expertise in the DOE Carbon Utilization and Storage Partnership (CUSP) community
Sepideh Razavi	srazavi@ou.edu	Chemical, Biological and Materials Engineering	Surfaces and interfaces, colloids, nanoparticles, surfactants, assembly and self-assembly	interface and colloid science lab, Langmuir trough, tensiometer, rheometer and interfacial rheology accessory, microscopy, dynamic light scattering
Daniel Resasco	dresasco@gmail.com	Chemical, Biological and Materials Engineering	Catalysis, hydrogen production, CO2 capture, hydrogen transportation, solid carbon production	autoclave reactors, pyrolysis, materials characterization equipent, IP for COMOCAT process , microscopy
Alberto Striolo	astriolo@ou.edu	Chemical, Biological and Materials Engineering	Hydrogen transportation, materials, hydrogen production, molecular interactions, separations, structure-transport relations, surfactants, colloids, interfacial systems - also interested in social and ethical aspects (e.g., social license to operate)	Supercomputing at national labs and OU, molecular computations and mesoscopic simulations
Bin Wang	wang_cbme@ou.edu	Chemical, Biological and Materials Engineering	Molecular and ab-initio computations, catalyst design, catalysis, hydrogen production	computing at OU and at national labs, ab-initio computing, molecular dynamics
Wislon Merchan-Merchan	wmerchan-merchan@ou.edu	Aerospace & Mechanical Engineering	Combustion of blended fuel (hydrogen-methane), hydrogen-oxygen enriched air combustion, study particle and gas emissions.	A microturbine, an adequate space to conduct hydrogen combustion experiments, GC and gas analyzers and electron Microscopy. Pertinent equipment for hydrogen-methane and oxygen-nitrogen blending (i.e. fuel mixing chambers, oxygen-air mixing chambers, flowmeters, etc.).

Earth Systems Energy-Related Research (Characterization, Management, Monitoring, Modelling, Storage, CCUS)				
Jason Vogel	jasonvogel@ou.edu	School of Civil Engineering and Environmental Science; Director, Oklahoma water Survey	Produced water reuse	The Oklahoma Water Survey is committed to providing leadership to facilitate research that includes both academic and non-academic stakeholders throughout the Oklahoma water community to develop innovative, interdisciplinary solutions for Oklahoma's water challenges.
Deepak Devegowda	deepak.devegowda@ou.edu	Petroleum and Geological Engineering	Carbon gas-sequestration, hydrogen gas-storage, reactive and non-reactive molecular modeling, machine learning, subsurface flow, flow in porous media including cements/soils.	Computational tools and software for optimization, modeling fluid flow at nano- to km-scale, and machine learning applications (http://asgc.ou.edu)
Chandra Rai	crai@ou.edu	Petroleum and Geological Engineering	Hydrogen gas-storage, carbon gas-sequestration, wellbore integrity, experimental rock physics and petrophysics, hydraulic fracturing, seismic monitoring.	6600 sq. ft experimental facility (Integrated Core Characterization Center, IC3) capable of high pressure, high temperature customized core- and well-scale.
John Pigott	jpigott@ou.edu	School of Geosciences	Carbonate Geology & Geophysics, Basin Analysis, Seismic Stratigraphy, Carbon Cycles; CCUS;	

Andrew Elwood Madden	amadden@ou.edu	Geosciences	nanogeoscience, nanoscale science and technology, geochemistry, materials science, chemistry of interfaces, environmental microbiology	petrographic microscopy, quantitative mineral chemistry via electron microprobe anaerobic chamber for performing redox chemistry, expertise working with redox chemistry and anaerobic processes / electron transfer reactions, powder X-ray diffraction and quantitative analysis of crystalline materials, thermodynamic modeling of mineral-water interactions, including precipitation and dissolution of carbonates, redox processes, characterization of redox reactions between solutions and materials, data analytics and statistical evaluation of chemical data tied to spatial analysis/ GIS with groundwater wells, etc. Raman microspectroscopy, pressure vessels for mineral-water interaction experiments, incubator systems for temperature-controlled microbial and/or mineral water interaction experiments
Matt Pranter	matthew.pranter@ou.edu	School of Geosciences	Subsurface reservoir characterization: geologic storage site characteristics including lithology of host and sealing formations, pore pressures, porosity, permeability, and other petrophysical properties 3-D reservoir modeling integrating machine learning and geostatistical methods Quantitative seismic interpretation for geological, petrophysical, and geomechanical properties of subsurface formations	Reservoir Characterization and Modeling Laboratory – high-end workstations for subsurface data analysis and interpretation and 3-D static/dynamic reservoir modeling of subsurface formations; Bruker Tracer III-SD Handheld X-ray Fluorescence Analyzer for major/minor/trace elements of rock samples
Xiaowei Chen	xiaowei.chen@ou.edu	School of Geosciences	Subsurface stress and fault/fracture distributions, and near-surface characterizations. Induced seismicity (e.g., related to subsurface fluid injection), and the related fluid pathways.	Field seismic equipment
Megan Elwood Madden	melwood@ou.edu	School of Geosciences	Low-temperature geochemistry; water-rock reactions, etc.	Hydrates lab (Low T, high P) for synthesis and study hydrogen clathrate. Pressure reactors, P-T monitors, etc
Berrien Moore	berrien@ou.edu	Dean, College of Atmospheric and Geographic Sciences , Director National Weather Center	Lead PI geostationary Carbon Cycle Observatory (GeoCarb), National weather center - https://www.ou.edu/nwc	Accurate prediction fo weather and climate are essential for sustainable renewable enery and early warning of severe weather impacts to the energy infrastructure. The National weather center works to improve our understanding of Earth's atmosphere, provide accurate and timely forecasts on severe weather, and to educate and train future meteorologists.
Greg McFarquhar	mcfarq@ou.edu	School of Meteorology	Cooperative Institute for Severe and High-Impact Weather Research and Operations (CISHWRO)	CISHWRO leverages OUs leadership in monitoring and modeling meteorological phenomena, weather radar, and regional climate to help produce better forecasts and warnings that save lives and properties. https://cimms.ou.edu/index.php/2021/06/15/ou-earns-lead-for-up-to-208-million-noaa-severe-weather-research-institute/
Timothy Filley	Filley@ou.edu	Department of Geography amind Environmental Sustainability; School of Geosciences	Organic geochemistry, deep soil gas monitoring - chemical composition and stable isotopes. Tools to explore below-ground leakage of CO2 and soil impacts at geologic storage sites. Filley directs the Organic Geochemistry and Stable Isotope and Mass Spectrometry facility at OU, which opens in Spring 2022.	Filley is the Director of the OVPRP Institute for Resilient Environmental and Energy Systems.
Caitlin Hodges	chodges@ou.edu	School of Geosciences	Deep soil gas dynamics/ monitoring. Tools to explore below-ground leakage of CO2 and soil impacts at geologic storage sites.	
Economics, Finance, Societal Interactions, Policy				
Monika Ehrman	mehrman@ou.edu	Professor of Law Faculty Director, Oil & Gas, Natural Resources, and Energy Center; Adjunct Associate Professor of Energy Management, OU Price College of Business	Oil & gas real property issues, Domestic and international energy policy & geopolitics, Natural resource property issues	OU Law is a national and international leader in oil and gas, natural resources, and energy law. Our expansive offerings are synthesized within our ONE Center, covering our academic degrees and certificates – J.D. certificates and an LL.M. in energy and natural resources, and an online M.L.S. in oil, gas, and energy law – and programming. OU Law hosts the annual Eugene Kuntz Conference on Natural Resources Law and Policy, the largest conference of its kind in the country, and is home to the Oil and Gas, Natural Resources, and Energy Journal (ONE J), the first journal of its kind.
Firat Demir	fdemir@ou.edu	Department of Economics	Development economics, Sustainable development, Structural change, macroeconomics, labor	
Jonathan McFadden	jmcfadden@ou.edu	Department of Economics	Environmental economics, agricultural economics, resource development	
Katerina Tsetsura	tsetsura@ou.edu	Journalism and Mass Communication	Assessment of community needs and perceptions; community and legislative communication and support; risk and crisis communication management; issues management; strategic communication, public relations, public affairs, and public support	robust multimedia production and distribution capabilities; mixed methods social scientific research to assess community perceptions and needs (surveys, focus groups, interviews); web and internet presence; https://www.ouheps.org
Shane Connelly	sconnelly@ou.edu	Department of Psychology	Dr. Connelly is the Director of the OVPRP "Institute for Society and Community Transformation" (ISCT). One relevant area of focus in the ISCT is understanding the intersection of technology and society. New technologies influence the world of work, communities, and society in profound ways, offering opportunities that can transform lives, but also introducing new threats, some of which undermine human health and well-being. A second area of focus within ISCT is advancing equity and opportunity by engaging in research and community partnerships to understand and address drivers of education, health, and workplace disparities.	
Zev Trachtenberg	ztrachtenberg@ou.edu	Department of Philosophy	Anthropogenic environmental transformation, social science, political ideas and transformation of environment	Blog on inhabiting the anthroposphere https://inhabitingtheanthropocene.com/
Dingjing Shi	dshi@ou.edu	Department of Psychology	Quantitative psychology, networks, public perception of technological changes	surveys, quantitative analysis tools for network analysis, statistics for decision making
Adam Feltz	afeltz@ou.edu	Department of Psychology	ethical decision making, communication of technical information to non-technical experts, moral judgement, public acceptance of hydrogen	Group and individual testing stations; eye-tracking; facial recognition and user experience equipment; ability to collect user experience and human factors in field studies
Dingjing Shi	dshi@ou.edu	Department of Psychology	quantitative psychology, networks, public perception of technological changes	surveys, quantitative analysis tools for network analysis, statistics for decision making

Farrokh Mistree	farrokh.mistree@ou.edu	Aerospace and Mechanical Engineering	Policies for disruptive innovation; realization and monitoring of complex cyber-physical-social (CPS) systems.	Four research monographs that are foundational to the realization and management of evolving cyber-physical-social systems: fail-safe supply networks, dynamic management of engineered systems, co-design of discrete multifunctional systems, cloud-based decision support. Plus software.
Gregory Burge	gburge@ou.edu	Department of Economics	Land use regulation	
Kevin Kuruc	kkuruc@ou.edu	Department of Economics	Agricultural economics, environmental economics	
Hunter Heyck	hheyck@ou.edu	History of Science and Medicine	19th- and 20th-century science; science and social thought; history of technology; information technology and society; technology and the environment	
Devin Carlson	decarlson@ou.edu	Department of Political Science	Operations of public policies and their effects on political, social, and economic outcomes of interest	
Sam Workman	samuel.workman.org	Department of Political Science	Regulatory Politics & Policy, Bureaucracy, American Politics, Public Policy, Agenda Setting, Research Methods	
Adam Feltz	afeltz@ou.edu	Department of Psychology	Theoretical and applied science for ethical and informed decision making.	
Joseph Suflita (Emeritis SLC)	jsuflita@ou.edu	Microbiology and Plant Biology	Anaerobic Microbiology, Biocorrosion, Biodegradation, Bioremediation, Microbial Ecology, Environmental Microbiology - Alternative fuels and biocorrosion MURI	
Emma Colven	emmacolven@ou.edu	International Area Studies	Geographer and political ecologist, socio-ecological change, environmental expertise, and environmental politics, social and environmental justice	
Teresa Shaft	tshaft@ou.edu	Management information systems	role of IS in environmental management	
Edward Cokely	cokely@ou.edu	Department of Psychology	Risk Literacy and Science for Informed Decision Making, Decision Vulnerability and Human Factors Engineering, Risk Communication, Data Visualization, and Adaptive Decision Support, Expert Performance, Skill Acquisition, and Training Technologies, Decision Analytics, Data Science, and User Experience (UX)	
Janet K. Allen	janet.allen@ou.edu	Industrial and Systems Engineering	Evolving cyber-physical-social-systems (CPS); managing uncertainty; predictive analytics.	Four research monographs that are foundational to the realization and management of cyber-physical-social systems: fail-safe supply networks, dynamic management of engineered systems, co-design of discrete multifunctional systems, cloud-based decision support. Plus software.
Linn Scott	slinn@ou.edu	Price College of Business (Finance)	Energy markets and energy prices; valuation and financing of energy ventures; real options; investment in infrastructure for the hydrogen economy.	Econometric/statistical expertise; simulation; macro as well as micro economic modeling.
Dipankar Ghosh	dghosh@ou.edu	Price College of Business (Accounting)	primary research interests are in managerial and energy accounting, specifically, accounting information for judgment and decision making, management control systems, performance measures, negotiation, and transfer pricing.	
C. Silva	clsilva@ou.edu	Department of Political Science; Director IPPRA: Institute for Public Policy Research and Analysis	New technology adoption; facility siting; socially informed engineering design; risk; risk perception; social valuation; market valuation; regulatory analysis; policy analysis; policy design; benefit cost analysis; public and stakeholder survey research; focus groups; social media analysis.	long running panel surveys in oklahoma; social media scraping capabilities; text analysis lab; social valuation measurement/calculation capabilities; panel of Oklahoma stakeholders in energy, water, and infrastructure; focus group/stakeholder facilitation; long-term expertise in energy and environmental policy
H. Jenkins-Smith	hjsmith@ou.edu	Department of Political Science; Director IPPRA: Institute for Public Policy Research and Analysis	New technology adoption; facility siting; socially informed engineering design; risk; risk perception; social valuation; market valuation; regulatory analysis; policy analysis; policy design; benefit cost analysis; public and stakeholder survey research; focus groups; social media analysis.	long running panel surveys in oklahoma; social media scraping capabilities; text analysis lab; social valuation measurement/calculation capabilities; panel of Oklahoma stakeholders in energy, water, and infrastructure; focus group/stakeholder facilitation; long-term expertise in energy and environmental policy
Jill Edy	jedy@ou.edu	Department of Communication	Political communication, public opinion, media and politics.	Methods for assessing the effects of communication. How communication shapes the political agenda.
Cynthia L. Rogers	crogers@ou.edu	Department of Economics	Behavioral economics. local economic development, state and local tax policy, sociohydrology.	Analysis of conservation pricing and consumer responses to social messaging.

Oklahoma Geological Survey				
Nicholas Hayman	hayman@ou.edu	Oklahoma Geological Survey	Geology, geophysics	Director of Oklahoma Geological Survey, Physical Experiments inc. w/borehole polymers, geological modeling and characterization inc. subsurface storage
Molly Yunker	yunker@ou.edu	Oklahoma Geological Survey	Education & Outreach for Earth Sciences	Resource room for public open house, K-12 Program, OGS workshop and publications
Jacob Walter	jwalter@ou.edu	Oklahoma Geological Survey	Geophysics (Seismology)	State Seismologist, Regional seismic network, geostorage hazards, lead on state coordinating council (OCC-OGS)
Richard Tarver	rtarver@ou.edu	Oklahoma Geological Survey	Oklahoma PEtroleum Information Center (OPIC)	State repository for well-logging data, Core repository
Leah Jackson	Leah.Jackson@ou.edu	Oklahoma Geological Survey	hydrogeology	hydrogeology including of geostorage, maintains field instrumentation (sondes), lab essentials
Ming Suriamin	huangziemming-1@ou.edu	Oklahoma Geological Survey	Petroleum GEology	Regional stratigraphy and reservoir characterization, geochemistry, resource geography (pipelines, well distribution), borehole geophysics
Carla Eichler	carla.eichler@ou.edu	Oklahoma Geological Survey	STATEMAP, geology	field geology, sedimentology, USGS STATEMAP program, geology laboratory
Lindsey Hunt	lahunt@ou.edu	Oklahoma Geological Survey	Mineral chemistry, petrology	Electron Microprobe Facility
Netra Regmi	netraregmi@ou.edu	Oklahoma Geological Survey	Remote Sensing, Surface Processes, Geomorphology	Remote Sensing Laboratory, NASA, FEMA, LIDAR

Ron Van Den Bussche
Senior Associate Vice President for Research
ron.van_den_bussche@okstate.edu

Ron will serve as the initial primary point of contact for Oklahoma State University with regards to this initiative

Hydrogen and CCUS

Faculty Member	Email	Department/School	Specific area(s) of research capabilities	Notes, including specialized tools or facilities
Camelia Knapp	camelia.knapp@okstate.edu	Boone Pickens School of Geology	Geophysical characterization for CO_2 sequestration in geologic strata; petroleum exploration; environmental geophysics; marine geophysics; hydrogeophysics, gas hydrates.	PI or co-PI on 4 major DOE carbon capture, utilization, and storage (CCUS). State of the art industry standard software used for CCUS applications including: (1) Halliburton's Landmark Solutions (~$30M donation); Schlumberger's Petrel Platform (~8M donation); (3) Paradigm Platform (~1.5M donation); (4) CGG Veritas – Hampson Russell (~3M donation), (5) Computer Modeling Group - GEM reservoir simulating software.
James Knapp	james.knapp@okstate.edu	Boone Pickens School of Geology	Structural and geodynamic evolution of the continental lithosphere through integration of surface geological and active and passive-source seismological data. Application of geological and geophysical analysis to hydrocarbon exploration and carbon sequestration using both 2-D and 3-D seismic reflection data. Design, acquisition, processing and interpretation of seismic experiments from shallow to lithospheric scale to solve structural and tectonic problems.	Same
Jack Pashin	jack.pashin@okstate.edu	Boone Pickens School of Geology	Sedimentary Geology; Coalbed Methane; Shale Gas; Conventional Reservoirs; Geological Carbon Sinks; Basin Analysis	Pioneering the CCUS arena in the U.S. as one of the founding members of the DOE funded carbon sequestration partnerships. Many research projects for CCUS funded by DOE including one of the 5 CarbonSafe projects for commercial deployment of CO_2 injection.
Javier Vilcaez	vilcaez@okstate.edu	Boone Pickens School of Geology	Experimental and computational research on the multiphase flow and reactive transport of CO_2 in geological storage sites at both the pore- and field scale levels; ML algorithms to predict flow properties of carbonate and siliciclastic rocks from well log data and pore-scale simulations; conduct field-scale multiphase reactive transport simulations to history-match field data and predict the fate of CO_2 in geological storage sites.	https://vilcaez.wordpress.com/lab/
Tingying Xu	tingying.xu@okstate.edu	Boone Pickens School of Geology	Aqueous geochemistry research for various geological setting; extensive experiences using synchrotron x-ray based techniques to characterize samples; design of in-house experiments best representing the geological reservoir conditions, collect samples from field and lab, and analyze samples using various techniques to ensure the safe storage of CO_2 and predict the change of geochemistry in geological storage sites.	X-ray Absorption Fine Structure (XAFS) spectroscopy X-ray Surface Scattering (XR and RAXR) Inductively coupled plasma-optical emission spectroscopy (ICP-OES) Inductively coupled plasma-mass spectrometry (ICP-MS) Powder X-ray diffractometry (XRD) Scanning electron microscope (SEM) Transmission electron microscope (TEM) BET analysis
Priyank Jayswal	priyank.jaiswal@okstate.edu	Boone Pickens School of Geology	Geophysics and advanced computer application; application of machine learning technology for the characterization of reservoirs and storage complexes; rock physics and poroelasticity; inverse theory.	
Michael Grammer	michael.grammer@okstate.edu	Boone Pickens School of Geology	Carbonate Sedimentology and Stratigraphy; Carbonate Reservoir Characterization; Petroleum Geology; Carbon sequestration.	Core and slabbed samples Outcrop and fieldwork Thin section petrography Image Analysis of Thin Sections DJI Inspire 1 Pro Drone (Drone photography) Digital Outcrop modeling with Agisoft Photoscan Software GigaPan Epic Pro for high resolution outcrop images Machine Learning: Artificial Neural Networks, K-Means Cluster, K-Nearest Neighbor Ion Mill Nuclear Magnetic Resonance Spectroscopy (NMR) Optical Cathodluminescence Scanning Electron Microscopy (SEM); Micro-CT
Jorge Gonzalez Estrella	jorgego@okstate.edu	Civil and Environmental Engineering	Engineered treatment of paperboard (and similar) waste streams for the production of hydrogen gas during decomposition	In Env. Eng., we have tools for microbial characterization (if H_2 production is microbial in nature) gas chromatography for H_2 (and any other gas) quantitative measurement. Nanomaterials characterization.
Mary Foltz	mary.foltz@okstate.edu	Civil and Environmental Engineering	Life cycle analysis of H_2 production, such as CO_2 impacts from production methods	
Clint Aichele	clint.aichele@okstate.edu	Chemical Engineering	CO_2 capture, separations, colloids, emulsions, interfacial phenomena, wettability alteration, hydrogels	high pressure gas/liquid separations, lab. scale distillation, phase doppler interferometer, diffusion NMR
Jeff White	jeff.white@okstate.edu	Chemical Engineering	heterogeneous catalysis as it relates to steam reforming of natural gas to CO and H_2 (blue hydrogen initiatives) with CCS	catalyst synthesis and testing equipment

David Carter	david.carter@okstate.edu	Finance / Spears School of Business	I have a B.S. in Chemical Engineering with an emphasis on Energy and Environment. Even though my Ph.D. is in another area, my ChemE degree gives me the background to appreciate the engineering issues related to the use of Hydrogen as an energy source. I have industry experience performing capital investment analysis for a natural gas pipeline company. I have published research on the hedging of jet fuel by airlines. I currently co-teach an Energy Business course. We cover renewable energy as part of the course material.	
Louis R Piccotti	louis.r.piccotti@okstate.edu	Finance/Spears School of Business	Asset pricing, market microstructure, quantitative finance	
Joe W. Byers	joe.w.byers@okstate.edu	Finance/Spears School of Business	Fuel Pricing, Structure products, Risk management, Strategic Planning, Price discovery, Supply chain/logistics	I have industry contacts
Dan Rickman	dan.rickman@okstate.edu	Economics/SSB	Regional/Rural/Urban economies, Applied Econometrics, Energy Economics, Regional Economic Forecasting	
Hongbo Wang	hongbo.wang@okstate.edu	Economics/SSB	Regional/Rural/Urban economies, Applied Econometrics, Energy Economics, Regional Economic Forecasting	
Ramesh Sharda	ramesh.sharda@okstate.edu	Mgmt. Sc.Info. Sys/SSB	Analytics/Data Science/AI, Energy analytics - worked with Central Electric to perform renewable energy performance analysis	
Laleh Tahsini		Chemistry	A part of the research in my group is focused on developing new synthetic methods to convert fossil fuel hydrocarbons to their alcohol derivatives as liquid fuels. Another research project is to develop cost-effective metal catalysts for hydrogen production from formic acid dehydrogenation as a clean and sustainable energy source	
Hunjoo Lee	hunjoo.lee@okstate.edu	Petroleum Engineering	Carbon capture and storage; basin modeling	
Mohammed Al Dushaishi	m.aldushaishi@okstate.edu	Petroleum Engineering	Carbon capture and storage; basin modeling	
Pankaj Sarin	pankaj.sarin@okstate.edu	Materials Science & Engineering	Proton conducting solid oxide fuel cells; High temperature materials and technology development for hydrogen production and carbon capture (in collaboration with Jim Smay (Materials Science & Engineering); Materials development for sustainable hydrogen and natural gas storage	Materials synthesis, microstructure characterization, in-situ high temperature investigation of materials and processes

Produced Water - Clean up

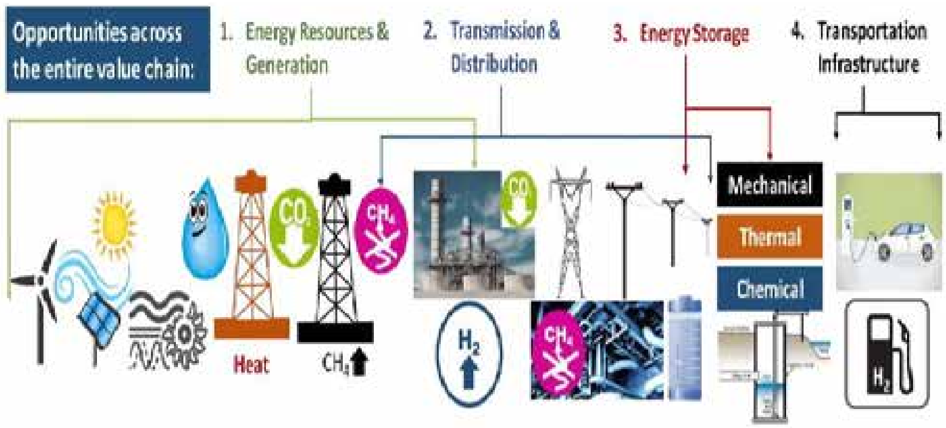
Faculty Member	Email	Department/School	Specific area(s) of research capabilities (list all relevant areas)	Notes, including specialized tools or facilities
Greg Wilbur		CEAT/CIVE	Biological Treatment of an Industrial Waste Stream Containing Waste Ink and Surfactants, Examining the Effects of Various Environmental Factors on the Biotransformation of Chlorinated Aliphatic Compounds in Landfills, nitroaromatic compounds (such as TNT and RDX) in soils and in engineered treatment systems	
Xiaoming Yang		CEAT/CIVE	Geosynthetics Ground improvement Geo-hazard Geothermal and energy pile foundation Hydraulic fracturing technology	
Peter Clark		CEAT/CHEME	Modeling Dynamic Fluid Loss Proppant Transport in Slick-water Fracturing of Shale-gas Formations The Crosslinking of Water-Soluble Polymers	
Clint Aichele		CEAT/CHEME	Emulsion Formation and Stability Improved Separations for Algae Fuel Production Gas Treating Life Cycle Assessment	
Babu Fathepure	babu.fathepure@okstate.edu	CAS/Microbiology & Molecular Genetics		
Javier Vilcaez	vilcaez@okstate.edu	CAS/Geology		
Khaled Sallam	khaled.sallam@okstate.edu	CEAT/Mechanical and Aerospace Engineering		
Prem Bikkina	prem.bikkina@okstate.edu	CEAT/Chemical Engineering		
Seok-Jhin Kim	seokjhin.kim@okstate.edu	CEAT/Chemical Engineering		
Todd Halihan	todd.halihan@okstate.edu	CAS/Geology		
Tracy Quan	tracy.quan@okstate.edu	CAS/Geology		
Tao Wu	wutao1981@gmail.com	CAS/Geology		
Jindal Shah	jindal.shah@okstate.edu	CEAT/Chemical Engineering		
Gopal Kakani	v.g.kakani@okstate.edu	FCA/Plant and Soil Science	CO2 sequestration by crop or native plants; Carbon farming; Life cycle analysis; Sensors and drones for data capture; Carbon intensity calculation	Small plot ot large scale field facilites to evaluate carbon farming and sequestration; State of the art sensors to measure GHGs; Drone based hyperspectral, LiDAR and thermal platforms ; Image and big data analytics
Kiranmayi Mangalgiri	kiranmayi.mangalgiri@okstate.edu	DASNR/BAE	Water quality, water chemistry, water and wastewater treatment, advanced oxidation processes, photolysis and photdegradtion, water reuse, contaminants of emerging concern	

Produced Water - Materials

Faculty Member	Email	Department/School	Specific area(s) of research capabilities (list all relevant areas)	Notes, including specialized tools or facilities
Tyler Ley		CEAT/CIVE	Concrete materials with an emphasis on concrete durability and sustainability. Three-dimensional chemical mapping of cements and mineral admixtures and the changes of these materials in chemistry and microstructure in different exposure environments. Development of inexpensive, passive, and wireless sensors Construction engineering with an emphasis on providing equivalent or superior structural systems through innovative methods and materials that increase speed, constructability, and economy. Structural engineering, specifically where structural design decisions impact concrete materials and vice versa.	
Geir Hareland		CEAT/CHEME	Drilling Optimization and Drill Bit Modeling Rock Mechanics in Drilling and Completion Operations Drilling Fluids and Hydraulics Drilling System Parameter Integration and Optimization Well Completions and Stimulation Optimization +D59:D61Cementing	
David McIlroy	dave.mcilroy@okstate.edu	CAS/Physics		
Pankaj Sarin	pankaj.sarin@okstate.edu	CEAT/Material Sciences	Low cost ceramic membranes for ultrafiltration/ nano filtration of produced water (in collaboration with Jim Smay, Materials Science & Engineering); novel high performance electrodes for produced water treatment through electrocoagulation. Capabilities: Materials synthesis, microstructure characterization	

Produced Water - Ag

Faculty Member	Email	Department/School	Specific area(s) of research capabilities (list all relevant areas)	Notes, including specialized tools or facilities
Mark Krzmarzick		CEAT/CIVE	Impact of oil/gas production fluids on soil microbial communities PCB and TCE bioremediation with the co-amendment of natural organochlorines Reduction of 2,4-dinitrophenol and study of nitro-reductase genes in soil bacterial communities	
Saleh Taghvaeian	saleh.taghvaeian@okstate.edu	BAE/DASNR	Ag water management, smart irrigation systems, irrigation scheduling, remote sensing of crop water use, managing high salinity in water, hydrology; DASNR Extension Specialist	
Gopal Kakani	v.g.kakani@okstate.edu	FCA/PSS	For Bioenergy Crop Production; Field and Greenhouse facilites to evaluate the impact of produced water; Bioamass quality analysis	
Hailin Zhang	hailin.zhang@okstate.edu	FCA/PSS	Soil and water chemical characterizations, and contaminated soil remediations.	
Jason Warren	jason.warren@okstate.edu	FCA/PSS	Utilizing produced water from crop production	
Ali Mirchi	amirchi@okstate.edu	DASNR/BAE	Water resources planning and management, system dynamics modeling for management and policy insight, watershed modeling and water quality management, sustainable socio-ecological systems, climate impacts	
John Long	johm.m.long@okstate.edu	DASNR/BAE	Intelligent machine systems, precision agriculture, crop management, field applications for agricultural technologies; DASNR Extension Specialist	



TU Research Contact:	Brenton McLaury	Vice Provost for Research & Dean of the Graduate School	

Lead Faculty Member	*e-mail address*	*Department/School/Affiliation*	*Specific area(s) of research capabilities (list all relevant areas)*	*Notes, including specialized tools or facilities*
Mohan Kelkar (Energy Transition Lead at TU)	mohan@utulsa.edu	**McDougall School of Petroleum Engineering**	Mohan Kelkar is currently Chair of Petroleum Engineering program at the University of Tulsa. With resurgence in discussion related to renewable energy sources, he has focused on transforming the existing PE program with emphasis on Energy Transition. While maintaining the focus on expertise in sub-surface engineering (which is the main domain of petroleum engineering), the program has introduced many new courses which capture the energy transition. These include: CCUS, Geothermal Energy, Intermittent Storage and Produced Water Management. He is currently focused on building research coalitions which would involve using existing infrastructure and re-purpose it for energy transition research.	TU has expertise in large scale fluid flow experiments, drilling and completion research, compact separation and artificial lift methods. With some modifications, the existing facilities can be used for hydrogen transport, hydrogen storage and hydrogen production.

Research Centers/Clusters/Programs at The University of Tulsa (not exhaustive)				
	e-mail address	*Department/School/Affiliation*	*Specific area(s) of research capabilities (list all relevant areas)*	*Notes, including specialized tools or facilities*
Evren Ozbayoglu	evren-ozbayoglu@utulsa.edu	**Tulsa University Drilling Research Projects**	Evren M. Ozbayoglu is currently a "Chapman Endowed Wellspring Professor" of The University of Tulsa (TU), McDougall School of Petroleum Engineering, and the Director of The University of Tulsa, Drilling Research Projects (TUDRP). Dr. Ozbayoglu has numerous publications and participated in several industrial projects on major drilling engineering topics as well as wellbore hydraulics, hole cleaning, and tubular mechanics. He was awarded for SPE Regional Drilling Engineer Award in 2019.	The Well Construction Technology Center is an advanced technology research center that incorporates high pressure, high temperature fluid flow applications using both field scale and lab scale equipment for the oil industry. Also, geomechanics facilities have the capability of simulating underground storage process in various formations including conventional reservoirs as well as salt.
Cem Sarica	Cem-Sarica@utulsa.edu	**Tulsa University Fluid Flow Projects (TUFFP.org)**	Dr. Cem Sarica is currently serving as the director of three industry-supported consortia at the TU: Fluid Flow, Paraffin Deposition, and Horizontal Well Artificial Lift Projects at the University of Tulsa. His research has primarily been funded by oil and gas industry through consortium format. He consistently manages over $2,000,000/year research budgets. He is a member of the Society of Petroleum Engineers (SPE) Projects, Facilities and Construction Advisory Committee (2002 – Present) and a member of the Executive Committee of Flow Assurance Technical Section of SPE (2013 – Present).	The Tulsa University Fluid Flow Projects (TUFFP) is a cooperative industry-University research group supported by several oil and gas production, consulting, service member companies and government agencies. The group was formed January 1, 1973 by Dr. James P. Brill. The mission of TUFFP is to conduct applied research and develop solutions for problems encountered by the member companies pertaining to multiphase fluid flow in pipes. At any given time, there could be between 4 and 7 research projects actively being conducted that are selected by the TUFFP member companies. Research is supported by annual membership fees.
Holden Zhang	hong-quan-zhang@utulsa.edu	**Tulsa University Artificial Lift Projects**	Dr Holden Zhang directs artificial lift projects	The Tulsa University Artificial Lift Projects (TUALP) is a cooperative industry-university consortium to conduct research on artificial lift technologies and strategies for petroleum production. Our primary objective is to provide our members with experimental results and theoretical analyses on the performances of various artificial lift methods, and useful tools for artificial lift applications and production optimization.
		Tulsa University Paraffin Deposition Project (TUPDP.org)	As stated above, Dr. Sarica also directs the Tulsa University Paraffin Deposition Project on TU's North Campus.	The objective of Tulsa University Paraffin Deposition Project (TUPDP.org) is to utilize the current test facilities at The University of Tulsa, as well as member company expertise, to enhance our understanding of paraffin deposition in single and two-phase (gas-oil) flows; conduct focused experiments to better understand various aspects of deposition physics; and utilize knowledge gained from experimental modeling studies to enhance the computer programs developed in the previous JIP for predicting paraffin deposition in single and two-phase flow environments. These refined computer models will then be tested against field data from member company pipelines.

Rami Younis	rami-younis@utulsa.edu	**TU Future Reservoir Simulation Systems & Technology**	Dr. Younis is an Associate Professor at the McDougall School of Petroleum Engineering at The University of Tulsa. He is the Founder and Director of the Future Reservoir Simulation Systems and Technology (FuRSST) joint-industrial research consortium. His research aims to: 1) develop fundamental advances in computational methods that are foundational to modeling technologies at the systems-scale; 2) advance algorithms and software infrastructure to enable automatic scalability and performance optimization of scientific research software; and 3) leverage data and computation to evaluate, optimize, and design more efficient and prudent operations. Dr. Younis serves as Associate Editor for the SPE Journal, Guest Editor for the Journal of Petroleum Science and Engineering, and Organizing Committee member for the SPE Reservoir Simulation Conference.	TU-FuRSST is an industry-University research consortium founded in 2015. The TU-FuRSST collaboration addresses significant and timely technical opportunities in subsurface engineering where computation plays a first-order role. Our approach combines engineering science, computational mathematics, and scientific computing to develop methods and workflows enabling engineering design, operations management, and early-stage technical innovation, all at the system scale.
		DOE-OSU: Large volume fragmentation of rock using targeted pulsed energy sources and seismic wave interactions	Dr. Younis is the Principal Investigator on a 1 year DOE supported project is developing a technology to emit high energy shock waves into subsurface formation in order to vastly increase permeability and create porosity. The mechanism applies short-duration energy pulses, and multiple benign seismic waves interact to create intense shear zones at target locations. This waterless technology may be applied to create large-scale subsurface storage zones in a geographically oblivious manner.	
Mustafa Onur	mustafa-onur@utulsa.edu	**Tulsa University Reservoir Exploitation Projects (TUPREP)**	Mustafa Onur is McMan Professor of the McDougall School of Petroleum Engineering at University of Tulsa and Director of TU Petroleum Reservoir Exploitation Projects (TUPREP). His current research is on the application of inverse problem theory, mathematical optimization, and data science to problems of relevance in optimal reservoir management and development, assisted history matching and uncertainty quantification for oil, gas, pressure and wireline formation testing, and conventional and unconventional geothermal reservoirs. He is currently the Associate Editors of SPE Journal and Journal of Petroleum Science and Engineering. He is the recipients of the 2010 SPE Formation Evaluation and 2018 Reservoir Description and Dynamics Awards and a distinguished SPE member.	The University of Tulsa Petroleum Reservoir Exploitation Projects (TUPREP) is a cooperative industry-university research project group founded in 1999 to address basic and applied research needs of the subsurface upstream energy industry in the areas of reservoir characterization, pressure, rate, and temperature transient data modeling and analyses methods, and the application of inverse problem theory, mathematical optimization and data science to problems of relevance in optimal reservoir management and development, assisted history matching and uncertainty quantification for conventional and unconventional oil, gas, and geothermal systems.
Ovadia Shoham	ovadia-shoham@utulsa.edu	**Tulsa University Separation Technology Projects (TUSTP)**	Dr. Shoham is the Floyd M. Stevenson Distinguished Professor of Petroleum Engineering. His research interests are in the production, transportation, and separation of multiphase flow, along with two phase flow module. He is the co-director of TUSTP, which is involved in many projects related to separation of oil, gas and water using compact seprators.	Established in 1994, the mission of Tulsa University Separation Technology Projects (TUSTP) university/industry is to advance the state-of-the-art of compact multiphase cyclonic separation technology for gas-oil-water-sand flow. This includes development of individual compact separator components, such as the Gas-Liquid Cylindrical Cyclone (GLCC©), the Liquid-liquid Cylindrical Cyclone (LLCC©), the Liquid-Liquid Hydrocyclone (LLHC), Horizontal Pipe Separator (HPS©), flow conditioning facilities such as the Slug Damper (SD©), and integrated compact multiphase separation system (CMSS©). More recently R&D on oil-water emulsion stability and breakup and produced water treatment.
Ram Mohan	ram-mohan@utulsa.edu	**Tulsa University Separation Technology Projects (TUSTP)**	Ram Mohan teaches and conducts research in the areas of control system design, compact separators, multiphase transport phenomena, dispersion characterization, system optimization, instrumentation and measurements, computer-aided design, and manufacturing processes. He is currently serving as the Co-Director of The Tulsa University Separation Technology Projects (TUSTP) and is the Site Director of the NSF Industry/University Cooperative Research Center on Multiphase Transport Phenomena at the University of Tulsa and directs several projects supported by Chevron TU Center of Research Excellence (TU-CoRE).	Dr. Mohan partners with Dr. Shoham on the R&D direction and result transition for the Tulsa University Separation Technology Projects (TUSTP) as described above.
Eduardo Pereyra	Eduardo-Pereyra@utulsa.edu	**Tulsa University Horizontal Well Artificial Lift (TUHWALP.org)**	Eduardo Pereyra is assistant professor at the McDougall School of Petroleum Engineering and associate director at the Fluid Flow Project and Horizontal Wells Artificial Lift Projects of The University of Tulsa. His research interests are multiphase flow systems and transport, flow assurance, artificial lift and separation technologies. Eduardo counts with several refereed journal and conference papers in his area of interest.	The Tulsa University Horizontal Well Artificial Lift Projects (TUHWALP) addresses the challenges of horizontal wells and develops new methods for advancing artificial lift and other production related technologies. Our mission is to work cooperatively with the oil and gas industry to develop data science and physics based models, technologies and predictive tools that enhance the knowledge and effectiveness related with the production of horizontal oil and gas wells. Visit our website for more information. Gain full access to our continuously developing technology and software by becoming a member.
Hema Ramsurn	hema-ramsurn@utulsa.edu	**Russell School of Chemical Engineering-Bioproduct Laboratory**	Dr. Hema Ramsurn has worked with sub- and supercritical water as a liquefaction and gasification medium to depolymerize biomass to produce biofuels, biochar and syngas.	The Bioproduct Laboratory has facilities to study catalysis, methane pyrolysis to hydrogen, biomass gasification to hydrogen, (bio)carbon materials, and activated carbon. In addition, Dr. Ramsurn efforst include graphene synthesis and graphene metal coating as corrosion prevention.
		DoE (co-PI):Carbonized Microvascular Composites for Gas Receivers	Dr. Ramsurn is also part of a 3-year DoE project on Carbonized Microvascular Composites for Gas Receivers.	This 3-year DoE funded project is investigating the synthesis of a novel carbon-carbon composite as a material for solar receivers using supercritical CO_2 as the heating fluid.
Nagu Daraboina	nagu-daraboina@utulsa.edu	**Daraboina Research Group**	Dr. Daraboina is an assistant professor in the Russel School of Chemical Engineering. His main research interest is in the areas of flow assurance, carbon dioxide capture & storage, petroleum thermodynamics, and polymer degradation. He has authored or coauthored more than 40 publications in these areas.	Dr. Daraboina's lab is equipped with facilities to study produced water desalination, carbon capture and sequestration, gas separation, and hydrocarbon thermodynamics.

		Tulsa University Paraffin Deposition Project (TUPDP.org)	Dr. Daraboina is the associate director of the Tulsa University Paraffin Deposition Project (TUDPD.org).	The objective of this program is to utilize the current test facilities at The University of Tulsa, as well as member company expertise, to enhance our understanding of paraffin deposition in single and two-phase (gas-oil) flows; conduct focused experiments to better understand various aspects of deposition physics; and utilize knowledge gained from experimental modeling studies to enhance the computer programs developed in the previous JIP for predicting paraffin deposition in single and two-phase flow environments. These refined computer models will then be tested against field data from member company pipelines.

Earth Systems Energy-Related Research (Characterization, Management, Monitoring, Modelling, Storage, CCUS)				
	e-mail address	*Department/School/Affiliation*	*Specific area(s) of research capabilities (list all relevant areas)*	*Notes, including specialized tools or facilities*
Evren Ozbayoglu	evren-ozbayoglu@utulsa.edu	**Petroleum Engineering**	Drilling, well completions, geomechanics, fluid flow	Large scale hydrogen underground storage and production in-situ simulation with the capability of Cartesian stress state environment, and corresponding geomechanical modeling of the system.
Holden Zhang	hong-quan-zhang@utulsa.edu	**Petroleum Engineering**	Artificial lift, multiphase flow, heat and mass transfer, oil and gas production, and flow assurance	Water cycle stability - the Sahara desertification process and how to reverse. Wrote book: Revive Eden - Green Sahara Now.
Rami Younis	rami-younis@utulsa.edu	**Petroleum Engineering**	Computational methods; Computer-aided engineering design and analysis; subsurface flow, mechanics, damage/fracture, and seimic response	Coupled full-physics simulation models for High Performance Computing machines to handle seismicity, non-isothermal and reactive multiphase transport, and rcok fracture
Jun Lu	jun-lu@utulsa.edu	**Petroleum Engineering**	Reservoir engineering, colloid science, emulsions, fluid-solid interactions, reservoir chemical treatment, geochemistry, carbon capture & sequestration, subsurface hydrogen storage	multiple high pressure, high temperature coreflood units; rheometers; microfluidics; goniometer; ICP-OES; IC; GC etc.
Eduardo Pereyra	Eduardo-Pereyra@utulsa.edu	**Petroleum Engineering**	Surface facilities, pipelines, flow measurement, separation and process	Field scale experimental facilities for fluid flow and process experiments. State of the art instrumentation.
Cem Sarica	Cem-Sarica@utulsa.edu	**Petroleum Engineering**	Multiphase flow, fluid flow transport, heat transfer, flow assurance	Unique large scale experimental facilities with advance instrumentation. Design and construction of customized experimental facilities
Mustafa Onur	mustafa-onur@utulsa.edu	**McDougall School of Petroleum Engineering**	Reservoir Engineering, application of inverse problem theory, mathematical optimization, and data science to problems of relevance in optimal reservoir management and development, assisted history matching and uncertainty quantification for oil, gas, conventional and enhanced geothermal systems.	High-fidelity reservoir simulator-based and machine-learning-based history matching and uncertainty quantification algorithms, roboust and deterministic life-cycle reservoir production optimization algorithms, new models and methods for modeling, monotroing, and analyzing pressure, production rate, and temperature transient data acquired from subsurface energy sources.

Cyber Security Research and Technology Development (not exhaustive)				
	e-mail address	*Department/School/Affiliation*	*Specific area(s) of research capabilities (list all relevant areas)*	*Notes, including specialized tools or facilities*
Tyler Moore	tyler-moore@utulsa.edu	**School of Cyber Studies**	Dr. Moore is the inaugural chair of the School of Cyber Studies. He is a founder of the area of security economics as demonstrated by an esteemed article in Science titled "The economics of information security". Dr. Moore's research blends security economics with cybercrime measurement and cybersecurity policy. He is a founding Editor in Chief of the Journal of Cybersecurity beginning 2014.	Dr. Moore manages StopBadware, a non-profit anti-malware organization.
John Hale	john-hale@utulsa.edu	**Tandy School of Computer Science**	Dr. John Hale is Chairperson and Professor of Computer Science. He holds the Tandy Endowed Chair in Bioinformatics and Computational Biology at the University of Tulsa. These projects include research on neuroinformatics, cyber trust, information privacy, attack modeling, secure software development, and cyber-physical system security. He has testified before Congress on three separate occasions as a cyber security expert, and in 2004 was awarded a patent on technology he co-developed to thwart digital piracy on file sharing networks.	He is a founding member of the TU Institute of Bioinformatics and Computational Biology (IBCB), and a faculty research scholar in the Institute for Information Security (iSec).
Mauricio Papa	mauricio-papa@utulsa.edu	**Tandy School of Computer Science**	Mauricio Papa is the Brock Associate Professor at The Tandy School of Computer Science. His primary research area is critical infrastructure protection and operational technology (OT) security, areas in which he has helped design process control testbeds to support cybersecurity efforts.	Dr. Papa is the Principal Investigator on a recent Army Engineer R&D Center multi-million dollar project to study OT threat analysis across multiple domains, such as electric power, gas pipelines, and additive manufacturing. The Critical Infrastructure Protection lab has a scaled-down version of an electric power substation using redundant controllers that communicate over the network using the DNP3 protocol. In the transportation sector, with funding from the Department of Justice and the NSF, he worked on projects involving heavy vehicles. In this area, he helped build forensic tools for use in crash reconstruction as well as a testbed that could be used for cybersecurity experimentation.
Peter Hawrylak	peter-hawrylak@utulsa.edu	**Department of Electrical and Computer Engineering**	Dr. Hawrylak is an Associate Professor in Electrical & Computer Engineering with a joint-appointment in The Tandy School of Computer Science. His primary research areas are high-performance computing and hardware/embedded system design. With respect to high-performance computing Dr. Hawrylak focuses on incorporation of heterogeneous computer architectures, specifically FPGAs into high-performance computing workflows.	He is a named inventor on numerous patents in the wireless and RFID areas with several being commercialized. Dr. Hawrylak led a multi-institution DOE NEUP effort (including The University of Tulsa, Washington State University, and PNNL) to investigate the cyber-security of the I&C systems in nuclear research reactors as they move from analog I&C systems to digital I&C systems. Significant outcomes of this research included a set of tools to model the cyber-physical attack surface of the I&C system and the development of a sandbox testbed platform to evaluate proposed mitigation tools, procedures and strategies.

College of Engineering and Natural Sciences Administration				
James R. Sorem, Jr.	james-sorem@utulsa.edu	**Dean**	Professor of Mechanical Engineering	
Rose F. Gamble	gamble@utulsa.edu	**Senior Associate Dean**	Tandy Professor of Computer Science & Engineering	
Daniel Crunkleton	daniel-crunkleton@utulsa.edu	**Associate Dean**	Professor of Chemical Engineering	

Photo courtesy of Gary Henry*US 412 in the Gloss Mountains*

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