Developing Clean Hydrogen State Roadmaps

A Clean Hydrogen State Working Group Resource

NASEO
National Association of State Energy Officials

Breakthrough Energy

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Introduction

In August 2022, the National Association of State Energy Officials (NASEO), representing the 56 State and Territory Energy Offices, launched a Clean Hydrogen State Working Group for State Energy Offices to exchange best practices, challenges, and programmatic considerations around clean hydrogen. While different State Energy Offices have different roles and responsibilities, they generally all provide recommendations to the Governor and State Legislature on energy policy and drive energy innovation through their programs and plans. Through the Working Group, State Energy Offices shared information on the value of state roadmaps for clean hydrogen[1]. As State Energy Offices explore ways to accelerate the deployment of clean hydrogen in their states and regions, a state-focused clean hydrogen roadmap can provide a path forward by offering an analysis of state and regional challenges and opportunities. These roadmaps can outline potential policy, regulatory, and programmatic action that can support clean hydrogen research, development, and demonstration (RD&D) and provide an overview of the landscape for clean hydrogen in a particular state. Some of the areas to explore through a roadmap include potential end uses, market considerations, the policy/regulatory environment, energy system impacts, infrastructure availability, collaborators and partnerships, and key benefits (e.g., economic development and jobs potential and decarbonization) as well as challenges (e.g., water availability, leakage risks, costs, and technical uncertainty). A thorough analysis of these and other pertinent topics also provides a State Energy Office with a better understanding of how clean hydrogen RD&D fits into their existing state plans and activities.

1 Based on Federal guidance in the Infrastructure Investment and Jobs Act and the Inflation Reduction Act, clean hydrogen is defined as hydrogen that is produced through a process that results in a lifecycle greenhouse gas emissions rate of not greater than 4 kilograms of CO2e per kilogram of hydrogen and with less than 2 kilograms of CO2e per kilogram of hydrogen at the point of production.

State Energy Offices may consider developing state clean hydrogen roadmaps in conjunction with other state agencies, universities, local governments, community-based organizations, Tribes, investor-and consumer-owned utilities, and the private sector. This can be done through official partnerships, such as the Minnesota Renewable Hydrogen Initiative or Alaska Hydrogen Working Group or they can be led by one entity with other groups brought in through stakeholder sessions or open comment forums. State Energy Offices have led the development of hydrogen roadmaps in several states utilizing federal funding or through funds appropriated by the state legislature. State Energy Offices or other state agencies have provided the funds to a university or outside contractor to develop the roadmap and lead stakeholder engagement on their behalf. Once completed, state roadmaps can produce recommendations to open the market for clean hydrogen and highlight potential action items for the State Energy Office and other relevant partners. Roadmaps can also be a valuable tool when exploring federal funding opportunities such as the U.S. Department of Energy (DOE) Regional Clean Hydrogen Hubs Program. States that have already developed clean hydrogen roadmaps include Colorado, Connecticut, New York, and Wyoming (see Table 1 below). Roadmaps under development include the states of California and Washington. Washington state will submit their Green Electrolytic Hydrogen and Renewable Fuels: Recommendations for Deployment in Washington to the state legislature in December 2023. In California, a roadmap is being developed through SB1075 which directs the California Air Resources Board, in collaboration with the California Energy Commission and California Public Utilities Commission, to develop a hydrogen report that looks at development, deployment, and use of hydrogen across all sectors and how it fits into existing state climate, air quality, and energy goals.[1] There was also an executive order by Governor Gavin Newson that directed the Governor's Office of Business and Economic Development to develop a Hydrogen Market Development Strategy for the state.[2] Other states, such as Oregon, have conducted studies that determined a roadmap would be beneficial to the state.

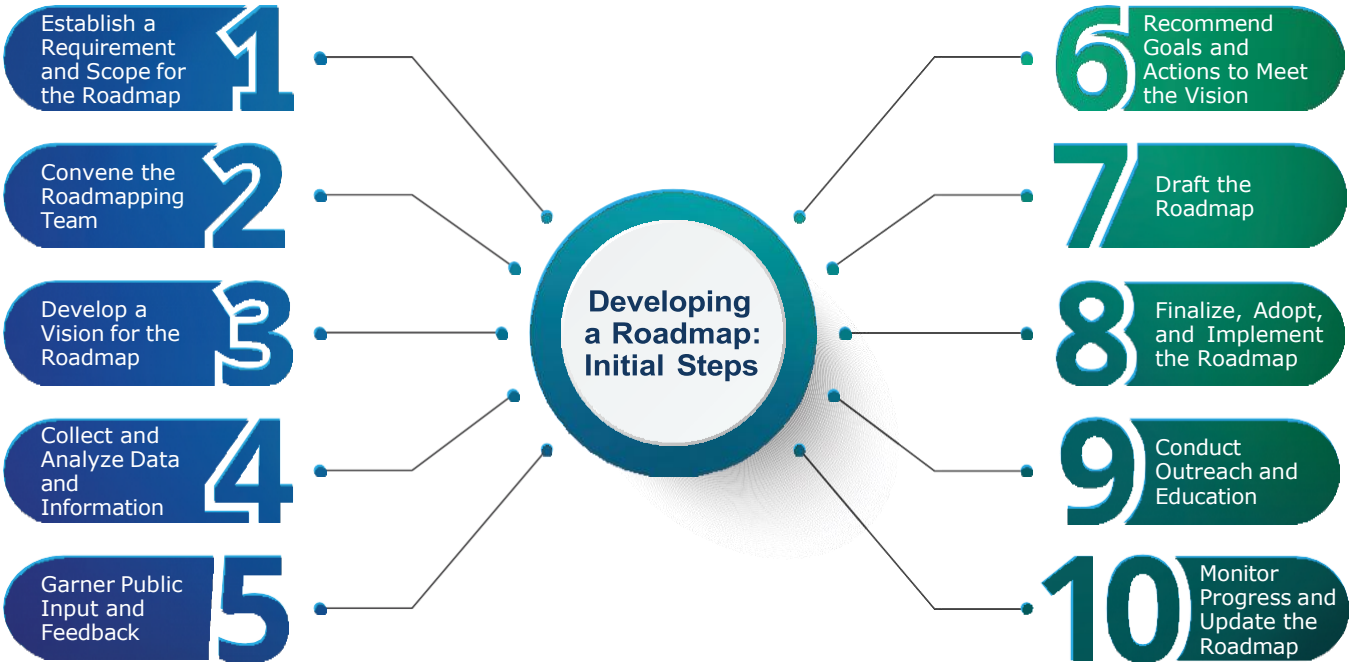
The goal of this guide is to provide State Energy Offices with information on the benefits and opportunities provided by a clean hydrogen roadmap with an overview of the steps other states have taken to complete a similar resource, what the data considerations and needs are, how clean hydrogen can be defined, and what different categories can be explored through a roadmap such as end use prioritization. Importantly, since every state has a different energy, policy, and regulatory landscape for clean hydrogen, the actions outlined in this guide should be considered recommendations with not every item covered in each roadmap applying to every state. As State Energy Offices utilize the *Developing Clean Hydrogen State Roadmaps* guide and explore the development of a state roadmap, they are also encouraged to reference the National Association of State Energy Official's (NASEO) paper *Hydrogen: Critical Decarbonization Element for the Grid, Manufacturing, and Transportation – State Energy Policy, Program, and Planning Considerations*.

Table 1: State Clean Hydrogen Roadmap, Study, and Report Examples

State	Study Name and Date	Author	Background
Colorado	Opportunities for Low-Carbon Hydrogen in Colorado: A Roadmap, (October 2021)	Energy and Environmental Economics	Funded by the Colorado Energy Office
Connecticut	Connecticut Hydrogen Task Force Study (January 2023)	Strategen and Connecticut Green Bank	Required by Special Act 22-8 The Connecticut Department of Energy and Environmental Protection (CT DEEP) served as a member of the Task Force
Iowa	Renewable Hydrogen in Iowa (August 2022)	Ideal Energy	Funded by the Iowa Economic Development Authority (State Energy Office) and U.S. Department of Energy
Michigan	Hydrogen Roadmap for the State of Michigan (September 2022)	University of Michigan	Funded by the Michigan Economic Development Corporation and the University of Michigan Office of Research
Minnesota	Minnesota Renewable Hydrogen Roadmap (April 2010)	Minnesota Department of Commerce (State Energy Office)	Requested by Minnesota Legislature (Minnesota Statue 216B.813)
Oklahoma	Hydrogen Production, Infrastructure, and Production Task Force Report & Roadmap, (November 2021)	Oklahoma State Task Force	Task force established by Senate Bill 1021. Study led by the Secretary of Energy and Environment
Oregon	Renewable Hydrogen in Oregon: Opportunities and Challenges (November 2022)	Oregon Department of Energy	Required by Senate Bill 333 (2021)
Wyoming	Wyoming Roadmap to Build a Hydrogen Economy (July 2022)	Wyoming Energy Authority and Cheyenne LEADS	Funded by the Wyoming Energy Authority and Cheyenne LEADS

Developing a Roadmap: Initial Steps

As State Energy Offices and other state agencies explore opportunities to develop clean hydrogen roadmaps and other action plans, there are certain considerations and practical aspects to bear in mind. A roadmap may be required through statute or executive order, or a State Energy Office may determine it is a logical next step as they explore options for decarbonization, economic development, and fuel diversification. As a starting point, State Energy Offices can review and consult the roadmaps, plans, and studies included in Table 1 prior to the development of a roadmap and throughout the process. A process outlined by the NASEO-NARUC Grid-Interactive Efficient Buildings Working Group report, *Roadmapping: A Tool for States to Advance Load Flexibility and Grid-interactive Efficient Buildings,* provides a standard process for developing a roadmap that can be utilized for other subject areas such as clean hydrogen. The steps are:



In addition, some of the questions that should be addressed prior to developing a roadmap include:

- Will the roadmap be developed by State Energy Office staff, or will an outside contractor be used?
    - If staff, how many people are available to work on the roadmap?
    - If a contractor, what will the Request for Proposals (RFP) process be? What will be included in the scope of work?
- What is the timeline for developing the roadmap?
- What funding is available to complete the roadmap?
- What information should the roadmap provide and what are the potential outcomes?
- What data is needed?
- Will a working group or task force be established to support the roadmap development process?
- What will the stakeholder engagement process look like? How can equity be incorporated into the process for developing the roadmap?
- How will the roadmap align with existing state plans?

As a whole, while this process will look different from state to state, State Energy Offices may want to consider utilizing these guiding steps and questions as a starting point or to provide more clarity internally on expectations and needs. To provide more context, a detailed walk through of the state of Connecticut's approach to developing a clean hydrogen study through a task force is included (See Box 1).

Box 1: Connecticut Hydrogen Task Force Study

Connecticut released its state Hydrogen Task Force Study in January 2023 which provided an expansive overview of its development process . Other states interested in better understanding the logical process for developing a state hydrogen task force may look to an example like Connecticut for guidance and suggestions for a possible process . As a result of the efforts of the Task Force, the Connecticut Legislature passed Public Act 23-156 "An Act Implementing Recommendations of the Hydrogen Task Force" which mandates CT DEEP to develop a Hydrogen Strategic Plan (roadmap). The roadmap is currently under development.

In May 2022, Special Act 22-8 was approved by the Connecticut General Assembly which required the state to establish a Task Force to study opportunities for hydrogen in the state and submit a report on findings and recommendations by January 2023 . Special Act 22-8 designated five participants of the Task Force including the Commissioner of the Connecticut Department of Energy and Environmental Protection and leadership from the Connecticut Green Bank . In addition, the State Senate and House of Representatives were required to nominate sixteen additional members to the Task Force . Final participation ranged from representatives of state government to environmental non-governmental organizations and industry . The first public meeting of the Task Force was held in July 2022, with six subsequent meetings held through January 2023 . Prior to the first meeting, a competitive RFP process was held to identify a contractor to author the study . Strategen was selected and funds were provided through the state's Renewable Energy Investment Fund . The role of Strategen was to conduct research, convene stakeholder meetings, and provide administrative support . The Task Force was broken into five working groups (1) Policy and Workforce Development; (2) Funding; (3) Hydrogen Sources; (4) Hydrogen Infrastructure; and (5) Hydrogen Uses . The public was invited to attend the Task Force and working group meetings and the meeting materials were posted on the Connecticut Green Bank's Task Force website with materials also translated into Spanish to reach a wider audience . In November 2022, the Connecticut Green Bank released a public request for written comment from stakeholders on several targeted questions that were incorporated into the report including:

- Do you believe that Connecticut should pursue a more stringent definition for clean hydrogen than the one that has been established by the Federal government? If so, why? If not, why not?
- When and how should the state of Connecticut engage with environmental justice and disadvantaged communities throughout the clean hydrogen planning and development process? What steps can the state take to support environmental justice and disadvantaged communities' engagement in these processes?
- The Hydrogen Task Force has been exploring hydrogen end uses including critical facilities, aviation, cargo ships, material handling equipment, long-haul heavy-duty trucks, fuel cells for peak power generation, high heat industrial processes, buses, ferries, rail, hydrogen blending in pipelines, and light-duty vehicles. How should the state address differing stakeholder perspectives about hydrogen end use prioritization? Which specific end uses are of greatest concern, and why? What actions can or should the state take to continue to solicit stakeholder feedback?

A public listening session was held in December 2022 for stakeholder feedback . All of this feedback and information was collected and analyzed and incorporated into the final study, which was finalized and submitted to the Connecticut Legislature in January 2023.[3]

Defining Clean Hydrogen

Most existing state roadmaps have utilized their own state-determined definitions of clean hydrogen. Some of these definitions were put in place through legislation, while others are developed as part of the roadmap process. Colorado, Montana, Washington, and Oregon are four states that have official definitions of clean hydrogen within statute.[4] Defining clean hydrogen as part of the roadmap process can help State Energy Offices fully explore the opportunities for supporting a clean hydrogen economy in their state. It alleviates potential confusion that may arise when projects are proposed, or programs are being established, and provides clarity to developers, policymakers, and the general public. Colorado HB23-1281 was signed into law in May 2023, and defines clean hydrogen as hydrogen that is derived from a clean energy resource that uses water as the source of hydrogen; or produced through a process that results in lifecycle greenhouse gas emissions rates that are less than 1.5 kilograms of carbon dioxide equivalent per kilogram of hydrogen.[5] Connecticut's Task Force study does not utilize a state-specific definition of clean hydrogen but makes the recommendation for the state Department of Energy and Environment to establish a definition of clean hydrogen for Connecticut. This definition will also be part of the state roadmap under development.

Box 2: State Definitions of Clean Hydrogen

State	Term	Definition
Colorado	Clean Hydrogen	Hydrogen that is derived from a clean energy resource that uses water as the source of hydrogen; or produced through a process that results in lifecycle greenhouse gas emissions rates that are less than 1.5 kilograms of carbon dioxide equivalent per kilogram of hydrogen.[6]
Montana	Green Hydrogen	Hydrogen that is produced from nonfossil fuel feedstock sources and does not produce incremental greenhouse gas emissions during its production. The term does not include hydrogen produced using steam reforming or any other conversion technology that produces hydrogen from fossil fuel feedstock.[7]
Oregon	Green Electrolytic Hydrogen	Hydrogen produced through electrolysis using: (A) A renewable energy source as defined in ORS 469A.005; (B) Nonemitting electricity that is not derived from a fossil fuel; or (C) Electricity that has a carbon intensity that is equal to or less than the average carbon intensity of the electricity served in this state in the calendar year in which construction or expansion of the facility that produces the green electrolytic hydrogen began.[8]
	Renewable Hydrogen	Hydrogen produced using: (a) A renewable energy source as defined in ORS 469A.005; (b) Nonemitting electricity that is not derived from a fossil fuel; or (c) Electricity that has a carbon intensity that is equal to or less than the average carbon intensity of the electricity served in this state in the calendar year in which construction or expansion of the facility that produces the renewable hydrogen began.[9]
Washington	Renewable Hydrogen	Renewable hydrogen: hydrogen produced using renewable resources both as the source for the hydrogen and the source for the energy input into the production process.[10]
	Green Electrolytic Hydrogen	Green electrolytic hydrogen: hydrogen produced through electrolysis and does not include hydrogen manufactured using steam reforming or any other conversion technology that produces hydrogen from a fossil fuel feedstock.[11]

The Infrastructure Investment and Jobs Act (IIJA) requires DOE to set a Clean Hydrogen Production Standard (CHPS) that defines clean hydrogen as hydrogen produced with a carbon intensity equal to or less than 2 kilograms of carbon dioxide-equivalent produced at the site of production per kilogram of hydrogen produced.[12] It will not be a regulatory standard but will serve to guide programming at the federal level. Compliance with CHPS will also be incorporated into certain DOE funding opportunities and decisions. In comments on CHPS, NASEO recommended that DOE work with states to streamline the process for verifying compliance with CHPS especially when states are already utilizing state determined definitions.

In November 2022, the Internal Revenue Service (IRS) released a request for comments on the clean hydrogen production tax credit (45V) through the Inflation Reduction Act (IRA) and how to define "clean hydrogen". Questions included:

(1) What, if any, guidance is needed to clarify the definition of qualified clean hydrogen? and (2) Section 45V defines "lifecycle greenhouse gas emissions" to "only include emissions through the point of production (well-to-gate)." Which specific steps and emissions should be included within the well-to-gate system boundary for clean hydrogen production from various resources?[13]

The IRS expects to release full guidance on the tax credit by the end of 2023. States may benefit from aligning their definitions so there is more clarity for developers and investors looking at projects in their states and regions and as they explore DOE funding opportunities.

Data Considerations and Needs

As part of the roadmap process, State Energy Offices will need an understanding of what clean hydrogen data is needed and the availability of that data. States may be able to look to other energy plans or programs to identify needed datasets. For example, a 2022 presentation prepared for the Washington State Department of Commerce (State Energy Office) outlined data that was required on hydrogen usage for the state energy strategy. Data that was requested included hydrogen demand by end use sector in the state, hydrogen converted to synthetic fuels to satisfy fuel demand, and electricity demand from hydrogen production.[14] Additionally, under development in Washington as of October 2023 is a Green Electrolytic Hydrogen and Renewable Fuels: Recommendations for Deployment report that was based on scoping questions such as what levels of green electrolytic hydrogen are needed in Washington state to most efficiently decarbonize and how much electricity and water are needed to deliver these levels of hydrogen?

Similar to Washington, states may be interested in collecting or mapping out current levels of hydrogen consumption, amount of water needed for hydrogen production, electricity demands of hydrogen production and the impact on the electricity grid, workforce and economic development impacts, and cost projections. This data can be interspersed throughout the report or included in annex sections. Data can often be found in existing state or federal datasets or mapping tools or through analyses conducted by the report authors. For example, Michigan highlighted opportunities to conduct interviews with key stakeholder groups as a way to get data on technical, economic, and social opportunities/ challenges associated with hydrogen.[15] Oklahoma included maps of the state's water supply

which are helpful when determining the future of clean hydrogen production in the state. The Oklahoma Department of Transportation developed a Hydrogen Application project which is a mapping tool that looks at high volume truck corridors, airports, water ways, ports, rivers, lakes, fueling stations, and other key data points.[16] Oklahoma also highlighted data on locations of viable pipelines for transport. Additionally, they referenced the U.S. Department of Energy's (DOE) Alternative Fuels Data Center which provides information on public hydrogen fueling stations in the country.

One of the challenges associated with data collection is availability and confidentiality. For example, there is no public data available on hydrogen consumption in the United States, which can be challenging for states attempting to make a state level analysis. The Oregon Department of Energy attempted to collect this information as part of their study process and had an extremely low response rate due to confidentiality concerns.[17] The U.S. DOE also does not publicly share any hydrogen information databases or collection of information on consumers in the country. In addition, other confidential information for renewable energy could be needed for a complete data analysis. In the Iowa study, the authors emphasized the lack of data on curtailed wind as most of the information is propriety. This information would provide a clearer picture of available clean energy for clean hydrogen production purposes. In addition, the study flagged the overarching lack of large-scale clean hydrogen projects in the United States to collect data from. This means developers and other project partners have a limited amount of reliable information when considering clean hydrogen production projects. One opportunity, as outlined in the U.S. National Clean Hydrogen Strategy and Roadmap, will come from the hubs funded by DOE. According to the DOE roadmap future data collected from the hydrogen hubs can help with market acceleration by showcasing optimal approaches and challenges and strategies to use existing infrastructure.[18] The hydrogen hubs may also provide information on economic development and workforce impacts regionally and state-wide which will be beneficial for future projects.

State Energy Offices may also benefit from assessing the impact of clean hydrogen production on the electricity grid. To produce one kilogram (kg) of hydrogen, about 50 to 55 kilowatt-hour (kWh) of electricity is needed.[19] According to a study by the National Renewable Energy Laboratory (NREL), "even in the unlikely event of the hydrogen market reaching its serviceable consumption potential size (106 Million Metric Tonnes [MMT]/year), the United States has more than enough resources to meet all foreseeable demands ".[20] The 106 MMT/year number was calculated by NREL using the H2@Scale analysis from Argonne National Laboratory and NREL research for each hydrogen demand opportunity, competitive hydrogen price points, and demand locations for oil refining, metals refining, ammonia, biofuels, synthetic hydrocarbons, natural gas supplementation, seasonal energy storage for the electric grid, light duty fuel cell electric vehicles (FCEV), and medium and heavy-duty FCEVs [21] For perspective, the International Energy Administration (IEA)'s net zero scenario forecasts 88 MMT/year of hydrogen to be used for generating power globally.[22] Currently, across sectors, global production is 120 MMT/year[23] According to the International Renewable Energy Agency (IRENA) this is similar to the annual energy consumption of the entire country of Germany.

Importantly for hydrogen from renewable resources, State Energy Offices will need to consider when and where the power being used to produce hydrogen is being generated when considering grid impacts in a roadmap. For example, if otherwise-curtailed renewables or surplus generated by nuclear energy overnight is used to generate clean hydrogen then the economic and environmental case for making hydrogen may be favorable and may not entail (much) increased generation and transmission. A project using curtailed solar power, such as the Intermountain Power Project explored later in this tool, to produce hydrogen is thus preferable than a project using grid electricity during a high demand period that might instead result in additional fossil fuel use.

Roadmaps can also explore opportunities for electrolysis facilities to support the electric grid by providing such services as load shedding, shifting, and modulation to reduce peak loads, moderate ramp rates (the rate at which that generation must increase or decrease to match demand), and avoid curtailing otherwise excess renewable power generation. According to a study by the Energy Futures Initiative (EFI), when there is more supply than demand of renewable generation on the electric grid, that can be used to power electrolyzers that produce clean hydrogen for storage purposes. Then, when demand exceeds supply, the clean hydrogen being stored can be used to produce clean electricity. EFI looked at this particular scenario by analyzing the Southeastern United States and determined that, through a theoretical scenario using real data from the region, the Southeast has enough surplus clean electricity generated to produce hydrogen that can be stored and then used when demand rises in the colder winter months.[24]

When considering the impacts on the grid, it is also important to consider hydrogen production using behind-the-meter versus front-of-the meter electricity. A recent study on *Minimizing Emissions from Grid-based Hydrogen Production in the United States*, looked at the Inflation Reduction Act (IRA) 45V production tax credit for clean hydrogen (clean hydrogen produced through a process with less than 4.0 kgCO2e/kgH2-to-gate lifecycle emission).[25] Federal guidance on the tax credit is expected to be released by the end of 2023. According to the IRA, a life cycle analysis tool developed by Argonne National Laboratory must be used to determine eligibility for 45V. The study points out that when hydrogen is produced by only behind the meter resources such as on-site wind or solar power, there is limited need for the tool – issues arise when clean hydrogen is produced through connection with the main electricity grid.[26] There will need to be a way to verify that the electricity being used for hydrogen production is clean and carbon free, which is not currently possible.[27] Colorado HB23-1281, signed into law in May 2023, will offer tax credits to users in hard to decarbonize industrial applications and heavy-duty transportation that are designed to complement 45V. In order to claim the tax credits, the hydrogen used must meet certain standards to demonstrate that the hydrogen meets lifecycle emissions intensity standards set in the statute. If electricity that was used for hydrogen production is claimed to be zero emissions, it must be located in the same geographic region and have come online within the last three years.[28] In order to support this effort, the state Public Utility Commission is required to develop an accounting standard that can be used by producers to prove that the electricity claimed to be zero carbon being used to produce the hydrogen is carbon-free and was developed in the last three years. There will also be hourly-matching requirements. [29]

States may also utilize the DOE H2Matchmaker tool for data on hydrogen producers, consumers, infrastructure, and key stakeholders in their states or regions. The tool is an online resource meant to help those entities self-identify and align potential needs in targeted geographic areas. According to DOE, the goals are to (1) increase hydrogen and fuel cell regional project awareness (2) support private sector development and (3) facilitate regional business development opportunities.[30] When using the tool, states should be aware that there are limits to the availability and scope of the data in the tool, mostly due to confidentiality and privacy concerns.

Overview of Roadmaps in Oregon, Colorado, and Oklahoma

The examples in Table 1 demonstrate the variety of different roadmaps, reports, and studies developed or supported by state governments, most often State Energy Offices. The recommendations proposed through these roadmaps and studies cover a wide spectrum of considerations for clean hydrogen, including investing in infrastructure; developing pilot projects or identifying potential end uses; and deploying state-level policies, regulations, and incentives. There is also an underlying message of prioritizing equity, safety, economic development, and workforce opportunities. This section will provide some more background on three state processes and the resulting recommendations.

The Oregon Department of Energy (ODOE) was directed to produce a report on the potential benefits of and barriers to production and use of renewable hydrogen in Oregon through SB 333, passed in 2021. Some of the specific items they were directed to cover included (1) identification of the total hydrogen volume currently used annually in Oregon among certain industries (I.e., technology and manufacturing); (2) identification of the potential applications of renewable hydrogen in Oregon by 2030 across transportation, industry, electricity generation, energy storage, and other sectors; (3) an assessment of the potential for coupling renewable electricity generation and renewable hydrogen production to increase resiliency; and (4) a discussion of forecasted costs and their impact on hydrogen adoption in the state.[31] The legislation also defined renewable hydrogen for the purposes of the report as "hydrogen gas derived from energy sources that do not emit greenhouse gases".[32] ODOE established a technical advisory committee to support the development of the study, which was made up of representatives from the state Department of Transportation, universities, Pacific Northwest National Laboratory, and the Northwest Power and Conservation Council. Representatives from the state Department of Environmental Quality and Public Utility Commission also reviewed the report. In addition to engaging these groups, ODOE hosted two stakeholder engagement workshops to facilitate discussion and hear concerns and thoughts on the study and ODOE reached out to the nine federally recognized tribes in the state. Some of the recommendations produced through this outreach and through the development of the report included building out an official renewable hydrogen roadmap for the state with support from a multi- agency working group led by state and local government representatives with input from environmental justice groups, labor unions, and Tribes; establishing codes and standards to ensure safety and equity within all stages of the hydrogen value chain; and the development of a workforce and educational training program through state universities and technical and community colleges.[33]

In Colorado, in January 2021, Governor Jared Polis, with support from the Colorado Energy Office, released the Colorado Greenhouse Gas Pollution Reduction Roadmap, which looked at how the state could reach their goal of reducing pollution from greenhouse gases by 90 percent by 2050 from 2005 levels. One of the items outlined in the plan was the use of low carbon fuels like hydrogen in decarbonizing the industrial and heavy-duty transportation sectors. To better understand the pathways for clean hydrogen in the state, the Colorado Energy Office engaged a contractor with existing state funds to develop their state roadmap, *Opportunities for Low-Carbon Hydrogen in Colorado*, which was released in October 2021. An RFP was released in late 2020 and a contract signed in January 2021. The goal of the roadmap was to look at defining low-carbon hydrogen, the state of the clean hydrogen market, opportunities for hydrogen in Colorado, barriers to building a hydrogen economy, and economic potential.[34]

Recommendations made in the Colorado roadmap included investigating the feasibility of a regional hydrogen hub, developing a state hydrogen plan to outline actionable ways to take advantage of the opportunities in the roadmap, supporting pilot projects including pilots related to blending hydrogen in gas infrastructure, and issuing a Request for Information (RFI) to get stakeholder input on the future role of clean hydrogen in the state.[35] In April 2023, Colorado along with the states of New Mexico, Utah, and Wyoming submitted their Western Interstate Hydrogen Hub application to compete for the DOE Regional Clean Hydrogen Hubs Program. Many of the other recommendations, including the issuing of an RFI, were incorporated into the action plan associated with the hub application.

The Oklahoma *Hydrogen Production, Infrastructure, and Production Taskforce Report and Roadmap* was released in November 2021 after being commissioned by the State Legislature through Senate Bill 1021 in April 2021. SB 1021 set up the Task Force to be chaired by the Oklahoma Secretary of Energy and Environment. Additional required members included representatives from the state departments of Commerce, Transportation, and Water Resources. The Task Force was required to hold meetings on various pertinent topics, including use and availability of water, cost for hydrogen production, and the development of a state-wide roadmap looking at infrastructure, production, distribution, transportation, and off-taker market uses. In developing the roadmap, the Task Force held five meetings in which updates on the roadmap were provided and a public comment period was held. Some of the issues brought up during the public comment periods included supply-chain management, hydrogen transport concerns, impacts on air quality, and high costs.[36] The roadmap was able to address these different items. In addition, four Task Force sub-committees were established to focus on specific opportunities and challenges and ways to implement public comments: production; distribution infrastructure; economic opportunities, taxation, and incentives; and market uses.[37] Specific recommendations in the roadmap included identifying goals for in-state production, strengthening engagement with utilities to incorporate hydrogen into their Integrated Resource Plans (IRP), identifying and supporting new legislation and regulation, developing and implementing pilot programs, and developing safety standards and trainings to assure industry safety.[38]

Roadmap Categories

State clean hydrogen roadmaps can cover a variety of topical areas, but some of the most pertinent items are explored below. These are overviews of complex topics and State Energy Offices are encouraged to explore other resources (including those listed on NASEO's Hydrogen page) to fully build out their roadmaps. There will also be unique state and regional considerations that cannot be fully captured here. Roadmaps provide a significant opportunity to do a deep dive into these, and other relevant topics, and identify specific state and regional challenges and opportunities. Some of the areas covered include infrastructure, potential end uses, policy and regulatory environment, benefits, challenges, economic development, and collaborators and partners. DOE's U.S. National Clean Hydrogen Strategy and Roadmap may also provide insights into potential focus areas and federal priorities.

End Uses

Roadmaps can serve to outline potential end uses for clean hydrogen in a specific state. State Energy Offices are well positioned to analyze existing resources and data and convene relevant stakeholders to weigh the benefits and challenges associated with each potential end use. Not every state will have a market for every end use or see value in using hydrogen for every potential end use, so State Energy Offices should consider what the best opportunities for their state may be. Potential items to consider are the availability of the feedstock needed to produce a certain type of hydrogen, how cost-competitive a certain end use is, current and prospective industrial infrastructure and demand for materials, and what the long-term prospect of a certain end use is. In addition, it is important to consider how hydrogen compares to other approaches for meeting a sector's energy needs and what future projections would be for other alternatives.

State Energy Offices can also examine what industries would benefit the most from utilizing clean hydrogen as a decarbonization pathway. While not the state roadmap, which is under development, in Connecticut's Task Force Study, Strategen outlined particular concerns from stakeholders on how end uses are being prioritized. The high priority end uses, as determined through the development of the study, include medium- and long-haul aviation, cargo ships, critical facilities, high heat industrial processes, hydrogen fuel cells for peak power generation, long haul trucks, and material handling equipment with long uptimes and charging space or time constraints. A Hydrogen Uses Working Group was assembled to look at potential end uses to support decarbonization efforts in the state and conduct assessments of the different end uses. The specific criteria that were considered when prioritizing end uses were (1) cost competitiveness with other decarbonization options; (2) potential to reduce GHG emissions in the state; (3) timeline for commercial deployment; (4) need to build out additional infrastructure; (5) ability to reduce pollution impact to disadvantaged and frontline communities; (6) impact on local workforce needs; and (7) value of improving resilience via a diversified fuel supply. Strategen then conducted a literature review of existing research and analyzed comments from key stakeholders to develop a qualitative assessment of each end use with the criteria above used to inform the assessment. This led to a determination of the high priority end uses for the state.

When weighing potential end use options, one other model that may be of interest to State Energy Offices is a series of reports from the Minnesota Department of Commerce to the state legislature conducted in the early 2000s. These reports, *Strategic Demonstration Projects to Accelerate the Commercialization of Renewable Hydrogen and Related Technologies in Minnesota*, were released in 2005, 2007, and 2009 and looked at potential end uses and pilot projects centered around relevant criteria including their role in advancing energy security, taking advantage of existing resources in the state, how economically competitive they are, how accessible they would be to the public, and what the market demand looks like. The reports emphasized that each potential end use application would have different infrastructure needs which also led the state to prioritize stationary applications over transportation applications due to the costs of building out a distribution and fueling network. Minnesota also found that end uses for hydrogen that involve blending, such as hydrogen blending with natural gas, offer the state the best opportunities as an existing market is in place and this would help decarbonize different sectors.

As seen in the Minnesota and Connecticut examples above, there are a variety of sectors that could benefit from clean hydrogen as a feedstock or energy source, such as the power, transportation, and industrial sectors. A roadmap can help State Energy Offices determine what end uses would be most beneficial and efficient for their states and within certain targeted sectors. The roadmap should also include a comparison of clean hydrogen versus potential alternative fuels and sources to understand potential benefits in a comparative setting. The section below will highlight examples of how other states have incorporated different prospective end uses into their roadmaps, studies, and reports and provide general information on these sectors.

TRANSPORTATION: When looking at opportunities for hydrogen in the transportation sector, states may consider approaching it in three parts: considering light-duty vehicles, medium/heavy-duty vehicles including trucking, and off-road transport such as rail, marine, and aviation modes.[39] Medium- and heavy-duty vehicles are used for transport, towing, waste collection, and other applications, while light duty-vehicles are usually passenger cars or trucks with minimal cargo.[40] Medium- and heavy-duty vehicles are also responsible for around 20 percent of emissions from the transportation sector and clean hydrogen could decrease those emissions.[41] The Colorado Energy Office's low-carbon hydrogen roadmap looked at the market for medium- and heavy-duty hydrogen fuel cell vehicles in the state and found that they are a cost-competitive solution compared to electric vehicles on a per weight basis. Iowa looked at the barriers to deploying hydrogen fuel cell buses and found that currently costs are higher for a similar number of diesel or electric vehicles, but those costs are expected to drop .[42] This initial cost included the buses, refueling stations, and production facility for the hydrogen suggesting that for states without existing hydrogen production capabilities or existing demand there may be higher up-front costs than for states like California with existing resources. Some of the concerns with light-duty are the lack of efficiency and higher costs.[43] There are also challenges associated with fueling infrastructure. According to the Energy Information Administration (EIA), there are around 60 hydrogen fueling stations in the United States and the majority are in California.[44] California has actively worked to provide incentives and support for the installation of stations across the state through their Clean Transportation Program. States may also work with equipment manufacturers and other industry leaders to better understand market readiness and vehicle availability. This information will be helpful when identifying potential end uses to prioritize.

INDUSTRIAL: The most common industrial sector end uses, according to the DOE roadmap, include petroleum refining; ammonia and methanol; and metals.[45] State roadmaps should focus on existing industries within their states and determine the potential for utilizing clean hydrogen to decarbonize. The Oregon Department of Energy looked at opportunities for their industrial sector and discussed the potential for certain industries to utilize hydrogen produced from natural gas paired with CCS [carbon capture and storage] before transitioning to fully renewable hydrogen.[46] For those harder-to-abate sectors, hydrogen can provide a key solution towards decarbonization. It can also be appealing when hydrogen production can be sited near industrial clusters, as mentioned as a near term action in Michigan's roadmap.[47] Additional information can be found in the NASEO publication, *Hydrogen: Critical Decarbonization Element for the Grid, Manufacturing, and Transportation.*

AMMONIA/FERTILIZER: Clean hydrogen is also a key potential feedstock for ammonia production. As natural gas is the most common feedstock for ammonia production currently, greenhouse gas emissions for the ammonia sector continue to be high. According to the DOE roadmap, the sector could be decarbonized by 90 percent if producers switch over to clean hydrogen.[48] Most of the ammonia produced today is used as fertilizer with production concentrated in areas already exploring clean hydrogen production including the Gulf Coast and western United States. The Oregon study outlines the potential for a hydrogen hub in the state where renewable hydrogen is used to produce green ammonia to produce low-carbon fertilizer.[49] There are also studies underway that look at the role of ammonia for transporting clean hydrogen. For example, at Northwestern University, research is looking at converting ammonia into clean hydrogen. This process is helpful in that there is already an existing distribution and transport network for ammonia, and it can travel to the off taker and be converted on site into hydrogen.[50]

ELECTRICITY: For the electricity sector, many state roadmaps look at opportunities to utilize clean hydrogen for electricity generation and/or long-duration energy storage. For example, the Wyoming roadmap highlights the need for the private sector to provide support in identifying and pursuing markets for hydrogen used for power generation and energy storage and recommends a regulatory framework to be established to further advance the potential for these end uses in the state.[51] The regulatory framework can be developed by the state's regulatory agencies in partnership with the University of Wyoming School of Energy Resources and other stakeholders. The framework should look at safety considerations along the entire hydrogen value chain and examine codes and standards, permitting, regulations for storage, pipeline integrity, operational safety, and more.[52] There are several storage projects underway that can be explored as examples including the Advanced Clean Energy Storage 1 project in Utah that will produce up to 100 metric tons a day of clean hydrogen which can then be stored in two caverns in a salt dome. The storage capacity will be around 300 gigawatt-hour (GWh) of clean energy.[53] Roadmaps can identify potential storage locations within a state and also identify the storage needs of the state based on connections with other studies or goals centered around energy storage. Many State Energy Offices are responsible for developing roadmaps or market assessments related to energy storage and this would be a good opportunity to examine potential intersections with clean hydrogen. Hydrogen can also be used for electricity generation as outlined in the plans for Utah's Intermountain Power Project and with a project announced

in 2022 between NevoHydrogen and TigerGenCo, LLC to develop a clean hydrogen production facility to help the city of Bayonne, New Jersey and New York City reduce their carbon emissions. The hydrogen will be produced at a facility in Bayonne and the power will be transported to New York City through an underwater cable.[54]

HOME AND SPACE HEATING: Utilizing hydrogen for home heating by blending in natural gas systems is an incredibly controversial end use that has many associated safety concerns. The California Public Utility Commission's *Hydrogen Impacts Blending Study* finds that hydrogen blends up to 5 percent are usually safe, but once the blend goes over that threshold the risk increases and would require modifications to stoves and water heaters to minimize the potential for leaks.[55] Hydrogen can extend the lifetime of several greenhouse gases if leaked into the atmosphere, has a higher potential for leakage than methane, and causes steel to become brittle.[56] So, it is important to minimize leakage for health, climate, and economic reasons. In addition to leakage, other potential challenges, especially when looking at using hydrogen for home heating, remain including a lack of efficiency (there is a significant amount of energy lost as heat during the production process) and a risk of slowing the overall decarbonization process as it will usually be blended with natural gas. There are also concerns with embrittlement of pipes, damage to pipes, and burner design based on concentration of hydrogen. A study by the Regulatory Assistance Project found that heat pumps, district heating, and solar thermal are all more efficient and less expensive options for home heating.[57] There are also significant technical upgrades that will be needed. Considering this, State Energy Offices interested in exploring opportunities to inject hydrogen into the natural gas system should carefully determine if this method of decarbonizing natural gas outweighs other low-carbon options, particularly when looking at home heating.

Infrastructure

As State Energy Offices explore the market for building out a clean hydrogen production, distribution, storage, and use value chain in their state or region, determining what existing infrastructure can be repurposed or where there is opportunity to site new infrastructure will be critical. Roadmaps should look at not only in-state resources, but also regional opportunities. States with limited existing infrastructure to serve as a resource may look at partnerships with neighboring states or focus on hydrogen produced with existing nuclear or renewable energy resources. A September 2022 study on *Building the Gulf Coast Clean Hydrogen Marke*t, developed by the Energy Futures Initiative, for example, determined that the Gulf Coast has a plethora of existing infrastructure including hydrogen producers, dedicated carbon dioxide and hydrogen pipelines, and demand from industry. The study also highlighted the benefit of existing workforce expertise and natural resources such as onshore and offshore salt domes for storage, renewable energy resources and available water for production.[58] State Energy Office-led roadmaps could follow a similar model and determine what a state's strengths and weaknesses are along the value chain.

State roadmaps should also look at the different opportunities for hydrogen production and potential avenues within the state. The DOE roadmap outlines the various production methods including electrolysis powered by nuclear or renewable energy, fossil fuel production paired with CCS, and biomass or waste feedstocks.[59] States should highlight what existing infrastructure in their state or region can be repurposed in the roadmap and

examine potential challenges. This is particularly important when looking at opportunities to transport hydrogen. According to DOE, infrastructure that is needed for hydrogen delivery includes pipelines, liquefaction plants, trucks, storage facilities, compressors, and dispensers.[60] The use of each depends on availability and location. There has been significant interest across the country from the public and private sectors in utilizing existing natural gas infrastructure for producing hydrogen (considered clean when paired with CCS). While there are benefits in identifying clean hydrogen production locations with end uses on site, hydrogen may need to be transported out of a state if an existing market is not already present.

PIPELINES: New and existing pipelines are critical to the transport of clean hydrogen. There are currently around 1,600 miles of hydrogen pipelines in the United States, and they are centered in areas with high numbers of off takers such as those in the Gulf Coast region.[61] Additional projects have also been announced, such as the Southern California Gas Company's plans for a clean hydrogen pipeline system that would bring hydrogen produced from clean energy to support industrial and heavy transportation users in the Los Angeles area.[62] The Wyoming roadmap also looks at opportunities to leverage existing rights-of-way for pipelines and other infrastructure.[63] Regulatory oversight is one gray area with dedicated hydrogen pipelines. The Federal Energy Regulatory Commission (FERC) has jurisdiction over crude oil, refined petroleum products, and natural gas liquid transport through pipelines under the Interstate Commerce Act. Hydrogen is not within those categories of jurisdiction, so, as a result, FERC does not have any responsibility over the siting of dedicated hydrogen pipelines - nor does any other federal agency.[64] The safety regulations associated with dedicated hydrogen pipelines fall to the U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Division, but there is no federal agency responsible for the regulation of rates and services associated with the pipelines.[65]

FERC does claim jurisdiction over interstate natural gas pipelines with a hydrogen blend, but there still needs to be a determination of what the percentage limit would be before additional authority might be required.[66] When blended with natural gas, clean hydrogen can not only take advantage of existing pipeline infrastructure, but it can also reduce upfront capital costs, increase demand for clean hydrogen, and support decarbonization efforts.[29] According to a study by the IEA, a 5 percent volume blend of clean hydrogen with natural gas would reduce carbon dioxide intensity of the natural gas by 2 percent.[30] Still, concerns about the efficiency, cost, and safety of transporting hydrogen through natural gas pipelines remain, and a state roadmap can serve as a starting point to further exploring these issues by compiling findings from existing pilot projects and studies and identifying information gaps and stakeholder concerns. A recent pilot project in Minnesota is experimenting with this process and looking at how the natural gas pipeline is impacted by the addition of blends of hydrogen.[67] CenterPoint Energy is blending hydrogen into the natural gas system to decarbonize the stove and furnaces of several customers in the state. States may also consider looking at existing state-led studies on hydrogen blending as a resource. For example, the California Public Utilities Commission filed a *Hydrogen Blending Impacts Study* in July 2022 that looked at operational and safety concerns with injecting hydrogen into existing natural gas pipelines. Leakage is a significant concern associated with the blending and pipeline transport process.

VEHICLES: Additional considerations that can be explored regarding infrastructure in state roadmaps are related to fuel cell vehicles. Hydrogen can power a vehicle through a fuel cell that converts the hydrogen to electricity or with an internal combustion engine that burns the hydrogen.[68] Light-duty vehicles can travel over 300 miles with the current storage capacity for hydrogen. The tank requires more space and higher pressure than those for other gaseous fuels due to the lower volumetric energy density of hydrogen when compared with gasoline.[69] For medium and heavy-duty trucks, a recent study expects their range to exceed 500 miles by 2035 due to advancements in fuel cell technology and clean hydrogen production.[70] In addition, hydrogen fueling stations are needed, but there are currently only 55 located in the United States with the majority in California.[71] Now that more incentives and financial support is available for hydrogen fuel vehicles, the market is expected to grow, which will encourage development of hydrogen fueling stations. For reference on the current state of play, in the roadmap for the state of Michigan, only two private fueling stations were identified in the state and zero public fueling stations. This information is helpful when considering what is needed to move the market for fuel cell vehicles forward in the state or region.

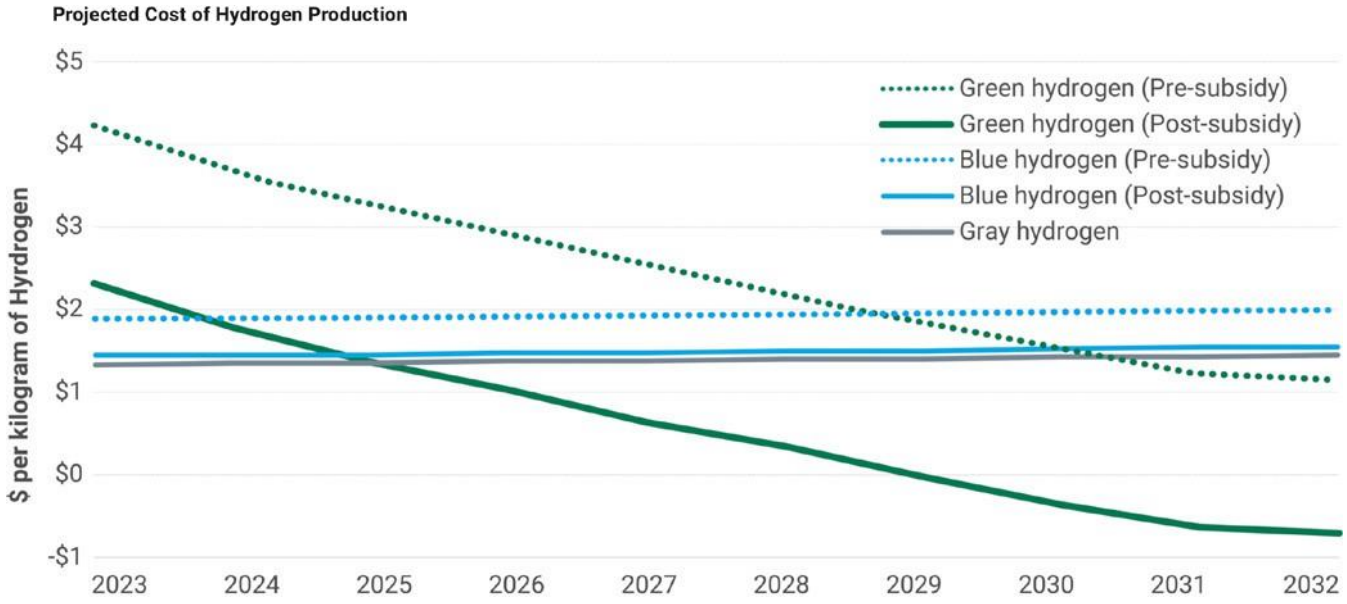
Policy and Regulatory Environment

This topic will be explored in more detail in a forthcoming NASEO resource, but it is important for State Energy Offices to be aware of the importance of exploring the policy and regulatory environment for clean hydrogen in any state roadmap. This section will briefly cover examples of supportive policies and regulations that may be included in a state clean hydrogen roadmap.

POLICY: Roadmaps can cover existing state policies that may be supportive of clean hydrogen, such as California's Low Carbon Fuel Standard or Minnesota's recently passed climate law that commits the state to achieving 100 percent carbon-free electricity by 2040 through a mix of renewables along with nuclear, hydrogen, and biomass. Roadmaps can also look at the implications of recent federal legislation on clean hydrogen. For example, Oregon included a figure (see Figure 1 below) that looked at the impact of the federal production tax credits (PTC) on hydrogen's cost. The study was adapted from an analysis by BloombergNEF that looked at the levelized cost of hydrogen before and after the IRA passed. Oregon's study pointed out that the PTC has the potential to bring renewable hydrogen prices into the negative by 2030.[72] Washington has also passed several pieces of hydrogen legislation including siting and permitting reform and incentives to support the development of green hydrogen in the state.

In addition, State Energy Offices can provide an overview of their role, and other relevant state agencies including the state legislature and PUC, in the hydrogen policy, program, regulatory, and siting processes. The policy and regulatory recommendations outlined in a roadmap may provide the impetus for state action around financial incentives to support RD&D, streamlining the permitting process, incorporating clean hydrogen into larger decarbonization or resilience goals, and more. For example, in their state roadmap Wyoming outlined the general role of the state's economic development office, the Wyoming Business Council, as being "an active partner with the private sector to advocate for and to drive approval of large incentives, or other policy needs supporting project development".[73]

Figure 1: Forecasted Effect of Production Tax Credits on U.S. Levelized Cost of Hydrogen[74]



Source: "Effect of production tax credits on US LCOH2 (Levelized cost of hydrogen)," BloombergNEF, 8/15/2022.

The Western Green Hydrogen Initiative's *Green Hydrogen Guidebook* covers several key policy and regulatory recommendations that can facilitate the deployment of clean hydrogen including establishing state and local leadership, developing sector-specific targets and roadmaps, creating a regional taskforce, defining clean hydrogen, establishing an emissions certification and electronic tracking framework, developing tariffs for electrolyzers, funding RD&D, clarifying authority for interstate hydrogen pipelines, and engaging in authentic environmental justice engagement.[75] Additional items highlighted in the NASEO publication, *Hydrogen: Critical Decarbonization Element for the Grid, Manufacturing, and Transportation*, include considering government procurements, tax and fiscal incentives, and a carbon price.[76] These broad recommendations can be expanded upon and explored in more detail in a state roadmap and can serve as a basis for State Energy Offices looking for a starting point. A supportive policy and regulatory framework for clean hydrogen is crucial to bringing the cost down and facilitating project deployment. A February 2023 study by the Energy Futures Initiative also acknowledged that there will be a cost gap between the supply-side incentives of the IRA and the conditions needed to form a hydrogen market in the United States which suggests supportive state policies and programs will have a key role to play in accelerating clean hydrogen deployment.[77]

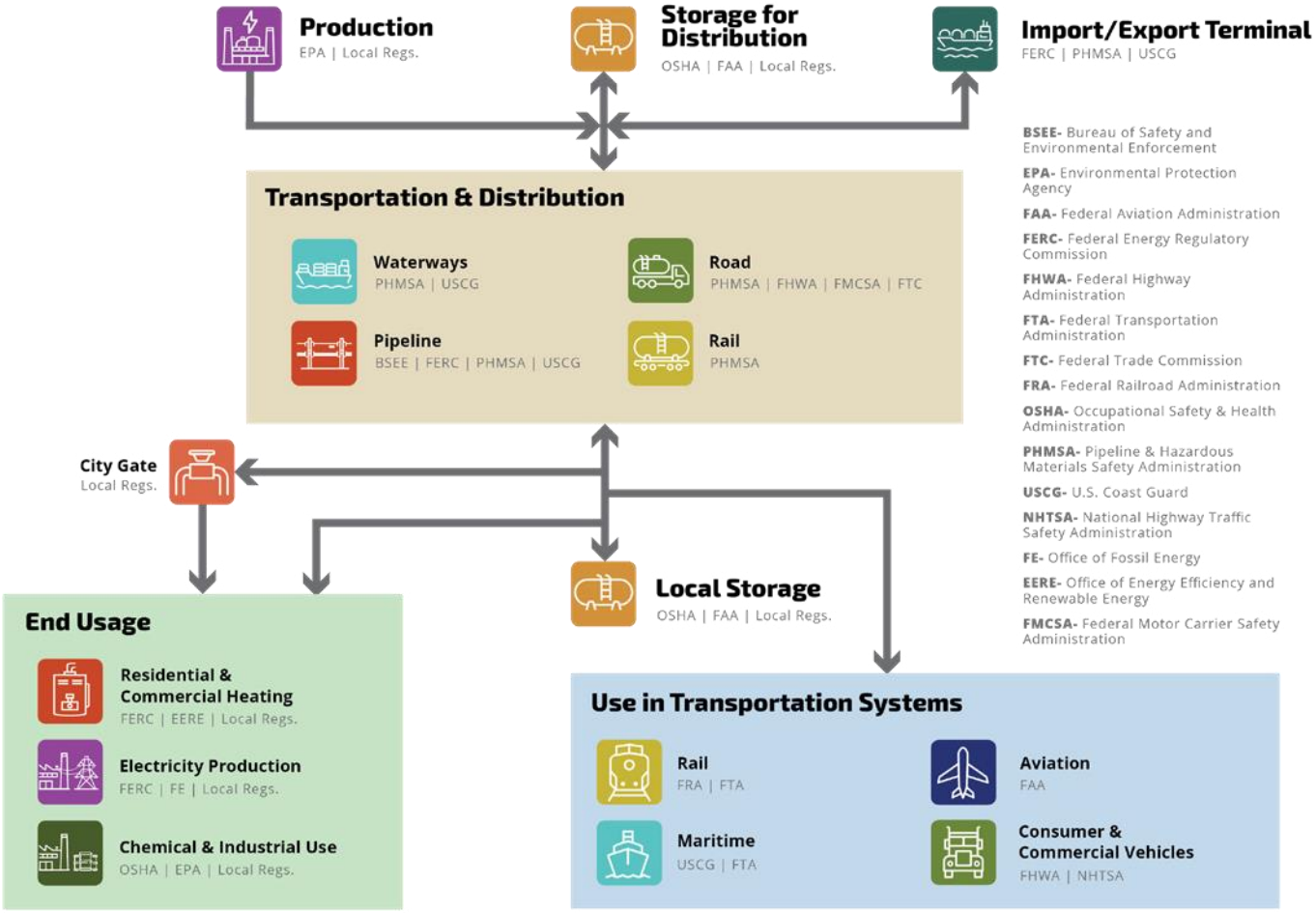
State roadmaps can also provide an outlet to discuss existing policies that may be a barrier to clean hydrogen development. For example, Iowa's study highlights the fact that their existing ratemaking policies are not flexible enough to provide a pathway for clean hydrogen. The study encourages the State Legislature to adopt a flexible ratemaking mechanism that allows for curtailed power to be sold back to the grid to be used by clean hydrogen producers which allows them to purchase power directly from utilities rather than entering into a more complicated power purchase agreement or become vertically integrated with a renewable power source.[78] In the Connecticut Hydrogen Task Force Study, recommendations were made for the Connecticut Department of Energy and Environment

to look at current fuel reduction measures and modify them if necessary to ensure applicability with medium and heavy-duty vehicles.[79]

REGULATORY: Regarding the regulatory environment for clean hydrogen, State Energy Offices are not usually directly involved, but may serve as a convener of relevant state agencies and other stakeholders or provide recommendations to the state legislature, PUC, state environmental agencies, or other state agencies. Regulatory considerations around clean hydrogen can cover a wide range from safety, planning, siting, and permitting to implications of the Clean Hydrogen Production Standard (CHPS). There are also technical and environmental, health, and safety standards that should be considered.

Figure 2 looks at the current federal landscape for regulations along the entire hydrogen value chain and additional key regulatory considerations are explored below.

Figure 2: Hydrogen Regulatory Map[80]



Source: U.S. Department of Energy Office of Scientific and Technical Information

- Market considerations: While CHPS is not a regulatory standard, it could be incorporated into state regulations to spur market growth and draw developers interested in federal financing opportunities that may require meeting the standard.
- PUC considerations: There are avenues to explore through the PUC such as flexible ratemaking mechanisms that can lower production costs, which the Iowa study encourages.[81] Oklahoma also recommends the State Energy Office work with the PUC to engage utilities in incorporating clean hydrogen into their Integrated Resource Plans. Utility tariffs and state incentives to support clean hydrogen are also worth exploring. In the case of consumer-owned utilities that are generally not regulated by the PUC, State Energy Offices should consider engaging municipal owned utilities and cooperatives.
- Siting/Permitting considerations: Pipelines are a gray area in the regulatory space. Again, while State Energy Offices are not usually directly involved in permitting, siting, and regulating pipelines, there are opportunities for State Energy Offices to engage with the relevant regulators and private sector representatives to coordinate and streamline the process. For example, the Wyoming Energy Authority (WEA) highlights plans for WEA to collaborate with other Wyoming state agencies and to leverage federal and private sector investments for pipeline infrastructure; particularly on state lands.[82] When looking at developing standards or regulatory requirements for clean hydrogen, states may benefit from examples from other energy sectors. For example, a study funded by the California Energy Commission and authored by UC Irvine's Advanced Power and Energy Program highlights the fact that the dairy sector's streamlined permitting process for dairy biomethane projects can serve as a model for hydrogen projects. CEC has also been helping to convene local stakeholders to help expedite permitting processes, a process that has helped get fueling stations developed.[83]
- Environmental/health/safety standards: States should consider the importance of having environmental, health, and safety standards in place related to clean hydrogen. DOE is working to develop practices and procedures related to hydrogen production, transport, and use and states can determine what opportunities exist within their own states to identify standard processes or model codes. Additional information can be found on the DOE website. The Center for Hydrogen Safety also provides resources and trainings that are worth exploring and including in a state roadmap.

Benefits

Benefits associated with clean hydrogen are widespread and states should plan to explore benefits within their state roadmap to determine their applicability and potential. Some of the benefits explored in this section include decarbonization, fuel diversification, resilience, and economic development.

DECARBONIZATION: Clean hydrogen has the potential to play a key role in the energy transition and in reducing the emissions of hard-to-decarbonize sectors. NASEO's publication, *Hydrogen: Critical Decarbonization Element for the Grid, Manufacturing, and Transportation* walks through the role of clean hydrogen as a long-term energy storage solution to meet demand; and clean hydrogen's role in decarbonizing chemical, metal, and material production processes; and in powering transportation – particularly heavy-duty trucking, rail, marine, and aviation.[84] This also means that many of the current production models for hydrogen, most commonly from methane in natural gas, will need to be paired with CCS or transitioned to clean production pathways with renewable energy or nuclear. States can consider supporting clean hydrogen RD&D projects to encourage acceleration, putting in place emissions limits or carbon prices, offering tax credits or incentives for clean hydrogen, and other pathways to encourage the growth of the clean hydrogen industry.[85] The Connecticut Task Force Study outlines some of these opportunities to account for the clean benefits of hydrogen including expanding clean transportation incentives, evaluating policies that facilitate the decarbonization of heavy-duty trucking and industry, exploring market-based approaches to reduce carbon intensity, and incorporating clean hydrogen into the state Renewable Portfolio Standard.[86] Clean hydrogen can also be incorporated into larger clean energy goals, policies, or plans. According to the DOE roadmap, clean hydrogen can reduce emissions in the United States by around 10 percent by 2050 relative to 2005 based on estimated production carbon intensities, production pathways, and demands from the transportation, industry, and energy storage sectors.[87]

FUEL DIVERSIFICATION: Clean hydrogen provides pathways to upgrade petroleum and bio-based fuels and can produce synthetic fuels which serve as alternatives to gasoline, diesel, and jet fuel using captured carbon dioxide. It can also serve as a heating fuel. This provides a multitude of opportunities to support decarbonization efforts in these sectors and provide alternate options for fuel. Oklahoma's roadmap highlights the key role of hydrogen as a fuel source for the heavy-duty trucking industry due to the longer range than batteries, heat and water as the only exhaust, and shorter refueling time when compared with diesel.[88]

RESILIENCE: The long duration storage opportunities afforded by clean hydrogen explored earlier in this report are particularly valuable during times of low supply from other renewable generation. Microgrids can also integrate hydrogen fuel cells and disconnect from the grid during blackouts or other disruptions. The recently launched H2 Innovation Experience in California is a clean hydrogen microgrid that will provide power to over 100 homes for up to seven days when disconnected from the grid. Solar energy powers the microgrid and the excess energy is converted into clean hydrogen to be stored until it is needed.[89] A recent EFI study looks at the role hydrogen fuel cells played during Superstorm Sandy when they provided emergency backup power to telecommunications towers.[90] As states prepare clean hydrogen roadmaps, they should look at these different opportunities such as long duration storage

or distributed hydrogen for resiliency and hazard mitigation to protect their communities and critical infrastructure. State Energy Offices can also build on the resiliency benefits by incorporating clean hydrogen into other state plans such as resiliency or energy security.

ECONOMIC DEVELOPMENT: Clean hydrogen implementation can support local, state, and regional economic development. Colorado's roadmap looked at the impact of a low-carbon economy on jobs. Their analysis determined that jobs related to hydrogen deployment would amount to between 6,000 and 12,000 in 2030 and could grow to 250,000 jobs in 2050. While most of these jobs would be found in Colorado, they also acknowledged that some of the manufacturing jobs might be out of state.[91] In the *Renewable Hydrogen in Iowa* study, the authors identified several economic development opportunities associated with renewable hydrogen including a $6.375 billion gross state product increase by 2050 and the creation of more than 7,000 new jobs by 2030. They also determined that the employment factor for clean hydrogen was higher than wind energy in the state. The New York State Energy Research and Development Authority (NYSERDA) is working on their own hydrogen roadmap but have also started the process of commissioning a market analysis study that will look at economic development opportunities related to hydrogen in New York.[92]

Box 3: Utah Intermountain Power Project Spotlight

The Utah Intermountain Power Project involves the transition of a coal-generation facility to a combined-cycle gas power plant that will initially run on a mixture of natural gas and hydrogen before transitioning to 100 percent hydrogen by 2045.[93] A report by the Utah Foundation on the economic impacts of the project found that the construction will support 500 jobs a year from 2022-2026. Construction will center on renewable energy and clean hydrogen infrastructure, opportunities for natural gas and other commodities storage, and the production, storage, and export of hydrogen gas.[94] These jobs will be concentrated in rural Millard County, and they will represent 10 percent of the county's average employment.[95] Other benefits include additional tax revenue to the state government, resulting in over $20 million in revenue annually.

State Energy Offices may also consider that economic development agencies are often crucial partners or stakeholders to engage in the roadmap process. There also may be interest from state economic development agencies in funding roadmaps. For example, in Michigan, the Michigan Economic Development Corporation provided funding to the University of Michigan to develop a hydrogen roadmap for the state.

Roadmaps can also explore regional collaboration opportunities to accelerate economic development opportunities such as a hydrogen hub. These local networks bring together producers, consumers, and the necessary infrastructure to produce, process, deliver, store, and use clean hydrogen.[96] This will provide more economic and workforce opportunities to the states involved in the regional partnership or collaboration by keeping all stages of the clean hydrogen deployment process within the same area. Certain states may have a more applicable market or need for clean hydrogen but lack some of the production capabilities. A regional partnership can ensure that the necessary infrastructure and end users are all in place and reduce potential for isolated projects with limited economic or market potential. There are also synergies with CCS and complementary infrastructure and operations.

The DOE roadmap also outlines the potential of introducing clean hydrogen technologies to regions with existing infrastructure that can transition to support clean hydrogen.[97] These transition opportunities will allow states and regions that have relied on fossil fuel infrastructure and the resulting economic and workforce benefits to continue to thrive. As mentioned in the Gulf Coast study, having an existing workforce that understands the process and how the infrastructure works is incredibly valuable. This can have the added benefit of providing opportunities to oil and gas workers as the energy industry transitions. Skills are especially valuable when looking at hydrogen produced with CCS or blending hydrogen into existing natural gas pipelines. Several of the public hydrogen hub concept papers highlight plans to reskill or retrain oil and gas workers and to provide training and educational opportunities for workers new to the industry. Skills related to petrochemicals, gas processing, and other methods of production can also be applied and retrained as needed. More information can be found in the NASEO guide on State Strategies to Develop and Support the Emerging Clean Hydrogen Workforce.

Challenges

There are several significant challenges associated with clean hydrogen production, transport, and use. These may differ from state to state, but roadmaps provide an opportunity to explore these challenges and potential solutions. Some of the challenges included in existing state roadmaps include transport, water, leakage, and cost.

TRANSPORT: Clean hydrogen can be transported on trucks, rail, ships, or through pipelines. Pipelines are the least expensive mode of transport. To transport hydrogen by truck, rail, or ship the hydrogen must first be compressed into gas or liquefied. The preferred method of transport will usually depend on the length of travel required (gas is usually used for travel under 200 miles, while cryogenic liquification covers longer distances as the transport process is more efficient).[98,99] State Energy Offices may look at the costs associated with the different options available based on the distance that the clean hydrogen will need to travel and potential risks of leakage. When analyzing the potential transport options for the state, Iowa's study looks at their key location for truck and rail travel and highlights their location as a transportation hub with a large railway, multiple highways, and truck stops found throughout the state to support hydrogen transport if needed.[100]

WATER: One of the methods of hydrogen production -- extraction from water -- can also lead to concerns regarding availability of water for different uses and stakeholders, drought and water quality. Roadmaps can address these concerns by identifying potential water sources or exploring alternative production methods such as steam methane reforming paired with CCS which would require much less water. There should also be considerations made of the desalination process that would be necessary for using salt or brackish water. Colorado highlights the importance of considering local water availability when identifying potential hydrogen production locations in the state.[101] The Oklahoma roadmap looks at the question of water supply in their state and identified highly treated municipal wastewater as the most readily available source for hydrogen production. This method is also being utilized by private sector companies. In 2022, Plug Power announced it was building a clean hydrogen production plant in California using treated sewage. Plug Power is building the production plant and a water treatment plant that will utilize treated sewage water and

recycle the water to be used for the production. The water treatment plant will produce 1.2 million gallons of recycled water each day and 120,000 of those gallons will be used by the hydrogen plant with the remaining amount going to the city.[102]

SAFETY AND LEAKAGE: Innovative energy technologies such as clean hydrogen are often associated with concerns around safety- particularly related to human health and climate change. This is partially due to unfamiliarity with the technology and misinformation, but there are some real risks that should be explored in state roadmaps so that states are both prepared to deal with these potential consequences and understand how to communicate about them to impacted stakeholders. One of the risks is centered around burning hydrogen for vehicles or home heating which generates nitrogen oxides (NO_x). According to a study by the National Centre for Atmospheric Science, University of York, in the United Kingdom, these nitrogen oxides will disproportionally impact urban poor living in high-density housing areas.[103] Another safety risk is leakage which can be harmful to human health and contribute to climate change as it impacts air quality and the ozone layer.[104] The potential risk of leakage is possible along the entire clean hydrogen value chain from production, transport, to end use. A 2023 study led by the Environmental Defense Fund found that hydrogen transport is estimated to generate the most emissions along the entire value chain, but the rates vary depending on the transport mechanism and process.[105] For clean hydrogen produced with natural gas paired with CCS, the leakage rate is approximately 1.5 percent.[106] When the Environmental Defense Fund study authors looked at available information and studies on emissions over the hydrogen value chain, rates ranged from 0.2% to 20%[107], suggesting more detailed assessments need to be conducted and additional information needs to be collected. Unfortunately, there are also few technologies available that support the detection and monitoring of leakage from clean hydrogen production, transport and use.[108] As one potential solution, states can look at establishing hydrogen blending limits within natural gas pipelines to reduce the risk of leakage and other concerns. There should also be standards in place on the handling of hydrogen and welding, pressure, and temperature tolerance associated with transport. It would also be beneficial to explore training modules for workers and first responders on these safety and leakage concerns.

COST: The cost of clean hydrogen is currently one of the biggest challenges. DOE's Hydrogen Shot is looking to bring the cost down to one dollar per kilogram in one decade and the IRA 45V tax credit will provide credits for qualifying projects. State Energy Offices can support this goal by providing additional grants or incentives for innovative RD&D of clean hydrogen. In their state roadmap, Oklahoma looked at some of the costs to produce clean hydrogen including electricity, labor and maintenance, and water. Specifically, the focus was on various scenarios of hydrogen production from 22 MMT to 41 MMT with the cost of electricity at 3.5 cents per kWh. Annually, these operational costs for hydrogen could reach over $1 billion with electricity being the highest expense. Oklahoma does acknowledge the benefit of their low electricity rates in the state as being beneficial to hydrogen producers.[109] According to the study by Oregon, electricity makes up between 30-75 percent of the production costs for clean hydrogen.[110] Electrolyzers cost between $650 and $900/kW, but with industry scaling up and federal support, the costs could fall by 40 percent through 2025.[111] It will also be important for states to consider the potential increase of consumer costs when using clean hydrogen for power generation with costs as high

as they are right now. According to a 2022 study by Energy Innovation, clean hydrogen is currently 6 to 15 times more expensive than natural gas and blending hydrogen with natural gas raises the price significantly.[112] In addition, the capacity factor concerns of electrolyzers should be explored. Running an electrolyzer full time will yield lower costs in that part of the cost of hydrogen than running it part time, but this could lead to higher electricity prices. According to a report in the *Compendium of Hydrogen Energy*, to keep the cost of hydrogen low, the use of the electrolyzer and electricity price should be balanced.[113]

Collaborators and Partners

It is important for state roadmaps to explore the key collaborators and partners that should be involved in and consulted with in the process of designing programs, policies, regulations, and projects to support clean hydrogen deployment. Examples include state agencies (such as economic development, transportation, and environmental quality), universities, local governments, communities and community-based organizations, Tribes, investor-and-consumer-owned utilities, the private sector (such as industry, financial institutions, business leaders, and developers). These collaborators and partners may be brought in to serve on an Advisory/Review Committee or Working Group to support the actual development of the roadmap, or the roadmap may outline the key players that should be involved in future clean hydrogen activity. Some current partnerships that may serve as examples include the Pacific Northwest Hydrogen Association (PNWH2A) and the Western Green Hydrogen Initiative. The impetus for PNWH2A was the launch of the DOE Hydrogen Hub program and an interest in exploring opportunities in Washington and Oregon. The group brings together the Washington and Oregon State Energy Offices, industry, universities, the Pacific Northwest National Lab (PNNL), utilities, Tribes, labor unions, and more to explore the potential for a Northwest hydrogen hub. Some of the strategies the PNWH2A are considering include the use of mapping and geospatial tools and data to advance equity, a workforce development and jobs plan, industry cluster development, and Tribal engagement. The Western Green Hydrogen Initiative brings together state government agencies, utilities, and universities to support states in designing state roadmaps for clean hydrogen.

Governors and State Energy Offices may also facilitate partnerships through formal agreements or Memorandums of Understanding (MOUs). For example, Governors Asa Hutchinson (Arkansas), John Bel Edwards (Louisiana), and Kevin Stitt (Oklahoma) facilitated a bipartisan three-state partnership to establish a regional hydrogen hub in March 2022. The partnership allows the three states to compete for IIJA funding together and includes provisions for promoting investment in infrastructure for production and transportation of low-carbon hydrogen; prioritizing direct capture of carbon for all phases of hydrogen development; working with industry, transportation networks and ports to connect major facilities with high carbon footprints to hydrogen infrastructure for fuel blending and reduction of carbon dioxide emissions; and working to support hydrogen production to support all phases of industry that can use hydrogen as a fuel source.[114] These types of regional partnerships between states provide opportunities for collaboration and are mutually beneficial as they bring together multiple pieces of the value chain and advantageous infrastructure and natural resources available in each of the states. For the

Oklahoma-Arkansas-Louisiana partnership this includes an inland seaport system; rail and pipeline infrastructure, and interstate freight highways.[115] Multi-state partnerships also expand the diversity of potential end users.

While these regional partnerships are valuable, especially when looking at infrastructure and market concerns for clean hydrogen, in-state collaboration and partnerships are also key. For example, the Alaska Hydrogen Energy Working Group brings together interested stakeholders in the state to share information on potential hydrogen projects in Alaska and to plan for a state roadmap. The Working Group is led by the Alaska Center for Energy and Power and has participation from the State Energy Office. In Minnesota, legislation created the Minnesota Renewable Hydrogen Initiative. As a result, the Minnesota Department of Commerce (State Energy Office) coordinated the initiative and brought in representatives from industry, academia, government, and non-government entities. Illinois similarly had a Hydrogen Economy Task Force formed through legislation to look at hydrogen deployment opportunities in the state. The goal of the Task Force was to establish a plan for a Hydrogen Hub in the state, identify opportunities to integrate hydrogen into existing sectors in the state such as transportation and industry, identify barriers to deployment, and recommend policies to the governor. Participants include state government, universities, manufacturing and trade associations, community groups, and more.

These partnerships can provide valuable insights and opportunities to address challenges and share information, which is particularly valuable when developing a roadmap for the state or region. These groups can also contribute to the development of a roadmap. Roadmaps should also outline the key role of the members of the partnerships and additional stakeholders. For states without existing formalized partnerships, roadmaps can also serve to outline who the key players are and what role they should play going forward. For example, Wyoming focused on the role of six main groups and structured the entire roadmap around their roles in facilitating different actions. These included (1) the Wyoming Energy Authority (2) private sector (3) the University of Wyoming School of Energy (4) State and local government (5) Economic Development Agencies and (6) Resource and Enabling Organizations such as the Western Green Hydrogen initiative, Labor Unions, community colleges, etc.

The role of stakeholder engagement, partnerships, and collaborations will be explored in more detail in a forthcoming NASEO report.

Incorporating Clean Hydrogen into Existing Plans

State Energy Offices are often balancing the need to develop and/or update multiple plans through their own offices or in collaboration with other state agencies including Comprehensive State Energy Plans, Energy Resilience Plans, Clean Energy Plans, and Economic Development Plans . As such, it is worthwhile to explore how State Energy Offices can incorporate clean hydrogen into existing plans and how state clean hydrogen roadmaps can align with existing plans. Existing plans may outline opportunities for the state around clean hydrogen that could be further explored through a roadmap. For example, the Oklahoma State Energy and Environment Plan of 2021 states that Oklahoma must "support development of hydrogen as a major fuel stock in the ever-growing decarbonized economy."[116] It also outlines the existing strong potential for a hydrogen economy in the state due to available renewable energy resources, storage space for producing hydrogen with CCS, and the central location of the state for transportation ease and along with the availability of an existing oil and gas workforce. The state roadmap then dived into these items further by looking at specific action items that the state can take including reviewing and augmenting existing rules and laws impacting clean hydrogen production and transport, creating a hydrogen collaborative of relevant stakeholders, and expanding the state's investments in clean hydrogen R&D. In addition, the 2022 Virginia Energy Plan suggests that the state should "develop a hydrogen roadmap with state, local, and private sector stakeholders to poise Virginia to capitalize on hydrogen generation opportunities".[117] Other states (that do not have existing roadmaps) could follow a similar model by articulating the benefits of doing so in their state energy plan. Clean hydrogen aligns with a variety of relevant state priorities (including resiliency, clean energy, and economic development) and it is important for State Energy Offices interested in clean hydrogen to consider this when developing cross cutting plans for the state.

Conclusion

As State Energy Offices explore opportunities to develop clean hydrogen roadmaps, this tool can provide a starting point for some of the key considerations and lessons learned from other states. Once the roadmap is developed, states should bear in mind the importance of monitoring progress for any suggested recommendations or next steps to assess accomplishments or needed modifications. This is especially important as new data becomes available or policy/regulatory changes arise. Clean hydrogen is one of many tools available to states as they explore opportunities for decarbonization and resilience, and they should be aware of the different challenges and opportunities associated with the clean hydrogen value chain and how it aligns with their state's needs.

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