DRAFT 2024 CONNECTICUT CLEAN HYDROGEN ROADMAP

Commissioned by the Connecticut Department of Energy and Environmental Protection

Prepared by ENGIE Impact

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The 2024 Connecticut Clean Hydrogen Roadmap was prepared by ENGIE Impact under the coordination of the CT Department of Energy and Environmental Protection (DEEP). It was designed to assess the potential role of hydrogen in helping the state realize its ambitious climate objectives.

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Abbreviations

ATAG	Air Transport Action Group
BEV	Battery Electric Vehicle
BNEF	Bloomberg New Energy Finance
CAPEX	Capital Expenditure
CARB	California Air Resources Board
CCUS	Carbon Capture, Utilization, and Storage
CEEJAC	Connecticut Equity and Environmental Justice Advisory Council
CHIT	California Hydrogen Infrastructure Tool
CHPS	Clean Hydrogen Production Standard
CO2	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
DEEP	Connecticut Department of Energy and Environmental Protection
DOT	Department of Transport
EIA	Energy Information Administration
EJ	Environmental Justice
EPA	Environmental Protection Agency
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCHEA	Fuel Cell and Hydrogen Energy Association
GC3	Governor’s Council on Climate Change
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GMF	Global Maritime Forum
H2	Hydrogen
ICE	Internal Combustion Engine
IES	Innovative Energy Solutions
IRA	Inflation Reduction Act
IIJA	Infrastructure Investment and Jobs Act
IRENA	International Renewable Energy Agency
ISO	Independent System Operator
LCFS	Low Carbon Fuel Standard
LCOH	Levelized Cost of Hydrogen
LOHC	Liquid Organic Hydrogen Carriers
LPG	Liquified Petroleum Gas
MACC	Marginal Abatement Cost Curve
MGO	Maritime Gas Oil
MTCO2	Metric Ton of Carbon Dioxide
MTCO2e	Metric Ton of Carbon Dioxide Equivalent
MW	Mega Watt
MWh	Mega Watt Hour
NACFE	North American Council for Freight Efficiency

NPV	Net present value
NOx	Nitrogen Oxides
O&M	Operation & Maintenance
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
PEM	Proton Exchange Membrane
PM	Particulate Matter
PPA	Power Purchase Agreement
PURA	Public Utilities Regulatory Authority
PV	Photovoltaic
RACT	Reasonably Available Control Technology
REC	Renewable Energy Credit
RNG	Renewable Natural Gas
RPS	Renewable Portfolio Standard
SAF	Sustainable Aviation Fuel
SOEC	Solid Oxide Electrolyzer Cell
SOx	Sulfur Oxides
TCO	Total Cost of Ownership
TRL	Technology Readiness Level
UI	United Illuminating
U.S. DOE	United States Department of Energy
WACC	Weighted Average Cost of Capital
WHEJAC	White House Environmental Justice Advisory Council

Executive Summary

A. Clean Hydrogen Roadmap Purpose

Connecticut has long been a leader in both hydrogen technology and decarbonization ambition, and now has a chance to merge those strengths by leading the transition to a clean hydrogen economy. Over the past few years, the state has established ambitious greenhouse gas (GHG) emission reduction targets:

- 45% below 2001 levels by 2030 as mandated by *An Act Concerning Climate Change Planning and Resiliency*
- 80% below 2001 levels by 2050 as mandated by *The Global Warming Solutions Act*
- 100% zero-carbon electric sector by 2040 as mandated by *An Act Concerning Climate Change Mitigation*

Achieving these targets will no doubt require a variety of solutions. While existing technologies like electrification paired with renewable energy can effectively decarbonize many energy uses, some applications lack readily available alternatives. In these cases, clean hydrogen emerges as a potential solution for particular end use applications, especially those that require high power when electricity is limited or unavailable.

This roadmap represents a crucial step towards establishing a reliable and sustainable hydrogen ecosystem in Connecticut. The roadmap seeks to achieve the following objectives:

- Articulate Connecticut's aspirations for clean hydrogen's integration into its energy landscape, outlining its potential contributions to decarbonization, economic growth, and environmental justice
- Encourage the use of hydrogen produced from renewable energy
- Guide strategic development of clean hydrogen production, infrastructure, and end use by identifying the target technologies and their associated volumes over time to scale Connecticut's hydrogen economy
- Identification of benefits and risks associated with hydrogen and tactics to address the identified risks
- Recommend policies, programs, and pilot projects to support clean hydrogen development and deployment in alignment with state goals

Hydrogen can be produced in many different ways, some of which present little or no emissions benefits. As a cornerstone of the roadmap, DEEP proposes defining clean hydrogen as hydrogen not produced from fossil fuel feedstocks and with a carbon intensity of ≤ 2 kg CO2e/ kg H2 on a life cycle basis that includes owned and retired environmental attributes. This proposed clean hydrogen definition supports the following statewide objectives:

1. Reduces carbon emissions in the near term over the lifecycle of hydrogen's production and use, and supports the state's overall climate goals
2. Advances net zero supply chains, leverages market mechanisms to grow renewable electricity supplies, and reduces reliance on fossil fuels
3. Adheres to environmental justice principles and the goals of the DEEP's key Energy Strategy Lenses: Climate, Equity, Affordability, Economic Development, and Reliability and Resilience

B. Hydrogen Costs

A variety of hydrogen production technologies have the potential to produce clean hydrogen based on Connecticut's definition, including but not limited to electrolysis, gasification, and pyrolysis. The roadmap assumes electrolysis will be the primary clean hydrogen production method in the state, but other production technologies can be considered on a project-by-project basis.

Connecticut has advantages and disadvantages when it comes to electrolytic hydrogen production. On the positive side, Connecticut has substantial precipitation and typically has ample supplies of water relative to other states, a key input to the electrolysis process[1]. However, Connecticut, and the northeast in general, has some of the most expensive electricity in the US, which will impact the cost of clean hydrogen production.

Figure 1 shows the levelized cost of hydrogen (LCOH) over 2027, 2032, and 2040. In all three time periods, electricity is the dominant contributor to the cost, though capex is a larger contributor in 2027 and decreases over

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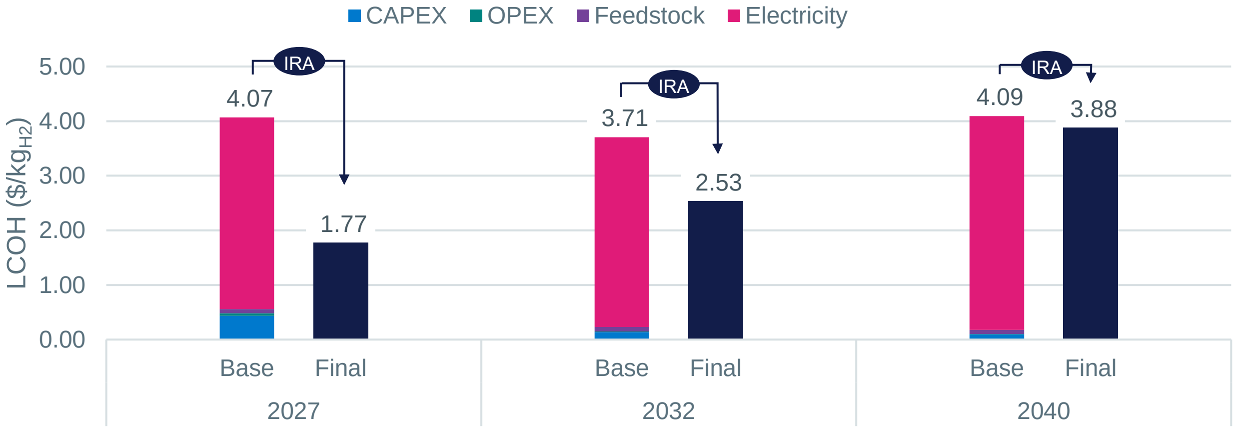
[1] While Connecticut is rich in water resources, the state also places a high priority on the conservation and sustainable management of these resources. This commitment to environmental stewardship does not pose a constraint to the hydrogen electrolysis process, but rather aligns with the overall goal of promoting clean and sustainable energy solutions.

time driven by technological improvements to the production process. For modeling simplification purposes, these costs assume electricity is provided by onshore wind produced in Connecticut specifically for the clean hydrogen production. The electricity costs utilized here are within the same range as the costs utilized by the U.S. DOE's National Clean Hydrogen Strategy and Roadmap, FCHEA's Roadmap to a US Hydrogen Economy, and Lazard's 2023 Levelized Cost of Energy+.. It is important to note that this assumption was utilized purely for analytical purposes. Although the roadmap utilizes such an assumption, it is not a recommendation for Connecticut to install the onshore wind power considered by the modeling or pursue the electricity price used. The electricity price of $0.077/kWh from onshore wind serves only as a simplified proxy of price, devoid of speculations, for modeling purposes. DEEP recognizes the amount of electricity produced by onshore wind required for clean hydrogen production may not be feasible or desired. In practice, a combination of generation methods would probably be used to power clean hydrogen production in Connecticut. The model also assumes that the renewable electricity supply matches the electricity demand on an annual basis.

For comparison, the *U.S. DOE Pathways to Commercial Liftoff: Clean Hydrogen* report projects that hydrogen will be $1.6/kg by 2030 before inclusion of the Inflation Reduction Act (IRA) Hydrogen 45V tax credit [i], which is about 55% cheaper than the 2032 LCOH this roadmap projects for Connecticut before inclusion of the 45V tax credit. The cost difference is driven almost entirely by Connecticut's higher electricity prices, relative to the national average used in the U.S. DOE's analysis.

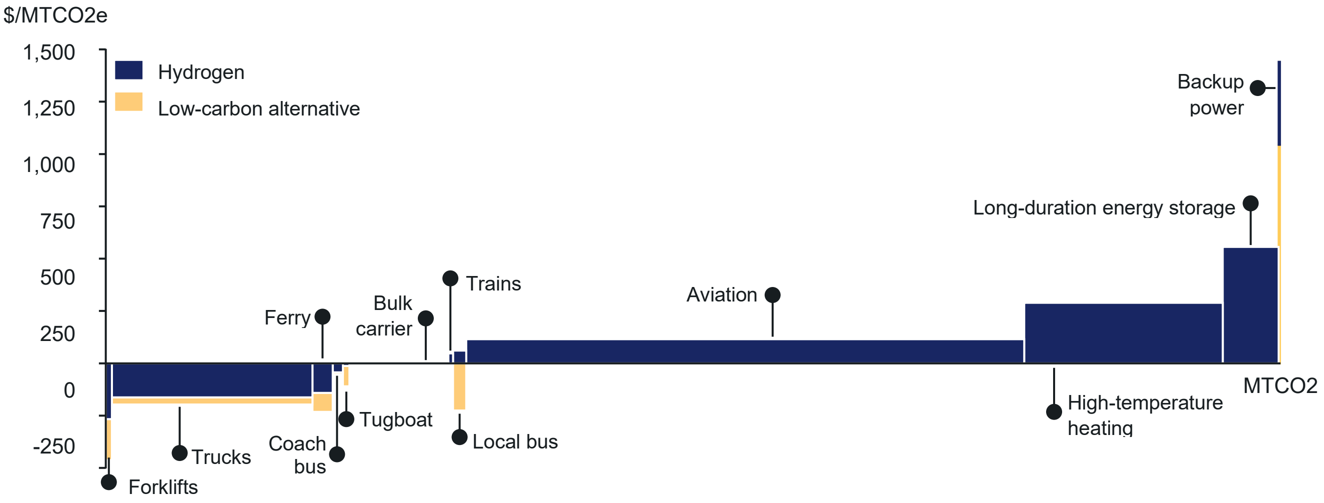
Figure 1 - LCOH with Electrolysis in Connecticut



Assumptions: 1. Hydrogen volumes of ~700 kg H2/hr in 2027, ~ 4,000 kg of H2/hr in 2032, and ~ 6,000 kg H2/hr in 2040; 2. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit), and IRA benefits for renewables, which are assumed to remain available through 2040; 3. Feedstock considered for electrolysis is water; 4. Annual matching requirement for electricity source.

More important than the LCOH is how it impacts the total cost of different end uses that have the potential to be decarbonized with hydrogen. One way to visualize the impact for each end use is to use a Marginal Abatement Cost Curve (MACC), as shown in Figure 2. In a MACC, the cost to abate a metric ton of CO2e ($/MTCO2e) is shown on the x-axis for different end uses that can be decarbonized with hydrogen. When an end use is below the x-axis in blue, that means that it is cheaper to use hydrogen for that end use than the fossil-based incumbent technology. If another low-carbon alternative is more cost-effective than hydrogen, it is shown in yellow below the hydrogen option.

Figure 2 - Mitigation Abatement Cost Curve – End Uses in Connecticut by 2032



Assumptions: 1. Weighted average cost of capital (WACC) 5%; 2. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit), the IRA benefits for renewables, which are assumed to remain available through 2040, and the IRA CAPEX grant for mobility end uses; 3. Analysis based on 20-year project evaluation.

Many hydrogen end uses, including forklifts, trucks, coach buses, ferries, and tugboats, are more cost effective than the fossil-based incumbent technologies in 2032. However, in all of those end uses, there is another low-carbon alternative that is more cost effective than hydrogen, typically electrification. There are also multiple end uses that will be more expensive to run on hydrogen compared to the fossil-based incumbent technology, including bulk carriers, trains, local buses, aviation, high-temperature heat, long-duration energy storage, and back-up power. However, in all end uses both above and below the x-axis, there will likely be some need for hydrogen, either in specific situations where hydrogen is the cheapest option, or for scenarios when hydrogen is the only decarbonization technology that can meet a specific energy demand.

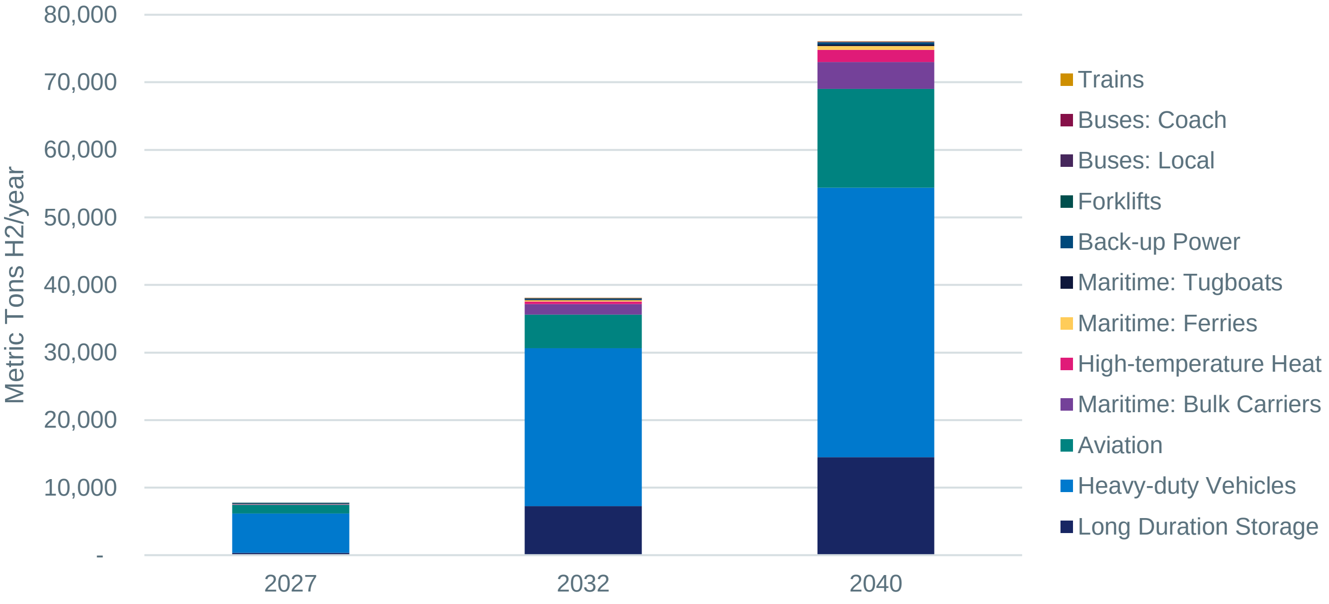
Considering the high hydrogen production costs in Connecticut, the idea of importing hydrogen from other states or countries was explored. However, the analysis concluded that local production still makes economic sense for multiple reasons. While many U.S. states, particularly those in the mid-west with abundant wind resources, can produce hydrogen at lower costs than Connecticut, the additional expenses associated with cross-country transportation of hydrogen offset these savings. As for international imports, despite the potential for cheaper production, foreign-produced hydrogen is ineligible for the 45V tax credit. This factor further incentivizes domestic production in Connecticut over international imports.

C. Hydrogen Demand

As noted in the previous section, even when hydrogen is not the most cost-effective option for a given end use, it still will have some rate of adoption, while coexisting with other low-carbon alternatives. To estimate the potential demand for hydrogen in Connecticut, this roadmap introduces three scenarios: Base Hydrogen, High Hydrogen, and Low Hydrogen. These scenarios consider various factors impacting hydrogen adoption, including economic considerations and the availability of competing technologies.

Figure 3 shows the hydrogen demand over time in the Base Hydrogen Scenario, which reflects a moderate growth trajectory for hydrogen, with a significant role in certain sectors but not becoming the dominant energy carrier for any end use by 2040. Hydrogen demand in this scenario is projected to be 7,700, 38,000, and 76,000 metric tons of hydrogen by 2027, 2032, and 2040 respectively. The top three end uses driving this demand are heavy-duty trucking, aviation, and long-duration energy storage, which account for 90% of total hydrogen demand by 2040. Other notable end uses include bulk carriers and maritime shipping, which contribute an additional 8% to the total hydrogen demand in 2040.

Figure 3- Base Hydrogen Scenario: Hydrogen Demand by End Use through 2040



D. Clean Hydrogen Impact and Resources Required

The cost and adoption rate analyses concluded that hydrogen will have an important, but limited, role to play in Connecticut's decarbonization journey. Assuming a carbon intensity of 0.45 kg CO2e/ kg H2, the upper carbon intensity limit for receiving the maximum benefit from the 45V tax credit, hydrogen would abate 472,000 tons of CO2e by 2040 and 781,000 tons of CO2e by 2050. The 2050 value is equivalent to 1.9% of Connecticut's total 2018 GHG emissions. For reference, the *U.S. DOE Pathways to Commercial Liftoff: Clean Hydrogen report* predicts that by 2050, clean hydrogen could reduce overall U.S. GHG emissions by 10% versus 2005 baseline levels. Hydrogen is projected to have a smaller role in decarbonization in Connecticut compared to the US average both because Connecticut does not have some heavy industries that hydrogen is well suited to decarbonize (e.g., steel, cement, ammonia), and because Connecticut has high electricity prices, which has an increased impact on the cost of hydrogen compared to electrification. As section 3.a.i shows, this roadmap considers as a base scenario hydrogen adoption rates in 2040 ranging from 2% (local buses) to 40% (long-term energy storage) depending on the end use. The adoption rate for 6 of the 12 end uses analyzed is less than 10% (local buses, trains, backup power, high temperature heat, coach buses, and heavy-duty trucking). Despite limitations, hydrogen can play an important complementary role for Connecticut's decarbonization goals, especially for hard-to-electrify end uses.

Achieving these volumes will require a significant amount of new renewable electricity, including 1,600 MW of renewables by 2040. For comparison, this is about 16% of Connecticut's current electricity use today. Under the roadmap modeling assumptions, scaling hydrogen will require just under $5 billion in capital investment through 2040, with the majority of investment going to renewable electricity construction. However, this number could be higher depending on the renewable energy mix and respective prices.

The transition to hydrogen energy is expected to create a net increase in jobs in Connecticut due to the expansion of the energy sector. It is estimated that 430 new sustained hydrogen-related jobs will be created by 2040, while the displacement of approximately 40 fossil fuel jobs is anticipated. However, with proper training and workforce development programs, these displaced workers should be able to find new opportunities within the hydrogen value chain.

Table 1- Clean Hydrogen Roadmap Key Targets and Resource Requirements Through 2040

	Short term: Through 2027	Medium term: Through 2032	Long term: Through 2040
Target hydrogen demand, *tons/year*	7,700 tons/year	38,000 tons/year	76,000 tons/year
Renewable capacity, *MW*	160 MW	800 MW	1,600 MW
GHG emissions reduced from hydrogen w/ carbon intensity of 0.45 kg CO2e/ kg H2, *tons/year*	63,000	224,000	472,000
Cumulative capital invested, *$ millions*	$530	$2,530	$4,990
Sustained jobs created	50 jobs	210 jobs	430 jobs

E. Barriers, Risks, and Environmental Justice

Of course, scaling the hydrogen economy will require more than just identifying key end uses and their target volumes. There are many barriers to adoption that will need to be addressed to achieve Connecticut's decarbonization goals, including:

1. **Affordability** of hydrogen technologies compared to fossil-based incumbent and low carbon alternatives
2. **Availability** of hydrogen, and hydrogen derivatives
3. **Accessibility** of hydrogen and hydrogen derivatives via transport and storage infrastructure
4. **Acceptance** of hydrogen by both stakeholders along the hydrogen value chain and the public

Additionally, hydrogen comes with a variety of risks that need to be managed to ensure that hydrogen scales in a way that is consistent with Connecticut's policy needs and considerations. Hydrogen was evaluated against five Energy Strategy Lens objectives to identify any potential risks from hydrogen and create a plan to address them.

Table 2 – Energy Strategy Lens Hydrogen Objectives

Energy Strategy Lens	Hydrogen Objectives
1. Affordability	Achieve cost competitiveness with fossil-based incumbent technologies and low carbon alternatives
2. Climate	Reduce GHG emissions in line with Connecticut's statewide decarbonization goals
3. Equity	Ensure physical accessibility of hydrogen infrastructure and enhance overall health & well-being benefits from reduced air pollution for all communities
4. Reliability & Resilience	Achieve reliability, resilience, and safety at least on par, and ideally better, than fossil-based incumbent technologies
5. Economic Development	Have a net positive impact on short- and long-term job creation

A key element of ensuring a just clean energy transition is guaranteeing that all residents, especially those belonging to disadvantaged groups or residing in environmental justice communities, benefit from its environmental, social, and economic advantages. Utilizing hydrogen technologies can enhance the quality of life for everyone, but only if it is implemented with consideration for the specific factors influencing environmental justice communities. While hydrogen can offer substantial benefits for these communities, it can also, in certain situations, worsen existing burdens. Therefore, DEEP has identified three equity-based principles to guide a hydrogen transition focused on inclusive development: Accessibility, Health and Wellbeing, and Sustainable Job Creation. These principles, aligned with DEEP's Environmental Justice Program and the recommendations of external groups, aim to reduce environmental burdens and promote equitable access to opportunities within hydrogen deployment. Each principle corresponds to specific aspects of the environmental and social lenses, guaranteeing that every hydrogen technology's potential to uphold these principles is thoroughly evaluated.

F. Policies, Programs and Pilot Projects

DEEP has identified policies, programs, and pilot projects as three enabling mechanisms to help scale hydrogen at the pace needed to meet Connecticut's decarbonization goals while establishing guardrails to ensure it is done in a manner that is consistent with all of Connecticut's values.

In the short term, DEEP recommends focusing support on the use cases with the highest technology readiness levels, such as heavy-duty trucking, and launching studies to address cross cutting topics such as safety and infrastructure. In the medium-term efforts should focus on scaling the technologies piloted in the short term, and piloting the next set of technologies, including long-duration energy storage, sustainable aviation fuel (SAF), and sustainable maritime fuels. The medium-term enablers should also focus on workforce development, hydrogen cluster formation, and innovation programs that will be key to ensuring the state maximizes the economic benefits from hydrogen adoption. The long-term enablers should focus on piloting the final set of technologies, including high-temperature heat, scaling hydrogen across all end uses, and re-evaluating earlier enablers based on feedback and performance data.

Table 3- Potential Timeline for Key Hydrogen Enablers

	Short term: 2024-2027	Medium term: 2028-2032	Long term: 2033-2040
Policies	• Connecticut Clean Hydrogen Definition • Loans for Net Zero Trucking • Financial Incentives for Net Zero Trucking and Fueling Stations in Environmental Justice Communities • Low Carbon Fuel Standards for Transportation Fuels • NOx Emissions Standards for Hydrogen Combustion	• Financial Incentives for Hydrogen Usage for Long-Duration Energy Storage and High-Temperature Heat • Loans for Sustainable Maritime CAPEX • Financial Incentives for Sustainable Aviation Fuel	• Utility Regulations for Long-duration Energy Storage • Incentives for Load Management
Programs	• Hydrogen Safety Resource Group • Assess Optimal of Hydrogen Fueling Stations • Study Reliability of Hydrogen Transport Methods in Severe Weather • Feasibility study of Underground Hydrogen Storage in Connecticut's Hardrock • Environmental Justice for Equitable Hydrogen Deployment Task Force	• Creation of Hydrogen Clusters • Equitable Hydrogen Job Transition Program • Connecticut Hydrogen Innovation Consortium	• Evaluate and modify, expand, or close previous programs based on stakeholder feedback, successes, and challenges
Pilot projects	• Hydrogen Production, Infrastructure, and Use for Heavy-duty Trucking • Sustainable Maritime Fuel Production, Infrastructure, and Use, including Forklifts	• Hydrogen Production, Infrastructure, and Use for Long-duration Energy Storage • Sustainable Aviation Fuel Infrastructure and Use	• Hydrogen Production, Infrastructure, and Use for High-Temperature Heat

G. Roadmap Methodology and Uncertainty

Connecticut's Clean Hydrogen Roadmap was developed through a collaborative, data-driven process encompassing five key stages:

1. **Goal alignment:** Aligning on a vision for the hydrogen economy to help support Connecticut's climate goals, including identification of potential technologies along each step of the value chain that are most relevant for Connecticut and creation of a clean hydrogen definition
2. **Energy Strategy Lens analysis:** Performing analysis against the 5 Energy Strategy Lenses for each applicable technology for Connecticut along each step of the value chain, including levelized cost of hydrogen and total cost of ownership for each hydrogen end use
3. **Value chain technology selection and quantification:** Selection of technologies for each step of the value chain based on Energy Strategy Lens analysis, calculation of hydrogen demand over time based on rate of adoption for each selected end use, and quantification of resources required to meet hydrogen demand
4. **Enabler identification:** Addressing Energy Strategy Lens risks and barriers to adoption through enablers, which include policies, programs, and pilot projects
5. **Prioritization and next steps:** Prioritization of key policies, programs, and pilot projects to pursue over the short, medium, and long term

While care was taken to ensure a thorough analysis at each stage, as with any forward-looking set of projections, there is uncertainty due to both assumptions taken in the analysis and with future unknowns that cannot be predicted at this time. Below are a few uncertainties that could impact the economics and/or hydrogen rates of adoption in the future:

- *45V tax credit temporality requirements:* The analyses assume that the 45V tax credit will require annual matching of renewable electricity. However, at the time of publishing, the US Treasury Department had recently released their proposed guidance for claiming the 45V Clean Hydrogen Production Tax Credit, which would require hourly matching to receive the tax credit starting in 2028. An hourly matching requirement would increase the cost of in state hydrogen production from electrolysis and increase the relative favorability of other hydrogen production methods, importing from lower renewable energy cost regions outside of Connecticut, and other low carbon alternatives that use less electricity than hydrogen electrolysis.
- *45V tax credit extension:* The analyses assumes that the 45V tax credit will expire as specified in the IRA, meaning hydrogen production plants that come online after 2032 will not be eligible, and those that come online before then will see their credits phase out within the 10-year period currently detailed in the law. If this 45V tax credit were to be extended, the economics for hydrogen compared to electrification for certain end uses would be improved.
- *Renewable electricity assumptions:* The cost of hydrogen is highly dependent on the cost of renewable electricity. Care was taken to project realistic estimates of future renewable costs in Connecticut and surrounding states, but prices could vary based on increased or decreased rates of technological improvements, the cost of land, and extensions, or lack thereof, of existing policy incentives. Increases in renewable electricity cost would favor electrification, while decreases would favor hydrogen. This is because relatively more electricity is required to decarbonize end uses with clean hydrogen compared to direct electrification.
- *Rate of improvements in hydrogen technologies:* Though hydrogen has been used in industry for decades, production via electrolysis and its use in many end use applications are newer technologies and are still projected to have many improvements that could drive down the costs. The total potential and rate of improvement are two uncertainties that will impact the cost competitiveness of hydrogen compared to other low carbon alternatives.

These uncertainties can be monitored and as some become clearer over time, the analyses can be updated to determine which end uses of hydrogen are more or less favored compared to the original analyses

1. Introduction

A. Purpose of Connecticut's Clean Hydrogen Roadmap

Connecticut is committed to a just transition to a clean energy economy that will provide a more livable future for current and future generations. The state has ambitious goals for greenhouse gas (GHG) emission reductions. An Act Concerning Climate Change Planning and Resiliency was signed into law in 2018, establishing a mandatory GHG reduction target of 45% below 2001 levels by 2030[ii]. The Global Warming Solutions Act, Section 22a-200a of the Connecticut General Statutes, requires a reduction of 80% below 2001 levels by 2050[iii]. In addition, An Act Concerning Climate Change Mitigation requires the state to achieve a 100% zero carbon electric sector by 2040[iv].

Connecticut's economy is diverse, and a variety of technologies will be needed to achieve its emission reduction goals. Many energy end uses can cost-effectively decarbonize with existing technologies, such as electrification. However, some applications do not have readily available, commercial-scale technologies to fully decarbonize. The United States[v] and several other countries around the world are exploring and advancing the production and use of clean hydrogen as a decarbonization option especially for these applications[2]. Using clean hydrogen for selected applications is also one of the many decarbonization strategies DEEP is exploring to further the state's climate goals, while ensuring equity, affordability, economic development, reliability and resilience. Moreover, Connecticut's worldwide leadership in hydrogen fuel cells systems provides the state with a significant competitive advantage to economically benefit from clean hydrogen opportunities, such as new jobs and business growth.

This roadmap is one of DEEP's first steps in recommending policies to help govern hydrogen projects in Connecticut (i.e., clean hydrogen production, processing, transportation, storage, and end uses). It provides an in-depth assessment of clean hydrogen opportunities and the steps needed to establish Connecticut's clean hydrogen pathway and its corresponding regulatory framework. The purpose of this roadmap is to provide the following:

1. Articulate Connecticut's aspirations for clean hydrogen's integration into its energy landscape, outlining its potential contributions to decarbonization, economic growth, and environmental justice
2. Guide strategic development of clean hydrogen production, infrastructure, and end use by identifying the target technologies and their associated volumes over time to scale Connecticut's hydrogen economy
3. Identification of benefits and risks associated with clean hydrogen and tactics to address the identified risks
4. Recommend policies, programs, and pilot projects to support clean hydrogen development and deployment in alignment with state goals

This roadmap also

B. Clean Hydrogen Definition

i. U.S. DOE Clean Hydrogen Production Standard

The U.S. Department of Energy (U.S. DOE) has created an initial Clean Hydrogen Production Standard (CHPS) to meet the requirements of the Infrastructure Investment and Jobs Act (IIJA) of 2021. The CHPS serves to guide the U.S. DOE's hydrogen programs, including initiatives such as the Regional Clean Hydrogen Hubs Program and the Clean Hydrogen Research and Development Program. The CHPS has established an initial target for lifecycle GHG of 4.0 kg CO2e/ kg H2. The standard also specifies that the carbon intensity at the site of production should not exceed 2.0 kg CO2e /kg H2[vi].

In an effort to achieve consistency in carbon intensity calculations between various hydrogen production methods and pathways, the CHPS created a Well-to-Gate[vii] lifecycle boundary for stakeholders to use when determining

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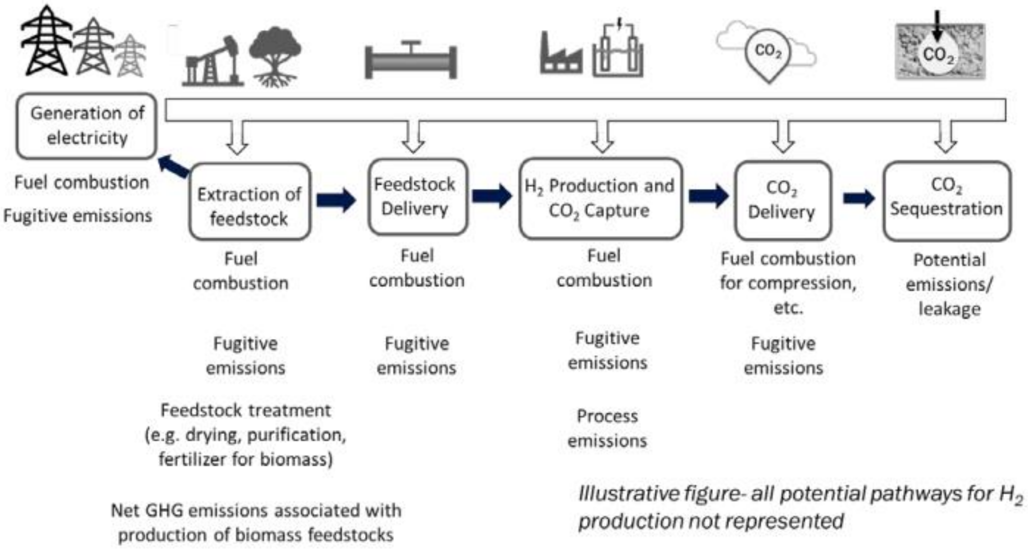
[2] More details about these applications and other technologies along the hydrogen value chain are noted in the Appendix Section 6A: Hydrogen 101

the carbon intensity of hydrogen. The Well-to-Gate boundary includes upstream processes such as electricity generation, hydrogen production, and a limited set of downstream processes such as the transport and sequestration of CO2.

This lifecycle approach allows for all relevant emissions sources to be accounted for in the final carbon intensity calculation while identifying the highest-emitting steps in the production process to prioritize for reduction efforts. Figure 4 depicting the Well-to-Gate boundary shows the key emissions sources that occur during the feedstock extraction/production, electricity generation, feedstock delivery, CO2 transport, and carbon capture and sequestration steps of the value chain.

Figure 4- Key Emissions Sources from the U.S. DOE Well-to-Gate System Boundary Definition[viii]



The parts of the value chain which have been excluded from the U.S. DOE lifecycle boundary include the production of equipment used along the hydrogen value chain and the transport of hydrogen from production location to end use locations. While U.S. DOE's Well-to-Gate boundary makes sense in calculating lifecycle emissions from hydrogen production, states should still measure and include within their own GHG inventories the downstream emissions associated with transport of the fuel to the end user.

ii. Proposed Clean Hydrogen Definition for Connecticut

As a foundational piece of the roadmap, DEEP is proposing a definition for clean hydrogen to guide what types of hydrogen projects will align with state climate and economic development goals, count towards state hydrogen targets, and be eligible for benefits from policy incentives.

DEEP proposes defining clean hydrogen as hydrogen not produced from fossil fuels feedstocks and with a carbon intensity of ≤ 2 kg CO2e/ kg H2 on a life cycle basis that includes owned and retired environmental attributes. This proposed Clean Hydrogen definition supports the following statewide objectives:

1. Reduces carbon emissions in the near term over the lifecycle of hydrogen's production and use, and supports the state's overall climate goals
2. Advances net zero supply chains, leverages market mechanisms to grow renewable electricity supplies, and reduces reliance on fossil fuels
3. Adheres to environmental justice principles and the goals of the 5 Energy Strategy Lenses: Climate, Equity, Affordability, Economic Development, and Reliability and Resilience

This carbon intensity limit is more aggressive than the current proposed federal limit of 4 kg CO2e /kg H2 on a lifecycle basis. A Connecticut definition of clean hydrogen that establishes a lower carbon intensity limit signals

Connecticut's commitment to ambitious climate goals and focuses the state's policies and resources on advancing the lowest carbon hydrogen deployment options.

iii. Key Value Chain Parameters

The treatment of renewable electricity inputs is an important topic of ongoing discussion that may impact future iterations of Connecticut's clean hydrogen definition. Specifically, this concerns to whether and to what extent renewable electricity inputs can align with the 'three pillars' of additionality, regional matching, and temporal matching. These pillars are described below, along with the approach to incorporating them into the modeling that informed the roadmap.

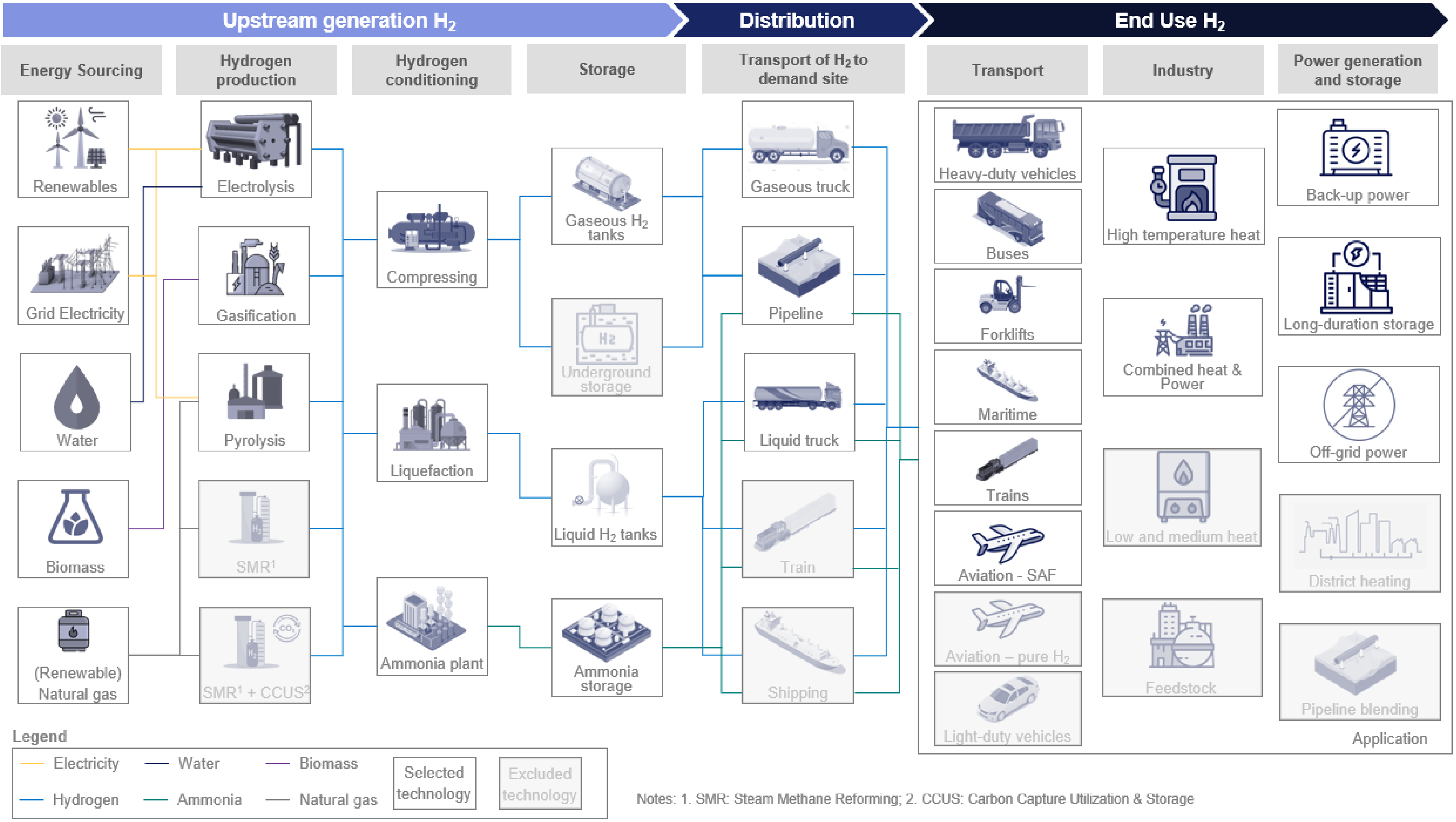
1. **Additionality** is the concept of ensuring that the production of clean hydrogen leads to a net increase in renewable energy generation. This implies that the renewable electricity employed to produce clean hydrogen must be new and additional, rather than simply substituting renewable energy that would have otherwise been used for other purposes. For the purposes of the modeling, we assume that all renewable electricity inputs are new and additional.
2. **Temporal matching** is the concept of ensuring that the renewable energy used to produce clean hydrogen is consumed simultaneously with its generation. Depending on the definition of clean hydrogen in the location of production, temporal matching can refer to hourly, monthly, or annual matching. In our modeling, we assume annual matching, but also demonstrate the cost impacts of switching to monthly and hourly matching.
3. **Geography matching** is the concept of ensuring that the renewable energy used to produce clean hydrogen is generated in the same region where it is consumed. This can help to minimize transmission losses and promote local renewable energy development. For the roadmap, we assume all renewable electricity generation takes place in the ISO-New England, or the neighboring New York-ISO.

At the time of publishing, the US Treasury Department had recently released their proposed guidance for claiming the 45V Clean Hydrogen Production Tax Credit across each of the above pillars. When this guidance is finalized, DEEP will review it and determine if and how these pillars will be incorporated into Connecticut's clean hydrogen definition and roadmap.

C. Hydrogen Value Chain Overview

Hydrogen is the lightest chemical element, found as a gas at atmospheric temperatures and pressures. Hydrogen is a very promising resource for the energy transition as it emits zero carbon emissions when used in fuel cells or combusted. The hydrogen value chain consists of a series of interconnected processes that span the production, infrastructure, and utilization of hydrogen. These high-level value chain steps can be further broken down, such as dividing production into feedstock inputs and production processes, or infrastructure into transport, storage, and refueling. Categorizing the hydrogen value chain into discrete sections is beneficial for both educating relevant stakeholders on the hydrogen value chain, as well as creating relevant groupings for cost, policy, and feasibility analyses.

Figure 5- Overview of the Hydrogen Value Chain



Notes: 1. SMR: Steam Methane Reforming; 2. CCUS: Carbon Capture Utilization & Storage

The next three subsections provide an overview of the most common hydrogen technologies spanning production, infrastructure, and end use. To determine which of these technologies are best aligned with Connecticut's values across a variety of lenses, detailed analyses have been conducted and documented in *Section 2: Energy Strategy Lens Analysis*. However, some technologies have been filtered out in this section if they met any of the following criteria:

1. End use is not present in Connecticut at a level at which switching to hydrogen would have a material impact on the state's GHG reduction goals.
2. Technology is obviously inconsistent with one or more Energy Strategy Lens objectives. As an example, producing hydrogen via steam methane reforming is obviously inconsistent with the Climate lens due to its high carbon intensity.
3. Technology would not work in Connecticut for feasibility reasons. For example, while underground salt caverns provide a low-cost hydrogen storage option, these are not present in Connecticut and have therefore been excluded from the analysis.

Technologies that meet any of these criteria are noted in grey in the technology tables. To clarify, exclusion from the Energy Strategy Lens analysis does not mean that the hydrogen technology should never exist in Connecticut, but rather it should not be prioritized for focused, state-level policies, programs, and pilot projects. Many of these hydrogen technologies can still be considered on a project-by-project basis.

For a more detailed introductory overview of the hydrogen value chain, see *Appendix Section 6.A: Hydrogen 101*.

i. Production

Hydrogen is the most abundant element in the universe, although capturing it in a usable form requires energy-intensive hydrogen production processes. There are many ways to produce usable hydrogen, some of which have zero GHG emissions, while others have high GHG emissions. To ensure that the use of hydrogen will align with Connecticut's GHG reduction targets, care must be taken to ensure that hydrogen production, as well as the rest of the hydrogen value chain, occurs with low, and ideally zero, GHG emissions. Table 4 provides details on some of the most common hydrogen production methods.

Table 4- Common Hydrogen Production Technologies

Production method	Description	Technology Evaluated in Energy Strategy Lens Analysis?
Electrolysis	Electricity is used to split water molecules into hydrogen and oxygen	Yes
Pyrolysis	Methane is heated at high temperatures, without oxygen, to decompose into hydrogen gas and carbon-containing byproducts	Yes. Pyrolytic hydrogen production can occur with natural gas or renewable natural gas as a feedstock. To meet the objectives of the climate Energy Strategy Lens, all pyrolysis analyses in this roadmap assume the feedstock is renewable natural gas
Gasification	Biomass is heated at high temperatures in the presence of oxygen to convert into a mixture of gases (syngas), including hydrogen	Yes
Steam methane reforming	Steam and methane reaction at high temperatures over catalyst to produce hydrogen with CO2 as a by-product	*No. Excluded for compatibility with climate Energy Strategy Lens due to level of CO2 as a byproduct and rate of methane leakage*
Steam methane reforming with carbon capture	Steam methane reforming as described above, where the CO2 is captured for storage or utilization	*No. Excluded for compatibility with climate Energy Strategy Lens due to rate of methane leakage*

ii. Infrastructure

Infrastructure is a key component of the hydrogen value chain, and includes transportation, storage, and fueling stations. Both transport and storage have multiple technologies to choose from, and the best option will depend on many factors such as volume of hydrogen, geology and terrain, and existing infrastructure. Table 5 provides details on some of the most common hydrogen infrastructure technologies.

Table 5- Common Hydrogen Infrastructure Technologies

Infrastructure Category	Specific Infrastructure	Description	Technology Evaluated in Energy Strategy Lens Analysis?
Transport	**Gaseous hydrogen trucking**	Gaseous hydrogen is transported in tube trailer trucks that contain compressed gaseous hydrogen at 180 bar[ix]	Yes
	Liquid hydrogen trucking	Liquid hydrogen is produced by cooling gaseous hydrogen to cryogenic temperatures (below -423 F) and transported in insulated tankers (10 bar)[x]	Yes
	Pipeline	Gaseous hydrogen is transported through pipelines for long-distance delivery, at pressure ranging from 25 to 130 bar[xi]	Yes
	Rail	*Liquid hydrogen is transported in standard tank wagons via rail*	*No. Excluded for feasibility as Connecticut's existing rail routes are insufficient for broad hydrogen transport.*
	Maritime shipping	*Hydrogen is transported via ships in gaseous or liquid forms, or by being converted to a more energy-dense carrier such as ammonia*	*No. Excluded for feasibility as Connecticut's existing waterways are insufficient for broad hydrogen transport.*
Storage	**Gaseous hydrogen tanks**	Gaseous hydrogen stored in high-pressure tanks at 350-700 bar[xii]	Yes
	Liquid hydrogen tanks	Liquid hydrogen is stored in cylindrical tanks with vacuum insulation and cryogenic temperatures (below -253°C) [xiii]	Yes
	Liquid ammonia	Liquid ammonia can be stored at ambient pressure and -33°C, or ambient temperatures and 10 bar[xiv]	Yes
	Underground storage	*Underground storage of hydrogen in salt caverns, depleted oil and gas fields, or hard rock outcroppings*	*No. Excluded because Connecticut does not have salt caverns, the most economic storage formation, but Connecticut does have hardrock outcroppings, which are proposed to be studied in proposed Program 9*
Fueling	**Refueling stations**	Liquified or compressed hydrogen is supplied at high pressures into vehicle storage tanks, typically 700 or 350 bar[xv]	Yes

iii. End Use

Hydrogen has historically been used as an industrial feedstock. The primary industries that use hydrogen today include petroleum refining, ammonia, and methanol production. Hydrogen has also been used in smaller quantities in many other industrial sectors, including specialty chemicals, textile fiber manufacturing, glass, electronics, and semiconductors. Looking ahead, hydrogen has the ability to expand beyond its current uses and play an important role in the global energy transition. Table 6 provides details on some of the most common hydrogen end use technologies.

Table 6- Common Hydrogen End Use Technologies

End Use Sector	End Use	Hydrogen Technology Description	Technology Evaluated in Energy Strategy Lens Analysis?
Transport	**Heavy-duty trucking**	Long haul trucks typically carrying heavy payloads that are powered by hydrogen fuel cells	Yes
	Buses	Local and coach buses that run on hydrogen fuel cells	Yes
	Forklifts	Forklifts, such as those used in warehouses or ports, which run on hydrogen fuel cells	Yes
	Maritime	Tugboats, ferries, and bulk carrier ships that run on hydrogen fuel cells, or hydrogen derivatives including ammonia (fuel cells or internal combustion engines), and methanol (internal combustion engines)	Yes
	Trains	Passenger and freight rail that runs on hydrogen fuel cells or hydrogen combustion engines	Yes
	Aviation	Short, medium, and long-haul flights that run on sustainable aviation fuel (SAF), a hydrogen derivative	Yes
	Light-duty trucking	*Passenger cars or light duty trucks powered by hydrogen fuel cells*	*No. Excluded for compatibility with Affordability Energy Strategy Lens due electrification being a more affordable low carbon option.*
Industry	**High-temperature heat**	Hydrogen combustion to generate high-temperature heat (>550°C) for industrial heating needs	Yes
	Low and medium-temperature heat	*Hydrogen combustion to generate low to medium temperature heat (<550°C) for industrial heating needs*	*No. Excluded for compatibility with the Affordability Lens due to other more affordable low carbon options.*
	Combined heat and power	*Hydrogen fuel cells and hydrogen turbines can be used to generate both electricity and heat for industrial process*	*No. Excluded for compatibility with the Affordability Lens due other more affordable low carbon options.*

	Feedstock	*Hydrogen used as a feedstock or reductant for various industries, including but not limited to chemicals, ammonia, and steelmaking*	*No. Excluded as use case does not exist in material volumes in Connecticut.*
Power generation and energy storage	**Backup power**	Hydrogen fuel cells used to supply back up power for critical infrastructure such as data centers and hospitals	Yes
	Long-duration energy storage	Hydrogen/ammonia storage in combination with hydrogen combustion or hydrogen fuel cells to supply electricity that can improve grid resiliency and economics	Yes
	Off-grid power	*Hydrogen fuel cells used to supply power for remote applications not able to connect to the grid*	*No. Excluded as use case does not exist in material volumes in Connecticut.*
	District heating	*Hydrogen combustion used to generate heat for buildings in district heating systems*	*No. Excluded as use case does not exist in material volumes in Connecticut.*
	Pipeline blending	*Blending hydrogen into natural gas pipelines to reduce the carbon intensity of the natural gas used for building and industry applications*	*No. Excluded for compatibility with the Climate Energy Strategy Lens as pipeline blending has the potential to extend use of natural gas in certain applications that could more effectively reduce emissions via electrification*

D. Clean Hydrogen Roadmap Methodology

i. Roadmap Process

The development of Connecticut’s Clean Hydrogen Roadmap was a data-driven and collaborative process that involved five key steps:

1. **Goal alignment:** Aligning on a vision for the hydrogen economy to help support Connecticut’s climate goals, including identification of potential technologies along each step of the value chain that are most relevant for Connecticut and creation of a clean hydrogen definition
2. **Energy Strategy Lens analysis:** Performing analysis against the 5 Energy Strategy Lenses for each applicable technology for Connecticut along each step of the value chain, including levelized cost of hydrogen and total cost of ownership for each hydrogen end use
3. **Value chain technology selection and quantification:** Selection of technologies for each step of the value chain based on Energy Strategy Lens analysis, calculation of hydrogen demand over time based on rate of adoption for each selected end use, and quantification of resources required to meet hydrogen demand
4. **Enabler identification:** Addressing Energy Strategy Lens risks and barriers to adoption through enablers, which include policies, programs, and pilot projects
5. **Prioritization and next steps:** Prioritization of key policies, programs, and pilot projects to pursue over the short, medium, and long term

ii. Energy Strategy Lenses

To ensure that all energy topics proposed and supported by DEEP are aligned with all of Connecticut's values, DEEP has identified five Energy Strategy Lenses to use to evaluate the impact of energy initiatives: Affordability, Climate, Equity, Reliability & Resilience, and Economic Development. These lenses have also been used in *Section 2: Energy Strategy Lens Analysis* of this roadmap to help identify the key benefits and risks of a clean hydrogen economy and select which technologies along each step of the value chain can best meet Connecticut's hydrogen goals while also meeting all objectives of the Energy Strategy Lenses.

Table 7–Hydrogen Objectives According to Each Energy Strategy Lens

Energy Strategy Lens	Hydrogen Objectives
1. Affordability	Achieve cost competitiveness with fossil-based incumbent technologies and low carbon alternatives
2. Climate	Reduce GHG emissions in line with Connecticut's statewide decarbonization goals
3. Equity	Ensure physical accessibility of hydrogen infrastructure and enhance overall health & well-being benefits from reduced air pollution for all communities
4. Reliability & Resilience	Achieve reliability, resilience, and safety at least on par, and ideally better, than fossil-based incumbent technologies
5. Economic Development	Have a net positive impact on short- and long-term job creation

iii. Environmental Justice

A critical component of fostering an equitable clean energy transition is ensuring that the environmental, social, and economic benefits of the transition are realized for all residents, particularly those identifying as disadvantaged or residing in environmental justice communities. Note that the Connecticut General Statutes defines an environmental justice community[xvi] as:

- A distressed municipality[xvii] as classified by the Connecticut Department of Economic and Community Development, OR
- Defined census block groups within Connecticut where 30% of the population is living below 200% of the federal poverty level

With the passage of the Inflation Reduction Act (IRA) and Infrastructure Investment and Jobs Act (IIJA), the White House has further solidified commitments to environmental and economic advancement by introducing regulations such as Justice40[xviii] whereby 40% of all federal investments in clean energy must flow directly to environmental justice communities marginalized by pollution. Similarly, the state of Connecticut recognizes and prioritizes the notion that all people should benefit from statewide environmental laws and are committed to passing legislation and implementing projects which improve air quality, reduce pollution, and create jobs for disproportionally affected low-income and disadvantaged groups.

Utilizing hydrogen technologies has the potential to improve the quality of life for all residents provided that it is implemented in a way that considers factors which affect environmental justice communities. Along with understanding the magnitude of benefits that could be realized for environmental justice communities, hydrogen can, in certain instances, exacerbate existing burdens. Therefore, to further advance DEEP's Environmental Justice Program[xix] aiming to reduce the environmental burdens faced by communities, and in accordance with the environmental justice recommendations of the Connecticut Equity and Environmental Justice Advisory Council (CEEJAC)[xx], the Governor's Council on Climate Change[xxi] (GC3), the White House Environmental Justice Advisory Council (WHEJAC)[xxii], and the Justice40 Initiative, DEEP has identified three equity-based principles to support a hydrogen transition rooted in inclusive development: Accessibility, Health and Wellbeing, and Sustainable Job Creation.

Adhering to these principles will be core to maximizing the positive impact that hydrogen can have on communities. As noted in Table 8, these principles each map to different dimensions of the Energy Strategy Lenses and thus, assessment of each hydrogen technology's ability to achieve the principles will be encompassed within the Energy Strategy Lens analysis, and enablers policies, programs, and pilot projects have been proposed for any risks that could prevent hydrogen from meeting the objectives of the principles and associated Energy Strategy Lenses.

In addition to the enablers that have been identified through the Energy Strategy Lens analysis, two additional cross cutting enablers have been identified to address best practices that have been identified by the environmental justice community: Community Stakeholder Engagement and Assessment of Ongoing Burdens and Risks. These enablers are further elaborated in both in Table 8 and *Section 4: Hydrogen Enablers*.

Table 8- Framework for Addressing Environmental Justice Principles in the Energy Strategy Lens Analysis

<table>
<tr><th colspan="4">Framework: Addressing Environmental Justice Principles in Energy Strategy Lens Analysis</th></tr>
<tr><th colspan="4">Environmental Justice Principles</th></tr>
<tr><td><i>Environmental Justice Principle</i></td><td>1. Accessibility</td><td>2. Health and Wellbeing</td><td>3. Sustainable Job Creation</td></tr>
<tr><td><i>Principle Objective</i></td><td>Ensure equitable distribution of project opportunities and benefits throughout project lifespan</td><td>Provide opportunities and mitigate harmful impacts related to health and wellbeing of vulnerable communities</td><td>Create inclusive, high-paying, sustainable jobs for the existing workforce and future generations</td></tr>
<tr><td><i>Integration within Energy Strategy Lens:</i></td><td>A. Affordability
Emphasizes the importance of proposed financial policy incentives to have provisions to ensure that investment is flowing to and directly benefiting projects that surround or employ vulnerable populations
B. Equity (Physical Accessibility)
Emphasizes the importance of ensuring that hydrogen infrastructure is available and easily accessible for all, particularly in and near environmental justice communities who are disproportionately affected by negative health impacts</td><td>C. Equity (Health & Well-being)
Emphasizes the importance of maximizing the health benefits and minimizing the health risks associated with hydrogen; One prominent example is hydrogen's potential to both reduce or increase NOx emissions based on its application, an air pollution and health issue that is particularly impactful for environmental justice communities</td><td>D. Economic Development
Emphasizes the importance of creating diverse hiring and training opportunities to reduce unemployment burdens and stimulate an inclusive local hydrogen economy</td></tr>
<tr><td><i>Examples of Proposed Policies, Programs, and Pilot Projects that address each principle (more details in Section 4: Hydrogen Enablers):</i></td><td>A. Policy 6: Financial Incentives for Net Zero Trucking and Fueling Stations in Environmental Justice Communities
B. Program 3: Assess Optimal Siting of Hydrogen Fueling Stations</td><td>C. Proposed Policy 8: NOx Emissions Standards for Hydrogen Combustion</td><td>D. Program 5: Equitable Hydrogen Job Transition Program</td></tr>
<tr><th colspan="4">Crosscutting Environmental Justice Enablers (See additional details in <i>Section 4: Hydrogen Enablers - Program 8</i>)</th></tr>
<tr><td><i>Enabler 1:</i> Community Stakeholder Engagement</td><td colspan="3">•Increase opportunities for active stakeholder participation in hydrogen projects and mitigate unintended consequences by engaging directly with local communities and organizations
•Promote long-term environmental, economic, and social success in clean energy projects</td></tr>
<tr><td><i>Enabler 2:</i> Assessment of Ongoing Burdens and Risks</td><td colspan="3">•Ensure that any further unintended consequences, either from existing project activities or from additional inclement weather, are mitigated by shifting implementation strategy</td></tr>
</table>

E. Contributors and Stakeholder Engagement

i. Contributors

Completion of Connecticut's Clean Hydrogen Roadmap would not have been possible without the participation of many groups. DEEP would like to thank the following groups for their support, and contributions in the process:

- Amogy
- Avangrid
- Colorado Energy Office
- Connecticut Department of Transportation
- Connecticut Green Bank
- LuftCar
- Nel
- Plug Power
- Synapse Energy

ii. Stakeholder Engagement

DEEP has participated in and led robust stakeholder engagement processes on hydrogen. On April 6, 2022, the agency held an online public technical session focused exclusively on hydrogen. This meeting, as well as technical sessions focused on alternative fuels (Nov. 4, 2022) and methane/natural gas distribution planning and policies (Dec. 8, 2022), featured presentations by hydrogen experts. During each technical session, the agency provided an opportunity for stakeholders to make oral comments and to pose written questions that were relayed to panelists for response. In conjunction with each session, DEEP also solicited written comments.

DEEP was also an active participant of a recent Hydrogen Power Task Force established by the legislature through Special Act 22-8. This task force, facilitated by the Connecticut Green Bank, submitted a report[xxiii] to the General Assembly on January 15, 2023, which included the following items:

1. A review of regulations and legislation needed to guide the development and achievement of economies of scale for the hydrogen ecosystem in the state
2. An examination of how to position the state to take advantage of competitive incentives and programs created by the federal IIJA
3. Recommendations for workforce initiatives to prepare the state's workforce for hydrogen fueled energy-related jobs
4. An examination of the sources of potential clean hydrogen, including, but not limited to, wind, solar, biogas and nuclear
5. Recommendations for funding and tax preferences for building hydrogen-fueled energy facilities at brownfield sites through the Targeted Brownfield Development Loan Program
6. Recommendations regarding funding sources for developing hydrogen fueled energy programs and infrastructure
7. Recommendations for potential end uses of hydrogen-fueled energy.

Out of the Hydrogen Task Force came Public Act No. 23-156 **"An Act Implementing Recommendations of the Hydrogen Task Force",** which required DEEP to develop this hydrogen strategic plan.

The meetings of both the task force and its topic-specific working groups were public and included opportunities for verbal public comments. Written comments were also solicited to inform the final task force report.

Public notices, meeting agendas, slide decks, recordings, and related documents regarding DEEP's process are available on the DEEP web page**.**

2. Energy Strategy Lens Analysis

The technologies along the hydrogen value chain that passed the preliminary filter in *Section 1C: Hydrogen Value Chain Overview* have been evaluated for their ability to meet the objectives of each of Connecticut's five Energy Strategy Lenses. These analyses serve two main purposes:

1. Identifying where there is potential for a technology to fall short of meeting the objectives of a particular Energy Strategy Lens, and will need an enabler such as a policy, program, or pilot project to ensure the technology meets the objectives of each Energy Strategy Lens. Enablers for all flagged technologies are addressed in *Section 4: Hydrogen Enablers*
2. Determining which technologies are not likely to meet the objectives of one or more Energy Strategy Lenses, even with the support of an enabler, and thus were eliminated from further roadmap modeling. Similar to the filter in *Section 1C: Hydrogen Value Chain Overview*, elimination in this stage does not mean the technology should never be considered in Connecticut, but rather, should not be prioritized for focused, state-level mitigating enablers.

The extent to which each technology was evaluated depended on its relevance against each Energy Strategy Lens. Some lenses, such as Affordability, required a separate analysis of each value chain technology. Others, such as Economic Development, were more suited to evaluate at a cross value chain, rather than technology specific, level.

To add consistency across topics, the below key has been created to denote how each technology fares against each Energy Strategy Lens dimension. When no Energy Strategy Lens risks were identified, the technology received a green rating, signaling that no additional enablers would be needed to meet the Energy Strategy Lens objectives. When risks were identified, but were likely to be mitigated with policy, program, or pilot project enablers, a yellow rating was received. Finally, when risks were identified that were unlikely to be mitigated even with the support of enablers, a red rating was received.

Table 9- Key for Energy Strategy Lens Analysis

Key for Energy Strategy Lens analysis	
🟩	*Likely to meet lens objectives without enablers*
🟨	*Enablers likely needed to meet lens objectives*
🟥	*Unlikely to meet lens objectives with or without enablers*

A. Lens 1: Affordability

The objective of the Affordability Lens analysis is to understand how the cost competitiveness of hydrogen technologies compare to both fossil-based incumbent technologies and alternative low-carbon technologies. This analysis covers production to end uses, considering the key variables that have the biggest cost impacts, as well as a holistic view of the value chain.

In this section, capital expenditures (CAPEX), operational expenditures (OPEX), and energy costs, are presented as part of the Levelized Cost of Hydrogen (LCOH) and the Total Cost of Ownership (TCO) for each relevant hydrogen technology. The LCOH is the cost to produce, and when relevant, transport and store, a kilogram of hydrogen, evaluated over a 20-year period, taking into account all relevant discounted CAPEX, OPEX, and energy costs during that time period. Similarly, the TCO is the total cost of ownership per unit of activity (e.g., mile traveled), evaluated over a 20-year time period, taking into account all relevant discounted CAPEX, OPEX, and energy costs during that time.

i. Production

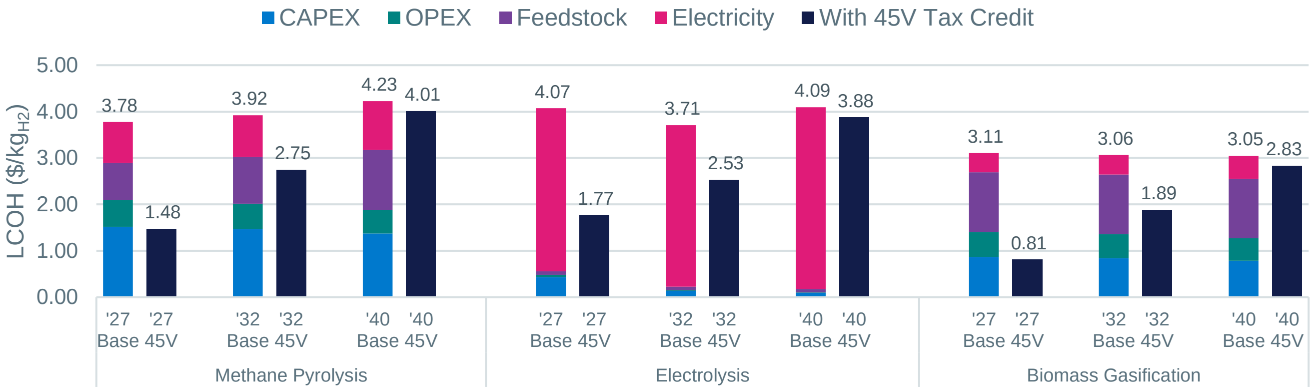
There are many variables to choose from when analyzing the cost of hydrogen production in a given region, including, but not limited to, the hydrogen production method, electricity source, and temporality matching requirements. All three of these variables were evaluated for the state of Connecticut to determine the lowest realistic cost for producing hydrogen.

First, the LCOH was calculated by varying the hydrogen production method and incorporating Connecticut’s specific energy costs and resource availability. Next, the LCOH was calculated using different electricity generation methods and locations to determine the lowest cost electricity source. Finally, a temporality analysis was performed to understand how varying requirements on temporal matching between renewable electricity and hydrogen production will impact the LCOH in Connecticut.

Hydrogen cost by production method

One of the factors that affects the cost of hydrogen is the production method. Among the three methods considered, methane pyrolysis is expected to have the highest LCOH due to the high capital expenditure and the rising price of renewable natural gas. Biomass gasification, on the other hand, has the lowest LCOH, but it relies on the availability of sustainable biomass feedstock, which may pose a challenge for Connecticut's reliability goals, as noted in the reliability lens section. Therefore, electrolysis was selected as the preferred production method for further modeling, as it has lower costs than pyrolysis and a more sustainable and scalable feedstock supply relative to gasification.

Figure 6 - LCOH per production method in Connecticut



Assumptions: 1. Hydrogen volumes of ~700 kg H2/hr in 2027, ~ 4,000 kg of H2/hr in 2032, and ~ 6,000 kg H2/hr in 2040; 2. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit), and IRA benefits for renewables, which are assumed to remain available through 2040; 3. Feedstock considered for pyrolysis, electrolysis and gasification are renewable natural gas, water and biomass, respectively. Gasification also requires water and steam in very small proportions, both considered in the LCOH calculations; 4. Annual matching requirement for electricity source.

Hydrogen production cost by electricity source

Between 2027 and 2040, the LCOH for electrolytic hydrogen produced in Connecticut can range from $1.4 to 6.0/kg H2 (inclusive of the H2 PTC from the IRA), and it is mainly influenced by the price of electricity, which accounts for more than 90% of the total cost. Therefore, depending on how and where the renewable electricity used for electrolysis is produced, the LCOH will vary accordingly. These results are key for Connecticut to understand to get clean hydrogen in the most cost-effective way.

For a detailed forecast on clean hydrogen costs, renewable energy power purchase agreement (PPA) costs were modelled in three states in the Northeast US (Connecticut, New York, and Maine). New York and Maine were chosen as they are in the same or neighboring ISO as Connecticut and are anticipated to have the lowest renewable electricity costs due to land availability. Energy and renewable energy certificate (REC) prices were included for solar photovoltaic (PV) energy, onshore wind energy, and offshore wind energy, and forecast for projects reaching commercial operations in 2027, 2032, and 2040.

As shown in Figure 7, the lowest LCOH is achieved by using onshore wind power in the state of NY, which has the cheapest electricity price. However, onshore wind power in Connecticut also offers a competitive LCOH, with a difference of only $0.3 /kg H2 from the lowest value in 2040. Onshore wind has the lowest costs in these models in all three states due to having lower land requirements than solar, and lower construction and equipment costs than offshore wind[3]. However, economics can vary significantly from project to project, and a combination of generation methods will likely be needed to power clean hydrogen production. The Connecticut price was chosen over the New York price to align with the Economic Development Lens, as in-state renewable electricity generation can create additional jobs in Connecticut and reduce the reliance on new transmission lines.

Onshore wind in Connecticut is being used only as a simplified proxy for electricity price modeling. The modeling approach minimizes uncertainty and speculations related to the effect of unspecified mix of renewable electricity on the grid[4]. The methodology is also consistent with the approach used to calculate hydrogen production electricity prices in other studies, such as the U.S. DOE's National Clean Hydrogen Strategy and Roadmap. The electricity rate of $0.077/kWh from onshore wind power installed for hydrogen production used in the model does not reflect a target price, nor does it suggest a policy recommendation to install the onshore wind power considered by the modeling or keep rates at that level or below to induce hydrogen production in the state of Connecticut. DEEP recognizes the amount of electricity produced by onshore wind required for clean hydrogen production may not be feasible or desired. In practice, a combination of generation methods would probably be used to power clean hydrogen production in Connecticut. Market forces and other factors will determine the real, future rate that hydrogen producers pay for electricity and the renewable energy mix.

The modeling also assumes that the renewable electricity supply matches the electricity demand on an annual basis.

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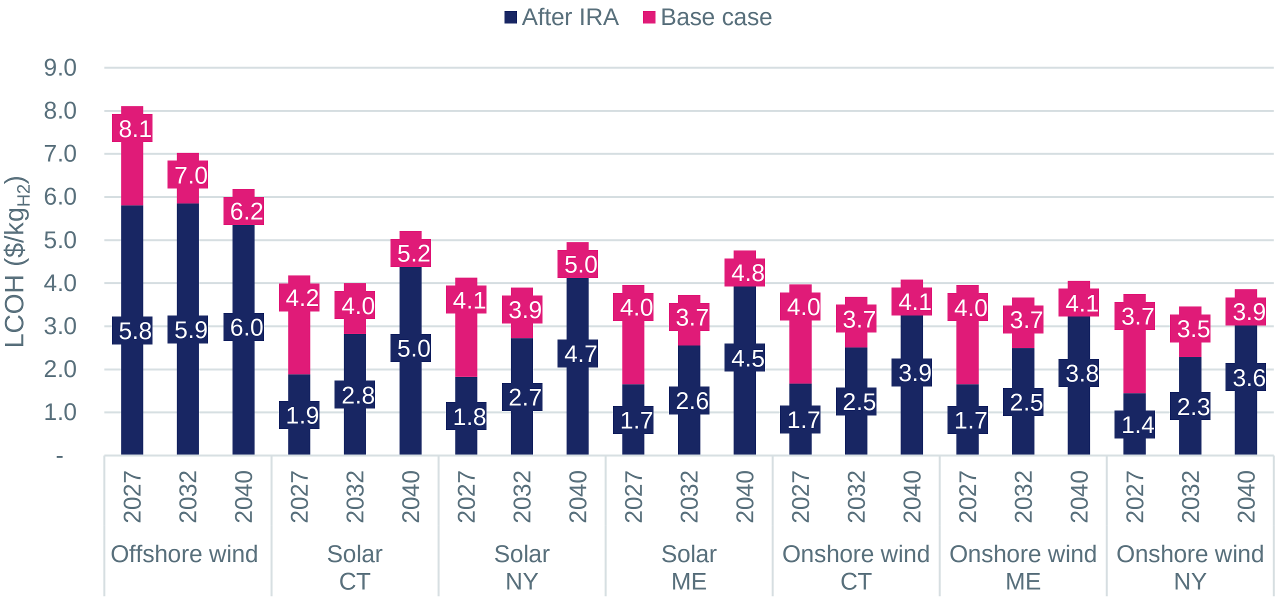
[3] For information on the inputs and approach used in the electricity price modeling, please refer to the methodology section in the appendix.

[4] See appendix C.1 for more details on the methodology.

Figure 7 - Prices for Electrolysis Production Under Different Renewable Sources and States



Assumptions: 1. Hydrogen volumes of ~700 kg H2/hr in 2027, ~ 4,000 kg of H2/hr in 2032, and ~ 6,000 kg H2/hr in 2040; 2. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit) and IRA benefits for renewables, which are assumed to remain available through 2040; 3. The electricity price forecasts account for transmission infrastructure needed from rural areas to demand, land availability influence in the price over time (as land costs increase and the most "productive" land is utilized), and a realistic and competitive pricing model for CT, based on a cost plus margin basis.

Impact of Temporality Matching on the Electrolysis LCOH

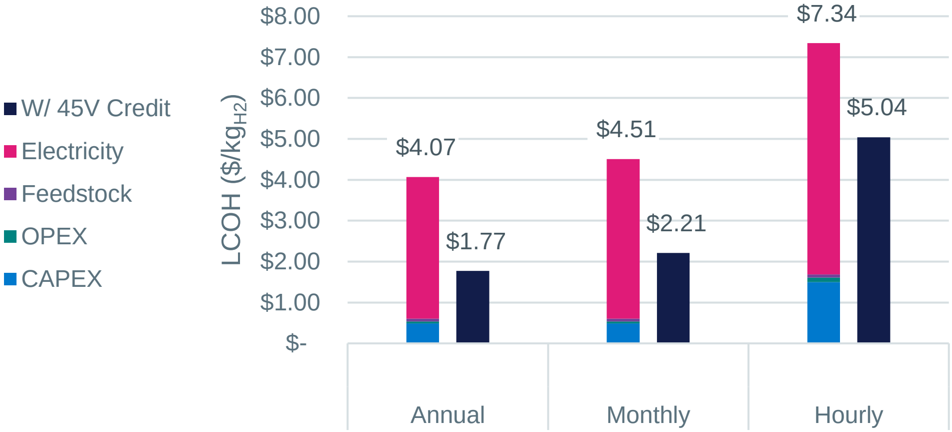
Temporality matching refers to the alignment of the supply and demand of a resource over time. In the context of clean hydrogen production through electrolysis, temporality matching is important because clean hydrogen is produced from renewable energy sources, such as solar or wind, which are both intermittent and variable. In hydrogen policy discussions, the debate has centered around the appropriate temporality boundaries – i.e., should renewable electricity be matched with hydrogen production on an annual, monthly, or hourly basis. All else being equal, the more precise the temporality requirements, the greater the overall costs of hydrogen production, because it increases the need for additional measures, such as storage or back-up systems, or necessitating a specific combination of solar and wind power renewable energy hourly profiles, increasing overall costs.

As presented in Figure 8, the impact of monthly matching on the LCOH in Connecticut is significant, representing an 11% increase compared to annual matching. The impact of hourly matching is even more profound, leading to an 80% higher LCOH than annual matching. The significance of the temporality requirement becomes more pronounced when we factor in the 45V tax credit. In this scenario, the transition from an annual to a monthly or hourly requirement leads to price increases of 25% and 185%, respectively.

Figure 8 also shows how different variables change to minimize LCOH while still meeting the needs of each temporality requirement. As the temporality requirements get more restrictive, the main drivers of the LCOH increase are:

1. **Oversizing renewable energy plants**, which are required to meet the hourly and monthly matching requirements during the hours and months with lower renewable electricity generation.
2. **Oversizing the electrolyzer,** which is required produce excess hydrogen during the hours and months with more renewable electricity generation to store for the periods with less renewable electricity.
3. **Additional energy storage,** in the form of batteries before the electrolyzer, or via hydrogen storage after production. This extra storage helps to balance the disparities in electricity generation and corresponding hydrogen production capacity across different days and months.

Figure 8 – Impact of Temporality Requirement on Connecticut LCOH in 2027



Solar PV / Wind size (MW)	0 / 1,871	1,976 / 956	2,977 / 1,226
Electrolyzer size (MW)	557	557	1,308
Electrolyzer utilization (%)	100%	100%	43%
H2 Storage (tons H2)	0	0	332

Assumptions: 1. Wind PPA and solar PV PPAs are 77.6 and 72.3 [$/MWh], respectively; 2 Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit) and IRA benefits for renewables, which are assumed to remain available through 2040; 3. The selling and buying price is 15 [$/MWh]; 4. A limit is set to maximum H2 storage.

In terms of carbon intensity, it is worth noting that, for modeling simplification, the above annual matching LCOH is assuming that the renewable energy that is powering the hydrogen production is additional to the existing renewable energy in Connecticut. Because of that, the carbon intensity of clean electrolytic hydrogen production lifecycle (well-to-gate) under annual matching is zero, i.e., there are no CO2 emissions associated. On the other hand, the LCOH under hourly matching is considering that part of the electricity used for the hydrogen production is supplied by existing renewable energy. This assumption was adopted so that the hydrogen production costs under annual matching were as low as possible but allowing hydrogen producers to receive the highest hydrogen production tax credit possible. As a result, the carbon intensity of electrolytic hydrogen production under hourly matching is 0.45 CO2e/kg H2. This modeling exercise shows that it is possible to have hydrogen production under an annual matching system that is cheaper and with a lower carbon intensity than under hourly matching. If the LCOH modeling under hourly matching considered that only new renewable energy generation was powering the hydrogen production, the carbon intensity would also be zero, just as the hydrogen production under annual matching; however, at an even higher cost.

Based on the results of this analysis, annual matching has been selected as the temporality requirement for further modeling in this roadmap. DEEP acknowledges that in order for Connecticut to achieve net zero emissions, eventually all hydrogen production would need to be supplied with zero carbon electricity on an hourly basis or and would be in line with Connecticut's 2040 zero emission electricity sector target. However, as hydrogen, renewable electricity, and electricity storage technologies are continuing to realize cost reductions, DEEP believes that annual matching is the best near-term temporality requirement to help hydrogen scale at the pace needed.

US Treasury 45V Draft Guidance: At the time of publishing, the US Treasury Department had recently released their proposed guidance for claiming the 45V Clean Hydrogen Production Tax Credit. Under the draft guidance, starting in 2028, clean hydrogen production facilities would need to achieve hourly matching with renewable electricity to receive the tax credit. This requirement would have significant implications for Connecticut's hydrogen roadmap, such as

- Increasing the cost of in state hydrogen production from electrolysis
- Increasing favorability of importing from regions with lower renewable electricity costs

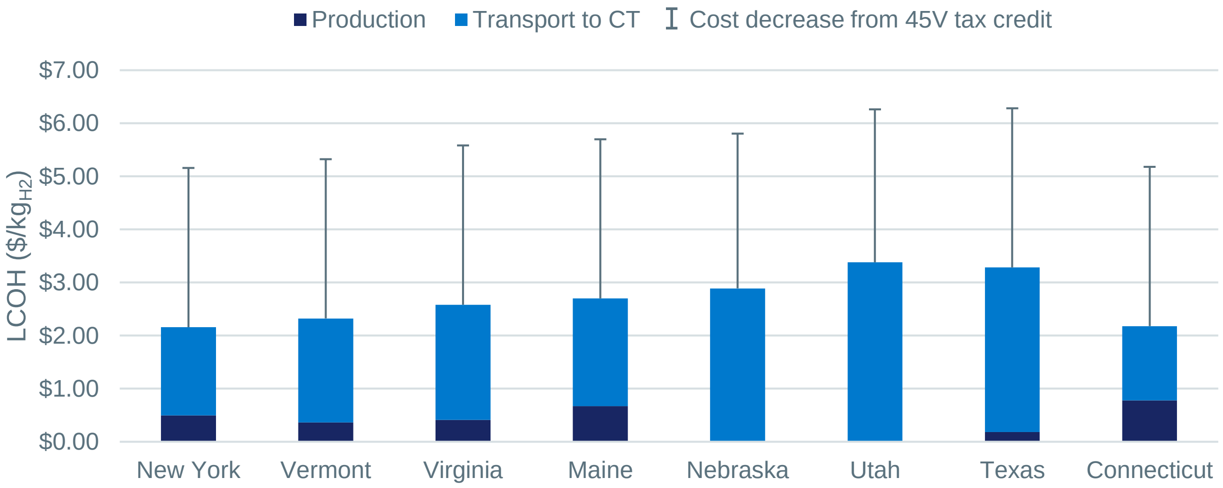
- Increasing favorability of other forms of hydrogen production with lower electricity requirements, for example steam methane reforming with carbon capture and storage.
- Increasing favorability of other low carbon alternatives over hydrogen

However, as this guidance is currently in draft form, we have chosen to maintain our existing analysis based on annual electricity matching requirements. We will continue to monitor these developments closely and are prepared to reassess our roadmap should this guidance be finalized. This underscores the dynamic nature of the renewable energy landscape and the need for our strategies to remain adaptable.

Cost of Domestic and International Imports of Electrolytic Hydrogen

Clean hydrogen supply options and their LCOH were evaluated for Connecticut under different scenarios of in state production versus importing from other states or countries. To assess domestic import options, seven states were selected, based on low LCOH and their proximity to Connecticut. As shown in Figure 9, the impact of the IRA H2 PTC is significant, with the transport cost accounting for most of the final LCOH in Connecticut. Even though some Midwest and Western states have lower hydrogen production costs than Connecticut, the additional cost of transport makes them not competitive with in state production in Connecticut in 2031.

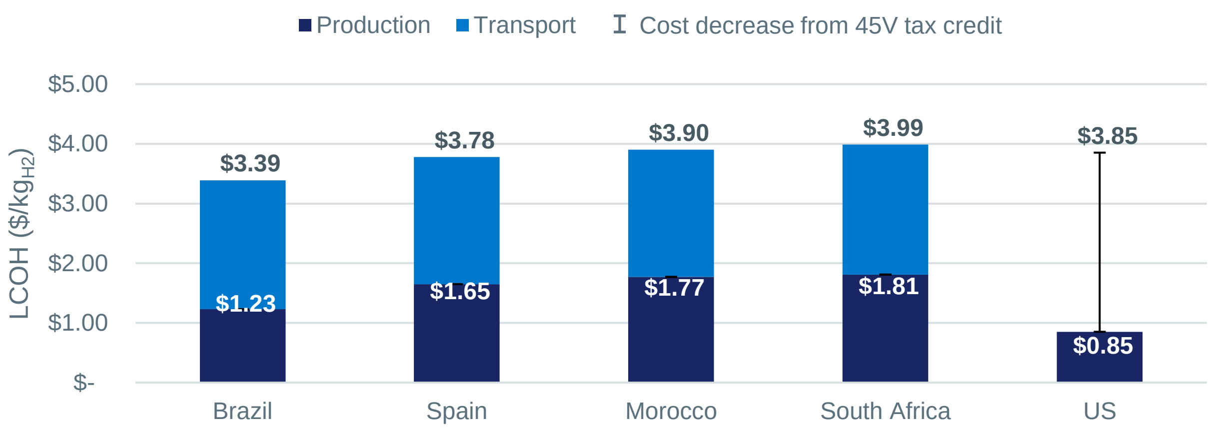
Figure 9 – 2031 Domestic Hydrogen Import Costs and the Impact of 45V Tax Credit



Assumptions: 1. Hydrogen is transported to Connecticut via truck; 2. The cost of transportation considers an average distance of 1,500 miles for the US and 30 miles for Connecticut. 3. The analysis used a combination of proprietary and publicly available data, as well as in-house ENGIE models.

In the case of international imports, Brazil, Spain, South Africa and Morocco were selected for the international analysis, based on their low LCOH. Results, presented in Figure 10, indicate similar conclusions as with domestic imports, with the IRA influence making international imports not competitive from an economic standpoint. Neither international nor domestic imports would offer significant benefits over developing a local hydrogen economy in Connecticut.

Figure 10 – 2030 International Hydrogen Import Costs and the Impact of the 45V Tax Credit



Sources: 1. BNEF 2H 2022 Hydrogen Levelized Cost Update Trending Higher; 2. ENGIE Impact internal calculations.
Assumptions: 1. H2 levelized cost of transportation was calculated considering shipping via ammonia.
Disclaimers: 1. Production prices are only directional to identify the lowest cost country based on these data sets; 2. International import options do not take into account potential tariffs/taxes for fuel imports.

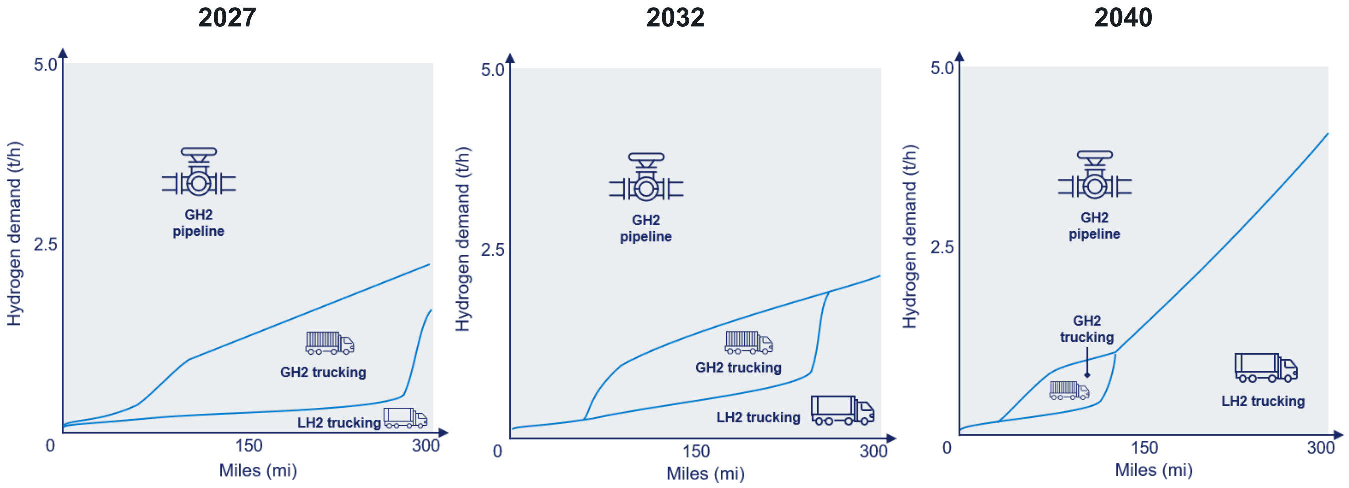
ii. Infrastructure

This section analyzes the cost of transporting and storing hydrogen, as well as the impact of refueling stations, if required, in the final hydrogen price.

Figure 11 shows the most competitive way of transporting hydrogen through Connecticut based on hydrogen volume and distance traveled. In Connecticut, distances are expected to be well below 150 miles, and the hydrogen volumes requiring transport are no more than 10 tons per hour (t/h). This analysis considers the renewable electricity cost involved in the compression of hydrogen, if needed, as well as the liquefaction and conversion to hydrogen carriers.

Results show that gaseous hydrogen trucking would be limited to a small range of applications. Nevertheless, since it is a well-established transport technology, it is the main hydrogen transport method for 2027 in the TCO analysis developed in the following section. From 2032 onwards, pipelines are included as the transport option in the TCO analysis.

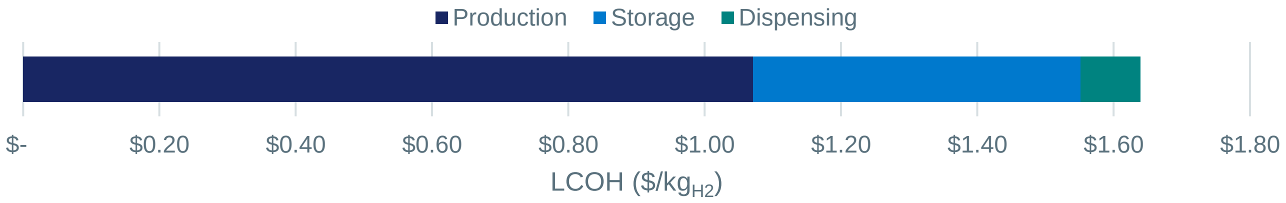
Figure 11- Cost Effectiveness of Different Hydrogen Transport Options in Connecticut



Assumptions: 1. Pipeline: 0.5% leakage of total flow, one compressor every 160 mi, pressure between 30 and 70 bar, hydrogen speed of 15 m/s, with diameters from 8 to 42 in depending on the case demand; 2. Gaseous truck: Average speed of 30 mph with efficiency of 3.69 km/L, 784 kg hydrogen capacity, 2 hours loading and unloading the truck; 3. Liquid truck: Average speed of 30 mph with efficiency of 3.69 km/L, 4,400 kg hydrogen capacity, 6 hours loading and unloading the truck, and inclusive of necessary exporting/importing infrastructure.

The most cost-effective method for storing hydrogen in a given scenario will depend on the volume of hydrogen and the required days of storage. Gaseous hydrogen storage has been the primary storage method assumed throughout the roadmap, with the exceptions of liquid hydrogen and ammonia storage for specific cases (e.g. in long-duration energy storage application). Figure 12 shows the additional costs of hydrogen storage and dispensing required for mobility use cases that will increase the total LCOH.

Figure 12- Impact of Storage and Refueling Station on Connecticut's LCOH in 2027

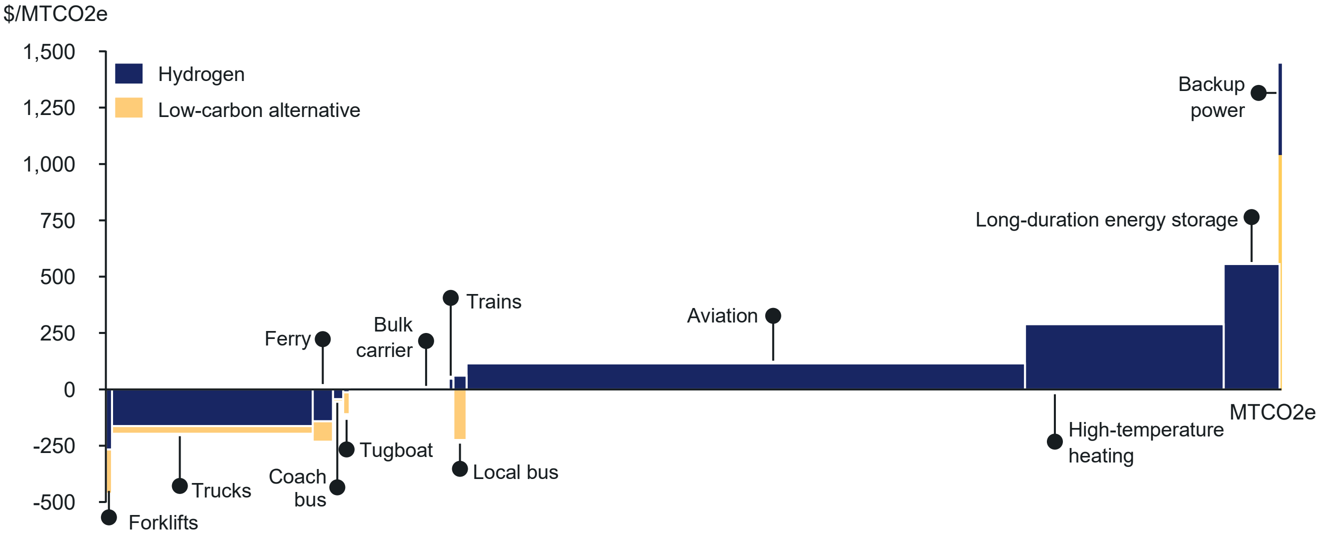


Assumptions: 1. Based on 5 ton/day hydrogen refueling station, with a one-day storage system of 5,000 kg. 2. Flow capacity of 5.2 kg/min at 350 bar discharge pressure with dual hose, at high level of utilization; 3. Policy incentives include the $3/kg 45V tax credit and IRA benefits for renewables; 4. Analysis based on 20-year project evaluation.

iii. End Use

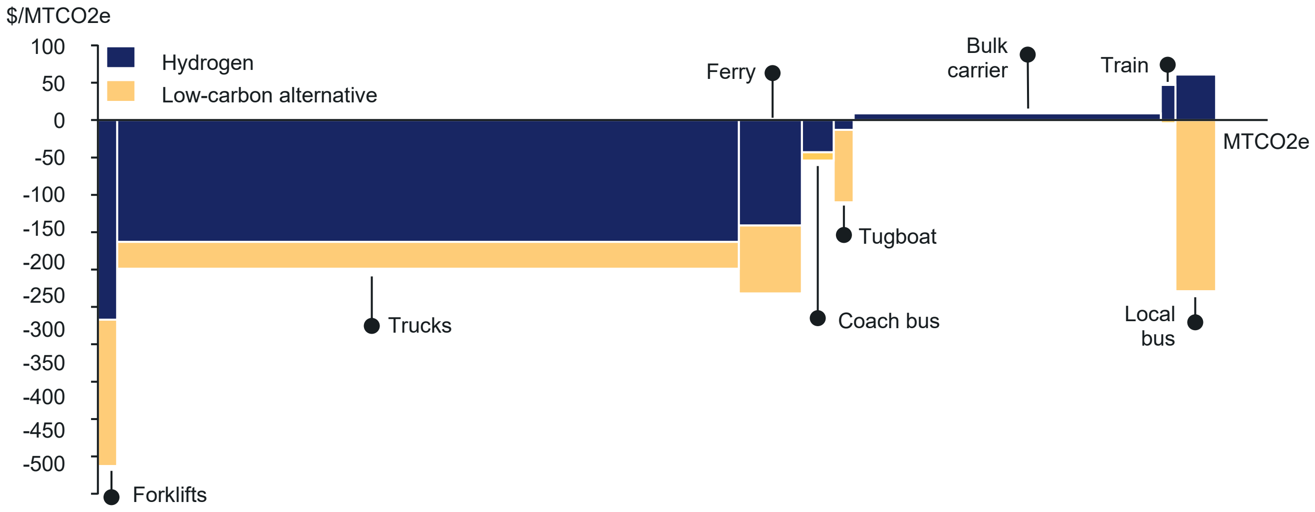
The following section presents the results of the technoeconomic analysis to calculate the TCO for each potential hydrogen end use for the fossil-based incumbent, hydrogen, and when applicable, low-carbon alternative technologies. First, results are summarized in relation to the cost of CO2 emissions mitigation when switching from the fossil-based incumbent technology to hydrogen (blue bars) or the most cost-effective alternative low-carbon technology (yellow bars), by 2032. This is achieved through a Marginal Abatement Cost Curve (MACC), in Figure 13 (and in Figure 14 for better visualization of mobility end uses). Costs are represented on the y-axis in US dollars per metric ton of CO2e ($/MTCO2e). If a low-carbon alternative is more cost-effective, it is shown in yellow below the hydrogen option. The width of each bar represents the total emissions that each end use can potentially mitigate with hydrogen solutions. For instance, emissions associated with high-temperature heating are high, but the cost of addressing these with clean hydrogen is also quite high. On the other hand, hydrogen is expected to be a very cost-effective decarbonization option for forklifts, but the total emissions that can be addressed through this end use are small.

Figure 13 - Marginal Abatement Cost Curve – End Uses in Connecticut by 2032



Assumptions: 1. Weighted average cost of capital (WACC) 5%; 2. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit), the IRA benefits for renewables, which are assumed to remain available through 2040, and the IRA CAPEX grant for mobility end uses; 3. Analysis based on 20-year project evaluation.

Figure 14 – Marginal Abatement Cost Curve – Mobility End Uses in Connecticut by 2032



Assumptions: 1. WACC 5%; 2. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit), the IRA benefits for renewables, which are assumed to remain available through 2040, and the IRA CAPEX grant for mobility end uses; 3. Analysis based on 20-year project evaluation.

The analysis shows that several hydrogen technologies can be more cost-effective than the fossil-based incumbent technologies by 2032. However, for all of those end uses, the low-carbon alternative is projected to be even more cost effective than hydrogen for the typical end use application.

The analysis assumes that most mature, fossil-based incumbent technologies have less room for improvement, therefore their CAPEX and OPEX stay relatively stable over time. On the other hand, hydrogen and other low-carbon alternative technologies that are newer to market are expected to decrease in their CAPEX and OPEX between now and 2040, due to technology improvements and benefits of increasing economies of scale. Each technology's cost curve is different and is based on expert interviews and original equipment manufacturer (OEM) data.

For fuel prices utilized in the analysis, it is assumed that the fossil fuel energy sources increase in costs over time, based on EIA projections[xxiv]. Clean hydrogen is assumed to have an important inflection point in 2032 when the 45V tax credit begins to phase out, gradually increasing its price per kilogram until 2042. Finally, it is assumed that renewable energy prices will increase over time in Connecticut due to different factors such as increasing land costs, which will impact the price of hydrogen over time as electrolysis production cost is primarily influenced by the electricity price.

Therefore, hydrogen use cases where hydrogen-related CAPEX and OPEX make up a larger portion of the TCO will tend to get more competitive over time, where hydrogen use cases that have fuel make up the largest portion of the TCO are likely to decline in competitiveness over time.

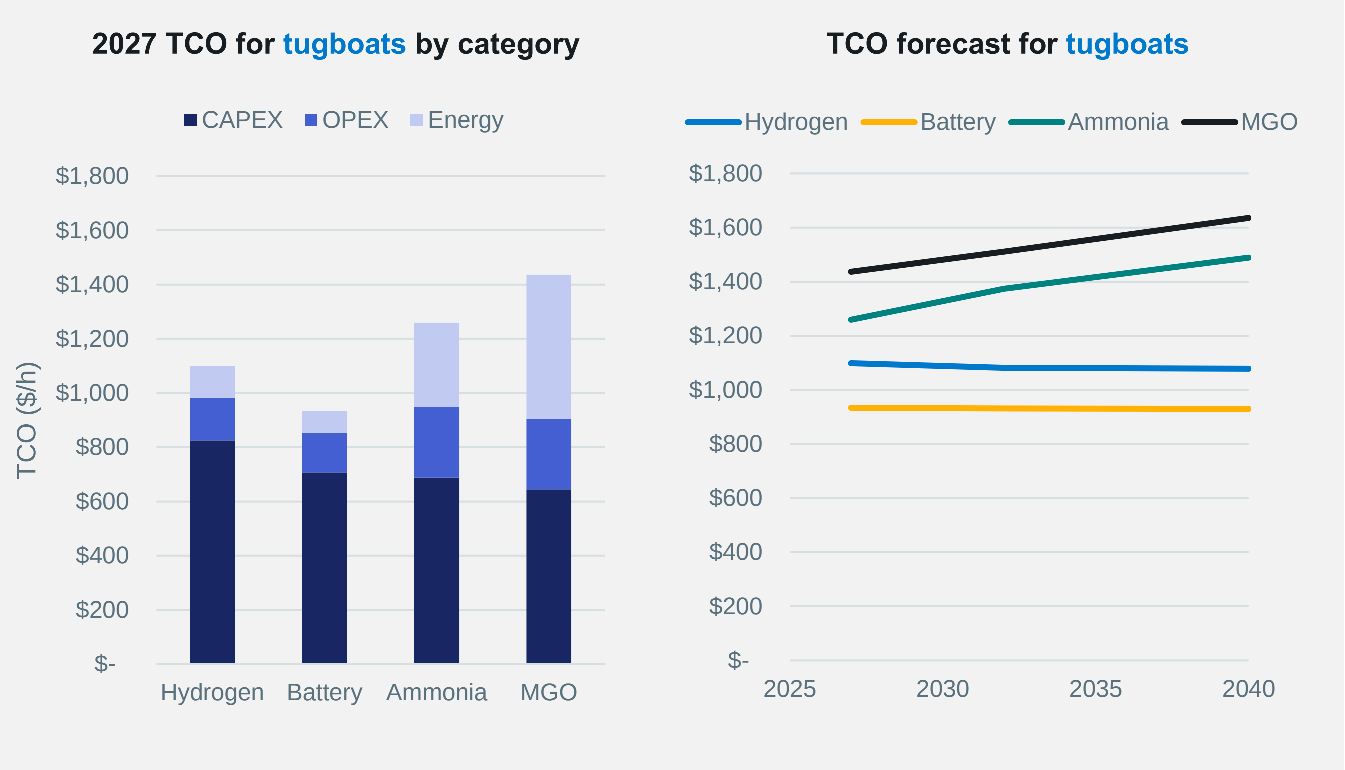
In the following pages, the detailed TCO results are represented for the hydrogen, fossil-based incumbent, and alternative low-carbon technologies for different end uses. Three different years provide the reader with a clear perspective of what is expected in 2027, 2032, and 2040. Performance of each end use against the Affordability lens is assessed in Table 10 which shows each end use against the fossil-based incumbent and the low-carbon alternative.

Table 10- Summary of Affordability Lens Analysis

End use		**Affordability Lens Evaluation**					
		Unit	**Incumbent TCO 2032**	**H2 TCO 2032**	**H2 against Incumbent**	**Alt TCO 2032**	**H2 against alternative**
Transport	**Heavy-duty trucks**	$/ton-mi	0.07	0.05	79%	0.05	115%
	Local buses	$/mi	3.83	4.03	105%	3.27	123%
	Coach buses	$/mi	2.98	2.69	90%	2.52	107%
	Forklifts	$/h	26.39	23.26	88%	21.30	109%
	Tugboats	$/h	1,510	1,081	72%	931	116%
	Ferries	$/ton	3.66	2.78	76%	2.21	126%
	Bulk carriers	$/ton	11.83	12.04	102%	*N/A*	*N/A*
	Trains	$/ton-mi	0.03	0.04	150%	0.02	156%
	Aviation	$/ton-h	101	121	120%	*N/A*	*N/A*
Industry	**High-temperature heating**	k$/MWh	0.02	0.12	483%	*N/A*	*N/A*
Power	**Backup power**	k$/MWh	1.12	2.70	241%	2.27	119%
	Long-duration energy storage	k$/MWh	0.09	0.27	298%	*N/A*	*N/A*
Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*	

See Figure 15 through Figure 26 for assumptions for each TCO calculation

Figure 15- Total Cost of Ownership – Tugboats

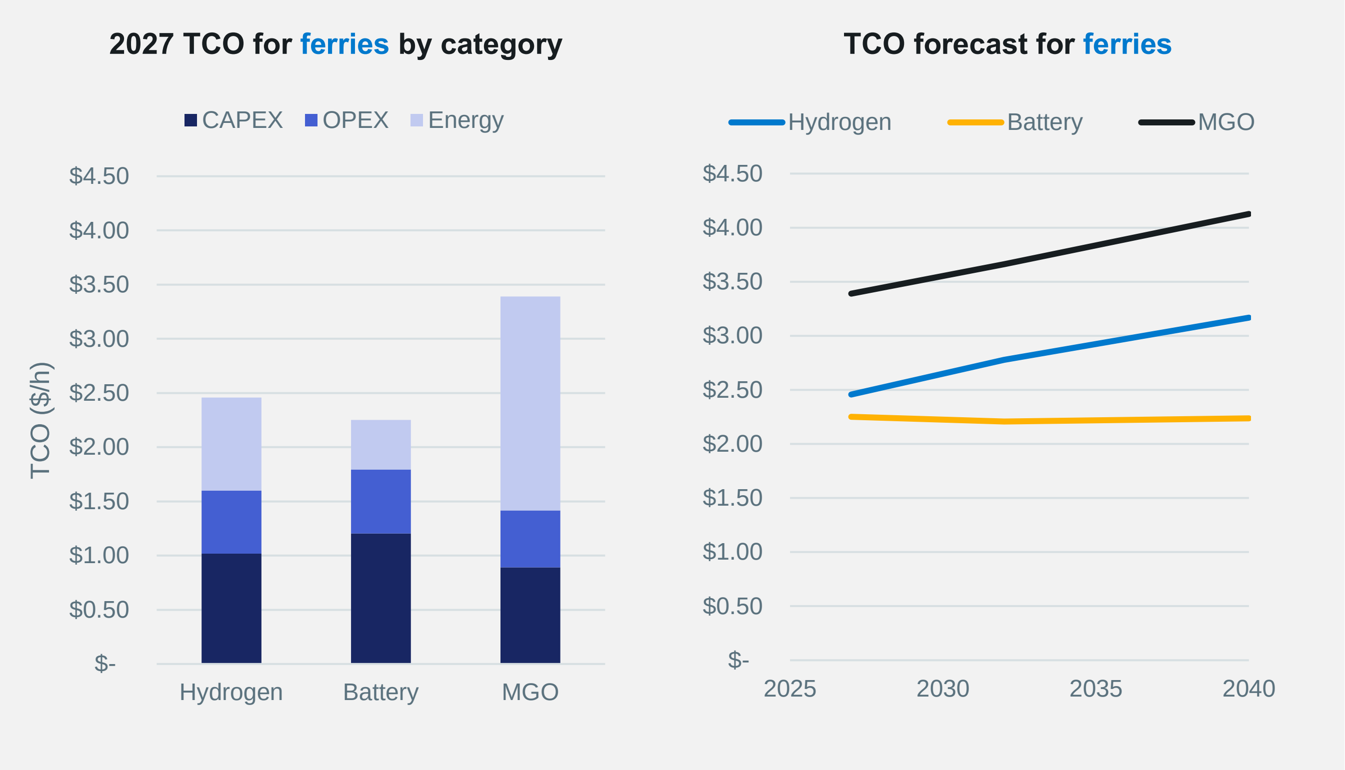


Assumptions: 1. On-site production, with fuel storage, and pipeline due to high demand and short distance; 2. WACC 5%; 3. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit) and IRA benefits for renewables, which are assumed to remain available through 2040; 4. Considered operations in the three main deepwater ports of CT: Bridgeport, New Haven and New London[xxv]; 5. A total of 10 tugboats are included in the analysis; 6. Characteristic working profile is assumed to estimate energy consumption and operating hours; 7. Analysis based on 20-year project evaluation.

By 2027, three low-carbon alternatives – batteries, hydrogen and ammonia – are projected to be more cost-effective than marine gas oil (MGO), the fossil-based incumbent. Among the low-carbon alternatives, battery power will be the most viable option, from a TCO standpoint, followed by hydrogen power. The main cost difference between battery and hydrogen systems will be the CAPEX component, which would be 17% higher for hydrogen in 2027. In this case, the CAPEX refers to the costs of purchasing new, or upgrading existing, fleets of tugboats to run on hydrogen. Ammonia, on the other hand, will have a lower CAPEX but a higher operational expenditure (OPEX).

The situation is not expected to change dramatically between 2027 and 2040. Hydrogen tugboats are projected to become more affordable and accessible due to CAPEX and OPEX reductions, which would offset the impact of the rising hydrogen price after IRA benefits begin to expire. Batteries, on the other hand, will maintain their dominance as the most cost-effective technology, with a TCO 43% lower than MGO and 14% lower than hydrogen by 2040. Ammonia is not expected to have a major role, although there are important uncertainties regarding its technological development and price reduction, which could change in the coming years.

Figure 16- Total Cost of Ownership – Ferries

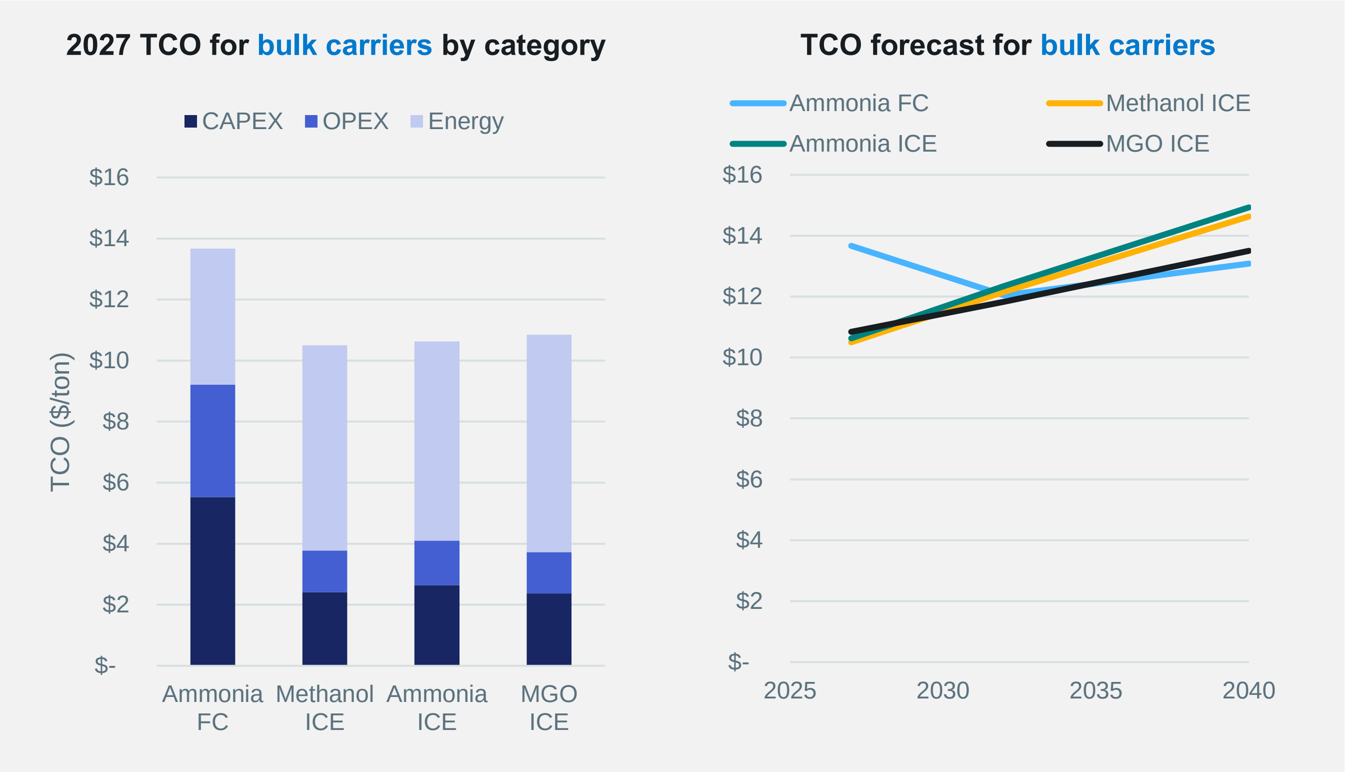


Assumptions: 1. On-site production, with fuel storage, and pipeline due to high demand and short distance; 2. WACC 5%; 3. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit) and IRA benefits for renewables, which are assumed to remain available through 2040; 4. Estimation based on the operation of the CT River Ferry (Chester - Hadlyme and Rocky Hill – Glastonbury), and the Long Island Ferry (Bridgeport – Port Jefferson, and the three seasonal express); 5. Characteristic working profile is assumed to estimate energy consumption and operating hours[xxvi]; 7. Analysis based on 20-year project evaluation.

The technology landscape for the decarbonization of ferries is expected to undergo a significant transformation by 2027. According to the analysis, batteries and hydrogen would be a more cost-effective way to operate the fleet instead of MGO. Batteries are expected to be slightly more competitive than hydrogen, mainly due to their low cost of energy (electricity), which is 47% lower than hydrogen. Operating with MGO would mean more than four times the energy cost compared to batteries, and more than twice against hydrogen. Therefore, similar to tugboats, switching to batteries or hydrogen would not only reduce the GHG emissions of the ferry sector, but also save money in the long run.

The expected evolution of these technologies and their cost shows a clear advantage for battery power systems over hydrogen and MGO. The TCO for hydrogen ferries is expected to increase, because the CAPEX and OPEX decreases are not expected to compensate for the increase of hydrogen price once the IRA PTC credit phases out. This represents a big difference from tugboats, where the hydrogen CAPEX is a larger part of the TCO. Battery power systems are expected to remain the most competitive technology, with an 8% TCO reduction by 2040 due to a reduction in the CAPEX and OPEX. Finally, MGO power system technology would increase its TCO more than 20% by 2040, due to projected increases in the cost of the fuel, limiting any option of being competitive. This indicates that battery power systems are the most promising solution for the decarbonization of ferries in Connecticut by 2027 and beyond, from a TCO standpoint.

Figure 17- Total Cost of Ownership – Bulk carriers

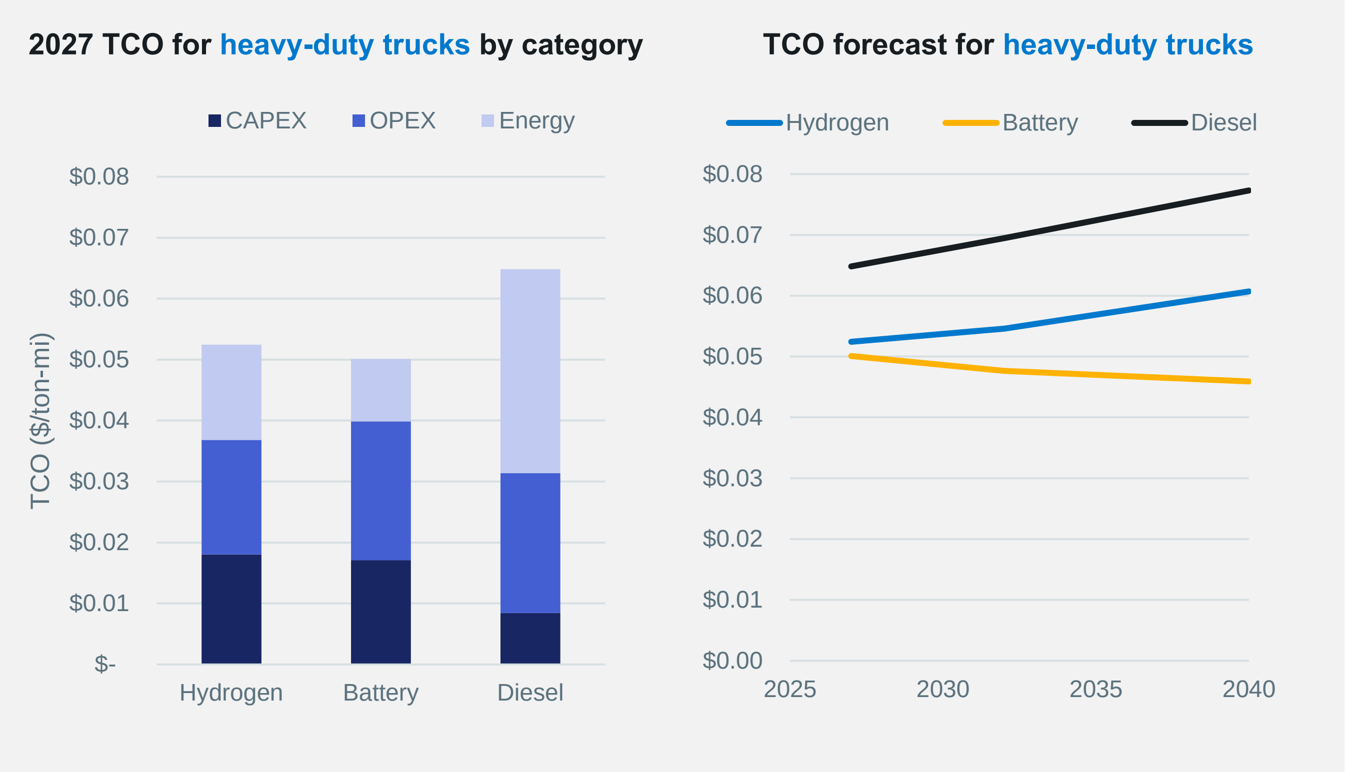


Assumptions: 1. On-site production, with fuel storage, and pipeline due to high demand and short distance; 2. WACC 5%; 3. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit) and IRA benefits for renewables, which are assumed to remain available through 2040; 4. Considered operations in the three main deepwater ports of CT: Bridgeport, New Haven and New London[xxvii]; based on goods movement available information; 5. CO2 storage is not included in e-methanol production; 6. Analysis based on 20-year project evaluation.

The technology landscape for the decarbonization of bulk carrier ships in Connecticut is expected to bring economically feasible low-carbon options by 2027. According to the analysis, methanol and ammonia internal combustion engines (ICE) are expected to have a 3% and 2% lower TCO, respectively, compared to the fossil-based incumbent technology MGO. Ammonia fuel cells, which include an ammonia cracker right before a regular hydrogen fuel cell, are still under development. Therefore, by 2027 the ammonia fuel cells are expected to be the least competitive option as shown in Figure 17.

The expected evolution of these technologies and their cost between 2027 and 2040 show a promising future for the low-carbon options. Reaching economies of scale, it is expected that by 2040 ammonia fuel cells would be competitive against MGO, which would continue increasing its TCO and be the most expensive technology. As a more mature technology, ammonia ICE loses competitiveness over time because there are relatively less improvements expected on the technology side that could lead to price reductions. This indicates that ammonia fuel cells are the most sustainable and cost-effective solution for the decarbonization of bulk carrier ships in Connecticut by 2040 and beyond, from a TCO perspective.

Figure 18- Total Cost of Ownership – Heavy-duty trucks

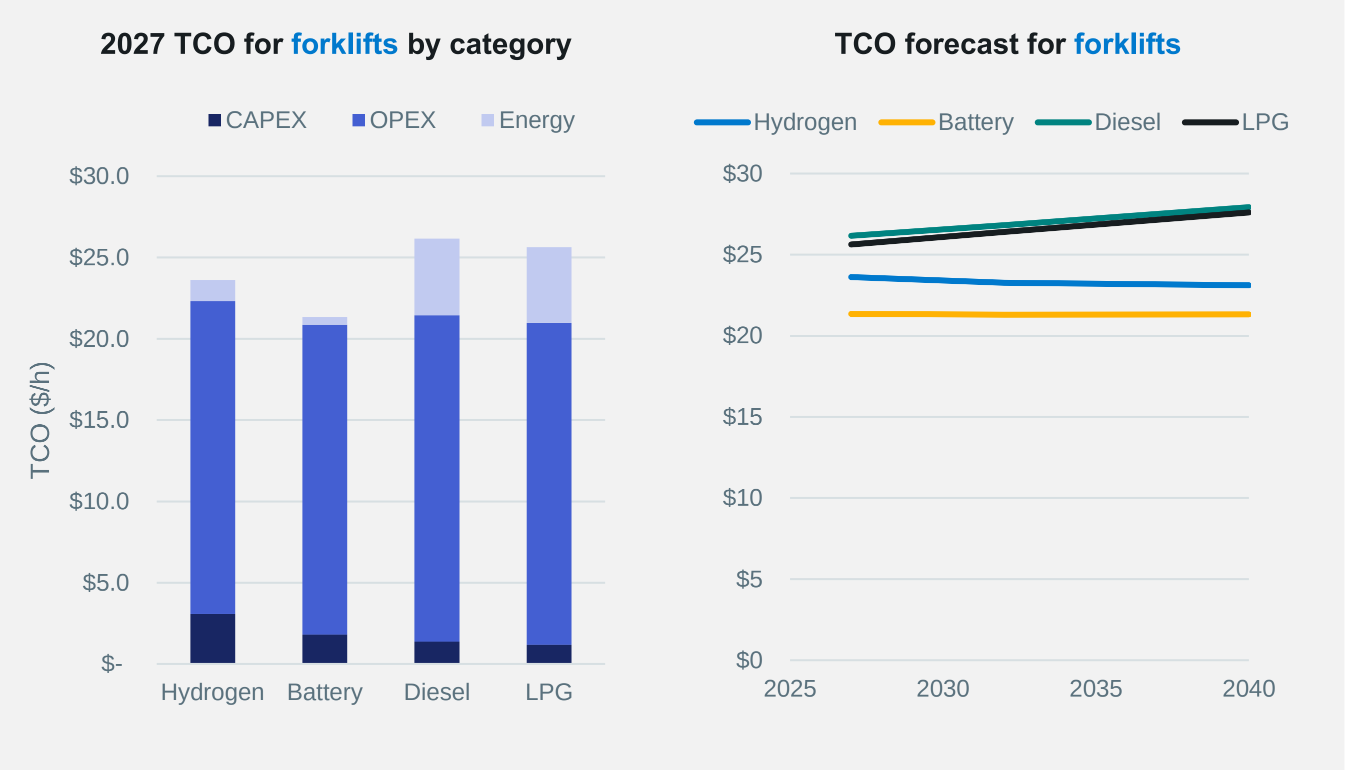


Assumptions: 1. On-site production, with a small-scale fuel storage; 2. WACC 5%; 3. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit), the IRA benefits for renewables, which are assumed to remain available through 2040, and the IRA CAPEX grant for mobility end uses (translated into $40,000/vehicle for this exercise); 4. The energy consumption is calculated based on the energy that is consumed by class 8 trucks moving more than 10 million tons of goods through Connecticut; 5. Analysis based on 20-year project evaluation.

Highly influenced by the IRA tax credits, hydrogen trucks are expected to be more competitive than diesel trucks by 2027. In that same time period, battery electric trucks, which can take the same CAPEX subsidies as hydrogen fuel cell trucks, are just slightly cheaper than hydrogen, on a TCO basis. While the vehicles themselves are less expensive, diesel trucks are not cost-effective due to the high fuel and maintenance costs.

The expected evolution of these technologies and their cost between 2027 and 2040 shows a clear advantage for battery electric trucks over hydrogen and diesel. Hydrogen trucks are expected to increase in overall TCO as the 45V tax credit expires, although some of this impact is muted by the reduction in CAPEX and OPEX costs. Battery electric trucks, on the other hand, are expected to continue decreasing their TCO, driven by a +20% decrease on CAPEX and OPEX. Diesel trucks TCO will continue increasing, making them less competitive over time. This indicates that battery electric trucks are the most cost-effective solution for the decarbonization of heavy-duty trucks in Connecticut. However, it is important to acknowledge that other factors might still favor the selection of hydrogen fleets, such as needing fast and long-distance delivery service, limited parking, or limited driver availability. In each of these scenarios, hydrogen can have an advantage over battery trucks due to the reduced payload capacity on battery trucks as a result of larger batteries.

Figure 19- Total Cost of Ownership – Forklifts

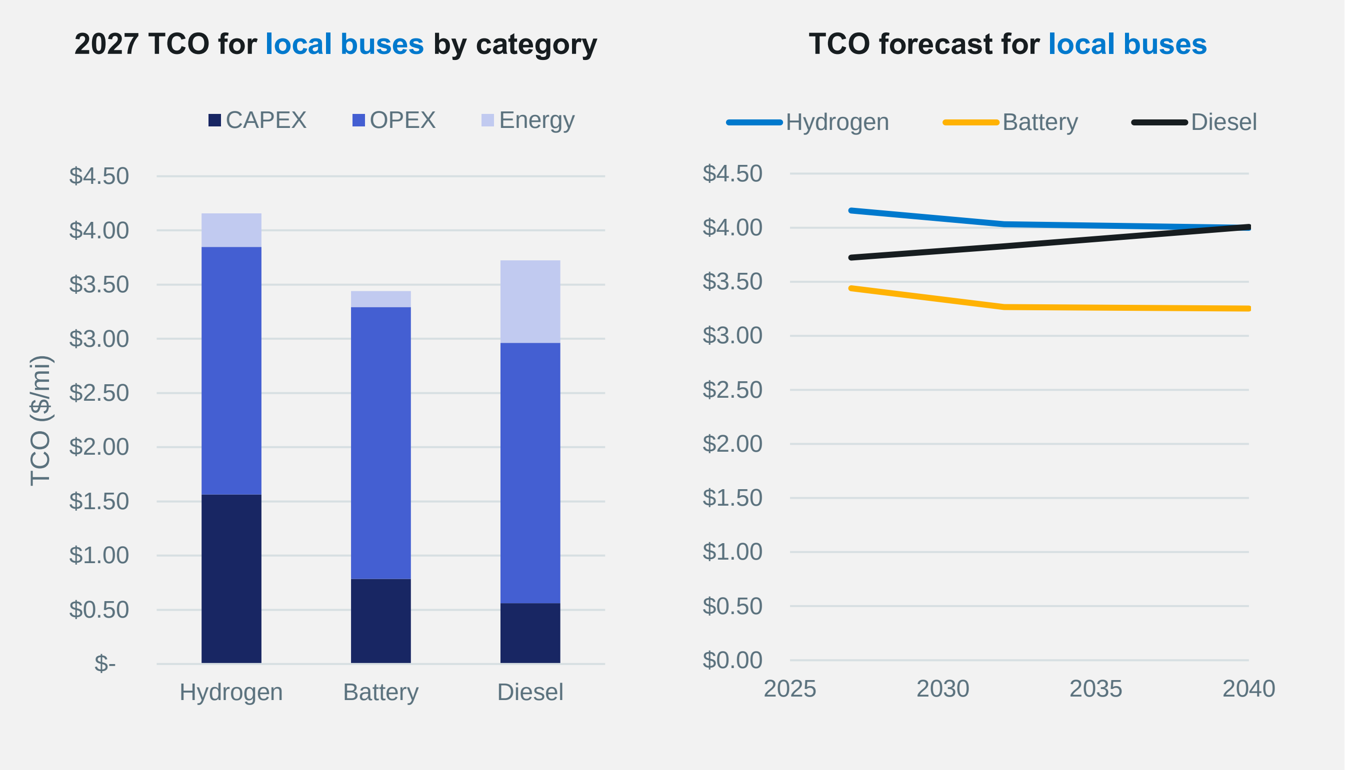


Assumptions: 1. Centralized production, distribution to small scale consumers with their own small storage and dispensing station; 2. WACC 5%; 3. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit) and IRA benefits for renewables, which are assumed to remain available through 2040; 4. Analysis based on 20-year project evaluation.

The technology landscape for the decarbonization of forklifts in Connecticut is looking favorable in 2027, with hydrogen and battery solutions projected to be more cost-effective than fossil fuel solutions. The largest contributor to those favorable TCOs is energy cost, which is much lower for hydrogen and battery forklifts than for diesel and liquified petroleum gas (LPG). Though more competitive than diesel and LPG, hydrogen is less competitive than batteries because its CAPEX and energy requirements are 70% and 180% higher, respectively. Worth noting, wages are a significant contributor to OPEX costs for all four technologies due to the low cost of the equipment and its operation, as well as a low energy consumption.

The expected evolution of these technologies between 2027 and 2040 show an advantage for battery forklifts over hydrogen and fossil fuel solutions. First, diesel and LPG solutions will continue being the most expensive options because their fuel prices are expected to increase, and no anticipated CAPEX changes are expected due to the maturity of both technologies. Battery forklifts are expected to continue being the most competitive from a TCO standpoint, thanks to their low energy consumption and maintenance costs. Hydrogen solutions are expected to experience a 24% decrease in the CAPEX and OPEX costs, which would position this technology closer to batteries, but still being 8% higher by 2040. This indicates that battery forklifts are the most cost-effective solution for the decarbonization of forklifts in Connecticut by 2040 and beyond. Nevertheless, it should be acknowledged that additional factors on a case-by-case basis could position hydrogen as a more competitive option instead of batteries, after analyzing the entire project in detail. For instance, the lack of space to park the forklifts while they are charged, which can take up to 3 hours, or the impact of low power when batteries are close to being empty.

Figure 20- Total Cost of Ownership – Local buses

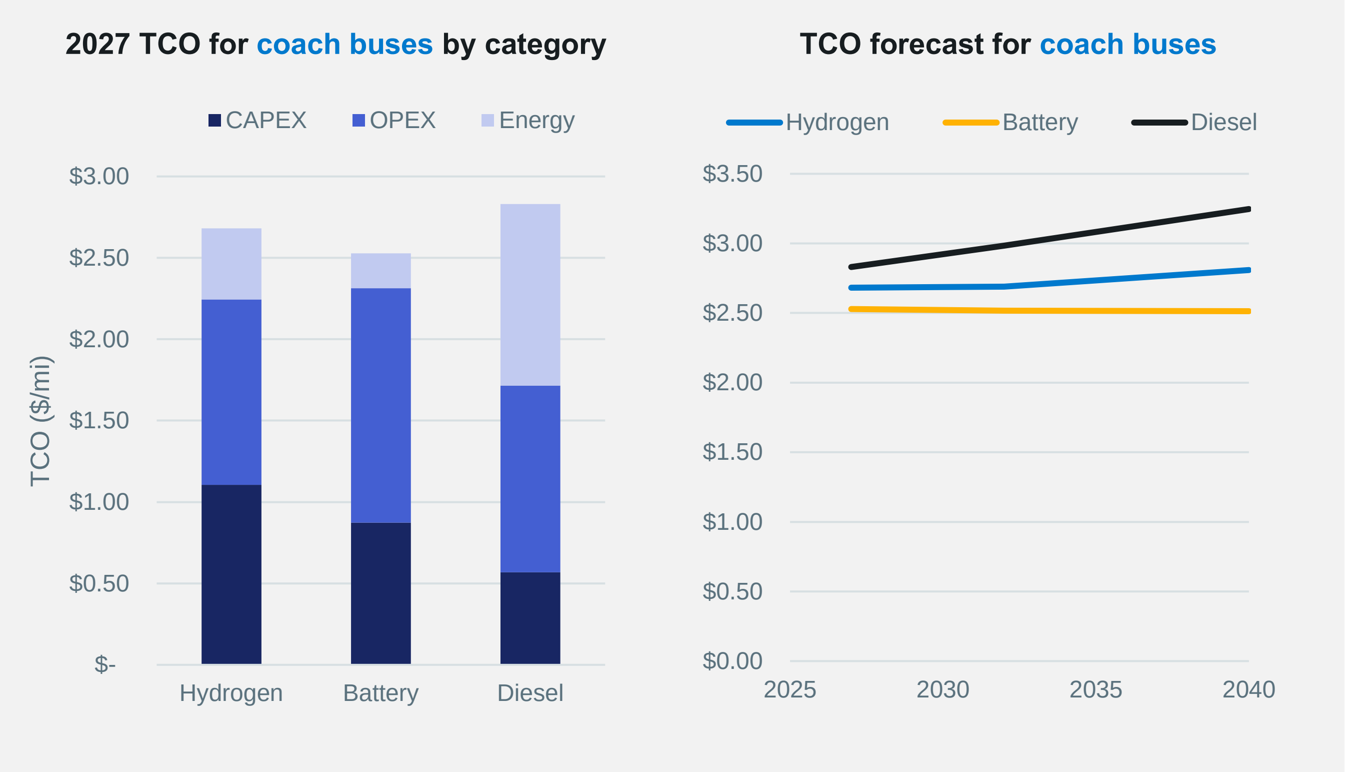


Assumptions: 1. On-site production, with a small-scale fuel storage; 2. WACC 5%; 3. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit), the IRA benefits for renewables, which are assumed to remain available through 2040, and the IRA CAPEX grant for mobility end uses (translated into $40,000 for this exercise); 4. Energy consumption is calculated based on the emissions report from 2018 and publicly available data from the Department of Transportation; 5. Analysis based on 20-year project evaluation.

Given the specific operating conditions of local buses that are favorable to electric vehicles, the technology landscape for their decarbonization in Connecticut is expected to have batteries as the most cost competitive option by 2027. During this time, hydrogen loses competitiveness against batteries and diesel because of the high CAPEX, which is twice as high as its low-carbon competitor. Similar to forklifts, wages have a significant influence on the total cost of ownership of local buses across the different technologies.

Hydrogen is expected to become more competitive than diesel by 2040, due to its 23% expected CAPEX reduction in 2040 compared to 2027. Battery buses, however, are expected to continue being the most competitive from a TCO standpoint, thanks to their low energy consumption and maintenance costs. This indicates that battery buses are the most cost-effective solution for the decarbonization of local buses in Connecticut by 2040 and beyond.

Figure 21- Total Cost of Ownership – Coach buses

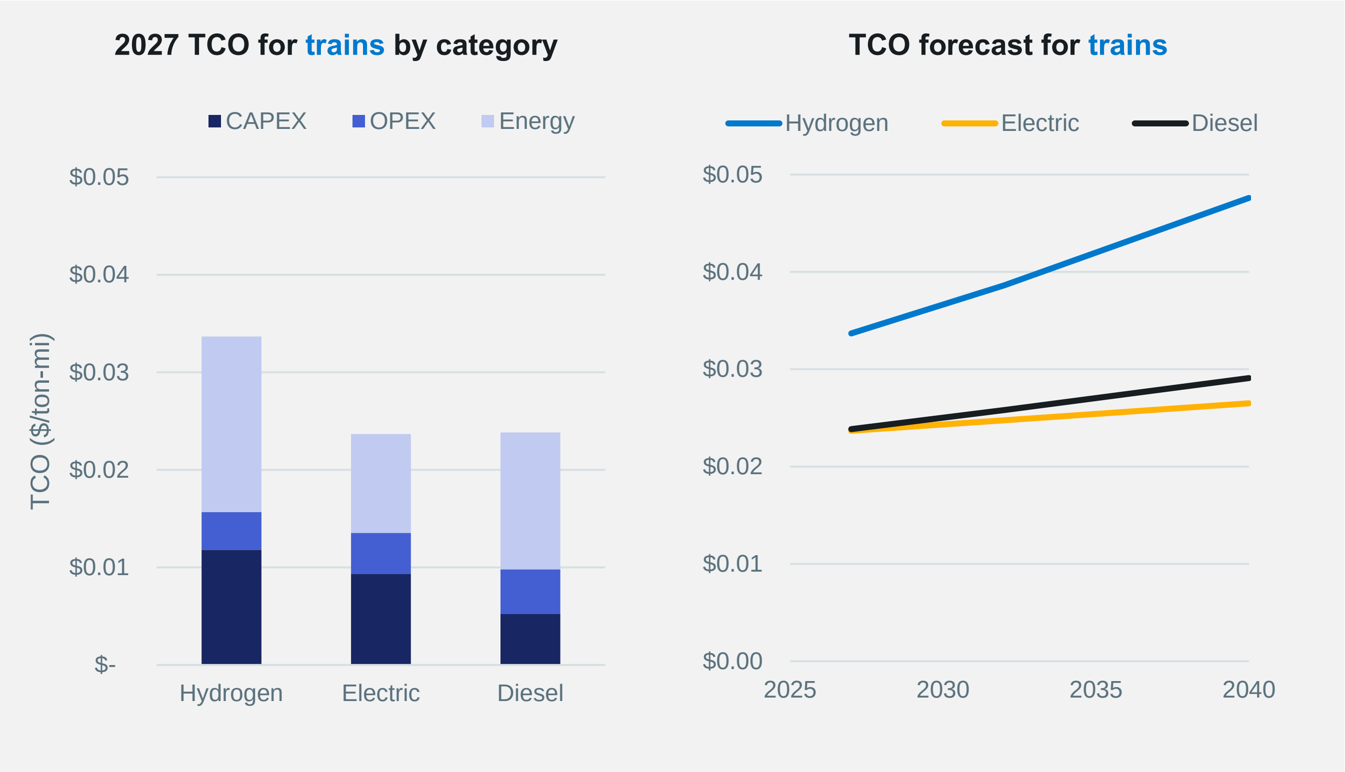


Assumptions: 1. On-site production, with a small-scale fuel storage; 2. WACC 5%; 3. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit), the IRA benefits for renewables, which are assumed to remain available through 2040, and the IRA CAPEX grant for mobility end uses (translated into $40,000 for this exercise); 4. Energy consumption is calculated based on the emissions report from 2018 and publicly available data from the Department of Transportation; 5. Analysis based on 20-year project evaluation.

The technology landscape for the decarbonization of coach buses in Connecticut is expected to look different from the local buses by 2027 due to different operating conditions. By 2027, battery and hydrogen coach buses are close in terms of TCO, with the former holding an advantage of 6% over the latter, and the more significant differences being on CAPEX and OPEX. Battery coach buses have cheaper CAPEX and energy costs compared to hydrogen coach buses. However, the battery buses fleet would need to be 29% larger than the hydrogen fleet due to batteries taking up more room and reducing payload compared to hydrogen buses. This larger battery bus fleet involves more drivers, therefore higher OPEX (maintenance and wages). Both battery and hydrogen are more cost-effective than diesel.

The expected evolution of these technologies between 2027 and 2040 shows a promising future for both batteries and hydrogen. Battery coach buses are expected to continue being the most competitive from a TCO standpoint, due to their low energy consumption and maintenance costs. Hydrogen is expected to reduce its CAPEX and OPEX significantly by 2040. Diesel, on the other hand, is expected to increase its TCO, due to its high emissions and fuel costs. Even though batteries are expected to have the lowest TCO for the average coach bus application, hydrogen buses have some benefits over electric buses that can make them more attractive for certain applications. One such example is that some battery electric buses have limited space for luggage, where hydrogen buses typically would have more room due to their fuel cells and storage tanks taking up less space than batteries for a given range[xxviii]

Figure 22- Total Cost of Ownership – Trains

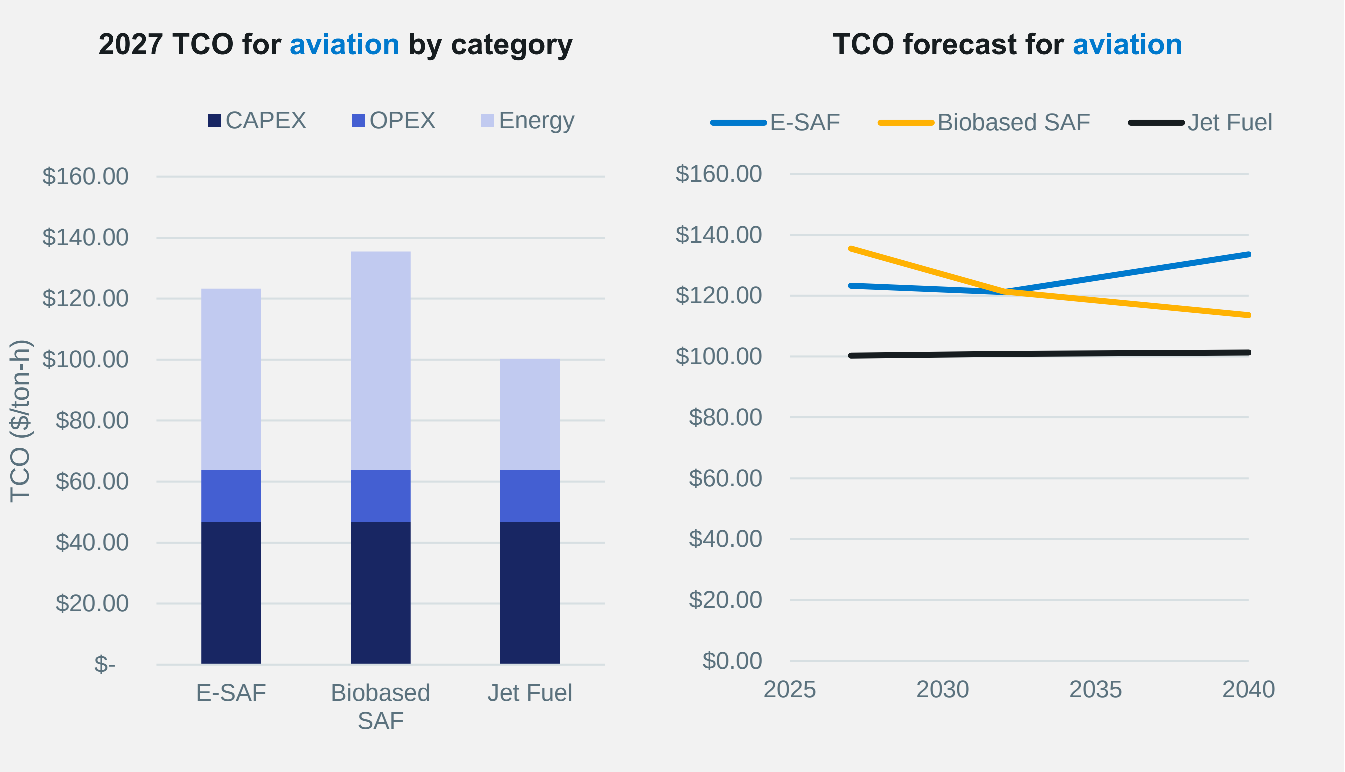


Assumptions: 1. On-site production, with fuel storage, and pipeline due to high demand and short distance; 2. WACC 5%; 3. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit) and IRA benefits for renewables, which are assumed to remain available through 2040; 4. Energy consumption is calculated based on the emissions report from 2018 and publicly available data from the Department of Transportation; 5. Train rails are not part of the CAPEX, because are assumed existent; 6. Analysis based on 20-year project evaluation.

With respect to the decarbonization of trains in Connecticut, hydrogen is not expected to be competitive in 2027, with a TCO well above diesel and electric trains. Overhead electric lines represent the biggest opportunity for decarbonizing trains in Connecticut, with a slightly lower TCO compared to diesel. Energy cost plays a big role on the final TCO, as electric trains have a much lower energy consumption and price than both hydrogen and diesel.

Looking ahead to 2032 and 2040, electric trains are projected to have an economic advantage over hydrogen and diesel. In the case of hydrogen, the benefit of the IRA PTC decreases over time, resulting in an increasing TCO curve, which is not balanced with significant improvements on the CAPEX or OPEX costs. Over time, electric trains are projected to improve in cost competitiveness compared to diesel, with electric trains achieving a 9% lower TCO than diesel by 2040. This indicates that electric trains are the most cost-effective solution for the decarbonization of trains in Connecticut, even with the energy cost increasing 28% from 2027 to 2040.

Figure 23- Total Cost of Ownership – Aviation

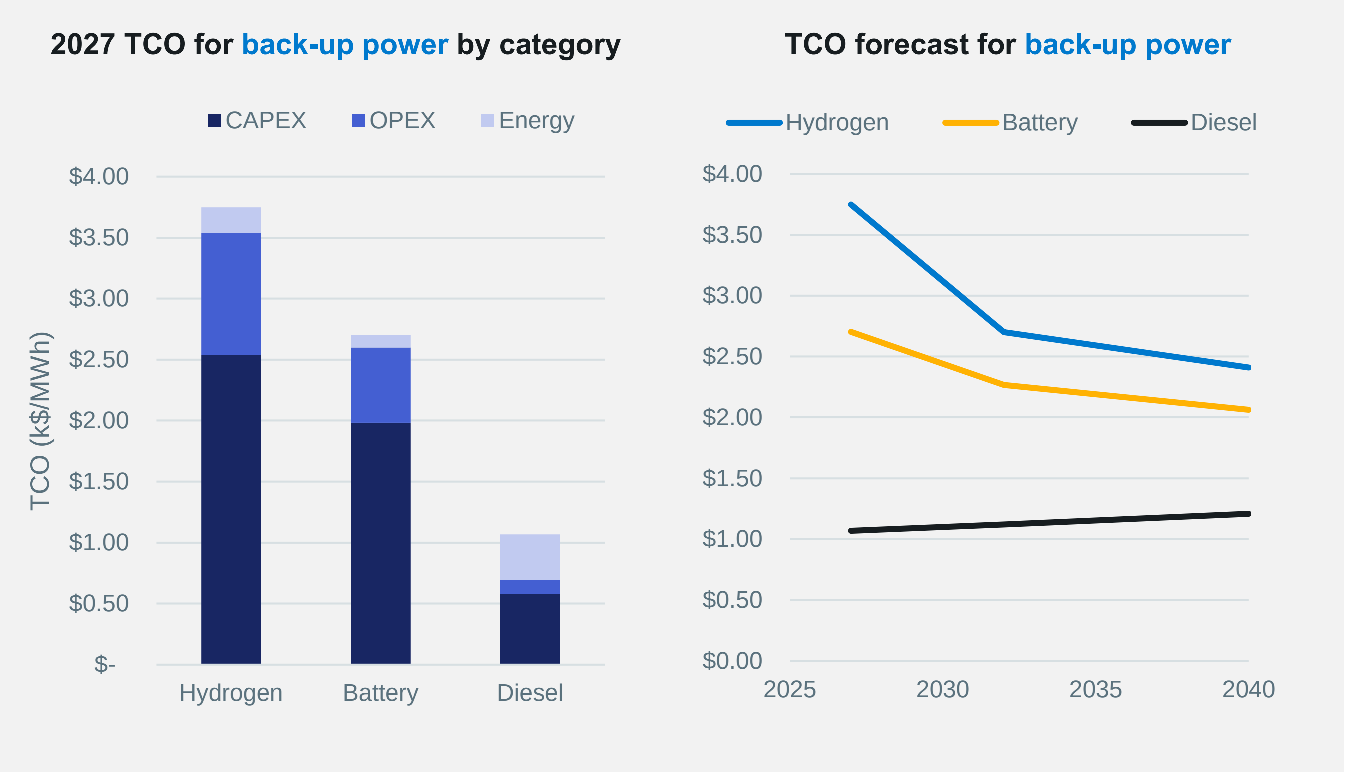


Assumptions: 1. WACC 5%; 3. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit), the IRA SAF credit in 2027, which assumes 99% and 78.5% reduction compared to fossil jet fuel for E-SAF and Biobased-SAF respectively, and IRA benefits for renewables, which are assumed to remain available through 2040; 4. Equivalent transport costs for all three fuels are included in the energy cost; 5. The plane is a commercial aircraft (Boeing 737-800) operating for 2,170 hours per year; 6. Analysis based on 20-year project evaluation.

By 2027, it is expected that low-carbon alternatives to jet fuel will not be cost-competitive for aviation in Connecticut. The energy related portions of the TCO for e-SAF and bio-based SAF are double compared to conventional jet fuel. The energy cost is the only driver of change in the TCO across the three cases. This is because both E-SAF and biobased SAF are “drop-in” fuels that require no changes to the aircraft or supporting infrastructure, meaning CAPEX and OPEX can be held steady across the cases. Although e-SAF is more expensive to produce than bio-based SAF, it has the potential to take advantage of more tax credits from the IRA because it can have lower carbon intensity compared to bio-based SAF, and because hydrogen makes up a larger percentage of its feedstock.

By 2032, both types of SAF are expected to decrease in cost due to improvements in the SAF production process, and because the hydrogen 45V tax credit will still be in effect. By 2040, the bio-based SAF TCO is projected to only have a 12% premium with the jet fuel TCO. Despite the anticipated improvements in technology, the price of e-SAF is expected to increase from 2032 to 2040, as the loss of the 45V tax credit benefit is projected to be larger than the anticipated cost impact of technology improvements, leaving the e-SAF TCO with a 41% premium over the TCO of jet fuel aviation.

Figure 24- Total Cost of Ownership – Backup power

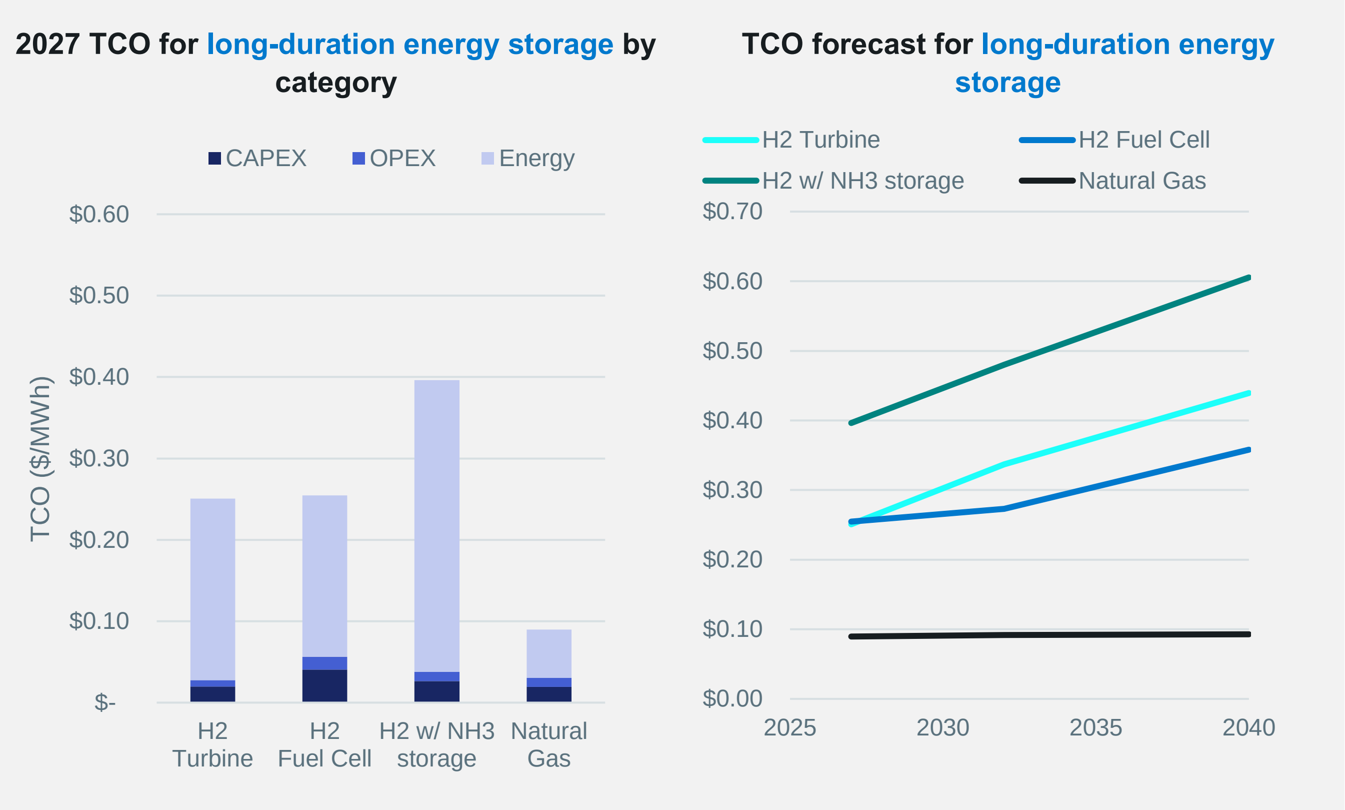


Assumptions: 1. Centralized production, distribution to small scale consumers with their own small storage; 2. WACC 5%; 3. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit) and IRA benefits for renewables, which are assumed to remain available through 2040; 4. Estimation of total back up energy consumption was based on GHG emissions report 2018; 5. Analysis based on 20-year project evaluation.

By 2027, hydrogen is projected to be a more expensive back up power option compared to both batteries and diesel as a result of high CAPEX and OPEX due to the low utilization. Energy costs play a small role due to the small energy consumption along the year of a back-up system. Batteries represent a mid-point between hydrogen and diesel. This means that hydrogen, in a majority of cases, would not be a viable option for replacing diesel generators, which have a much lower TCO.

Hydrogen costs are expected to show significant improvement between 2027 and 2040. The TCO for hydrogen and batteries get closer by 2040, with hydrogen only 15% above batteries. Still, hydrogen remains far from diesel generators, which are half as expensive on a TCO basis. This indicates that diesel generators are still the most cost-effective solution for the back-up power of Connecticut by 2040. Considering the state’s decarbonization imperative, Connecticut should still look to switch to either hydrogen or batteries for its back-up power needs. Because they are expected to be close in costs, the choice between hydrogen and batteries for back-up power needs may vary depending on specific additional requirements, such as available space and hydrogen supply options.

Figure 25- Total Cost of Ownership – Long-duration energy storage

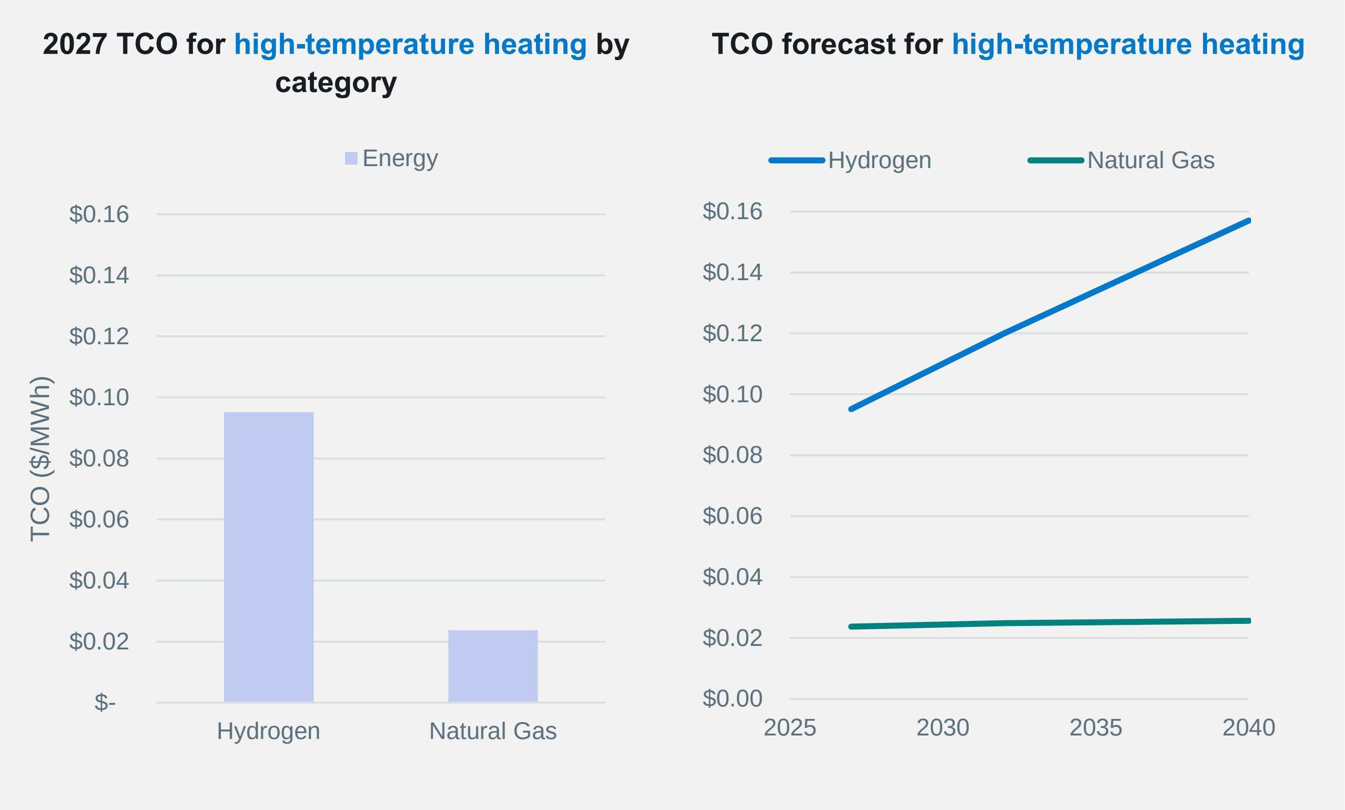


Assumptions: 1. On-site production, with large storage; 2. WACC 5%; 3 Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit) and IRA benefits for renewables, which are assumed to remain available through 2040; 4. Analysis based on 20-year project evaluation.

Natural gas is likely to be the most economic option for long-duration energy storage in Connecticut by 2027 due to its low CAPEX and energy costs compared to hydrogen turbines, hydrogen fuel cells, and hydrogen turbines with ammonia storage.

The results show that the evolution of the technologies and their cost between 2027 and 2040 will continue to favor natural gas over the three hydrogen solutions for long-duration energy storage in Connecticut. The hydrogen solutions will increase their TCO as the 45V tax credit phases out. Fuel cells will have higher efficiency than hydrogen turbines, but they will still be more costly than natural gas turbines. Still, considering the state’s decarbonization objectives, policies and investments in hydrogen for long-duration energy storage needs will be necessary, considering the uncertainty of more attractive decarbonization options, which are yet to be developed (e.g. redox flow batteries).

Figure 26- Total Cost of Ownership – High-temperature heating



Assumptions: 1. On-site production, with large storage; 2. WACC 5%; 3. Policy incentives include the $3/kg 45V tax credit (decreasing in value from 2032 to 2040 as production plants come online that don't qualify for the credit) and IRA benefits for renewables, which are assumed to remain available through 2040; 4. Only energy cost considered, since CAPEX and OPEX will vary case-by-case; 5. Analysis based on 20-year project evaluation.

Natural gas is projected to be more cost competitive than hydrogen for high temperature (>550°C) heating applications in 2027 due to having lower CAPEX, OPEX, and energy costs.

Despite an anticipated faster rate in technological improvements in hydrogen technologies compared to natural gas, due to the declining benefit of the 45V tax credit over time (as plants come online after 2032 that are not eligible for the credit), natural gas is projected to be even more cost competitive than hydrogen by 2040 than 2027.

Worth noting, hydrogen is not the only low-carbon option available to decarbonize high-temperature heat. Other options include but are not limited to electrification, biomass, and renewable natural gas. Electrification was not modeled because the economics will be highly dependent on the specific application and temperature need. Biomass and renewable natural gas were not included in the analysis due to potential availability issues of feedstock that would meet Connecticut's sustainability criteria. However, users of high-temperature heat should consider all options when evaluating the best decarbonization solutions for their specific facilities.

iv. Affordability Lens Conclusion

Under the modeling assumptions, most hydrogen technologies and end uses are projected to be able to meet the objectives of the Affordability Lens if supported by existing and proposed enablers. Examples of these enablers are listed in Table 11, with details on each noted in *Section 4: Hydrogen Enablers*.

Table 11- Affordability Lens Risks to be Addressed via Enablers

Value Chain Step and Technology *(if applicable)*	**Lens Risk to be Addressed**	**Mitigating Policy, Program, or Pilot Project,** *(details in Section 4)*
Production: Electrolysis	High electricity prices driving up cost of hydrogen production	• *Proposed Policy 9:* Incentives for Load Management
Infrastructure: All technologies	High costs of transport, storage, and fueling when handling small volumes of hydrogen that increase the LCOH	• *Program 1:* Creation of Hydrogen Clusters
End use: Heavy-duty trucking	Hydrogen TCO cheaper than fossil-based incumbent technology, but hydrogen CAPEX greater than incumbent CAPEX	• *Proposed Policy 5:* Loans for Net Zero Trucking, Forklifts, and Coach Buses • *Proposed Policy 6:* Financial Incentives for Net Zero Trucking and Fueling Stations in Environmental Justice Communities • *Proposed Policy 7:* Low Carbon Fuel Standards for Transportation Fuels
End use: Ferries, Tugboats, Bulk carriers	Hydrogen TCO cheaper than fossil-based incumbent technology, but hydrogen CAPEX greater than incumbent CAPEX	*Proposed Policy 4:* Loans for Sustainable Maritime CAPEX • *Proposed Policy 7:* Low Carbon Fuel Standards for Transportation Fuels
End use: Long-duration energy storage	Hydrogen TCO greater than incumbent fossil-based technology	• *Proposed Policy 2:* Financial Incentives for Hydrogen Usage for Long-Duration Energy Storage, High-Temperature Heat, Backup Power, Trains, and Local Buses • *Proposed Policy 9:* Incentives for Load Management
End use: Aviation	Hydrogen TCO greater than incumbent fossil-based technology, and driving factor is fuel cost	• *Proposed Policy 3:* Financial Incentives for Sustainable Aviation Fuel • *Proposed Policy 7:* Low Carbon Fuel Standards for Transportation Fuels
End use: High-temperature heat	Hydrogen TCO greater than incumbent fossil-based technology, and driving factor is fuel cost	• *Proposed Policy 2:* Financial Incentives for Hydrogen Usage for Long-Duration Energy Storage, High-Temperature Heat, Backup Power, Trains, and Local Buses
End use: Forklifts, Coach buses	Hydrogen TCO cheaper than fossil-based incumbent technology, but hydrogen CAPEX greater than incumbent CAPEX	• *Proposed Policy 5:* Loans for Net Zero Trucking, Forklifts, and Coach Buses • *Proposed Policy 7:* Low Carbon Fuel Standards for Transportation Fuels
End use: Trains, Local buses	Hydrogen TCO greater than incumbent fossil-based technology	• *Proposed Policy 2:* Financial Incentives for Hydrogen Usage for Long-Duration Energy Storage, High-Temperature Heat, Backup Power, Trains, and Local Buses • *Proposed Policy 7:* Low Carbon Fuel Standards for Transportation Fuels
End use: Backup power	Hydrogen TCO greater than incumbent fossil-based technology	• *Proposed Policy 2:* Financial Incentives for Hydrogen Usage for Long-Duration Energy Storage, High-Temperature Heat, Backup Power, Trains, and Local Buses

B. Lens 2: Climate

As new technologies are developed to support the energy transition, it is important to understand their GHG reduction potential, both in terms of the total volume of metric tons of CO2e reduced, and percent reduction compared to fossil-based incumbent technologies to ensure that resources are spent on the technologies with the biggest potential for emissions reduction. In this analysis, each technology has been evaluated on the basis of:

1. *Total potential reduction by volume:* This represents the total tons of emissions an end use contributes to Connecticut's economy today. It should be noted that hydrogen will not be able to address 100% of the emissions associated with each end use, as many will require multiple technologies to decarbonize.
2. *Percent reduction compared to fossil-based incumbent technology:* The emissions reduction compared to fossil-based incumbent technologies will assume that the hydrogen has a carbon intensity of 2 kg CO2e / kg H2, matching the carbon intensity of Connecticut's clean hydrogen definition.

i. Total Emissions by End Use

Connecticut emitted a total of 41 million MTCO2e in 2018 across all end uses within the industry, building, transport, power, waste, and agriculture sectors. Of those six sectors, three of them have end uses that could potentially be decarbonized by switching to hydrogen technologies: industry, transport, and power.

The only potential hydrogen end use that comprises more than 10% of Connecticut's total emissions is heavy-duty vehicles. Grid power comprises 19% of Connecticut's GHG emissions, but emissions reductions from low-carbon long-duration energy storage technologies will only contribute ~1-3% of that activity. Potential hydrogen end uses that comprise over 1% of total emissions include aviation, and industrial natural gas use, which includes high-temperature heat. Finally, end uses that comprise 1% or less of total emissions include maritime shipping, back-up power, buses, forklifts, and trains. Although these end uses only have a small number of emissions relative to the entire Connecticut economy, all end uses will need a pathway to net zero emissions to meet Connecticut's decarbonization goals. However, more policy, program, and pilot project resources should be dedicated to the end uses associated with higher volumes of GHG emissions, especially in the near term.

Note that it is unlikely that any of these end uses would be entirely decarbonized with hydrogen, as many could also be decarbonized with electrification and other decarbonization technologies. Assumed hydrogen rates of adoption for each end use are discussed in Value Chain Section 3.A: Hydrogen Demand.

Table 12- Climate Lens Evaluation: Total Addressable Emissions by End Use

End uses		**Climate Lens: Total Emissions**		
			Emissions associated with end use[5], *tCO2e*	**Percent of total CT emissions,** *%*
Transport	**Heavy-duty vehicles**	🟩	750,000	1.8%
	Buses	🟨	20,000	0.05%
	Forklifts	🟨	11,000	0.03%
	Maritime	🟨	175,000	0.3%
	Trains	🟨	42,000	0.1%
	Aviation	🟩	985,000	2%
Industry	**Industrial natural gas use, including high-temperature heat**	🟩	1,283,000	3%
Power	**Backup power**	🟨	112,000	0.3%
	Grid power, of which long-duration energy storage is a small component.	🟩	7,988,000	19%

Key	🟩	*High priority for mitigating enablers*	🟨	*Medium priority for mitigating enablers*	🟥	*Low priority for mitigating enablers*

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[5] Emissions from Connecticut's 2018 GHG inventory, except for maritime, forklifts, and heavy-duty vehicles, as detailed in the Methodology Section of the appendix.

ii. Emission Reductions Compared to Fossil-based Incumbent Technologies

Cross cutting

One climate-related concern that will be important to address is hydrogen leakage, which can happen at any stage of the hydrogen value chain. While hydrogen is not itself a GHG, it can react with potent gases in the atmosphere and thereby amplify harmful pollutants such as ozone and methane which contribute to global warming[xxix]. While it is not anticipated that enough hydrogen leakage would occur to entirely offset the greenhouse emissions reductions associated with swapping from fossil fuels to hydrogen, high leakage rates might undermine the climate benefits of clean hydrogen and could make it a less attractive decarbonization option relative to other low carbon alternative technologies.

While industry knowledge of hydrogen leakage impact is still nascent, adequate resources should be allocated to both understand effects across the value chain and infrastructure and implement solutions within the Connecticut Hydrogen Clean Roadmap (addressed in the policy section).

Table 13- Climate Lens Evaluation: Impact of Leaks

Climate Lens: Cross Value Ranking and Comments						
Hydrogen leaks	🟨	High rates of hydrogen leakage can dampen the climate benefits of clean hydrogen and could make it a less attractive decarbonization option relative to other low carbon alternative technologies.				
Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

Production

As noted in the introduction, hydrogen can be produced from a variety of processes that have varying levels of GHG emissions. All three hydrogen production methods detailed in this section have the potential to meet Connecticut's clean hydrogen carbon intensity limit of ≤ 2 kg CO2e/ kg H2, but each must meet the conditions outlined below for that to be the case.

Table 14- Climate Lens Evaluation: Production Method Carbon Intensity

Production Method	Climate Lens: Production Method Carbon Intensity Evaluation and Comments	
Electrolysis	🟨	Hydrogen produced via electrolysis powered by 100% renewable electricity has the potential for a carbon intensity of zero. However, electrolytic hydrogen powered from a grid that has even a relatively modest amount of fossil fuels will have a very high carbon intensity.[xxx] In that case, using Environmental Attributes Certificates is necessary to ensure GHG emissions remain at very low levels.
Gasification	🟨	Biomass is the feedstock for gasification, and it consumes CO2 from the atmosphere as it grows. Therefore, any carbon released during the hydrogen production process could still be considered net zero emissions. However, for this to be true, the biomass must be produced in a sustainable manner, which should include but is not limited to: 1. Producing biomass in a way that does not lead to deforestation, degradation of habitats, or loss of biodiversity 2. Harvesting biomass in a sustainable manner, where the rate of harvest does not exceed the rate of regrowth 3. Converting biomass to hydrogen in an efficient manner, where energy output is maximized while minimizing waste and emissions The electricity powering gasification will also need to be run mostly renewable electricity. However, gasification has a much lower electricity demand per kilogram of hydrogen compared to electrolysis, so it does not have as large of an impact on its carbon intensity.

Pyrolysis	🟨	One emissions concern with pyrolysis is methane leakage upstream of and at the point of production. Because this roadmap assumes that pyrolysis would use renewable natural gas as a feedstock where the carbon emitted originally came from the atmosphere rather than from fossil sources, the GHG emissions impact is lessened, but still present. In order for pyrolysis to have near zero emissions, the renewable natural gas must meet certain requirements, including but not limited to being produced from: 1. Waste sources that are not diverted from composting or anaerobic digestion facilities that are already producing biogas 2. Waste sources that are not associated with deforestation or other land use changes The electricity powering pyrolysis will also need to be run on mostly renewable electricity. However, pyrolysis has much lower electricity demand per kilogram of hydrogen compared to electrolysis, so it does not have as large of an impact on its carbon intensity.

Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

NOTE: No enabler has been created to mitigate the pyrolysis and gasification risks as these production methods were eliminated in the Reliability and Resilience Lens analysis.

End Use

When thinking about the climate impacts of hydrogen, it is important to understand the specific emissions reduction associated with each potential end use of hydrogen. Table 15 compares the emissions reduction potential of switching from fossil fuels to hydrogen for various end uses. For most applications, hydrogen can achieve at least an 80% reduction in GHG emissions even when produced at the upper edge of Connecticut's carbon intensity threshold of 2 kg CO2e/ kg H2. However, for a few specific end uses, achieving deep emissions reductions may require hydrogen with lower carbon intensity. This is because, for some end uses, such as high-temperature heat, the direct, on-site combustion of fossil fuels is already done in a relatively efficient manner, lessening the carbon reduction impact potential of switching to clean hydrogen.

To demonstrate the potential range of climate impacts of switching to hydrogen for different end uses, the analysis in Table 15 has been conducted at both 2.00 and 0.45 kg CO2e/kg H2, representing the upper edge of Connecticut's carbon intensity threshold, and the upper carbon intensity limit to receive the maximum tax credit from 45V, respectively. Note that if the hydrogen was produced under the assumptions used in the LCOH modeling discussed in section 2.A.i (Affordability: Production), i.e., with a carbon intensity of zero, the GHG emissions reduction would be near to 100% for all end uses.

Table 15- Climate Lens Evaluation: Lifecycle GHG Emissions Reduction by End Use

End uses		**Climate Lens: Lifecycle GHG Emissions Reduction by End Use Evaluation**			
			Fossil-Based Incumbent Technology	**Emissions Reduction compared to Fossil-Based Incumbent Technology, %**	
				2.00 kg CO2e/ kg H2	***0.45 kg CO2e/ kg H2***
Transport	**Heavy-duty trucking**	🟩	Diesel	81%	96%
	Buses	🟩	Diesel	82%	96%
	Forklifts	🟩	Propane	81%	96%
	Maritime	🟩	MGO	84%	96%
	Trains	🟩	Diesel	84%	96%
	Aviation	🟨	Jet Fuel	76%	95%
Industry	**High-temperature heat**	🟨	Natural Gas	70%	93%
Power	**Backup power**	🟨	Diesel	74%	94%
	Long-duration energy storage	🟩	Natural Gas	81%	96%

Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

Assumptions: i) GHG emissions from hydrogen production were calculated on a lifecycle basis (well-to-gate), ii) hydrogen production and renewable energy generation were matched on an annual basis, and iii) the calculations do not include potential GHG emissions associated with hydrogen transportation from point of production to point of use.

iii. Climate Lens Conclusion

The results of the Climate Lens analysis indicate that all considered production methods and end use technologies have the potential to meet the objectives of the Climate Lens, although many may require policies, programs, or pilot projects to ensure the objectives are met. Suggested policies, programs, and pilot projects are listed in the table below, and specific details on these policies are noted in *Section 4: Hydrogen Enablers*.

Table 16- Climate Lens Risks to be Addressed via Enablers

Value Chain Step and Technology *(if applicable)*	**Lens Risk to be Addressed**	**Mitigating Policy, Program, or Pilot Project,** *(details in section 4)*
Cross Value Chain	*Climate:* Unintentional increases in GHG emissions due to hydrogen leaks along the value chain	• *Program 2:* Hydrogen Safety Resource Group
Production: Electrolysis	*Climate:* Potential for increased GHG emissions with electrolytic hydrogen production by using an electricity source with a high carbon intensity.	• *Proposed Policy 1:* Connecticut Clean Hydrogen Definition
End Use: Aviation, High-temperature heat, Backup power	*Climate:* Potential for lower GHG emissions reduction for certain end uses due to lower delta in emissions between fossil-based incumbent and hydrogen technology	Create a required GHG emission reduction target that must be met for climate-related projects to receive public financial incentives. This is applicable to the following policies: • *Proposed Policy 2:* Financial Incentives for Hydrogen Usage for Long-Duration Energy Storage and High-Temperature Heat • *Proposed Policy 3:* Financial Incentives for Sustainable Aviation Fuel • *Proposed Policy 4:* Loans for Sustainable Maritime CAPEX • *Proposed Policy 5:* Loans for Net Zero Trucking • *Proposed Policy 6:* Financial Incentives for Net Zero Trucking and Fueling Stations in Environmental Justice Communities • *Proposed Policy 7:* Low Carbon Fuel Standards for Transportation Fuels
Production: Pyrolysis, Gasification	*Climate:* Potential for increased GHG emissions with gasification or pyrolysis hydrogen production by using biomass or renewable natural gas feedstock that was not sourced in a sustainable manner	No enablers were proposed as pyrolysis and gasification did not pass the reliability and resilience Energy Strategy Lens.

C. Lens 3: Equity

As the use of hydrogen technologies scales in Connecticut, it will be important to ensure that hydrogen infrastructure is accessible and the corresponding health & well-being benefits from reduced air pollution are realized by all communities. In this Equity Lens analysis, two dimensions will be assessed: physical accessibility, and health & well-being. Physical accessibility is assessed for each end use technology, as that is the portion of the value chain where accessibility by a wide variety of potential hydrogen users is most important, as opposed to production and infrastructure, which only need to be accessible for a few stakeholders. Health and well-being impacts can be felt by communities along any part of the hydrogen value chain, so this dimension has been assessed for all production, infrastructure, and end use technologies.

i. Physical Accessibility

<u>End use</u>

In order for hydrogen to be physically accessible for those who need it, hydrogen must either be produced at the site of demand, or transport infrastructure, in the form of pipelines, trucks, or fueling stations, must be in place. Hydrogen is anticipated to be most accessible for the end uses that consume hydrogen at the site of production, or end uses where the number of demand locations is limited. End uses that are likely to fall into this category include maritime, trains, aviation, and long-duration energy storage. All other end uses may be subject to limited hydrogen accessibility, especially in the short term, but as hydrogen production and infrastructure scales, and enablers are put in place, accessibility should be more widespread for all applicable end uses.

Table 17- Equity Lens Evaluation: Physical Accessibility by End Use

End uses		Equity Lens: Physical Accessibility Evaluation and Comments	
Transport	**Heavy-duty Trucking**	🟨	Though hydrogen fueling stations might not be widely available initially, fueling stations can be prioritized on the main routes that trucks and buses take. Careful planning will need to take place to ensure that fueling stations will be available where heavy-duty hydrogen vehicles will want to access.
	Buses	🟨	
	Forklifts	🟨	Due to the anticipated distribution of forklift demand across Connecticut, there may be some hydrogen accessibility issues in the short term before hydrogen transport infrastructure is built out. As hydrogen production scales in Connecticut, it will be easier to supply hydrogen for forklifts to commercial users via truck or pipeline.
	Maritime	🟩	Because most of the shipping activity will be concentrated within Connecticut's three main ports, there is not anticipated to be significant accessibility issues, assuming that there is storage and fueling infrastructure for the hydrogen derivatives used as sustainable maritime fuel at each of the three ports.
	Trains	🟩	Because most of the train activity will be along set routes, there is not anticipated to be significant accessibility issues since as hydrogen production scales in Connecticut, it will be easier to supply hydrogen for refueling trains at a finite number of locations
	Aviation	🟩	As hydrogen production scales in Connecticut, it will be easier to supply hydrogen derivatives for aviation via truck or pipeline due to the finite number of airports.
Industry	**High-temperature heat**	🟨	Due to an anticipated dispersed distribution of high-temperature heat demand across Connecticut, there may be some hydrogen accessibility issues in the short term before hydrogen transport infrastructure is built out. However, as hydrogen production scales in Connecticut, it will be easier to supply hydrogen for industrial heating via trucks or pipelines, as there should be a limited number of equipment using high-temperature heat applications.
Power	**Backup power**	🟨	Due to the anticipated distribution of back-up power demand across Connecticut, there may be some hydrogen accessibility issues in the short term before a clear system for efficiently refueling generators is created. Particularly for non-commercial end users of hydrogen generators, more effort may be required to refuel generators with hydrogen since hydrogen must be delivered to the end user via truck, whereas diesel fuel is able to be picked up by an end user from central locations at the end user's convenience.
	Long-duration energy storage	🟩	Long-duration energy storage is likely to be concentrated to a few locations, so now accessibility issues are anticipated as hydrogen production can be co-located at the site of demand.
Key	🟩 *Likely to meet lens objectives without enablers*	🟨 *Enablers likely needed to meet lens objectives*	🟥 *Unlikely to meet lens objectives with or without enablers*

ii. Health & Well-being

The opportunity to transition from fossil fuels to a hydrogen-based economy presents significant potential for enhancing health & well-being for Connecticut residents, particularly benefiting environmental justice communities. Such benefits include:

- **Improving air quality:** Implementing hydrogen technologies throughout the state can reduce nitrogen oxides (NOx) pollutants in the air, which causes respiratory issues and degrades water quality. Utilizing hydrogen fuel cells in place of the fossil-based incumbent technologies only releases water as a byproduct and does not contribute to air pollution.

However, implementing hydrogen will have considerations that need to be addressed within the roadmap strategy to ensure health & well-being, such as:

- **NOx emissions as a result of hydrogen combustion:** The process of hydrogen combustion releases NOx emissions, which at times can be comparable to or even higher than emissions from fossil fuels.
- **Short-term emissions increase through hydrogen technology construction:** It is anticipated that there could be short-term increases in air pollution due to any needed construction for hydrogen production facilities and related infrastructure.

Note that this health & well-being section covers acute and chronic health impacts. Any other safety concerns are noted in the safety section of the Reliability and Resilience Lens.

Cross Value Chain

While many of the technologies and end uses along the hydrogen value chain have the potential to reduce NOx and other harmful emissions, there may be short-term NOx emissions increases during the construction of these applications. Policy will be needed to ensure these pollutants are reduced to the extent possible and that necessary measures are taken to minimize the health impacts of those construction emissions that cannot be eliminated.

Table 18- Equity Lens Evaluation: Cross Value Chain Health and Well Being

<table>
<tr><th colspan="7">Equity Lens: Health and Well Being Ranking and Comments</th></tr>
<tr><td colspan="3">Cross Value Chain</td><td>🟨</td><td colspan="3">There is potential for increased NOx emissions along the hydrogen value chain during the construction period.</td></tr>
<tr><td><i>Key</i></td><td>🟩</td><td><i>Likely to meet lens objectives without enablers</i></td><td>🟨</td><td><i>Enablers likely needed to meet lens objectives</i></td><td>🟥</td><td><i>Unlikely to meet lens objectives with or without enablers</i></td></tr>
</table>

Production

Electrolysis, gasification, and pyrolysis are all likely able to meet the Equity Len’s health & well-being objectives, but each will need enablers or other guardrails to ensure those objectives are met. Electrolysis uses a significant amount of water as feedstock, so care will need to be put in place to ensure it is not overdrawn in any locations prone to water scarcity. Gasification also has feedstock considerations, as the biomass must come from sustainable sources to ensure that there are no negative impacts on land use change or food availability. Finally, pyrolytic hydrogen production using renewable natural gas feedstock has the potential for SOx and NOx emissions that will need to be managed to minimize negative health impacts.

Table 19- Equity Lens Evaluation: Health and Well Being by Production Methods

<table>
<tr><th>Production Method</th><th colspan="2">Equity Lens: Health and Well Being Ranking and Comments</th></tr>
<tr><td>Electrolysis</td><td>🟩</td><td>The production of hydrogen via electrolysis creates no emissions that could cause negative health impacts and the only by-product is oxygen.
Electrolytic production of hydrogen does consume water as a feedstock and has the potential to exacerbate water resource concerns when a large volume of hydrogen production occurs in water scarce areas. However, by 2040, the annual water demand from hydrogen is expected to be less than 0.05% of Connecticut’s total annual use, so this is not projected to be an equity risk.</td></tr>
</table>

Gasification	🟨	Biomass, the feedstock for gasification, if it is not sustainably and responsibly sourced, has the potential to negatively impact land use change and communities.
Pyrolysis	🟨	Renewable natural gas, the feedstock for pyrolysis hydrogen production, often has impurities that need to be removed to ensure that the production of hydrogen does not create SOx or other undesired emissions. NOx emissions will also need to be managed at pyrolysis production facilities.

Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

NOTE: No enabler has been created to mitigate the pyrolysis and gasification risks as these production methods were eliminated in the Reliability and Resilience Lens analysis.

Infrastructure

Since hydrogen itself is a nontoxic gas, there are minimal health and wellbeing concerns associated with the usage of hydrogen for transport and storage infrastructure. However, various safety concerns are present with the safe handling and usage of hydrogen, which are described in the safety section of the Reliability and Resilience Energy Strategy Lens. On the other hand, ammonia leaks from liquid ammonia tanks for storage applications pose significant health and wellbeing risks, and thus appropriate regulatory measures should be taken to reduce risk.

Table 20- Equity Lens Evaluation: Health and Well Being by Infrastructure Technology

Infrastructure		Equity Lens: Health and Well Being Ranking and Comments	
Transport	**Gaseous hydrogen trucking**	🟨	The increase in trucking associated with the transport of hydrogen via could cause an increase in NOx emissions alongside routes (assuming the trucks are not zero emission vehicles), posing potential health impacts from air pollution for those who live nearby.
	Liquid hydrogen trucking	🟨	
	Pipeline	🟩	While the potential of hydrogen leakage from pipelines can cause safety concerns (as noted in the safety dimension of the Reliability and Resilience Lens), because hydrogen itself is a non-toxic gas, there are no anticipated significant health & well-being concerns from the increase of hydrogen pipelines.
Storage	**Gaseous hydrogen tanks**	🟩	Though the leakage of hydrogen can cause safety concerns (as noted in the safety dimension of the Reliability and Resilience Lens), because hydrogen itself is a non-toxic gas, no significant health & well-being concerns are anticipated to arise from the increase of gaseous hydrogen storage. The storage of gaseous hydrogen uses refrigerants such as helium. Like hydrogen, while these chemicals can pose safety risks, they are not toxic and therefore do not pose any acute or chronic health concerns.
	Liquid hydrogen tanks	🟩	Though the leakage of hydrogen can cause safety concerns (as noted in the safety dimension of the Reliability and Resilience Lens), because hydrogen itself is a non-toxic gas, no significant health & well-being concerns are anticipated to arise from the increase of liquid hydrogen storage. The storage of liquid hydrogen uses refrigerants such as helium[xxxi] and neon. Like hydrogen, while these chemicals can pose safety risks, they are not toxic and therefore do not pose any acute or chronic health concerns.
	Liquid ammonia tanks	🟨	Ammonia leaks could cause adverse health effects as exposure to ammonia can be irritating to skin, eyes, throat, and lungs, and higher concentrations can cause lung damage.[xxxii]
Refueling		🟩	While the potential of hydrogen leakage from refueling stations can cause safety concerns (as noted in the safety dimension of the Reliability and Resilience Lens), because hydrogen itself is a non-toxic gas, there are no anticipated significant health & well-being concerns from the increase of hydrogen fueling stations.

Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

End use

Many end uses are anticipated to meet the health & well-being dimension of the Equity Lens through existing policy or implementation of new policies that largely control NOx pollution.

Transportation end uses such as heavy-duty trucking, buses, forklifts, and maritime, meet health & well-being goals since they utilize hydrogen fuel cells which do not emit NOx pollutants. Similarly, power end uses including back-up power, long-duration energy storage, and off-grid power also use hydrogen fuel cells and therefore do not have NOx emissions, unlike the fossil-based incumbent diesel technologies.

End uses such as aviation, trains, and high-temperature heating will likely still need additional policies to meet health & well-being needs since they utilize hydrogen combustion which emits NOx.

Table 21- Equity Lens Evaluation: Health and Well Being by End Use

End uses		Equity Lens: Health and Well Being Ranking and Comments	
Transport	**Heavy-duty trucking**	🟩	Hydrogen fuel cell trucks produce zero NOx emissions, unlike the incumbent diesel vehicles. This can be particularly beneficial for environmental justice communities which are often disproportionally located near trucking routes causing exposure to NOX and other pollutants.
	Buses	🟩	Hydrogen fuel cell buses produce zero NOx emissions, unlike the incumbent diesel vehicles. This can be particularly beneficial for environmental justice communities which are often disproportionally located near bus routes causing exposure to NOX and other pollutants.
	Forklifts	🟩	Hydrogen fuel cell forklifts produce zero NOx emissions, unlike the incumbent fossil powered forklifts.
	Maritime	🟩	Hydrogen derivatives methanol and ammonia produce zero NOx when consumed in shipping fuel cells.
	Trains	🟨	Hydrogen fuel cell trains will have zero NOx emissions, but hydrogen combustion trains will emit NOx.
	Aviation	🟩	SAF, a hydrogen derivative, has similar NOx to incumbent jet fuel.
Industry	**High-temperature heat**	🟨	Although the combustion of hydrogen yields NOx, it may be easier to control NOx levels in industrial settings through equipment and operating conditions.
Power	**Backup power**	🟩	Hydrogen fuel cell generators produce zero NOx emissions, unlike the fossil-based incumbent technology diesel generators.
	Long-duration energy storage	🟩	Hydrogen fuel cell generators produce zero NOx emissions, unlike the fossil-based incumbent technology, natural gas peaking plants.
Key	🟩 *Likely to meet lens objectives without enablers*	🟨 *Enablers likely needed to meet lens objectives*	🟥 *Unlikely to meet lens objectives with or without enablers*

iii. Equity lens conclusion

Both maritime transportation and long-duration energy storage end uses are anticipated to meet the health and wellbeing and physical accessibility objectives of the Equity Lens without any additional enablers.

Several hydrogen technologies and end uses are projected to meet the objectives of the Equity Lens if supported by existing and proposed enablers, which are outlined below in Table 22. Specific details on these proposed policies, programs, and pilot projects are noted in *Section 4: Hydrogen Enablers*.

Table 22- Equity Lens Risks to be Addressed via Enablers

Value Chain Step and Technology *(if applicable)*	**Lens Risk to be Addressed**	**Mitigating Policy, Program, or Pilot Project** *(details in section 4)*
End Use: High-temperature heat	*Health & well-being:* Potential for increased NOx emissions from the combustion of hydrogen as compared to incumbent natural gas technology	• *Proposed Policy 8:* NOx Emissions Standards for Hydrogen Combustion
End Use: Rail	*Health & well-being:* Potential for increased NOx emissions from transportation utilizing hydrogen combustion processes, even when compared to fossil-based incumbent technology	• *Proposed Policy 8:* NOx Emissions Standards for Hydrogen Combustion
Infrastructure: Liquid ammonia tanks	*Health & well-being:* The potential for ammonia leaks from equipment such as liquid ammonia tanks to cause negative health impacts such as irritating organs and/or lung damage	• *Program 2:* Hydrogen Safety Resource Group
End Use: Heavy-duty trucking, Local and coach buses	*Physical accessibility:* If fueling stations are not installed quickly or in convenient locations, the accessibility of hydrogen vehicles for the general consumer will be reduced.	• *Proposed Policy 6: F*inancial Incentives for Net Zero Trucking and Fueling Stations in Environmental Justice Communities • *Proposed Policy 5:* Loans for Net Zero Trucking • *Program 1:* Creation of Hydrogen Clusters • *Program 3:* Assess Optimal Siting of Hydrogen Fueling Stations
End Use: Backup power	*Physical accessibility:* Reduced accessibility to refuel back-up generators with hydrogen due to distributed nature of backup power locations	• *Program 1:* Creation of Hydrogen Clusters

D. Lens 4: Reliability & Resilience

i. Reliability

The reliability lens assesses how dependable and functional hydrogen technology is under normal operating conditions in comparison to fossil-based incumbent technologies and other low-carbon alternatives. Many parts of the hydrogen value chain have already demonstrated acceptable reliability, but in some instances, enablers will be needed to achieve a hydrogen economy as dependable as the fossil-based energy systems of today.

Production

Hydrogen production methods are not expected to show significant reliability problems at the production facilities, although some methods are still under development. However, consistent feedstock supply for pyrolysis and gasification that meets all desired sustainability criteria is not guaranteed at the scale needed for Connecticut.

Table 23- Reliability Evaluation: Hydrogen Production Methods

Production Method	Reliability and Resilience Lens: Reliability Evaluation and Comments	
Electrolysis	🟩	Hydrogen production through electrolysis can be done by different technologies, and two of them are currently available in the market with high technology readiness level (TRL): Alkaline and Proton Exchange Membrane (PEM)[xxxiii]. These two options offer high reliability.
Gasification	🟥	Current technologies for biomass gasification produce low quality syngas, and advanced gasification technologies that would be necessary for hydrogen are not widely available in the market. The TRL and output quality are still below electrolysis.[xxxiv] A consistent supply of biomass feedstock that meets all the sustainability criteria is not guaranteed.
Pyrolysis	🟥	While different known technologies for methane pyrolysis are under development, they are not widely available in the market today, with a lower TRL than electrolysis.[xxxv] A consistent supply of sustainable renewable natural gas feedstock is not guaranteed.

Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

Infrastructure

The infrastructure and equipment needed to transport and store hydrogen is commercially available and widely used in the industry, demonstrating high reliability. This applies to gaseous and liquid hydrogen, and hydrogen carriers such as ammonia and methanol.

Table 24- Reliability Evaluation: Infrastructure Technology

Infrastructure		Reliability and Resilience Lens: Reliability Evaluation and Comments	
Transport	**Gaseous hydrogen trucking**	🟩	Gaseous trucks are one of the most common methods for transporting hydrogen and have historically demonstrated high reliability.[xxxvi]
	Liquid hydrogen trucking	🟩	Insulation and the boil-off and venting (releasing built-up pressure to ensure safety), present added cost and challenges to system performance. Nevertheless, considerable progress has been made in the last decade[xxxvii], and high levels of reliability are expected for the coming years.
	Pipeline	🟩	More than 1,600 miles of hydrogen pipelines currently operate in the US with high reliability[xxxviii].
Storage	**Gaseous hydrogen tanks**	🟩	Gaseous hydrogen tanks are readily available and widely used in the industry and have historically demonstrated high reliability[xxxix] .
	Liquid hydrogen tanks	🟩	The need for insulation as well as the boil-off and venting (releasing built-up pressure to ensure safety) present added cost and challenges to system performance. However, the newest liquid hydrogen tanks have successfully addressed these challenges and are commercially available.
	Liquid ammonia tanks	🟩	Ammonia storage is highly reliable, since millions of tons of ammonia are imported and exported through US coastal ports each year[xl], and is widely used in the national economy.
Refueling		🟩	The main challenge refueling stations face today is hydrogen supply[xli], which is anticipated to improve over time. On the technical reliability, most of the unscheduled maintenance is due to problems with the dispenser system[xlii], on which improvements are expected in the near future.

Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

End use

Most of the mobility end uses considered in this assessment are expected to be reliable in comparison to fossil-based incumbent technologies, due to less moving parts which reduces the risk that equipment or infrastructure might break or degrade. These end uses include heavy-duty trucking, buses, forklifts, maritime shipping, and trains. Regarding aviation, hydrogen-based SAF has been found to have equal reliability to conventional jet fuel. As a drop-in fuel, SAF use does not require any engine or other aircraft modifications.

On the stationary applications, backup power hydrogen fuel cell generators demonstrate equal reliability to fossil-based incumbent diesel generators and potentially better operational capacity due to less maintenance required. On the other hand, grid-level Long-Duration Energy Storage is expected to require additional enablers to ensure that hydrogen-based alternatives are just as reliable as natural gas due to the inherent complexities of such a large-scale storage system.

Finally, with respect to heating, due to its nascent stage, the end use of high temperature heat will likely require additional enablers before hydrogen can meet the reliability levels of fossil-based incumbent technologies.

Table 25- Reliability Evaluation: End Uses

End uses			Reliability and Resilience Lens: Reliability Evaluation and Comments
Transport	**Heavy-duty vehicles**	🟩	It is expected that fuel cell electric vehicles (FCEVs) will have improved reliability compared to ICE counterparts as FCEVs have fewer moving parts causing potential physical misalignment than their ICE counterparts. Still, more experience is needed to confirm this hypothesis. Compared to alternative low-carbon technologies, BEV trucks are less complex than FCEVs, with lower O&M costs and potentially higher reliability[xliii]. However, at 32°F, BEVs can observe a range decrease by 20%, affecting their reliability, a notable disadvantage against FCEVs.
	Buses	🟩	
	Maritime	🟩	Compared to the fossil-based incumbent technology MGO, hydrogen and hydrogen derivative power systems are expected to demonstrate high levels of reliability[xliv]. If using fuel cells, hydrogen and carriers have the potential for improved reliability due to less moving parts than their ICE counterparts, though more experience will be needed to confirm.
	Rail	🟨	Hydrogen trains have the potential for equal or improved reliability compared to incumbent diesel technology due to less moving parts, though more experience will be needed to confirm this. When compared to alternate low-carbon technologies such as electrification, hydrogen cannot yet demonstrate the same reliability as electric trains have been commercially available for decades.
	Forklifts	🟩	Hydrogen forklifts have improved reliability compared to incumbent propane forklift technology, due to less moving parts. Unlike battery forklifts, hydrogen forklifts do not suffer from voltage drops as energy is drawn, which can cause poor power quality and decrease the lifecycle of the battery[xlv]
	Aviation	🟩	Hydrogen-derived SAF is chemically identical to the incumbent jet fuel technology, and thus has the same reliability performance.[xlvi] SAF is the only commercially available low carbon aviation technology available today, as both pure hydrogen and battery electric planes have low TRLs.
Industry	**High-temperature Heat**	🟨	Natural gas furnaces that have been retrofitted to run on hydrogen (e.g., through burner replacements and upgrades to moisture removal systems) demonstrate lower reliability compared to running on natural gas. However, purpose-built hydrogen furnaces have the potential for equivalent reliability as natural gas furnaces, though more data is needed to validate this.[xlvii] The reliability of hydrogen compared to electric, biomass, and biogas furnaces depends on the specific industrial application.
Power	**Backup power**	🟩	Hydrogen fuel cells demonstrate equal reliability to incumbent diesel generators. Fuel cells actually require less maintenance, having the potential for improved reliability, though more experience is needed with hydrogen fuel cells to confirm this. In comparison to batteries, hydrogen FCs offer longer continuous runtime.[xlviii]
	Long-duration energy storage	🟨	Natural gas, the fossil-based incumbent technology, is a more reliable long-duration energy storage option than hydrogen. This is due to the decades of experience and advancements with natural gas technologies, compared to the difficulties presented by building and operating new large-scale hydrogen storage system. Compared to other low carbon technologies such as batteries, hydrogen fuel cells have improved reliability due to the higher energy density in hydrogen and lower rate of self-discharge.
Key	🟩 *Likely to meet lens objectives without enablers*	🟨 *Enablers likely needed to meet lens objectives*	🟥 *Unlikely to meet lens objectives with or without enablers*

ii. Resilience

The resilience lens assesses how dependable and functional hydrogen technology is under extreme operating conditions (e.g. harsh weather) in comparison to fossil-based incumbent solutions and other low-carbon alternatives. Temperatures in the winter in Connecticut can reach sub-zero with high levels of snow and rain.

Different elements of the hydrogen value chain will be impacted differently by extreme events, such as snowstorms, extreme low temperatures, or heatwaves. The following section shows how production, infrastructure, and end uses can be impacted in extreme conditions, and how they compare against fossil-based incumbent technologies.

Production

A key resilience factor for hydrogen production is the feedstock supply. Therefore, the analysis is based mostly on how feedstock supply for each production method is affected under extreme scenarios. It is important to acknowledge that there is still more research needed, and as the industry develops, there will be more data points to clarify the resiliency challenges and impact on performance.

Table 26- Resilience Evaluation: Hydrogen Production Methods

Production Method	Reliability and Resilience Lens: Resilience Ranking and Comments	
Electrolysis	🟩	Water and electricity are the inputs for electrolysis. Total volumes of water needed for electrolysis are relatively small, therefore supply problems are not anticipated in Connecticut. On the other hand, electricity supply is more exposed to disruptions during a heat wave[xlix],[l]. While this threat will need to be considered and mitigated, it is an existing threat that any electricity using activity must address. For the hydrogen production process itself, an increase in ambient temperature is not anticipated to have noticeable impacts on electrolyzer performance.[li]
Gasification	🟨	The transport of biomass from its point of origin to final use could be disrupted by severe storms and snow events that cause road closures.
Pyrolysis	🟩	Renewable natural gas might offer a more reliable supply in the case of weather events assuming its transport is based on a well-established pipeline infrastructure.

Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

Infrastructure

Transport and storage of hydrogen are well-known technologies that currently show strong performance under a resilience lens, except under the scenario of road closures or other disruptions that impact trucking routes.

Table 27- Resilience Evaluation: Infrastructure Technologies

Infrastructure		Reliability and Resilience Lens: Resilience Ranking and Comments	
Transport	**Gaseous hydrogen trucking**	🟨	Storms, heavy snow, or other adverse conditions that block transport routes could pose resiliency challenges for transporting hydrogen via truck.
	Liquid hydrogen trucking	🟨	
	Pipeline	🟩	Pipelines are a resilient way of transporting hydrogen, holding up in high and low temperatures and typically unimpacted by severe storms and power outages.
Storage	**Gaseous hydrogen tanks**	🟩	Storage systems are nowadays widely used in the industry, with high levels of resiliency even during adverse weather events.
	Liquid hydrogen tanks	🟩	
	Liquid ammonia tanks	🟩	
Refueling		🟩	Hydrogen refueling stations are equally resilient to traditional gas stations.

Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

End use

All evaluated hydrogen end uses are anticipated to have fairly robust resiliency for the extreme conditions that could be experienced in Connecticut.

Table 28- Resilience Evaluation: End Uses

End uses		Reliability and Resilience Lens: Resilience Ranking and Comments	
Transport	**Heavy-duty trucking**	🟩	Both hydrogen and fossil-based trucks and buses perform well even in extreme weather conditions such as high and low temperatures. Battery vehicles, on the other hand, can see a drop in performance during cold weather, such as a 40% reduction in range.
	Buses		
	Maritime	🟩	Any failures on essential ship components at sea pose a huge safety risk, therefore resiliency to extreme conditions is critical. Hydrogen-related technology is expected to have similar levels of resiliency as the fossil-based incumbent technologies.
	Rail	🟩	Hydrogen trains are more resilient to network-wide disruptions that can affect electric trains during extreme weather events, such as power outages as a result of downed power lines.
	Forklifts	🟩	In the case of exposure to extreme temperatures, hydrogen fuel cell forklifts are expected to perform better than battery forklifts, and no differences are expected compared to fossil-based forklifts.
	Aviation	🟩	Hydrogen-derived SAF is chemically identical to conventional jet fuel, and thus has the same resilience performance.
Industry	**High-temperature Heat**	🟩	The differences between a hydrogen combustion system and a natural gas system, should not represent any major changes related to its resiliency.
Power	**Backup power**	🟩	Hydrogen systems can store large amounts of energy, which make them more resilient than battery systems in the case of a long blackout or adverse conditions.
	Long-duration energy storage	🟩	Hydrogen is expected to perform with similar levels of resiliency as natural gas turbines because of the similarities between both systems.

Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

iii. Safety

Hydrogen has advantages and disadvantages in relation to safety. On the one hand, it is a non-toxic gas and dissipates quickly in the event of a leak, while also having a flame with lower radiation than natural gas. On the other hand, it has a wide range of flammable concentrations, lower ignition energy than gasoline and natural gas (i.e., can ignite more easily), can embrittle some materials[lii], is considered a hazardous material[liii], and produces a flame that is nearly invisible with a higher temperature and speed than natural gas. Accidents occur with low frequency but high impact, and the consequences of these events could severely affect communities and the hydrogen industry.

Key concerns are around events involving equipment failure and hydrogen leaks, which can cause explosions, jet flames, and asphyxiation. Hydrogen leaks, especially if in confined spaces, represent a considerable risk as hydrogen can quickly accumulate and ignite due to the low energy required (friction can be enough)[liv].

To address these concerns, the main guidelines, standards, and codes can be found listed in the dedicated *Safety, Codes and Standards* website of the U.S. Department of Energy[lv], and the Hydrogen Technology code[lvi] NFPA2, which is widely used in the industry as the national code for hydrogen safety[lvii].

Production

While all hydrogen production methods have the potential to operate safely, and electrolysis processes have been doing so safely, there are still risks of equipment failure that could lead to loss of hydrogen that need to be managed through enablers.

Table 29- Safety Evaluation: Hydrogen Production Methods

Production Method	Safety Lens: Ranking and Comments	
Electrolysis	🟨	Among these three methods, electrolysis is the only one that has been operating for decades[lviii], proving to be a relatively safe production method. However, all three methods, there is the risk of equipment failure during the production, compression, or purification processes, which can cause fire or an explosion (e.g. failure that generates a mixing of hydrogen and oxygen)[lix]. The risk is increased for plants that have equipment in enclosed spaces where hydrogen gas can accumulate in the event of a leak.
Gasification	🟨	
Pyrolysis	🟨	

Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

Infrastructure

All hydrogen infrastructure technologies have some risk due to the potential of hydrogen leakage, with increased risk if the equipment is located in a confined space. However, all infrastructure technologies should be able to meet safety objectives if the proper enablers are put in place.

Table 30- Safety Evaluation: Infrastructure Technologies

Infrastructure		Safety Lens: Ranking and Comments	
Transport	**Gaseous hydrogen trucking**	🟨	If leaks happen in open roads, the capacity of hydrogen to quickly rise and disperse helps minimize risks; however, high-pressure storage may lead to high-momentum hydrogen jets that may remain at ground level for a certain distance and time before rising. In addition, if a leak occurs in a tunnel or confined space, there is the risk of accumulation. In addition, there is the risk of equipment failure in the facilities where trucks are loaded and unloaded (e.g. failures on the cooling or pre-cooling systems), which can also generate explosions or fire.
	Liquid hydrogen trucking	🟨	
	Pipeline	🟨	Transporting hydrogen in pipelines is potentially more dangerous than conventional natural gas systems[lx]. Dedicated large-scale mid and long-distance hydrogen pipelines are new and pose associated safety risks[lxi]. Finally, metal pipelines are exposed to embrittlement[lxii], and leaks are difficult to detect.
Storage	**Gaseous hydrogen tanks**	🟨	Hydrogen storage in traditional industrial settings like refineries and chemical plants have been operating for decades and are typically located outside in open-air settings that can reduce potential for accumulation. However, as hydrogen is used for new applications, storage in commercial buildings with reduced ventilation increases, and creates an increased safety risk as hydrogen leaks can easily accumulate indoors[lxiii].
	Liquid hydrogen tanks	🟨	
	Liquid ammonia tanks	🟨	Similar to hydrogen, ammonia leaks represent significant risk, particularly when located in settings with reduced ventilation that can lead to accumulation. A concentration of just 30 ppm (e.g., from a small leak or even regular operation) can cause breathing difficulties if a person is exposed to it for more than 15 minutes. Ammonia leaks can be deadly[lxiv], and there are concerns about this toxicity as ammonia transport and storage scales[lxv].
Refueling		🟨	Hydrogen application for transport is a newer use of hydrogen, and so the associated infrastructure and equipment, such as refueling stations, have also had less time to test and mitigate associated safety concerns. Fueling stations are often located outdoors, but can be located indoors, such as when used to refuel forklifts in a warehouse. For indoor refueling stations, the risk of accumulation of hydrogen increases. For instance, the equipment that vaporizes hydrogen operates with important pressure and temperature changes[lxvi], leading to cyclic stress, which could lead to leaks.

Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

End use

Almost all hydrogen end technologies will be utilizing hydrogen in a much higher volume than has been used historically, which creates some safety risks as noted in the table below. However, all end technologies should be able to meet safety objectives if the proper enablers are put in place.

Table 31- Safety Evaluation: End Uses

End uses		Safety Lens: Ranking and Comments	
Transport	**Heavy-duty trucking**	🟨	Accidents of hydrogen vehicles or buses can lead to equipment failure that could cause hydrogen leaks, which could have large safety implications if the leaks occur in tunnels or other confined spaces.
	Buses	🟨	
	Maritime	🟨	Since maritime applications occur in open environments, hydrogen leaks do not represent a particularly big risk if there is proper ventilation. On the other hand, if ammonia is used as a fuel and a leak occurs, even with proper ventilation, its toxicity represents a risk for direct operators of the ship, as well as the surrounding facilities; therefore, ammonia may potentially be a more suitable solution for bulk carriers, rather than tugboats or ferries, that operate in more densely populated areas.[lxvii]
	Rail	🟨	Similar to trucks and buses, equipment failure of hydrogen trains that causes leaks do not have significant safety concerns when occurring in open spaces. However, leaks in tunnels or other confined spaces could have significant safety implications.
	Forklifts	🟨	If forklifts are stored indoors (e.g. warehouses), leaks could cause an accumulation of hydrogen and represent a significant safety risk.
	Aviation	🟩	Because SAF is considered a drop-in fuel, no additional safety concerns are identified that are not already present with traditional jet fuel.
Industry	**High-temperature Heat**	🟨	Leaks can occur when storing hydrogen in confined spaces and with hydrogen connections and transfers. Additionally, the higher speed of the hydrogen flame compared to natural gas creates additional risks when operating equipment.
Power	**Backup power**	🟨	Outdoor generators do not represent additional safety risks as hydrogen leaks can disperse quickly. However, if the equipment is located indoors, there is the risk of hydrogen accumulation in the presence of leaks.
	Long-duration energy storage	🟨	Outdoor equipment and large-scale storage are not exposed to significant accumulation of hydrogen if these have leaks, assuming they have proper ventilation. However, if the power equipment (e.g. hydrogen turbine) is located indoors, there is the risk of hydrogen accumulation in the presence of leaks

Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

iv. Reliability & Resilience Lens Conclusion

Multiple hydrogen technologies and end uses are projected to meet the objectives of the Reliability and Resilience Lens without any additional policy, program, and pilot project enablers. Mobile end uses, such as heavy-duty trucking, buses, maritime shipping, forklifts, and aviation, meet the needs of both lens goals. Hydrogen back-up power also demonstrates equal reliability and resilience as compared to the incumbent diesel technology. A few hydrogen technologies and end uses are projected to be able to meet the objectives of the Reliability and Resilience Lens if supported by existing and proposed enablers.

From the safety lens, the majority of the hydrogen technologies along the value chain have the potential to meet Connecticut's safety objectives, but will need enablers, such as more demonstrations of the technologies, to prove that they can achieve this potential. Details for all enablers to help meet the reliability, resilience, and safety goals are noted in Table 32.

Biomass gasification and renewable natural gas pyrolysis are deprioritized as production methods due to reliability issues related to the feedstock supply uncertainties.

Table 32- Reliability and Resilience Lens Risks to be Addressed via Enablers

Value Chain Step and Technology *(if applicable)*	Lens Risk to be Addressed	Mitigating Policy, Program, or Pilot Project, *(details in section 4)*
Infrastructure: Gaseous hydrogen trucking, Liquid hydrogen trucking	**Resiliency**: Disruption of hydrogen transport via trucking during extreme weather conditions	• *Program 4:* Study Reliability of Hydrogen Transport Methods in Severe Weather
End Use: High-temperature heating	**Reliability**: Reduced reliability of high-temperature heating via hydrogen compared to electric and natural gas technologies	• *Pilot Project 5:* Hydrogen Production, Infrastructure, and Use for High-Temperature Heating
End Use: Long-duration energy storage	**Reliability**: Reduced reliability of long-duration energy storage via hydrogen compared to natural gas	• *Pilot Project 3:* Hydrogen Production, Infrastructure, and Use for Long-Duration Energy Storage
End Use: Rail	**Reliability**: Reduced reliability of rail transport via hydrogen compared to electric rail	Through later analysis it was determined that rail will not constitute a significant component of Connecticut's hydrogen demand, so specific enablers to address its reliability are not being proposed at this time.
Cross cutting	**Safety:** Negative consequences that result from a loss of containment of hydrogen, such as explosions, jet fires, or asphyxiation	• *Program 2:* Hydrogen Safety Resource Group

E. Lens 5: Economic Development

The transition from fossil fuels to lower-carbon forms of energy like clean hydrogen is a major undertaking that will have an impact on Connecticut's economy, including the job market. Some jobs that are currently supported by the fossil fuel industry will be lost, but new jobs will be created in the hydrogen and broader clean energy economy. The Economic Development Lens analysis seeks to understand the anticipated net job impact from switching from fossil fuels to hydrogen, in order to develop policies and programs to support workers who may be displaced by the transition.

While many of the Energy Strategy Lens analyses have evaluated each technology and end use separately for each step of the value chain, jobs impact analyses for technologies associated with the energy transition are traditionally conducted at the cross-value chain level as they consider the net impacts of the adoption of a given technology holistically. The economic impact analysis in this roadmap follows a similar approach by analyzing the net impact the hydrogen economy would have for jobs at the cross-value chain level, with a callout for specific parts of the value chain when appropriate.

i. Existing and Future Hydrogen Jobs

Hydrogen already contributes jobs to Connecticut, as the state has both electrolyzer and fuel cell manufacturing facilities. NEL has an electrolyzer manufacturing facility in Wallingford, which is going to expand to 500 MW of capacity by 2025[lxviii]. Fuel Cell Energy is headquartered in Danbury and has a manufacturing plant in Torrington, and the company estimates that the fuel cell industry creates over 6,000 direct, indirect, and induced jobs for Connecticut's economy[lxix].

A scale up of hydrogen in Connecticut can create additional jobs that encompass the entire value chain, from upstream renewables used to power hydrogen production, to pipelines that transport hydrogen, to hydrogen end use equipment. A variety of types of jobs will be needed at each step as well, from operators and maintenance workers, to engineers, to sales reps. The below table provides more examples of the sustained jobs that would be needed at every step of the value chain to support the hydrogen economy.

Table 33- Hydrogen Value Chain Activities and Associated Sustained Jobs

Value Chain Step	Potential hydrogen activity	Associated sustained jobs (not exhaustive)
Upstream	Renewable energy production, such as onshore wind	Operators and maintenance workers for wind turbines.
Production	Production of hydrogen via electrolysis	Operators and maintenance workers for electrolyzers
Infrastructure	Transport of hydrogen via trucks and pipelines. Storage of hydrogen in above ground tanks.	Pipeline operators and maintenance workers. Hydrogen truck drivers and maintenance workers.
End Use	Consumption of hydrogen and hydrogen derivatives in transport, including heavy-duty trucking, maritime, and forklifts. Consumption of hydrogen in electricity generation such as long-duration energy storage and back-up power. Consumption of hydrogen in industry for High-temperature heat.	Vehicle drivers and maintenance workers for trucks, ships, airplanes and forklifts. Powerplant operators and maintenance workers. Industrial heating installers and maintenance workers.
Cross-cutting	Professional services that support the value chain from the business side.	Professional services such as engineers, accountants, marketers, and trainers.

In addition to the above sustained jobs, many construction workers will be needed as well to build renewable energy needed to power the hydrogen production, hydrogen production plants, hydrogen transport and storage infrastructure, and retrofits for end use equipment that will need to be modified to run on hydrogen.

ii. Fossil Jobs at Risk

When looking at all the jobs that hydrogen can create, it is important to also consider the fossil fuel jobs that hydrogen could displace. Connecticut had 71,570 energy workers statewide in 2021, representing 4.5% of total state employment. Of these energy jobs, the ones that are most closely associated with fossil fuels include 991 in natural gas generation, 3,982 in fuels (natural gas and petroleum), and 9,836 in transmission, distribution, and storage[lxx].

While these numbers are non-negligible, Connecticut's economy as a whole is better positioned to withstand any fossil-based job losses arising from the hydrogen transition due to having one of the least energy-intensive state economies in the country. Connecticut uses less energy to produce one dollar of gross domestic product (GDP) than all other states except for California, Massachusetts, and New York[lxxi]. In addition, Connecticut does not currently operate any coal, natural gas, or crude oil reserves or production facilities, and largely imports petroleum and natural gas from nearby states through local ports. The table below provides more details into Connecticut's current fossil fuel activities.

Table 34- Fossil Fuel Value Chain Activities and Associated Jobs

Value Chain Step	Current fossil fuel activity[lxxii]	Associated jobs (not exhaustive)
Upstream	Connecticut has no coal, natural gas, or crude oil reserves to extract	None as there is no upstream fossil fuel activity in Connecticut.
Production	Connecticut does not have any oil refineries or natural gas processing.	None as there is no fossil fuel production activity in Connecticut.
Infrastructure	Petroleum enters Connecticut through the ports of New Haven, New London and Bridgeport. A pipeline originating in New Haven delivers petroleum products to central Connecticut Interstate pipelines bring in the natural gas the state uses. Just more than half of the natural gas that enters Connecticut is consumed in the state, and the rest is transported on to Rhode Island and New York.	Pipeline operators and maintenance workers Port workers, such as mechanics, electricians, crane and forklift operators, dockers, and security guards.
End Use	70% of the petroleum in Connecticut is used in the transport sector (primarily gasoline and diesel), 20% is used in the residential sector, and 10% is used in the commercial and industrial sectors. 60% of the natural gas in Connecticut is used in the power sector, 20% in the commercial sector, 17% in the residential sector, <10% in the industrial sector, and the remainder on transport Connecticut's last coal-fired power plant closed in the summer of 2021.	Truck drivers and maintenance workers. Powerplant operators and maintenance workers. Building heating installers and maintenance workers.
Cross-cutting	Professional services that support the value chain from the business side.	Traders and professional services such as engineers, accountants, marketers, and trainers.

iii. Net Jobs Impact

The hydrogen economy poses a massive employment opportunity globally with the potential of creating over 10.3 million net new jobs by 2030[lxxiii], with a majority in the mobility, energy efficiency, and power generation sectors. The US DOE Liftoff report also cites an anticipated net increase in jobs related to the build-out of new hydrogen capital projects and infrastructure[lxxiv]. Given that third party reports project a net increase in both short-term and sustained jobs due to the hydrogen transition, coupled with the fact that Connecticut does not currently have many fossil-fuel based jobs and largely imports from neighboring states, a transition to a hydrogen-based economy is projected to a produce a net increase in sustained, and short-term, jobs in the state.

Even with a net increase in jobs, concerted effort will be required from public and private sector stakeholders to ensure that there are enough trained workers to fill the types of hydrogen jobs needed, and that these trainings and transition resources are made available to workers whose jobs will be displaced by the transition. Targeted programs will also be needed to ensure that clean hydrogen jobs are in environmental justice communities, and that residents of those communities have adequate training and resources to fill those positions.

Finally, the state should consider dedicating resources to build on hydrogen innovation momentum that already exists from Connecticut's electrolyzer and fuel cell manufacturing industries. In addition to jobs that will be created by Connecticut's own consumption of hydrogen, there is an opportunity for Connecticut to further capitalize on this opportunity by exporting fuel cells and electrolyzers to other states, yielding both job and economic benefits for the Connecticut. While the state has an advantage with existing manufacturing capacity, coordinated efforts will help Connecticut stay competitive in the hydrogen market.

Table 35- Economic Development Lens Evaluation: Jobs Impacts

Jobs impact dimension	Economic Lens: Jobs Impact Ranking and Comments	
Net jobs impact	🟩	The scale up of hydrogen in Connecticut is anticipated to create a net increase in jobs
Availability of trained workers	🟨	Without additional action, there is potential for there to be a shortage of qualified workers to fill all of the hydrogen jobs created.
Infrastructure to support displaced fossil workers	🟨	Without additional action, there is potential that the fossil fuel workers whose jobs are displaced by the hydrogen transition will not have access to the resources needed to be able to transfer their skills to hydrogen jobs.
Availability of jobs to members of environmental justice communities	🟨	Without additional action, there is risk that a proportionally low number of jobs are available to members of environmental justice communities.
Job impact from exporting hydrogen equipment	🟨	Without additional action, there is risk that Connecticut is not able to take full advantage of its existing hydrogen knowledge and manufacturing capacity to increase job and economic development in the state.

Key	🟩	*Likely to meet lens objectives without enablers*	🟨	*Enablers likely needed to meet lens objectives*	🟥	*Unlikely to meet lens objectives with or without enablers*

iv. Economic Development Lens Conclusion

To properly take advantage of the level of economic development that could be fostered due to a clean hydrogen transition in Connecticut, various programs have been identified that can support job creation and training and are listed in Table 36. Specific details on these programs are noted in *Section 4: Hydrogen Enablers*.

Because the economic development analyses were conducted at a cross value chain level rather than specific analyses for each step, no technologies or end uses have been called out as not aligning with the goals of the Economic Development Lens. Addressing the items raised in Table 36 via enablers will be the best way to ensure that the Economic Development Lens objectives are met throughout the hydrogen transition.

Table 36- Economic Development Lens Risks to be Addressed via Enablers

Value Chain Step and Technology *(if applicable)*	**Lens Risk to be Addressed**	**Mitigating Policy, Program, or Pilot Project**, *(details in section 4)*
Cross-value chain	Shortage of qualified workers to fill all hydrogen jobs created on the needed timelines	*Program 5:* Equitable Hydrogen Job Transition Program
Cross-value chain	High unemployment rates among displaced fossil-fuel workers who don't have the correct skills to enter the hydrogen workforce	*Program 5:* Equitable Hydrogen Job Transition Program
Cross-value chain	Proportionally low number of jobs available to members of environmental justice communities.	*Program 5:* Equitable Hydrogen Job Transition Program
Cross-value chain	Inability to capitalize on existing hydrogen knowledge and manufacturing capacity to increase in state economic development.	*Program 6:* Connecticut Hydrogen Innovation Consortium

F. Energy Strategy Lens Conclusion

The completion of the Energy Strategy Lens analysis yielded promising results for hydrogen to be scaled in a way that meets all of Connecticut's energy objectives. The majority of technologies analyzed passed all five lenses, and at least one technology passed for every step of the value chain.

The analysis concluded that electrolysis should be the main hydrogen production method that Connecticut pursues, as pyrolysis and gasification were eliminated in the reliability section due to anticipated feedstock constraints. With respect to infrastructure, all analyzed transport (gaseous trucking, liquid trucking, and pipeline) and storage (gaseous hydrogen, liquid hydrogen, and ammonia) methods, as well as fueling stations, passed all 5 Energy Strategy Lenses. Finally, the analysis indicated that all of the end uses should be at least partially decarbonized with hydrogen:

- *Transport:* Heavy-duty trucking, aviation, maritime bulk carriers, ferries, tugboats, forklifts, local buses, coach buses, and trains
- *Industry:* High-temperature heat
- *Power:* Long-duration energy storage, back-up power

While the majority of technologies passed all 5 lenses, the analyses also identified many technology specific, as well as cross cutting, hydrogen risks that will need to be addressed, such as higher costs compared to fossil-based incumbent technology, safety considerations, and potential for increased NOx due to hydrogen combustion. To mitigate these risks, policies, programs, and pilot projects have been proposed to ensure that hydrogen can scale in a way that meets all of Connecticut's energy objectives. These are noted in detail in *Section 4: Hydrogen Enablers*.

3. Connecticut Hydrogen Value Chain

This section of the roadmap details the hydrogen demand by end use across three distinct timeframes: 2027, 2032, and 2040, with the significance of each year noted below:

- 2027 as the year for pilot projects to begin
- 2032 is the last year that new hydrogen production plants can be commissioned and receive the 45V tax credit
- 2040 is the year Connecticut must achieve its statutory goal of a net zero power grid

In addition to hydrogen demand, this section outlines the necessary resource requirements to meet those demands, including electrolysis and renewables capacity, water requirements, and capital investments. This section also identifies the impacts that hydrogen on this scale would have, from GHG and NOx emissions reduction to net impact on jobs.

A. Hydrogen Demand

After completion of the Energy Strategy Lens analysis, hydrogen produced through electrolysis has been identified as a target decarbonization technology for 12 end uses in Connecticut. However, with most of the end uses, hydrogen will be one of multiple technologies used for decarbonization, and there will be situations for each end use when another low carbon alternative is the better technology for cost or other feasibility reasons.

Given the multiple low carbon alternatives for each hydrogen end use, a hydrogen rate of adoption has been estimated for each end use to determine the total hydrogen demand for each time period. The rate of adoption for each end use is the projected percentage of each end use that can reasonably be expected to be decarbonized with hydrogen in order for Connecticut to meet its decarbonization goals of zero electricity sector emissions by 2040 and an 80% economy-wide emissions reduction from 2021 by 2050. As there are multiple undetermined variables that will influence how much hydrogen would be needed within each end use, three hydrogen scenarios have been created: Base hydrogen, High hydrogen, and Low hydrogen.

i. Base Hydrogen Scenario

The Base Hydrogen Scenario represents a moderate growth trajectory for hydrogen adoption, with hydrogen playing a significant role in decarbonizing certain sectors but not becoming a dominant energy carrier. In this scenario, the hydrogen demand is about 7,700, 38,000, and 76,000 metric tons of hydrogen per year in 2027, 2032, and 2040 respectively. The top three end uses are heavy-duty trucking, aviation, and long-duration energy storage, making up 91% of total hydrogen demand in 2040. Heavy-duty trucking is a large end use, so even a modest rate of adoption for hydrogen for that end use equates to a high hydrogen demand. Long-duration energy storage has a large hydrogen demand due to having a high rate of adoption since hydrogen is one of the best long-duration energy storage technologies available today, though many others are in development. Sustainable aviation fuel, which uses hydrogen as a feedstock, even for bio-based SAF, is the only technology available today to decarbonize aviation, so it is anticipated to have a high rate of adoption in 2040. Bulk carriers and maritime round out the top 5 end uses, accounting for a combined 8% of 2040 hydrogen demand.

Figure 27- Base Hydrogen Scenario: Hydrogen Demand by End Use through 2040

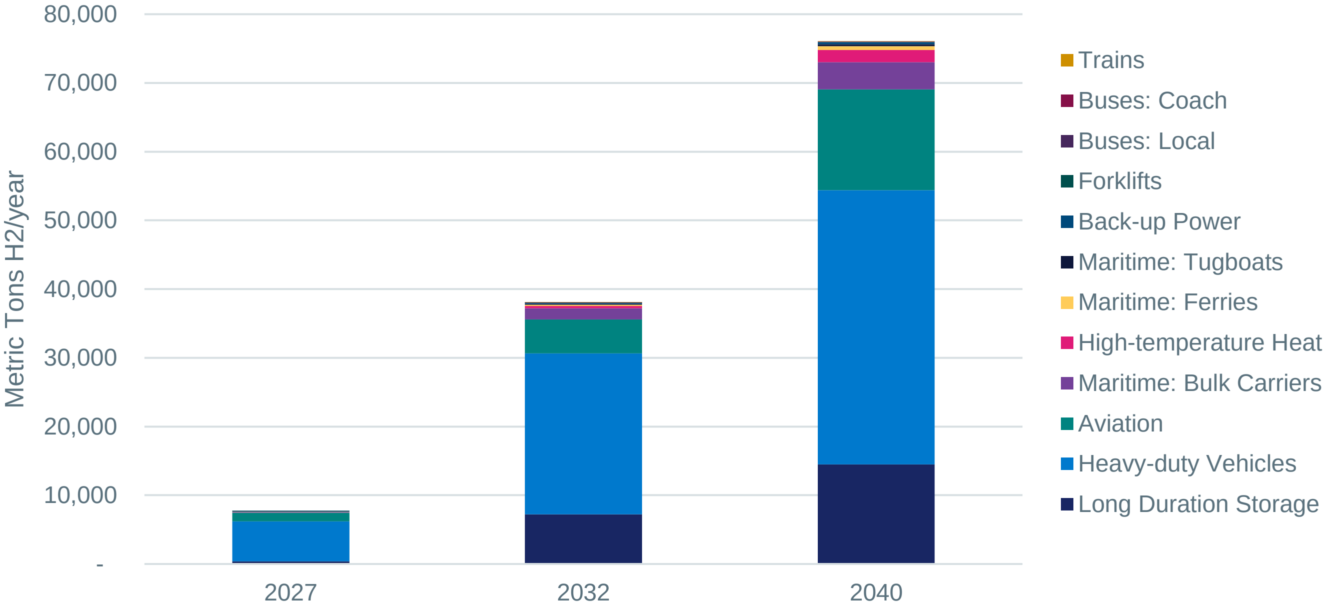


Table 37- Base Hydrogen Scenario: End Use Rate of Adoption for Hydrogen Technologies

Hydrogen End Use	2027	2032	2040	Logic
Heavy-duty trucking	1%	6%	10%	Base Hydrogen Scenario in the FCHEA US Hydrogen Roadmap
Aviation	5%	7%	32%	Aligned with E-SAF and Biobased SAF rate of adoption figures in the ATAG Waypoint 2050 Report, *Scenario 3: Aspirational and Aggressive Technology Deployment*
Long-duration energy storage	1%	20%	40%	ENGIE Analysis based on CT's 2040 net zero power sector emissions law and assumption that in this scenario hydrogen is one of multiple cost-effective Long-duration Energy Storage options
Maritime: Bulk carriers	0.7%	10%	24%	Aligned with the e-ammonia adoption figures in the IRENA: Pathway to Decarbonize the Shipping Sector report
High-temperature heat	0%	1%	4%	Base Hydrogen Scenario in the FCHEA US Hydrogen Roadmap
Maritime: Ferries	1%	6%	18%	ENGIE analysis based on properties that indicate adoption rate of ferries would be lower than for tugboats due to reduced advantage of hydrogen's ability to move heavy loads with ferries compared to tugboats
Maritime: Tugboats	2%	10%	29%	Previous ENGIE analysis indicating even split between hydrogen and electric tugboats in 2050
Backup power	1%	**1%**	3%	Base Hydrogen Scenario for back-up outages in the FCHEA US Hydrogen Roadmap
Forklifts	3%	10%	16%	same general inputs in the FCHEA US Hydrogen Roadmap
Buses: Local	0%	0.6%	2%	Base Scenario in the FCHEA US Hydrogen Roadmap
Buses: Coach	0%	0.4%	7%	Base Scenario in the FCHEA US Hydrogen Roadmap
Trains	0%	0.4%	3%	Base Scenario in the FCHEA US Hydrogen Roadmap

ii. High Hydrogen Scenario

The High Hydrogen Scenario envisions a more aggressive, but not widespread, adoption of hydrogen. This scenario uses hydrogen for all the same end use cases as the Base Hydrogen Scenario, but with higher rates of adoption. In this High Hydrogen Scenario, the hydrogen demand is about 15,000, 73,000, and 170,000 metric tons of hydrogen per year in 2027, 2032, and 2040 respectively. A significant portion of the increase is driven by higher rates of adoption among heavy-duty trucking and high-temperature heat, due to assumptions about relatively more rapid rates of improvements in hydrogen technologies and enduring policy support. Like the Base Hydrogen Scenario, the top 5 end uses still comprise 98% of the hydrogen demand in 2040.

Figure 28- High Hydrogen Scenario: Hydrogen Demand by End Use Through 2040

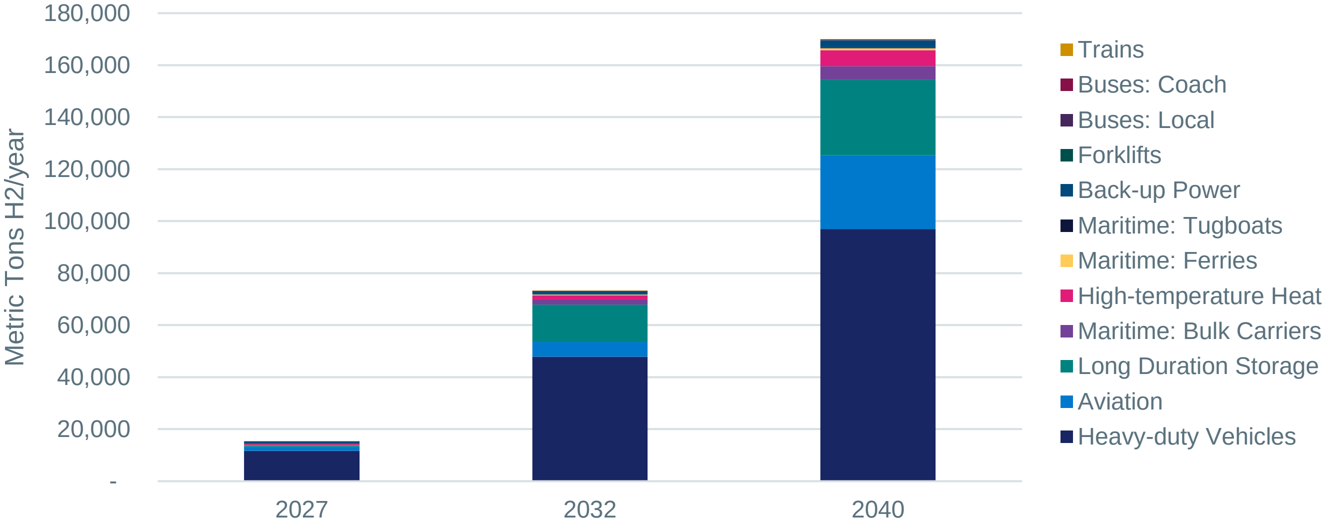


Table 38- High Hydrogen Scenario: End Use Rate of Adoption for Hydrogen Technologies

Hydrogen End Use	2027	2032	2040	Logic
Heavy-duty trucking	3%	12%	24%	Ambitious scenario in the FCHEA US H2 Roadmap
Aviation	7%	18%	53%	Aligned with E-SAF and Biobased SAF rate of adoption figures in the ATAG Waypoint 2050 Report, *Scenario 2: Aggressive Sustainable Fuel Deployment*
Long-duration energy storage	1%	40%	80%	ENGIE Analysis based on Connecticut's 2040 net zero power sector emissions law and assumption that in this scenario hydrogen is the most cost-effective Long-duration Energy Storage option
Maritime: Bulk carriers	0.7%	11%	33%	Aligned with the e-ammonia, e-methanol, and hydrogen adoption figures in the IRENA: Pathway to Decarbonize the Shipping Sector report
High-temperature heat	1%	3%	12%	Ambitious scenario in the FCHEA US H2 Roadmap
Maritime: Ferries	2%	8%	23%	ENGIE analysis that assumes adoption rate would be lower than for tugboats due to reduced advantage of hydrogen's ability to move heavy loads with ferries compared to tugboats
Maritime: Tugboats	3%	14%	38%	Building on previous ENGIE analysis assuming hydrogen has over half of tugboat market in 2050
Backup power	8%	11%	24%	Ambitious scenario for back-up outages in the FCHEA US H2 Roadmap
Forklifts	6%	19%	36%	Ambitious scenario in the FCHEA US H2 Roadmap
Buses: Local	0%	2%	10%	Ambitious scenario in the FCHEA US H2 Roadmap
Buses: Coach	0%	5%	22%	Ambitious scenario in the FCHEA US H2 Roadmap
Trains	0%	0.5%	3%	Ambitious scenario in the FCHEA US H2 Roadmap

iii. Low Hydrogen Scenario

The Low Hydrogen Scenario suggests a more limited role for hydrogen in the future energy mix, with its adoption primarily confined to specific applications where it offers clear advantages. In this Low Hydrogen Scenario, the hydrogen demand is 4,300, 19,000, and 42,000 metric tons of hydrogen per year in 2027, 2032, and 2040 respectively. While heavy-duty trucking is still the biggest source of hydrogen demand, the rate of adoption decreases significantly with the assumption that there is an increase uptake in electric trucking. Aviation has passed heavy-duty trucking as the biggest end use due to a decrease in heavy-duty vehicle hydrogen demand from increased electric vehicle uptake, while the aviation hydrogen demand does not decrease significantly from the base as there are not many commercially viable alternatives to SAF. In this scenario, trains, coach buses, and local buses have no hydrogen uptake because electric buses and trains can supply all of Connecticut's needs.

Figure 29- Low Hydrogen Scenario: Hydrogen Demand by End Use Through 2040

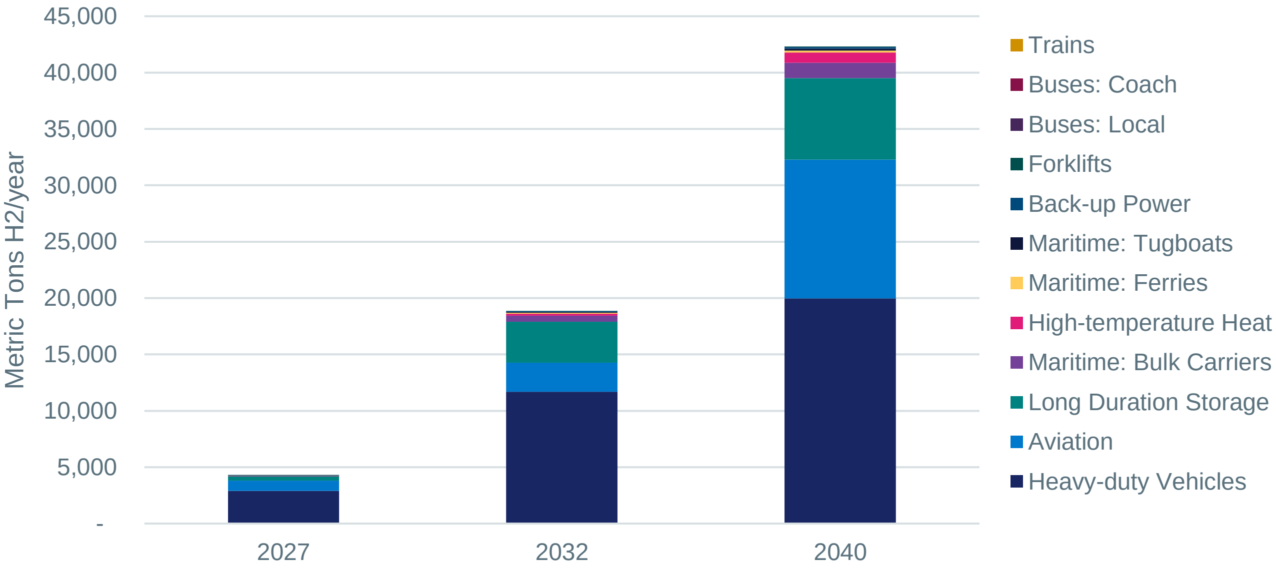


Table 39- Low Hydrogen Scenario: End Use Rate of Adoption for Hydrogen Technologies

Hydrogen End Use	2027	2032	2040	Logic
Heavy-duty trucking	1%	3%	5%	Assume half of Base Hydrogen Scenario adoption rate
Aviation	4%	7%	22%	Aligned with E-SAF and Biobased SAF rate of adoption figures in the **ATAG Waypoint 2050 Report**, *Scenario 0: Continuation of Current Trends*
Long-duration energy storage	1%	10%	20%	ENGIE analysis based on assumption that there are breakthroughs in batteries or another alternative storage option that can address majority of demand
Maritime: Bulk carriers	1%	7%	20%	Assumes same rate of adoption as base case, but total demand declines due to less petroleum imports
High-temperature heat	0%	0.4%	2%	Assume half of Base Hydrogen Scenario adoption rate
Maritime: Ferries	0%	2%	6%	ENGIE analysis that assumes adoption rate would be lower than for tugboats due to reduced advantage of hydrogen's ability to move heavy loads with ferries compared to tugboats
Maritime: Tugboats	1%	7%	20%	Previous ENGIE analysis indicating electric tugboats would have majority of adoption by 2050
Backup power	1%	1%	3%	Assume half of Base Hydrogen Scenario adoption rate
Forklifts	1%	5%	8%	Assume half of Base Hydrogen Scenario adoption rate
Buses: Local	0%	0%	0%	Assumes all can be decarbonized with electric technologies

Buses: Coach	0%	0%	0%	Assumes all can be decarbonized with electric technologies
Trains	0%	0%	0%	Assumes all can be decarbonized with electric technologies

B. Hydrogen Production and Infrastructure Requirements

i. Electrolysis

Meeting the hydrogen demand in the Base Hydrogen Scenario would require approximately 50, 230, and 460 MW of electrolyzer capacity in 2027, 2032, and 2040 respectively. Electrolyzer production facilities achieve the best economies of scale when sized for at least 20 MW, meaning there could be up to 20-25 electrolyzer production facilities in Connecticut by 2040, or less if larger plants are built. For reference, the IEA estimates that there will globally be approximately 2,900 MW of electrolyzer capacity installed by the end of 2023, and 560,000 MW needed by 2030 to be in line with its net zero scenario[lxxv].

ii. Renewables

Electrolytic hydrogen production requires a significant amount of renewable electricity. Meeting the hydrogen demand required to achieve Connecticut's decarbonization goals, will require approximately 160, 800, and 1,600 MW of clean electricity for 2027, 2032, and 2040 respectively. These values are over 3 times higher than the electrolyzer MW capacity they are powering. The reason for this is because onshore wind in Connecticut has a capacity factor of about 29%, so in order to ensure that the renewable production can match the electrolyzer electricity demands on an annual basis, the wind installations need to be oversized. For comparison, Connecticut's total electricity capacity today is slightly over 10,000 MW, and its renewable capacity is around 1,000 MW. The new capacity required for hydrogen production can likely be achieved with a combination of in state onshore wind and solar production, in addition to importing renewable electricity from nearby states like New York and Maine. Other renewable energy mix, such as incorporating offshore wind, is also another possibility.

Following the assumptions used in the roadmap modeling, if all the renewable capacity was supplied with onshore wind, it will require about 130, 640, and 1,280 acres of land in 2027, 2032, and 2040. In 2040, the total land requirement would be just about 0.04% of the state's total area, but of course, this land requirement will change based on the mix of electricity generation sources. However, Connecticut is a small, densely populated state without large tracts of available land that lend themselves well to renewables production. Therefore, it is likely that Connecticut may wish to import some of this electricity. Nearby states such as New York and Maine are anticipated to have land available for additional renewables. With regards to land constraints, offshore wind was also evaluated as it eliminates any challenges associated with land constraints but was ultimately dismissed for modeling purposes due to high costs, and ongoing production and permitting uncertainty. However, as technology advances and specific projects in the northeast progress, it might become viable to power a portion of hydrogen production using offshore wind energy.

iii. Water

Aside from electricity, water is the other main feedstock for electrolytic hydrogen production. Meeting Connecticut's hydrogen demand will require 20, 110, and 220 million gallons of water in 2027, 2032 and 2040 respectively, just for hydrogen feedstock. In addition to water for feedstock, additional water is consumed at hydrogen production plants for cooling and purification. While this demand varies from plant-to-plant, it is anticipated this would require an additional 125% water use on top of the water used for feedstock, bringing the total demand to 500 million gallons per year by 2040. When viewed in absolute terms, this is a significant amount of water, but in relative terms equates to about the annual average water use of 4,400 households, or about 0.04% of the state's total water demand [lxxvi].

iv. Infrastructure

Multiple types of hydrogen infrastructure will be needed to support the storage, transport, and dispensing of hydrogen to its various end uses. It is estimated that Connecticut would need about 5 fueling stations by 2040 to meet anticipated demand for heavy-duty trucking and buses. Hydrogen production could be co-located at each fueling station, minimizing or eliminating the need for additional transport. Long-duration Energy Storage could also have hydrogen production and storage co-located at the location of fuel cells used to generate electricity, leaving maritime, back-up power, forklifts and trains that will need hydrogen transport infrastructure. In the short term, when there is lower demand for hydrogen, trucking will be the primary transport method, with an estimated need of about 15 trucks by 2027. By 2032, hydrogen demand would increase enough to where pipelines could be the most feasible transport option for some end uses. An estimated 30 miles of pipeline would be needed, primarily for ports and trains. The total truck need would then drop to approximately 6, due to a shift of some hydrogen to pipelines. While hydrogen demand will increase from 2032 to 2040, the transport infrastructure of about 6 trucks and 30 miles of pipeline could stay relatively constant, as each method is projected to have excess capacity in 2032. For reference, the US currently has 1,600 miles of hydrogen pipeline, almost entirely in the gulf coast, but that number is expected to increase significantly in the coming years with the development of hydrogen hubs[lxxvii].

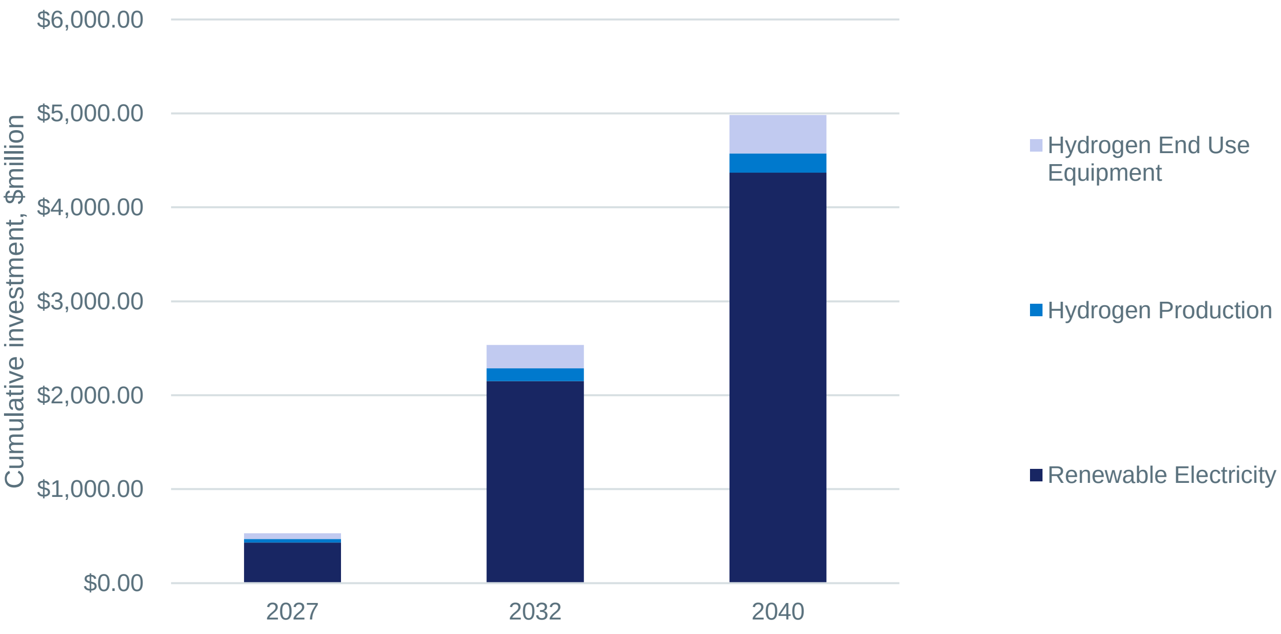
Storage will be needed for all end uses, production methods, and at some designated distribution locations. Because the volume of storage required will be very dependent on the specifics of each project, volumes are not projected, though some of the largest storage needs are anticipated to be for Long-duration Energy Storage, and ports.

C. Capital Investment Requirements

Just under $5 billion of cumulative capital investment is needed to scale Connecticut's hydrogen economy through 2040, with nearly 90% of this investment coming from renewable capital costs. Because electricity costs make up the majority of the levelized cost of hydrogen, it stands to reason that it would also make up the majority of the capital cost.

A variety of private sector investors would support these investments, in many cases with the assistance of federal, and potentially, state incentives. Federal tax credits for renewables and hydrogen from the IRA are anticipated to incentivize investment in renewable electricity and hydrogen production facilities. Similarly, federal incentives are available for some infrastructure and end use equipment, including hydrogen fueling stations and hydrogen fuel cell vehicles.

Figure 30- Total Cumulative Capital Investment Needed by Year for Base Hydrogen Scenario



D. Impact

i. Climate Impact

The reduction in GHG emissions associated with the adoption of hydrogen will be dependent on the carbon intensity of hydrogen. Assuming a carbon intensity of 2.0 kg CO2e/ kg H2, the upper limit of Connecticut's clean hydrogen definition, hydrogen would abate 355,000 tons of CO2e by 2040 in the Base Hydrogen Scenario. If the carbon intensity was lowered to 0.45 kg CO2e/ kg H2, the upper carbon intensity limit for receiving the maximum benefit from the 45V tax credit, hydrogen would abate 472,000 tons of CO2e by 2040 or 1.1% of Connecticut's 2018 emissions. Looking even further to 2050 with the same carbon intensity, hydrogen would abate 781,000 tons of CO2e, or 1.9% of Connecticut's total. In the High Hydrogen Scenario, the abated emissions would increase to 1,200,000 tons of CO2e, or 2.9% of Connecticut's total GHG emissions. For reference, the US *DOE Pathways to Commercial Liftoff: Clean Hydrogen report* predicts that by 2050, clean hydrogen could reduce overall U.S. GHG emissions by 10% versus 2005 baseline levels[lxxviii]. A couple factors contribute to Connecticut's reduced hydrogen emissions abatement potential compared to the US projection. The first reason is because, nationally, one of the main sectors that will use hydrogen to decarbonize is heavy industry, including steel, cement, ammonia, and other chemical production. These activities are almost non-existent in Connecticut. A second reason is because Connecticut has a comparatively higher cost of renewable electricity compared to the national average, which reduces the economic attractiveness of hydrogen compared to electrification- this may seem counterintuitive, but the reason is because most hydrogen applications have a lower overall energy efficiency compared to direct electrification, so any increase in electricity cost has an increased impact on the cost of hydrogen compared to electrification. Nevertheless, hydrogen will remain an important part of Connecticut's decarbonization pathway as it reduces emissions for many end uses that cannot easily be decarbonized with electrification.

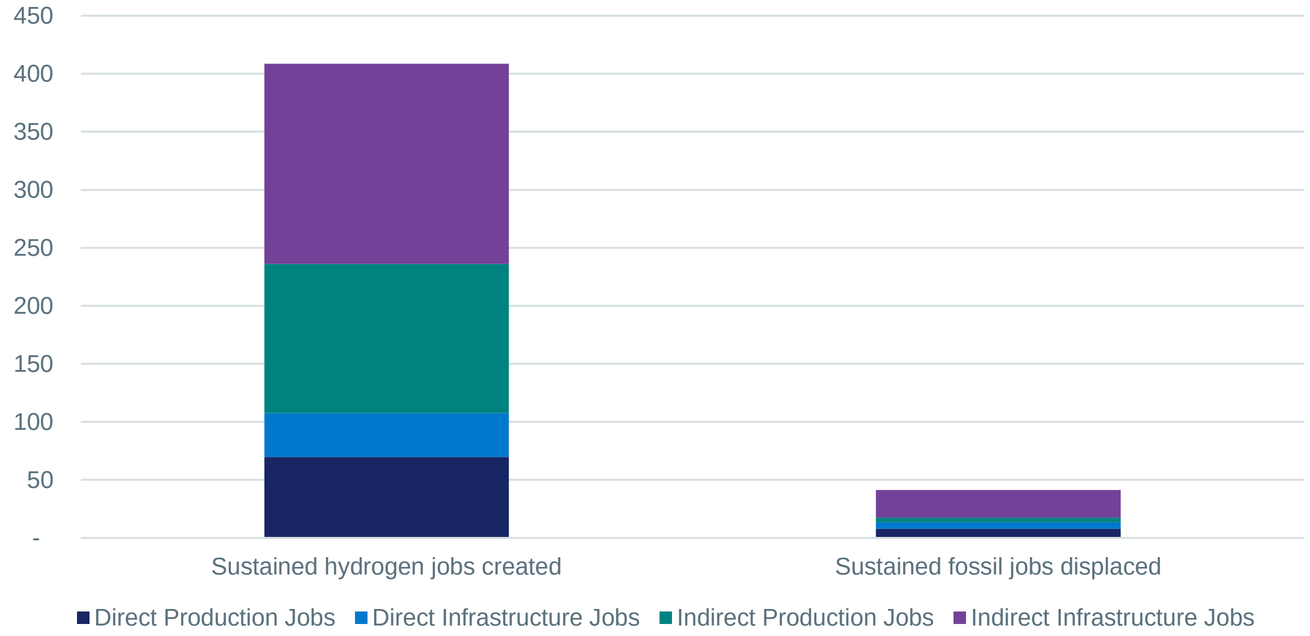
ii. Jobs Impact

The economic development analysis considers the potential hydrogen jobs that can be created, fossil fuel jobs that could disappear, and the anticipated net job impacts that could occur by factoring in multipliers from industry research along with Connecticut-specific data. Within the analysis, direct jobs are classified as jobs created along the hydrogen value chain where primary activities will occur in Connecticut, namely: hydrogen production, infrastructure, and end use applications. Indirect jobs are jobs where primary revenue-generating activities are not direct levers within the value chain, such as: upstream jobs created within the raw material supply chain and from the growth in renewable electricity production.

Impact on Sustained Jobs

The hydrogen transition is project to have a net positive impact on sustained job creation due to increasing the total direct energy production within Connecticut, with 430 hydrogen jobs projected to be created by 2040. While approximately 40 fossil fuel jobs are anticipated to be displaced, if aided by appropriate training and workforce development programs, there should be opportunities for them to find corresponding jobs in the hydrogen value chain. Details about how to manage this transition effectively are noted in Program 5- Equitable Jobs Transition Program under *Section 4: Hydrogen Enablers.*

Figure 31- Sustained Jobs Net Impact from Hydrogen Transition, 2040

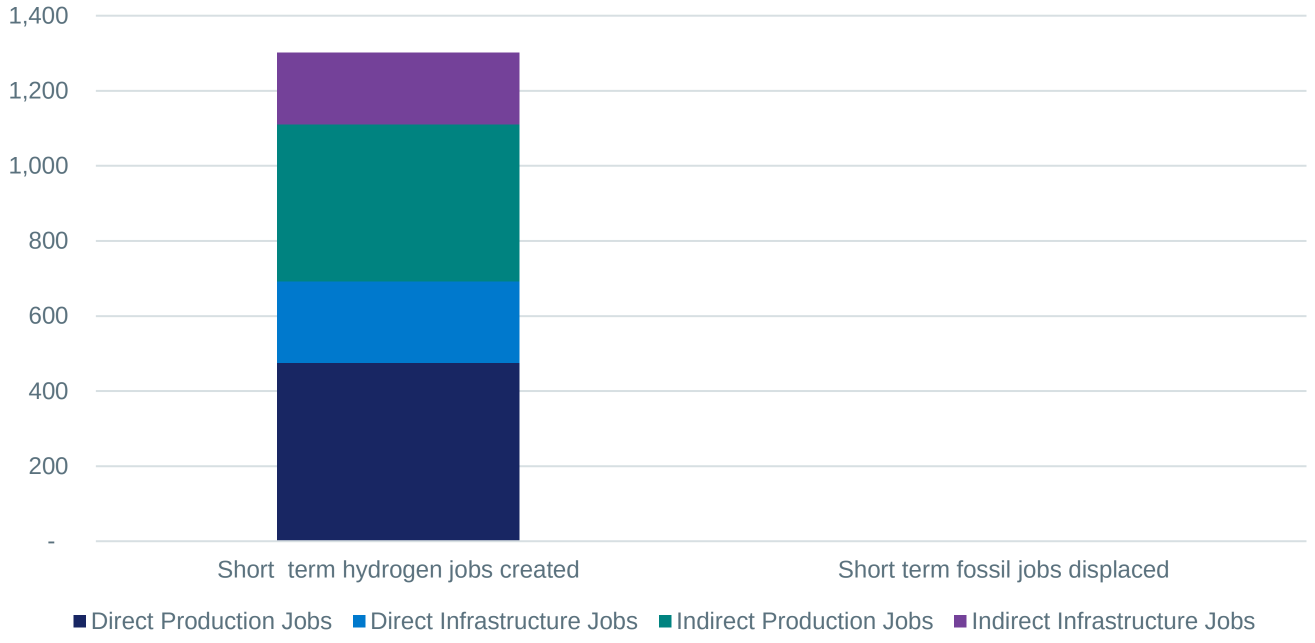


Note that this jobs analysis did not specifically include the impact of hydrogen on port jobs. Petroleum represents a material portion of Connecticut's deepwater ports[lxxix], and the adoption of hydrogen in Connecticut would reduce some of that demand. However, hydrogen also has the potential to increase port activity through imports of associated hydrogen value chain equipment, or hydrogen derivatives. Due to the numerous uncertainties around the impact of hydrogen on port activities, it was decided to exclude it from the analysis.

Impact on Short-term Jobs

The hydrogen economy is also anticipated to create nearly 1,400 short-term construction jobs by 2040. In an ideal scenario, this would translate into over 170 sustained construction jobs if all hydrogen projects were evenly spaced between 2024, and 2040, assuming a 2-year construction period for each project. While perfectly spaced projects would be difficult to orchestrate, there will be opportunity to coordinate construction for hydrogen infrastructure along with other energy transition projects to increase the outlook for construction workers in Connecticut. No short-term fossil construction jobs are anticipated to be displaced due to lack of fossil fuel construction in the state.

Figure 32- Short-Term Jobs Net Impact from Hydrogen Transition, 2040



E. Barriers to Scalability

i. Types of Barriers

Achieving the hydrogen demand outlined in this section will require Connecticut to overcome multiple barriers to scalability. While individual projects may have their own unique barriers, four cross-cutting ones have been identified that will likely need to be addressed for the majority of hydrogen projects:

1. **Affordability** of hydrogen technologies compared to fossil-based incumbent and low carbon alternatives
2. **Availability** of hydrogen, and hydrogen derivatives
3. **Accessibility** of hydrogen and hydrogen derivatives via transport and storage infrastructure
4. **Acceptance** of hydrogen by both stakeholders along the hydrogen value chain and the public

Many of the barriers to scalability overlap with Energy Strategy Lens risks, such as Affordability (Affordability lens), Accessibility (Accessibility dimension of the Equity lens), and Acceptance (Reliability and resilience lens). However, they are being mentioned again here as the barriers and lens analyses approach these topics from different angles. Barriers are obstacles that will need to be addressed to ensure that hydrogen can scale to the volume needed to meet Connecticut's emission reduction targets, while the lens analysis identified risks associated with hydrogen that will need to be mitigated to ensure the scaling of hydrogen occurs in a way that is in line with Connecticut's values.

ii. Barrier Analysis for Top 5 End Uses by Volume

The five end uses with the highest projected hydrogen demand are anticipated to account for 97% of Connecticut's total hydrogen demand by 2040. For this reason, the barrier analysis has been conducted on just those top 5 end uses, as well as cross cutting barriers that apply to most end uses of hydrogen. The specific barriers to adoption were based on the modeling's assumptions.

Table 40- Hydrogen Barriers to Adoption and Enablers to Address

End Use	Barrier Category	Specific Barriers to Adoption	Enabler
1. Heavy-duty trucking	Affordability	Lower overall TCO, but higher CAPEX compared to fossil-based incumbent technology	• *Proposed policy 6:* Financial Incentives for Net Zero Trucking and Fueling Stations in Environmental Justice Communities • *Proposed policy 5:* Loans for Net Zero Trucking
	Availability	Limited availability of hydrogen	• *Pilot Project 1*: Hydrogen Production, Infrastructure, and Use for Heavy-duty Trucking • *Program 3:* Assess Optimal Siting of Hydrogen Fueling Stations
	Accessibility	Limited hydrogen fueling stations	
	Acceptance	Reliability concerns with new hydrogen technology	
2. Long-duration energy storage	Affordability	Higher OPEX and CAPEX compared to fossil-based incumbent technology	• *Proposed policy 2:* Financial Incentives for Hydrogen Usage for Long-Duration Energy Storage and High-Temperature Heat • *Proposed Policy* 9: Incentives for Load Management
	Availability	Limited availability of hydrogen	• *Pilot Project 3:* Hydrogen Production, Infrastructure, and Use for Long-duration Energy Storage *Proposed Program 7:* Feasibility Study of Underground Hydrogen Storage in Connecticut's Hardrock
	Accessibility	Limited hydrogen transportation and storage infrastructure	
	Acceptance	Reliability concerns with new hydrogen technology	
3. Aviation	Affordability	Higher OPEX compared to fossil-based incumbent technology	• *Proposed policy 3:* Financial Incentives for Sustainable Aviation Fuel
	Availability	Limited availability of SAF	• *Pilot Project 4:* Sustainable Aviation Fuel Infrastructure and Use
	Accessibility	Limited infrastructure from SAF production sites to CT airports	
	Acceptance	Though SAF is a 'drop in fuel', there is currently a 50% blend limit with traditional jet fuel, which may lead to acceptance concerns before the technology is demonstrated on a larger scale	
4. Maritime: Bulk carriers	Affordability	Higher OPEX and CAPEX compared to fossil-based incumbent technology	• *Proposed policy 4:* Loans for Sustainable Maritime CAPEX
	Availability	Limited availability of clean ammonia	• *Pilot Project 2:* Sustainable Maritime Fuel Production, Infrastructure, and Use, including Forklifts
	Accessibility	Limited ammonia transportation and storage infrastructure	
	Acceptance	Reliability concerns with new ammonia technology	
5. High-temperature heat	Affordability	Higher OPEX compared to fossil-based incumbent technology	• *Proposed policy 2:* Financial Incentives for Hydrogen Usage for Long-Duration Energy Storage and High-Temperature Heat
	Availability	Limited availability of hydrogen	• *Pilot Project 5:* Hydrogen Production, Infrastructure, and Use for High-Temperature Heat
	Accessibility	Limited hydrogen transportation infrastructure	
	Acceptance	Reliability concerns with new hydrogen technology	
Cross cutting	Accessibility	Limited hydrogen transportation and storage infrastructure	• *Program 1:* Creation of Hydrogen Clusters
	Acceptance	Reliability concerns with hydrogen transport infrastructure	• *Program 4:* Study Reliability of Hydrogen Transport Methods in Severe Weather

4. Hydrogen Enablers: Policies, Programs, and Pilot Projects

Policies, programs, and pilot projects will be a vital component of Connecticut's strategic approach to integrating hydrogen into the energy landscape. These enablers will serve two distinct yet interrelated purposes. Firstly, they serve to address any risks that were identified during the analysis in *Section 2: Energy Strategy Lens Analysis*, ensuring that Connecticut's entrance into a hydrogen economy aligns with the state's core values. Secondly, these enablers will be key for overcoming any barriers to adoption identified in *Section 3E: Barriers to Scalability* that could hinder the scaling of hydrogen technologies at the speed necessary to meet the state's climate goals. The enablers section of the roadmap is broken up into three sections: Policies, Programs, and Pilot projects, each defined in Figure 33:

Figure 33 – Types of Hydrogen Enablers

Policy	Program	Pilot Project
Implementation of financial incentives and regulations for decarbonizing specific high-emitting and/or costly end uses based on TCO analysis and mitigating cross-cutting barriers to reduce overall lifecycle emissions in Connecticut	Creation of public-private partnerships amongst stakeholders to enhance hydrogen-based activity and conduct research studies on improving the safety, reliability, and resilience of end-uses	Development of hydrogen demonstration projects for decarbonizing specific end-uses with technological, logistical, or financial barriers

The enablers proposed are examples of potential ways that each identified barrier and risk can be addressed. In some cases, multiple enablers have been identified that can address the same barrier or risk, and while there may be benefits to having multiple enablers address the same challenge, it may not be required.

Each of these enablers have been categorized by at least two dimensions:

- ***Dimension 1 (all enablers):*** Step in the hydrogen value chain
- ***Dimension 2 (all enablers):*** Energy Strategy Lens or barrier to scalability addressed
- ***Dimension 3a (policies):*** Type of policy
- ***Dimension 3b (programs):*** Type of program

Because dimensions 3a and 3b are relevant to policies and programs respectively, those dimensions are further elaborated in their respective enabler sub-sections.

A. Policies

i. Policy Approach and Framework

Existing and new policies will be key enablers in the successful integration and adoption of hydrogen in the state of Connecticut. Policies play a pivotal role in lowering costs, fostering innovation, and mitigating risks associated with hydrogen technologies. This sub-section details existing federal and state policies applicable to hydrogen, as well as new proposed state-level policies that can further advance hydrogen adoption in Connecticut.

As noted in the enabler intro section, each policy will be categorized by three dimensions: 1. Step in the hydrogen value chain, 2. Risk/barrier addressed, and 3. Type of policy. An overview of each policy type is noted below:

1. **Targets, Quotas, and Planning**: Policies that pertain to goals, targets, and roadmaps which guide public and private stakeholders on future objectives for hydrogen technologies
2. **Financial Incentives:** Policies that reduce the cost of developing or using hydrogen technologies and their associated infrastructure, such as loans, grants, and federal tax credits
3. **Research and Development:** Policies directed toward accelerating the research, development, and deployment of hydrogen technologies
4. **Regulation and Creation of Standards:** Policies to ensure the safe, efficient, and sustainable use of hydrogen technologies

i. Existing Policies

The United States federal and Connecticut state governments have recognized that to achieve a net zero economy, robust policies will need to be enacted to support the adoption of hydrogen for a clean energy transition. These policies, among other things, establish financial incentives for hydrogen production, define standards for what counts as clean hydrogen, and establish carbon intensity requirements for production to ensure real GHG benefits from hydrogen's use.

Existing Federal Policies

Recent federal policies within the United States have enabled both public and private stakeholders to begin transitioning equitably and affordably to a hydrogen-based clean energy economy. Federal incentives in the form of tax credits and grants, and guidance through regulations and standards, are beginning to catalyze hydrogen adoption throughout the nation. Table 41 below lists the most relevant federal policies that various stakeholders within Connecticut can utilize, both to decarbonize existing costly end uses and unlock new market segments for research and development and further investment.

Table 41- Existing Federal Policies Applicable to Hydrogen Adoption

Federal Policy 1: **Clean Hydrogen Production Tax Credit 45V (2022 IRA)**		
Value chain step: Production	***Policy type:*** Financial Incentives	***Energy Strategy Lens and/or Barrier(s)****:* Affordability
Details: 45V is a tiered 10-year production tax credit [lxxx] introduced in the IRA of up to \$3/kg of clean hydrogen produced for qualifying projects with lifecycle GHG emissions intensity of less than or equal to 4 kg CO2e/kg H2, assuming prevailing wage and apprenticeship requirements are met. ***Impact****:* Tax incentives can drive innovation and reduce the cost of hydrogen production and/or imports in Connecticut to further enable hydrogen adoption in the state.		
Federal Policy 2: **Clean Hydrogen Production Standard (2021 IIJA)**		
Value chain step: Cross value chain	***Policy type:*** Regulation, Creation of Standards	***Energy Strategy Lens and/or Barrier(s)****:* Climate
Details: In 2022, the US DOE released an initial standard for the carbon intensity of hydrogen[lxxxi] in coordination with the EPA, whereby the term "clean hydrogen" is defined as hydrogen that is produced with a carbon intensity equal to or less than 4 kg of CO2e /kg of H2 on a well-to-gate lifecycle basis. This standard is updated on a five-year basis. ***Impact:*** The Clean Hydrogen Production Standard establishes clear nationwide guideline for the carbon intensity of hydrogen production that can help advance clean energy initiatives that reduce emissions.		
Federal Policy 3: **US National Clean Hydrogen Strategy and Roadmap**		
Value chain step: Cross value chain	***Policy type:*** Targets, Quotas, and Planning	***Energy Strategy Lens and/or Barrier(s)****:* Climate, Accessibility, Availability
Details: The US National Clean Hydrogen Strategy and Roadmap [lxxxii] is a living strategy that provides a snapshot of hydrogen production, transport, storage, and use in the United States today, as well as an assessment of the opportunity for hydrogen to contribute to national decarbonization goals across sectors over the next 30 years. It prioritizes three key strategies to ensure that clean hydrogen is developed and adopted as an effective decarbonization tool for maximum benefit to the United States: **1.** Target strategic, high-impact uses for clean hydrogen **2.** Reduce the cost of clean hydrogen **3.** Focus on regional networks ***Impact:*** The roadmap creates clear guidelines for public and private stakeholders along the hydrogen value chain of what infrastructure and end uses should be prioritized, and what aspects need to be addressed to make them a success. The release of unified strategies like this roadmap makes it easier for stakeholders to identify partnership and collaboration opportunities.		

***Federal Policy 4:* Renewable Energy Provisions (2022 IRA)**

Value chain step: Feedstock/Electricity	***Policy type:*** Financial Incentives	***Energy Strategy Lens and/or Barrier(s)****:* Affordability

Details: The IRA established multiple clean energy tax provisions[lxxxiii] around extending and expanding renewable energy production and investment, including:

1. Production Tax Credit for Electricity from Renewables
2. Investment Tax Credit for Energy Property
3. Clean Electricity Production Tax Credit
4. Clean Electricity Investment Tax Credit
5. Advanced Energy Project Credit

These credits can be amplified by the low-income communities' bonus credit, which provides an additional investment tax credit for small-scale solar and wind facilities on tribal land and in low-income communities, as well as the prevailing wage and apprenticeship bonus requirement which offers 5 times the base credit value. Additionally, the renewable energy provisions can be stacked with the 45V tax credit to further incentivize the use of hydrogen as a decarbonization lever.

Impact: Because renewable electricity is the biggest cost driver for clean hydrogen, any incentives that lower the cost of renewable electricity will have a corresponding impact on the affordability of clean hydrogen.

***Federal Policy 5:* Hydrogen Shot Initiative**

Value chain step: Cross value chain	***Policy type:*** Research and Development	***Energy Strategy Lens and/or Barrier(s)****:* Affordability

Details: The Hydrogen Shot, which is part of the U.S DOE's Energy Earthshots Initiative[lxxxiv] aims to advance domestic research and development efforts to reduce the cost of clean hydrogen to $1/kg in one decade. Along with reducing the overall cost of clean hydrogen, the Hydrogen Shot also establishes a framework for clean hydrogen deployment in the American Jobs Plan[lxxxv] through the deployment of hydrogen demonstration projects in overburdened communities.

Impact: Reducing the total costs of clean hydrogen will accelerate adoption at scale across industries and unlock new markets in hard-to-decarbonize sectors such as steel manufacturing and heavy-duty trucking.

***Federal Policy 6:* Sustainable Aviation Fuel Tax Credit (2022 IRA)**

Value chain step: Production	***Policy type:*** Financial incentives	***Energy Strategy Lens and/or Barrier(s)****:* Affordability

Details: The SAF tax credit[lxxxvi] in the IRA applies to specific fuel mixtures containing SAF sold or used between January 1st, 202**3**-December 31st, 2024. The credit establishes a financial incentive of $1.25/gallon of SAF in a qualified mixture, which is defined as the SAF having a 50% minimum reduction in lifecycle GHG emissions. To further incentivize the production of qualified SAF mixture, there is a supplemental credit of $0.01/percentage of GHG reductions exceeding 50% (up to $0.50/gallon).

Impact: With ambitious tax credits in place for specific SAF fuel mixtures, producers will be incentivized to produce cleaner SAF to abate transportation emissions.

***Federal Policy 7:* Justice40 Initiative**

Value chain step: Cross Value Chain	***Policy type:*** Targets, Quotas, and Planning	***Energy Strategy Lens and/or Barrier(s):*** Economic Development

Details: The Justice40 Initiative[lxxxvii] has established a target that 40% of overall benefits of certain federal investments should go to environmental justice communities. Through the IRA, IIJA, and American Rescue Plan, various existing and new federal agencies are making critical investments and engaging communities to advance environmental justice. The Justice40 initiative also created "covered programs", which include any federal government program that falls within Justice40 criteria because it includes investments that can benefit environmental justice communities across one or more of the following areas: climate change, clean energy and energy efficiency, clean transit, affordable and sustainable housing, training and workforce development, remediation and reduction of legacy pollution, and development of clean water and wastewater infrastructure.

Impact: With the federal government laying the environmental justice roadmap by making historic investments and requiring robust stakeholder engagement and impact measurement of the initiatives, other stakeholders implementing clean energy projects will be further encouraged to embed equitable metrics into projects to mitigate environmental and social burdens for environmental justice communities.

It is worth noting that the IIJA will provide up to $8 billion of federal funding to establish at least four Hydrogen Hubs across the nation through the Hydrogen Hub program administered by the U.S. Department of Energy. Connecticut submitted a joint application with the states of Maine, Massachusetts, New Jersey, New York, Rhode Island, and Vermont. The compelling proposal included more than a dozen projects across the states aiming to advance clean electrolytic hydrogen production, consumption, and infrastructure projects for hard-to-decarbonize sectors, including transportation and heavy industry. Although the Northeast application moved forward to the final selection step, it was not selected as one of the seven hydrogen hubs to be funded.

Federal funding is critical for the development of nascent technologies and its ecosystems, such as clean hydrogen clusters. This is especially true for hubs focused on clean electrolytic hydrogen, given the higher production costs compared to other hydrogen types. Although much welcomed, seven hydrogen hubs are a limited number to foster the hydrogen economy across the country. Other regions not contemplated by the hydrogen hub funding should also receive federal support to develop a self-sustaining clean hydrogen ecosystem. In that sense, DEEP recommends that the federal government expand the Hydrogen Hubs Program to fund more clusters nationwide.

The Northeast is the ideal location to receive federal support to promote a clean hydrogen hub given its environment of ambitious climate goals, robust green innovation, abundant sources of clean (e.g., nuclear, wind, solar, and hydro), and clean hydrogen industrial leaders. Moreover, as a result of the hydrogen hub application process, a regional coordination between state agencies and more than 100 private and non-profit organizations was developed. Particularly regarding Connecticut, its longstanding leadership in fuel cell development and manufacturing positions the state to be a frontrunner in hydrogen development. Federal support would act as a catalyst for all these elements.

Existing Connecticut State Policies

The state of Connecticut has enacted policies in the past decade which have supported the movement towards a clean energy transition. Table 42 lists existing state policies which are most relevant to driving hydrogen adoption in the state and achieving the objectives of the Energy Strategy Lenses.

Table 42- Existing State Policies Applicable to Hydrogen Adoption

<table>
<tr><th colspan="3">State Policy 1: An Act Concerning Climate Change Mitigation (Public Act 22-5)</th></tr>
<tr><td>Value chain step:
Feedstock/Electricity; End Use</td><td>Policy type:
Targets, quotas, and planning</td><td>Energy Strategy Lens and/or Barrier(s):
Climate, Equity</td></tr>
<tr><td colspan="3">Details: Released in 2022, the act[lxxxviii] requires the state to eliminate GHG emissions from electricity supplied to customers by January 1, 2040.

Impact: Cleaner forms of electricity supply to customers will help advance GHG reduction goals as well as promote health & well-being for all communities – particularly in more polluted regions within Connecticut. A decarbonized grid will provide steady supplies of zero carbon electricity, the key input to clean hydrogen production.</td></tr>
<tr><th colspan="3">State Policy 2: Reduction of GHG emissions: Mandated Levels (Conn. Gen. State. 22a-200a)</th></tr>
<tr><td>Value chain step:
Cross value chain</td><td>Policy type:
Targets, quotas, and planning</td><td>Energy Strategy Lens and/or Barrier(s):
Climate</td></tr>
<tr><td colspan="3">Details: Released in 2019, the act[lxxxix] requires the state of Connecticut to reduce GHG emissions by 45% below 2001 levels by 2030, and 80% below 2001 levels by 2050.

Impact: Clearly defined statewide GHG reduction goals provide the framework to drive aggressive decarbonization efforts across sectors, of which hydrogen will be a critical lever and accelerator.</td></tr>
</table>

***State Policy 3:* Connecticut Renewable Portfolio Standard**

Value chain step:	***Policy type:***	***Energy Strategy Lens and/or Barrier(s):***
Feedstock/Electricity, End Use	Targets, quotas, and planning	Climate

Details: The Connecticut Renewable Portfolio Standard (RPS) [xc] requires that electric providers offset a certain percentage or amount of energy they generate or sell by purchasing renewable energy credits (RECs) from renewable sources. In addition, the standard sets financial incentives for the development of renewable energy projects and creates qualifiers for electricity generation projects.

Impact: The RPS drives renewable electricity adoption in the state, which reduces GHG emissions and enables clean hydrogen production.

***State Policy 4:* NOx Limits (Conn. Gen. Stat 22a-174-22e & Conn. Gen. Stat. 22a-174-22f)**

Value chain step:	***Policy type:***	***Energy Strategy Lens and/or Barrier(s):***
Production	Regulation, Creation of Standards	Equity

Details: Released in 2016, the act [xci]sets limits for NOx emissions from fuel-burning equipment at major stationary sources of NOx (i.e. combustion turbines). This equipment includes fossil-fuel fired stationary sources such as boilers, simple cycle combustion turbines, combined cycle combustion turbines, gas or oil-fired emissions units, and emergency engines.

Impact: Setting rigorous NOx limits will reduce harmful pollution and emissions, particularly for communities surrounding facilities that are overburdened with negative air quality. In addition, setting NOx limits addresses a key negative environmental impact from end use applications where hydrogen combustion occurs, such as high-temperature heat for industrial processes.

***State Policy 5:* Economic Development Grants Program (Conn. Gen. Stat. 32-7F)**

Value chain step:	***Policy type:***	***Energy Strategy Lens and/or Barrier(s):***
Cross Value Chain	Targets, quotas, and planning	Economic Development

Details: This program authorizes the Commissioner of Economic and Community Development to establish an economic development grant program to expand hydrogen and fuel cell industries. The activities of the program include developing a small business incubator program, expanding in-state hydrogen and fuel cell manufacturing capabilities, promoting supply chain integration, providing training for small and medium sized businesses, advancing research and innovation, and providing technical assistance to small business owners.

Impact: Implementing a grant program specifically focused on enabling small and medium sized businesses to play a role in expanding the Connecticut hydrogen and fuel cell industry will incentivize more stakeholders to get involved, accelerate existing and future hydrogen-related work, and drive new job growth.

***State Policy 6:* PURA's Energy Storage Solutions Program**

Value chain step:	***Policy type:***	***Energy Strategy Lens and/or Barrier(s):***
Production	Research and Development	Economic Development, Reliability & Resilience

Details: Established in 2022, the Connecticut Energy Storage Solutions program [xcii]offers a statewide electric storage program for all Eversource and United Illuminating (UI) residential, commercial, and industrial customers to offer a more reliable and resilient electric distribution system particularly benefiting vulnerable communities. The 9-year program administered by the Connecticut Green Bank, supports the Public Act 21-53[xciii] goal of deploying 1,000 MW of energy storage by 2030 by establishing commercial and industrial financial incentives funding 50% of the upfront project cost and offering performance-based incentives based on the average power an electric storage project contributes to the grid when stressed. In addition, the program provides additional incentives to customers in historically underserved communities and small businesses that experience the most frequent and longest duration storm-related outages.

Impact: By providing funding for project developers and utilities to test and demonstrate innovative energy storage technologies and offering financial incentives to increase resiliency of the grid, Connecticut can ensure more reliable infrastructure during times of distress and reduce electricity costs over the long term. Hydrogen can become a critical storage solution to enable grid resiliency and help meet the goal of deploying 300 MW of energy storage by Dec 31, 2024, and ultimately 1,000 reliable MW of energy storage by 2030.

ii. New Policies for Consideration

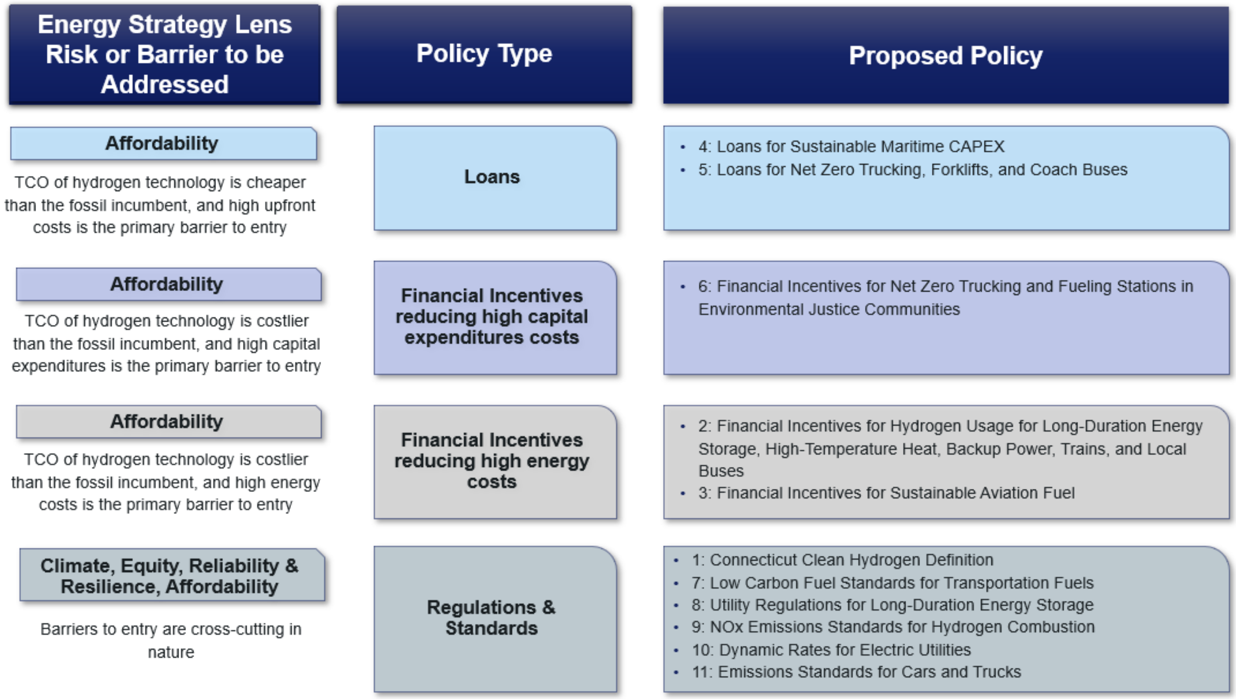
Priority policies for consideration

In addition to the federal and state policies currently in effect, there are multiple policies that Connecticut should consider implementing to help meet the various objectives of the Energy Strategy Lenses and propel hydrogen to scale at the pace required to achieve ambitious decarbonization goals. These policies include but are not limited to financial incentives that decarbonize specific high-emitting and/or costly end uses and regulations which address cross-cutting Energy Strategy Lens risks and hydrogen adoption barriers. The below guiding principles were applied to ensure that policies were consistent across the hydrogen value chain, and that the proposed policies were addressing the highest priority barriers and risks:

1. If hydrogen and other low carbon alternatives have similar TCOs, policy should be technology agnostic
2. If hydrogen is the only or best low carbon option, policy can be hydrogen specific
3. Policies should target bottlenecks revealed by modeling, i.e. largest contributor to TCO or most expensive part of the value chain

These policy recommendations are informed by the Energy Strategy Lens analysis, especially the TCO modelling conducted as part of the affordability assessment. Generally speaking, the financial incentives are designed to be fit-for-purpose and address the biggest cost drivers identified through the TCO analysis. For example, as shown in Figure 34, when the TCO for the hydrogen alternative is higher, and CAPEX is revealed to be the biggest cost driver, grants targeting equipment costs are proposed. On the other hand, when energy costs are the biggest contributor to a higher TCO, financial incentives that lower the price of the hydrogen fuel are preferred. In instances where the financial barrier is cross-cutting in nature or a non-financial issue poses a significant barrier, new regulations are proposed that can help advance hydrogen, often doing so without requiring significant new public expenditures.

Figure 34- Type of Policy based on Energy Strategy Lens Risk or Barrier Addressed



Energy Strategy Lens Risk or Barrier to be Addressed	Policy Type	Proposed Policy
Affordability TCO of hydrogen technology is cheaper than the fossil incumbent, and high upfront costs is the primary barrier to entry	**Loans**	• 4: Loans for Sustainable Maritime CAPEX • 5: Loans for Net Zero Trucking, Forklifts, and Coach Buses
Affordability TCO of hydrogen technology is costlier than the fossil incumbent, and high capital expenditures is the primary barrier to entry	**Financial Incentives reducing high capital expenditures costs**	• 6: Financial Incentives for Net Zero Trucking and Fueling Stations in Environmental Justice Communities
Affordability TCO of hydrogen technology is costlier than the fossil incumbent, and high energy costs is the primary barrier to entry	**Financial Incentives reducing high energy costs**	• 2: Financial Incentives for Hydrogen Usage for Long-Duration Energy Storage, High-Temperature Heat, Backup Power, Trains, and Local Buses • 3: Financial Incentives for Sustainable Aviation Fuel
Climate, Equity, Reliability & Resilience, Affordability Barriers to entry are cross-cutting in nature	**Regulations & Standards**	• 1: Connecticut Clean Hydrogen Definition • 7: Low Carbon Fuel Standards for Transportation Fuels • 8: Utility Regulations for Long-Duration Energy Storage • 9: NOx Emissions Standards for Hydrogen Combustion • 10: Dynamic Rates for Electric Utilities • 11: Emissions Standards for Cars and Trucks

Full List of Proposed Policies for Consideration

Table 43 represents potential policies that Connecticut can consider implementing in the form of financial incentives and cross-cutting regulations, to further drive decarbonization in costly and high-emitting end use applications.

Table 43- Proposed State Policies Applicable to Hydrogen

<table>
<tr><th colspan="3">Proposed Policy 1: Connecticut Clean Hydrogen Definition</th></tr>
<tr><td>Value chain step: Production</td><td>Policy Type: Regulation, Creation of Standards</td><td>Energy Strategy Lens and/or Barriers: Climate</td></tr>
<tr><td colspan="3">Details: Set a Connecticut-based definition for clean hydrogen that includes the allowed carbon intensity threshold, lifecycle assessment boundaries, and standards for eligible renewable energy sources for production. Connecticut's proposed clean hydrogen definition includes:
1. A prohibition on the use of fossil fuel feedstocks
2. A carbon intensity threshold of ≤ 2 kg CO2e/ kg H2 on a life cycle basis that includes owned and retired environmental attributes

Impact: Setting ambitious statewide regulations around clean hydrogen provides predictability and certainty to businesses and other stakeholders on the criteria hydrogen must meet to qualify for public support.

Existing or proposed policies in other regions: The state of Colorado proposed the 'Advance of Use of Clean Hydrogen'[xciv] bill to specify three pillars of hydrogen production, including additionality, temporality, and geography. This framework requires that hydrogen producers receiving any hydrogen-based state tax credits meet a carbon intensity threshold of ≤ 1.5 kg of CO2e/kg H2 while certifying that the energy input is 100% renewable on a 24/7 basis.</td></tr>
</table>

***Proposed Policy 2:* Financial Incentives for Hydrogen Usage for Long-Duration Energy Storage, High-Temperature Heat, Backup Power, Trains, and Local Buses**

***Value chain step:* End Use**	***Policy Type:*** Financial Incentives	***Energy Strategy Lens and/or Barriers:*** Affordability

Details: Under the modeling assumptions, long-duration energy storage, high-temperature heat, backup power, trains and local buses all have higher TCOs for hydrogen than their fossil-based alternative technologies, with the much of the difference driven by higher fuel costs. In this instance, financial incentives that subsidize ongoing fuel costs make most sense in improving the competitiveness of hydrogen as a decarbonization lever.

Impact: Financial incentives can lower fuel costs, improve the competitiveness of hydrogen as a decarbonization lever, and increase adoption in these use cases. In particular, the long-duration energy storage incentives will help Connecticut meet its 2040 goals for a decarbonized power grid while incentives focused on high-temperature heat address an end use sector with very limited decarbonization options.

Existing or proposed policies in other regions: In 2023, the Colorado state legislature passed a new law that provides tax credits of up to $1/kg for users of clean hydrogen in hard-to-abate sectors, including heavy-duty trucks, aviation, industrial heat of at least 150°C and higher, and feedstock for industrial purposes[xcv]. Although Colorado used state tax credits, subsidies can take other forms.

***Proposed Policy 3:* Financial Incentives for Sustainable Aviation Fuel**

***Value chain step:* End Use**	***Policy Type:*** Financial Incentives	***Energy Strategy Lens and/or Barriers:*** Affordability

Details: Hydrogen derived SAF has a higher TCO than traditional jet fuel, driven almost entirely by higher fuel costs, making it an end use application ripe for fuels-focused financial incentives. SAF incentives can be aimed towards airlines operating in Connecticut to financially incentivize the adoption of SAF that reduces overall lifecycle GHG emissions by a certain percentage as compared to the fossil-based incumbent. Additional qualifiers can be placed to ensure that the credit better incentivizes the usage of hydrogen-based fuels by utilizing a lifecycle GHG reduction threshold of 85% or more when compared to conventional jet fuels consistent with the criteria set by the First Movers Coalition[xcvi].

Impact: By supplementing existing federal SAF incentives from the IRA with statewide incentives, Connecticut can propel faster production and adoption of low emissions fuels in the aviation sector. In addition, since production of SAF may be costly in Connecticut, financial incentives aimed at the end users will allow airlines operating in the state to more cost-effectively uplift SAF made in states with lower production costs.

***Existing or proposed policies in other regions*:** Illinois[xxxvi] passed a statewide Sustainable Aviation Fuel Credit[xcvii] in 2023, offering $1.50 for every gallon of SAF sold to or used by an air carrier from June 1, 2023-June 1, 2033. This tax credit only applies to domestic flights and is only available to airlines operating in the state that buy the fuel and not the fuel producers themselves. In addition, this tax credit offers a cap on the volume of soybean oil-derived SAF that airlines can claim credits for to 10 million gallons/year and places constraints on the eligible SAF by specifying that it must reduce carbon emissions by at least 50% throughout its lifecycle. Similarly, in early 2023 the state of Washington enacted a SAF production incentive[xcviii] to encourage the production and usage of fuels by providing a $1/gallon tax credit for SAF that has at least 50% less CO2e emissions than conventional jet fuel. The measure also mandates a 2% increase in the incentive for every additional 1% reduction in CO2e emissions beyond 50% (up to $2/gallon). This credit is aimed at fuel producers or consumers such as airlines and will be available when a manufacturing facility produces at least 20 million gallons/year.

***Proposed Policy 4:* Loans for Sustainable Maritime CAPEX**

***Value chain step:* End Use**	***Policy Type:*** Financial Incentives	***Energy Strategy Lens and/or Barriers:*** Affordability

Details: Sustainable maritime fuels often include hydrogen derivatives such as ammonia and methanol, and are a key lever to decarbonize the shipping sector. While the TCO for ships running on sustainable maritime fuel is projected to be cheaper than fossil-based incumbent technology MGO, the high capital expenditures of these low emissions ships can still be a barrier to adoption. Thus, to reduce costs, low-interest loans can be offered to encourage the usage of ships powered by sustainable maritime fuel. These loans would offer additional support for the initial purchase and installation of low emissions maritime equipment and could be paid back in part through savings generated by the lower operating costs. In addition, offering financial incentives to adopt more ships running on sustainable maritime fuel has the potential to enhance the production and import of ammonia and methanol to create a greater supply of zero-carbon fuels in the market. Additional qualifiers can be placed on the types of eligible sustainable maritime fuel that can be utilized for the loan, with a particular incentive for hydrogen derivates to be produced using renewable energy (e.g. clean ammonia).

Impact: Implementing financial incentives to reduce the overall cost of adopting clean energy technologies for shipping and maritime applications will help decarbonize high-emitting sectors in Connecticut. Addressing the CAPEX bottleneck will increase demand for sustainable maritime fuel, sending a signal to producers to ramp **up** output, bringing down costs over time.

Existing or proposed policies in other regions: The Global Maritime Forum (GMF) created the 'Getting to Zero Coalition'[xcix], which is advocating for the shipping industry to be fully decarbonized by 2050. To do so, the coalition has emphasized the potential for ammonia to be a key input and lever for net zero fuels and outlines the need for additional pilot and demonstration projects, regulatory collaboration, and cost measures to be taken to produce at scale. While not a government policy itself, initiatives like GMF signal demand for clean fuels and provide an important base of support for policies that reduce the cost of clean shipping fuels.

***Proposed Policy 5:* Loans for Net Zero Trucking, Forklifts, and Coach Buses**

***Value chain step:* End Use**	***Policy Type:*** Financial Incentives	***Energy Strategy Lens and/or Barriers:*** Affordability

Details: Even though the hydrogen and BEV TCOs in Connecticut for heavy-duty trucking, forklifts, and coach buses are projected to be cheaper than the incumbent fossil-based technologies, according to the modeling assumptions, the high upfront costs of these low emissions vehicles over fossil vehicles can still be a barrier to adoption. Low-interest loans can be offered to provide end users with the capital they need to cover these upfront costs. These loans could be paid back in part through savings generated by the lower operating costs from hydrogen or BEV vehicles, relative to the fossil-based incumbents. The loans should be performance-based, and technology neutral, due to the similar TCOs for hydrogen and battery electric vehicles.

Impact: Providing capital to cover the high upfront costs for clean alternatives will address one of the largest barriers to adoption of hydrogen and electric vehicles. Increased adoption of low emissions vehicles would also reduce air pollution along common routes and improve overall health and wellbeing for surrounding communities.

Existing or proposed policies in other regions: The Connecticut Green Bank[c] offers smart e-loans to Connecticut-based residents for clean energy improvements.

***Proposed Policy 6:* Financial Incentives for Net Zero Trucking and Fueling Stations in Environmental Justice Communities**

***Value chain step:* Infrastructure; End Use**	***Policy Type:*** Financial Incentives	***Energy Strategy Lens and/or Barriers:*** Affordability

Details: As a complement to *Proposed Policy 5: Loans for Net Zero Trucking*, Connecticut should consider grants or other financial incentives to reduce the high capital expenditures of low emissions vehicles, specifically along routes located in and around environmental justice communities. Prior to offering the incentive to project developers, various factors can be assessed such as the degree of daily usage, existing amount of diesel fuel being consumed, proximity of routes alongside environmental justice communities, and proposed equitable employment standards. Furthermore, the financial incentive should specify a required percentage of GHG emissions reduction that must be met for applications to receive funding and ensure environmental outcomes are met.

Impact: Creating direct financial incentives for adoption of hydrogen vehicles in environmental justice communities will help ensure air pollution reduction occurs in the places that need it the most.

Existing or proposed policies in other regions*:* In 2018, the California Air Resources Board (CARB) created the Zero and Near Zero Emission Freight Facility Program [xxxv] awarding up to $205 million in grant funding for projects adopting clean freight technologies and reducing air pollution in the state. All projects were specifically focused near environmental justice communities heavily affected by harmful pollution from freight facilities. In addition, the state of Colorado implemented a Fleet-ZERO Grant Program[ci] which addresses air pollution by offering competitive grant funding for EV vehicles and charging stations. This would not only help save fleet owners and operators costs, but also prioritize funding and investment for disproportionally impacted communities.

***Proposed Policy 7:* Low Carbon Fuel Standards for Transportation Fuels**

***Value chain step:* Production**	***Policy Type:*** Financial Incentives	***Energy Strategy Lens and/or Barriers:*** Affordability

Details*:* This policy would create a market-based mechanism to reduce the carbon intensity of transportation fuels and reduce air pollution in Connecticut. Such low carbon fuel standards (LCFS) will encourage the production and usage of cleaner low-carbon transportation fuels and will require that Connecticut-based providers of transportation fuels provide information on the carbon intensity of fuels used for each compliance period.

Impact*:* LCFS will allow Connecticut to decarbonize the transport and shipping industries at a scale that is on par with other states such as California and Oregon. As a market-based measure, LCFS can incentivize clean fuels production and adoption with much less direct public expenditures relative to tax credits and grants. On the other hand, LCFS credit values vary, based on market forces, producing less predictability for businesses.

Existing or proposed policies in other regions: California's LCFS[cii] is designed to decrease the carbon intensity of the statewide transportation fuel pool to reduce overall GHGs and air pollution. Likewise, Oregon's Clean Fuels Program[ciii] outlines the required reductions in average carbon intensity or level of carbon emissions when combusted for both gasoline and diesel fuel by 2035. These standards are applicable for the importers of gasoline, diesel, ethanol, biodiesel, and renewable diesel fuel. Similarly, the state of Washington has adopted LCFS to enable the maritime industry to meet GHG reduction targets and improve air quality for communities located near ports.

***Proposed Policy 8:* NOx Emissions Standards for Hydrogen Combustion**

***Value chain step:* Production, End Use**	***Policy Type:*** Regulation, Creation of Standards	***Energy Strategy Lens and/or Barriers:*** Climate

Details: Implement additional supplementary limits on NOx emissions from hydrogen combustion processes for long-duration energy storage and high-temperature heat. This would include stationary sources such as power plants as well as mobile sources such as heavy-duty trucks.

Impact: Connecticut is designated non-attainment for the National Ambient Air Quality Standards for ground-level ozone. Connecticut's air permitting requirements includes review and consideration of Reasonably Available Control Technology (RACT) program and would include requirements to meet stricter standards for NOx emissions from hydrogen combustion processes specifically for high-emitting applications. These federal Clean Air Act requirements are designed to ensure that Connecticut can reduce air pollution along with negative public health consequences related to poor air quality such as asthma or other respiratory diseases.

Existing or proposed policies in other regions: Eleven states have adopted the California Advanced Clean Truck Rules (ACT) for Medium and Heavy-Duty vehicles and the Low NOx Omnibus Rules for heavy-duty

trucks) [civ] which requires that medium and heavy-duty vehicle manufacturers sell zero-emissions vehicles as a target percentage of all new vehicle sales beginning in 2025. The Low NOx Omnibus Rules ultimately strengthen emissions standards for conventionally fueled new build heavy-duty truck engines for NOx and PM2.5 where by 2027, the limit for NOx emissions is decreased by 90% as compared to the 2023 standard.		
***Proposed Policy 9:* Incentives for Load Management**		
***Value chain step:* Feedstock/ Electricity**	***Policy Type:*** *Financial* Incentives	***Energy Strategy Lens and/or Barriers:*** Affordability, Reliability & Resilience
Details: DEEP could utilize the Conservation and Load Management Programs to help industrial and other customers shift their energy demand to times of peak renewable electricity production and, potentially, incentivize investment in energy storage systems. Incentives for using electricity at times of peak renewables penetration have special implications for hydrogen production. In this incentive environment, hydrogen producers can ramp output to match the lower cost/higher renewables periods and store any excess hydrogen, which can later be converted back to electricity when grid prices are high. ***Impact****:* Incentives have the potential to save electricity consumers money on energy bills, reduce or eliminate renewables curtailment, and improve the cost effectiveness of energy storage systems. ***Existing or proposed policies in other regions:*** Demand response incentives are common across the utility sector, including in Connecticut, but this mechanism has not yet been applied specifically for hydrogen projects.		
***Proposed Policy 10:* Emissions Standards for Cars and Trucks**		
***Value chain step:* End Use**	***Policy Type:*** Regulation, Creation of Standards	***Energy Strategy Lens and/or Barriers:*** Climate
Details: Connecticut proposed updated emissions standards for light-duty passenger, medium, and heavy-duty vehicles[cv]. These standards aim to make new cars and trucks up to 90% cleaner and will require vehicle manufacturers to deliver more low- and zero-emission and other advanced-technology vehicles. ***Impact:*** These standards aim to deliver cross-cutting benefits such as sending strong market signals for clean mobility solutions, reducing NOx and particulate matter emissions, and creating quality jobs in Connecticut. ***Existing or proposed policies in other regions:*** The proposed emissions standards are modeled after California's proposed regulations for mobility decarbonization.		

B. Programs

i. Program Overview

Programs are another key enabler that can help facilitate the integration of hydrogen into Connecticut's existing infrastructure. As noted in the enabler intro section, each program will be categorized by three dimensions: 1) Step in the hydrogen value chain, 2) Risk/barrier addressed, and 3) Type of program. An overview of each program type is defined below:

1. **Collaboration platforms** that can connect various types of hydrogen stakeholders to facilitate and optimize hydrogen activity in Connecticut
2. **Resource sharing networks** that ensure all best practices and knowledge related to hydrogen are identified and made available to the right stakeholders working on each part of the hydrogen landscape
3. **Studies** that can inform decision-making and strategic planning

ii. Programs

Table 44 details the recommended programs to address identified hydrogen risks and barriers to adoption.

Table 44- Proposed State Programs Applicable to Hydrogen

Program 1: **Creation of Hydrogen Clusters**

Value chain step:	***Program type:***	***Energy Strategy Lens and/or Barriers:***
Cross Value Chain	Collaboration platform	Affordability

Details: Hydrogen clusters can be developed as a market transformation mechanism for yielding state-wide benefits in terms of cost, policy, and pilot project opportunities. DEEP defines hydrogen clusters as regions with a high concentration of potential off-takers, with feasible access to hydrogen supply either by local production or through transport pathways such as pipelines, ports, and highways. These clusters would be beneficial in leveraging economies of scale to reduce the overall cost of hydrogen and de-risk infrastructure investment. Additional features related to this program include:

- Establishing a Hydrogen Cluster team within DEEP to identify potential locations, engage stakeholders, assess demand, supply, and infrastructure needs. Connect clusters to government programs for accelerated hydrogen adoption.
- Removing geographical and institutional barriers, prioritizing environmental justice for affected areas
- Supporting the identification, design, and planning for pilot projects within clusters
- Enabling high job creation concentrated in and around clusters
- Create a resource platform for best practices in hydrogen production and applications that leverages cluster partners for relevant studies and incentivize adoption
- Strengthening the regional collaboration with northeast states established throughout the application process for the Hydrogen Hubs federal opportunity

Impact: Creating hydrogen clusters will further propel investment, resources, and knowledge-sharing towards targeted regions and help form better connectivity between various stakeholders working within the clusters.

Existing or proposed programs in other regions: The state of Louisiana has established the H2theFuture Initiative[cvi], which is responsible for building a clean hydrogen energy cluster to decarbonize the South Louisiana industrial corridor through the execution of various projects.

Program 2: **Hydrogen Safety Resource Group**

Value chain step:	***Program type:***	***Energy Strategy Lens and/or Barriers:***
Cross Value Chain	Resource sharing network	Reliability and Resilience: Safety

Details: Create a resource group centered around disseminating safety requirements and best practices for all activities associated with hydrogen production, infrastructure, and end use. The duties of the Hydrogen Safety Coalition could include:

- Ensuring that all stakeholders working with hydrogen understand the U.S. DOE Hydrogen & Fuel Cell Technologies Office Safety, Codes, and Standards and the National Fire Protection Association Hydrogen Technologies Code, and have implemented appropriate best practices within their activities
- Collaborating with local fire departments and hospitals to provide comprehensive training on handling hydrogen incidents and resource allocation
- Creating and continually updating a best practices safety document through observing industry trends and collaborating with relevant in and out of state hydrogen groups. This document should be shared with all relevant stakeholders, including recipients of state resources for hydrogen activities and translated into multiple languages.
- Compiling a yearly safety report on all hydrogen-related safety incidents while emphasizing the need for additional safety protocols and resources
- Collaborating with academics and industry stakeholders to develop best practices for monitoring the impact of leaks across the hydrogen value chain and implementing mitigation measures
- Promoting a safety-focused culture in dealing with hydrogen applications, especially in educational, laboratory, and factory settings.

Impact: A hydrogen transition must be conducted in tandem with the highest safety standards to ensure that no accidents or injuries occur. By prioritizing safety knowledge in each interaction, Connecticut can cultivate a safety-based decarbonization culture that can lead to the responsible scaling of hydrogen in the state.

Existing or proposed programs in other regions: The New York State Energy Research and Development Authority recently joined the Center for Hydrogen Safety, a global nonprofit dedicated to promoting hydrogen safety and best practices, to enable knowledge sharing on recent safety measures. The Center for Hydrogen Safety is comprised of members across government, academia/research, and industry, and convenes an expert Hydrogen Safety Panel for project safety reviews.

Program 3: Assess Optimal Siting of Hydrogen Fueling Stations

Value chain step: Infrastructure	***Program type:*** Study	***Energy Strategy Lens and/or Barriers:*** Affordability, Equity

Details: Conduct a study which assesses optimal siting for hydrogen fueling stations across Connecticut, considering infrastructure needs and financial barriers. Study activities could include:

- Collaborating with industry and academic partners to develop a geospatial and economic analysis tool that can identify ideal sites for hydrogen fueling stations in Connecticut, considering factors like high-traffic routes and proximity to environmental justice communities.
- Evaluating the financial feasibility of establishing public hydrogen fueling stations, including capital expenditures and ongoing maintenance costs.
- Investigate and address legal and infrastructure challenges within both Connecticut and neighboring states that may hinder hydrogen fueling station adoption
- Working with corporate partners to assess interest in placing hydrogen stations on private property for public use
- Ensuring proposed station locations account for environmental justice communities, addressing potential negative effects with mitigation strategies

Impact: Implementing a study dedicated towards determining the most optimal location for hydrogen fueling stations will be crucial as a first step prior to investing additional financial and infrastructure resources and time.

Existing or proposed programs in other regions: California conducted a study and created a geospatial analysis tool, California Hydrogen Infrastructure Tool (CHIT) [cvii] in 2017 to identify the areas of greatest need for fueling infrastructure development.

Program 4: Study Reliability of Hydrogen Transport Methods in Severe Weather

Value chain step: Cross Value Chain	***Program type:*** Study	***Energy Strategy Lens and/or Barriers:*** Reliability & Resilience

Details: Conduct a study to assess the reliability and resilience of the usage of hydrogen in times of weather distress, with particular attention to impact on its use for back-up power for critical facilities (e.g. hospitals, data centers, airports). This study would include assessing whether critical facilities have a mechanism for receiving hydrogen transported via trucks when needed, particularly during storms and other extreme weather incidents, and if alternate back-up measures such as extra on-site hydrogen storage would be financially or practically feasible.

Impact: As increased climate change brings about more frequent extreme weather events in Connecticut, it will be important to continuously assess reliability and resilience plans, particularly for critical facilities where lives may be dependent on receiving timely access to energy sources.

Program 5: Equitable Hydrogen Job Transition Program

Value chain step: Cross Value Chain	***Program type:*** Resource sharing network	***Energy Strategy Lens and/or Barriers:*** Economic Development

Details: Develop an Equitable Hydrogen Job Transition Program which creates and disseminates training and development material for employees transitioning to hydrogen and clean energy jobs. Key activities of the transition program include:

- Creating a comprehensive training toolkit with videos and written content covering hydrogen clean energy basics, decarbonization goals, safety protocols, and strategic skills. These resources should be translated into commonly spoken languages in Connecticut for wider accessibility.

- Developing a statewide plan to increase employment from environmental justice communities (particularly from counties in Connecticut which face high unemployment burdens according to the U.S. Council on Environmental Quality Climate & Economic Justice Screening Tool) and minority groups
- Establishing a statewide equitable employment target for hydrogen-based clean energy jobs
- Promoting hydrogen and clean energy jobs at local community colleges and universities through career fairs and student-led organization events
- Creating a Women-in-Hydrogen Panel to encourage women from technical and non-technical backgrounds to pursue careers in hydrogen and other clean energy technologies

Impact: The hydrogen transition is an opportunity to foster diversity and equitable employment in the clean energy space, and implementing effective programs aimed at ensuring workers are trained and knowledgeable in skills that are relevant to green industries will be crucial as hydrogen activity expands in Connecticut.

Existing or proposed programs in other regions: The state of Illinois created various programs to support the goals of the Climate and Equitable Jobs Act, including the Clean Jobs Workforce Network Program[cviii], Energy Transition Navigator Program, and Clean Energy Contractor Incubator Program. These initiatives support entities such as community-based organizations, community colleges, nonprofits, and local governments. Illinois' Climate Works Pre-apprenticeship Program aims to prepare workers in construction and building trades for employment in clean energy jobs with the overall goal of creating a qualified and diverse hiring pipeline.

Program 6: Connecticut Hydrogen Innovation Consortium

Value chain step:	***Program type:***	***Energy Strategy Lens and/or Barriers:***
Cross Value Chain	Collaboration platform	Economic Development, Affordability

Details: Create a Connecticut Hydrogen Innovation Consortium which fosters and bolsters business development from hydrogen activity in the state by connecting various public and private stakeholders. Key activities of the consortium could include:

- Sharing hydrogen updates, insights, and roadblocks through an open forum with other consortium participants to encourage connectivity and open dialogue during the hydrogen transition
- Identifying relevant hydrogen market-based opportunities for all stakeholders participating in the hydrogen transition
- Hosting programs and hackathons to foster innovative thinking to address barriers to hydrogen adoption.
- Connecting potential investors with Connecticut-based startups and businesses working on critical hydrogen issues

Impact: Creating a platform where various stakeholders in Connecticut are routinely connected and engaged on various innovative and market-based projects will be crucial to further expand hydrogen activity in the state. The creation of new, small businesses is a key objective of this consortium to help ensure hydrogen-related job growth occurs within the state. In addition, creating a consortium will help connect participants who may be able to work on various projects together and solve critical barriers for adopting hydrogen at scale.

Existing or proposed programs in other regions: The state of Louisiana has created the H2theFuture initiative, of which a critical pillar is supporting innovation by bolstering local university research for lowering hydrogen costs and creating the H2Business Development project responsible for recruiting and retaining businesses supporting a clean energy transition. H2Business includes projects such as business retention and expansion, disadvantaged business enterprise, and lead generation.

Program 7: Feasibility Study of Underground Hydrogen Storage in Connecticut's Hardrock

Value chain step:	***Program type:***	***Energy Strategy Lens and/or Barriers:***
Infrastructure	Study	Affordability, Accessibility

Details: Conduct a study to determine the feasibility of large-scale storage of hydrogen in Connecticut's hard rock outcroppings, which are underground caverns surrounded by hard, low permeability rock, which can be lined to hold pressurized hydrogen.

Impact: Identify if Connecticut has the potential to store hydrogen underground, which would increase hydrogen storage volumes and reduce costs from above ground storage.

Existing or proposed programs in other regions: The U.S. DOE cited lined hard rock storage in the pathways to commercial Liftoff Report for Clean Hydrogen[cix], noting that while it is an earlier stage technology than salt caverns, it is expected to allow higher storage pressures.

***Program 8:* Environmental Justice for Equitable Hydrogen Deployment Task Force**

Value chain step:	***Program type:***	***Energy Strategy Lens and/or Barriers*:**
Cross Value Chain	Resource sharing network	Affordability, Accessibility

Details: Create an Environmental Justice for Equitable Hydrogen Deployment Task Force as a subsection of the Connecticut DEEP Environmental Justice Program responsible for assessing and ensuring that critical environmental justice principles of accessibility, health and wellbeing, and sustainable job creation are being upheld across all hydrogen policies, programs, and pilot projects. This task force should be diverse and representative of the population of Connecticut, focused in discussing hydrogen technologies and associated environmental justice impact for communities. The Task Force would work in collaboration with the Connecticut Equity and Environmental Justice Advisory Council (CEEJAC), providing presentations to the full council or its Energy Subcommittee. In addition, a CEEJAC member should sit in the Task Force. Key activities of the Task Force could include:

- Creating best practices for all stakeholders to follow when integrating environmental justice ideals in hydrogen projects
- Creating an Assessment of Ongoing Burdens and Risk template which will assess unintended consequences associated with hydrogen adoption and help develop their mitigation strategies
- Developing a Community Stakeholder Engagement template that project developers can use to effectively engage all types of communities that will help incorporate benefits and mitigate unintended consequences associated with hydrogen adoption.
- Conducting environmental justice landscape assessments with appropriate measurement of economic and environmental impact to share with all relevant stakeholders to inform future hydrogen adoption strategy

Impact: To fuel a long-lasting hydrogen transition, it is important to embed environmental justice principles and metrics from the advent of project implementation.

Existing or proposed programs in other regions: Similar to the Connecticut Equity and Environmental Justice Advisory Council, several states have established environmental justice councils specifically responsible for providing recommendations and guidance to the state on how best to implement environmental justice requirements in clean energy and climate programs. For example, the state of Washington has created the Washington Environmental Justice Council[cx], which is responsible for identifying issues related to overburdened communities and tracking progress towards health and equity goals.

C. Pilot Projects

Pilot projects can play a crucial role in the scale up of Connecticut's hydrogen economy by providing real-world experience and data that are essential for the successful development and deployment of hydrogen technologies. Specifically, these projects can serve several key purposes:

1. ***Technology Demonstration and Risk Mitigation:*** Pilot projects allow for the demonstration of new hydrogen technologies in real-world settings, providing valuable insights into their performance, cost, reliability, and feasibility. They also provide a controlled environment to assess and mitigate potential risks associated with hydrogen technologies This practical experience is crucial for identifying and addressing potential challenges before large-scale deployment.
2. ***Community Engagement and Public Acceptance:*** Pilot projects offer opportunities to engage with local communities and stakeholders, fostering public understanding and acceptance of hydrogen technologies. This engagement can help address concerns and build support for wider adoption of hydrogen solutions.
3. ***Collaboration and Knowledge Sharing:*** Pilot projects often involve collaborations among various stakeholders, including technology developers, industry partners, research institutions, and government

agencies. This collaborative approach facilitates knowledge sharing, accelerates innovation, and promotes a shared understanding of the challenges and opportunities associated with hydrogen technologies.

4. ***Policy Development and Regulatory Framework:*** Data and insights from pilot projects can inform policy decisions and regulatory frameworks related to hydrogen technologies. This evidence-based approach can ensure that policies and regulations are aligned with technological advancements and market needs.

A. Best Practices for Pilot Projects

Successful implementation of pilot projects will require careful planning, execution, and evaluation to ensure they achieve their intended goals and pave the way for additional scale up. Below are best practices to follow to help pilot projects meet their objectives:

1. ***Define clear objectives and scope:*** Before embarking on a pilot project, clearly define its specific objectives, scope, and deliverables. This ensures that all stakeholders are aligned on the project's purpose and expectations.
2. ***Identify key stakeholders and foster collaboration:*** Early on, identify and engage all relevant stakeholders, including technology developers, industry partners, research institutions, government agencies, and community members. Encourage open communication and collaboration among all stakeholders throughout the project. Regular meetings, progress reports, and feedback sessions can help identify and address issues promptly.
3. ***Establish evaluation criteria and implement robust data collection and analysis:*** Determine the key metrics and evaluation criteria that will be used to measure the success of the pilot project that are aligned with the project's objectives, including during more extreme conditions such as a typical Connecticut winter. Establish a systematic approach to data collection and analysis throughout the project. This data will be crucial for evaluating the project's performance, identifying areas for improvement, and making informed decisions.
4. ***Document lessons learned and share knowledge:*** At the conclusion of the pilot project, document the lessons learned, challenges encountered, and best practices identified. Sharing this knowledge can benefit future projects and contribute to the broader advancement of hydrogen technologies.
5. ***Establish clear transition and scale-up plans:*** If the pilot project is successful, develop clear plans for transitioning from the pilot phase to full-scale deployment. This includes addressing any remaining technical challenges, securing necessary funding, and expanding partnerships.

B. Proposed Pilot Projects

The proposed pilot projects have been selected in an effort to maximize their success and value by choosing projects that are likely to meet the following criteria:

1. ***Alignment with strategic objectives:*** Pilot projects should align with Connecticut's overall objectives for hydrogen technology development and deployment. This ensures that the projects will contribute to the achievement of broader goals and provide clear paths for future efforts.
2. ***Address a specific barrier or ES risk:*** The pilot projects should address a specific ES risk or barrier to help overcome or mitigate them
3. ***Strong stakeholder engagement:*** The pilot projects should involve active engagement from key stakeholders, including hydrogen suppliers, off takers, and infrastructure developers, in addition to government agencies and community members. Many of the proposed pilot projects target hydrogen end uses where stakeholders have already indicated interest.

Table 45 outlines proposals for five pilot projects that are expected to meet all of the above criteria.

Table 45- Proposed Connecticut Pilot Projects Applicable to Hydrogen

Pilot Project 1: **Hydrogen Production, Infrastructure, and Use for Heavy-duty Trucking**	
Value chain step: Cross-value chain	***Energy Strategy Lens and/or Barriers****:* Availability, Accessibility, Acceptance
Details: Project that spans the hydrogen production, fueling infrastructure, and FCEV fleets needed to create a heavy-duty trucking hydrogen value chain on a key route in Connecticut	

Objectives:

1. Address hydrogen availability and accessibility concerns for heavy-duty trucking by connecting a hydrogen fleet user with hydrogen supplier, and creating the fueling station supply chain that will allow the fleet to be supplied with hydrogen at the needed mileage intervals
2. Increase acceptance of hydrogen heavy-duty trucking by testing its reliability during a pilot, and iterating based on feedback before expanding to more fleets and fueling stations

***Pilot Project 2:* Sustainable Maritime Fuel Production, Infrastructure, and Use, including Forklifts**

Value chain step:	***Energy Strategy Lens and/or Barriers**:*
Cross-value chain	Availability, Accessibility, Acceptance, Reliability & Resilience

Details: Project that includes the production, transport, storage, and fueling of sustainable maritime fuel at a Connecticut port, including forklifts to move around shipping containers

Objectives:

1. Address sustainable maritime fuel availably and accessibility concerns by connecting sustainable maritime fuel producer with a maritime offtaker and creating the associated transport and storage infrastructure to fuel at a Connecticut port.
2. Address the acceptance of sustainable maritime fuel by testing its reliability in pilots and iterating based on findings before scaling to more ships and ports

***Pilot Project 3:* Hydrogen Production, Infrastructure, and Use for Long-duration Energy Storage**

Value chain step:	***Energy Strategy Lens and/or Barriers**:*
Cross-value chain	Availability, Accessibility, Acceptance, Reliability & Resilience

Details: Project that spans the hydrogen production, transport, storage, and hydrogen turbines needed to test the ability of hydrogen to reliability address Long-duration Energy Storage needs in Connecticut

Objectives:

1. Address hydrogen availability and accessibility concerns for Long-duration Energy Storage by connecting a utility with a hydrogen supplier, and creating the associated transport and storage infrastructure
2. Address acceptance of Long-duration Energy Storage with hydrogen by testing its reliability and iterating during the pilot before scaling

***Pilot Project 4:* Sustainable Aviation Fuel Infrastructure and Use**

Value chain step:	***Energy Strategy Lens and/or Barriers**:*
Infrastructure, End Use	Availability, Accessibility, Acceptance

Details: Project that includes the transport of SAF from an out of state facility to be fueled in planes at airports in Connecticut

Objectives:

1. Address SAF availability and accessibility concerns by connecting out of state SAF producer with off takers in Connecticut, and creating the associated transport infrastructure
2. Address the acceptance of SAF by demonstrating its reliability in pilots that increase in ratio of SAF to jet fuel over time

***Pilot Project 5:* Hydrogen Production, Infrastructure, and Use for High-Temperature Heat**

Value chain step:	***Energy Strategy Lens and/or Barriers**:*
Cross-value chain	Availability, Accessibility, Acceptance, Reliability & Resilience

Details: Project that includes the production, transport, storage, and use of hydrogen for industrial high-temperature heating needs in Connecticut

Objectives:

1. Address hydrogen availability and accessibility concerns for Long-duration Energy Storage by connecting a hydrogen supplier with an industrial heat user, and creating the associated transport and storage infrastructure
2. Address the acceptance of hydrogen for high-temperature heat by testing its reliability and iterating based on findings before scaling to more industry heat users

5. Next Steps and Conclusion

A. Summary of Key Findings and Recommendations

The assessment of hydrogen throughout each step of this roadmap has confirmed that hydrogen can play an important role in Connecticut's clean energy transition. It can help decarbonize hard-to-electrify end uses, including but not limited to long-duration energy storage, heavy-duty trucking, aviation, maritime shipping, and high-temperature heat. Much of the hydrogen production, associated renewable electricity, and hydrogen infrastructure, can occur in state, increasing Connecticut’s energy independence, and supporting economic growth and job creation. Key hydrogen targets and their associated impacts are summarized in Table 46. They are based on modeling assumptions and represent a conservative approach. Actual numbers may differ according to the renewable energy mix and feedstock used for the hydrogen production and its carbon intensity.

Table 46- Clean Hydrogen Roadmap Targets Through 2040

	Short term: Through 2027	**Medium term: Through 2032**	**Long term: Through 2040**
Target hydrogen demand, *tons/year*	7,700 tons/year	38,000 tons/year	76,000 tons/year
Electrolyzer capacity, *MW*	50 MW	230 MW	460 MW
Renewable capacity, *MW*	160MW	800MW	1,600MW
Hydrogen pipeline, *miles*	0	30	30
Hydrogen transport trucks	15	6	6
GHG emissions reduced from hydrogen w/ carbon intensity of 0.45 kg CO2e/ kg H2, *tons/year*	63,000	224,000	472,000
Cumulative capital invested, *$ millions*	$530	$2,530	$4,990
Sustained jobs created	50 jobs	210 jobs	430 jobs

Throughout the roadmap evaluation process, a number of hydrogen risks and barriers have been identified, including:

- Increased costs of hydrogen compared to the fossil-based incumbent for certain end uses
- Potential for increased NOx emissions when hydrogen is combusted
- Not having enough qualified workers to fill the jobs that will be created by hydrogen, and/or risk that the jobs created are not available to displaced fossil fuel workers or environmental justice communities
- Feasibility and reliability concerns with technologies that have not yet been proven
- Safety concerns associated with scaling up hydrogen and using it in new ways

A number of policies, programs, and pilot projects have been proposed to address these risks and barriers, such as:

- Financial incentives to help put hydrogen at cost parity with fossil-based incumbent technologies
- Expansion of existing NOx regulations to minimize NOx emissions and ensure that those that do occur do not lead to negative health effects for any population
- Creation of inclusive job training programs that ensure the right number of workers are trained and are available to both displaced fossil fuel workers and environmental justice communities
- Pilot projects that can begin to build out needed hydrogen and hydrogen derivative infrastructure, and identify and address any reliability and resilience risks

- Safety programs that can disseminate existing safety best practices and lessons learned to all key personnel involved with hydrogen projects.
- Additional staff resources would be needed at CT DEEP would likely be needed to implement these contemplated programs.

B. Next Steps for Implementation

While each proposed policy, program, and pilot project can play a key role in the scale up of Connecticut's hydrogen economy, the timelines at which they will be most valuable, and feasible, differ. In the short term, the focus should be on enabling and piloting the use cases with the highest technology readiness levels (e.g., heavy-duty trucking), while also launching early studies to analyze safety and infrastructure issues which will impact later scaling of hydrogen. The medium-term efforts should be focused on scaling the technologies piloted in the short term, while piloting the next wave of technologies, including long-duration energy storage, SAF, and sustainable maritime fuel, while ensuring that hydrogen job, cluster, and innovation programs are in place as total hydrogen demand increases. Finally, the long-term goals should include scaling hydrogen across all end-uses at the rate needed to achieve Connecticut's decarbonization goals, through program reevaluations, load management incentives, and piloting and eventually scaling hydrogen for high-temperature heat. Table 47 outlines the ideal implementation time for each enabler that would support the successful scale up of Connecticut's hydrogen value chain.

Table 47- Recommended Timeline for Key Hydrogen Enablers

	Short term: 2024-2027	Medium term: 2028-2032	Long term: 2033-2040
Policies	• Connecticut Clean Hydrogen Definition • Loans for Net Zero Trucking • Financial Incentives for Net Zero Trucking and Fueling Stations in Environmental Justice Communities • Low Carbon Fuel Standards for Transportation Fuels • NOx Emissions Standards for Hydrogen Combustion	• Financial Incentives for Hydrogen Usage for Long-duration Energy Storage and High-Temperature Heat • Loans for Sustainable Maritime CAPEX • Financial Incentives for Sustainable Aviation Fuel	• Utility Regulations for Long-duration Energy Storage • Load management incentives
Programs	• Hydrogen Safety Resource Group • Assess Optimal Siting of Hydrogen Fueling Stations • Study Reliability of Hydrogen Transport Methods in Severe Weather • Feasibility study of Underground Hydrogen Storage in Connecticut's Hardrock • Environmental Justice for Equitable Hydrogen Deployment Task Force	• Creation of Hydrogen Clusters • Equitable Hydrogen Job Transition Program • Connecticut Hydrogen Innovation Consortium	• Evaluate and modify, expand, or close previous programs based on stakeholder feedback, successes, and challenges
Pilot projects	• Hydrogen Production, Infrastructure, and Use for Heavy-duty Trucking • Sustainable Maritime Fuel Production, Infrastructure, and Use, including Forklifts	• Hydrogen Production, Infrastructure, and Use for Long-duration Energy Storage • Sustainable Aviation Fuel Infrastructure and Use	• Hydrogen Production, Infrastructure, and Use for High-Temperature Heat

C. Conclusion

Hydrogen is a key enabler of a clean energy future, and Connecticut is well-positioned to lead the way in its development and deployment. The roadmap presented here outlines a clear path forward for Connecticut to build a thriving clean hydrogen economy. By implementing the roadmap's recommendations, Connecticut can:

- Decarbonize hard-to-electrify sectors, such as heavy-duty transportation, industrial processes, and power generation.
- Create jobs and support economic growth.
- Improve air quality and protect the environment.
- Advance Connecticut's leadership in hydrogen technology and innovation.

The implementation of the roadmap's recommendations will require the coordinated effort of government, industry, and other stakeholders. Ongoing monitoring and analysis of technology and market trends will be needed over time. While the roadmap’s recommendations are based on the best available data, clean hydrogen is still a relatively new technology that is competing with other decarbonization levers that are also rapidly maturing. Connecticut should revisit its policy agenda over time to make sure it is incentivizing the most appropriate and cost-effective technologies to meet its decarbonization objectives. Based on current data and analyses, however, it is clear that clean hydrogen is a viable decarbonization lever for a range of use case that will produce significant environmental and economic benefits to the state of Connecticut.

6. Appendix

A. Hydrogen 101

Hydrogen is a chemical element, with many special properties. It is the lightest of all chemical elements and is the most abundant element in the universe. On earth, it is typically found in gaseous form, made up of two hydrogen atoms combined together, making its chemical symbol H_2. It has many existing applications as both a fuel and a raw material, or feedstock. Hydrogen also has the potential to support the clean energy transition. When hydrogen is used as a fuel, it creates no GHG emissions, so it can be a great alternative to fossil fuels for many end uses. It is also possible to produce hydrogen with low to no GHG emissions. However, some hydrogen value chains do produce carbon and other emissions, so it is important to understand the different ways to produce, transport, and use hydrogen, and the different considerations associated with each. This section provides an introduction to each step of the hydrogen value chain.

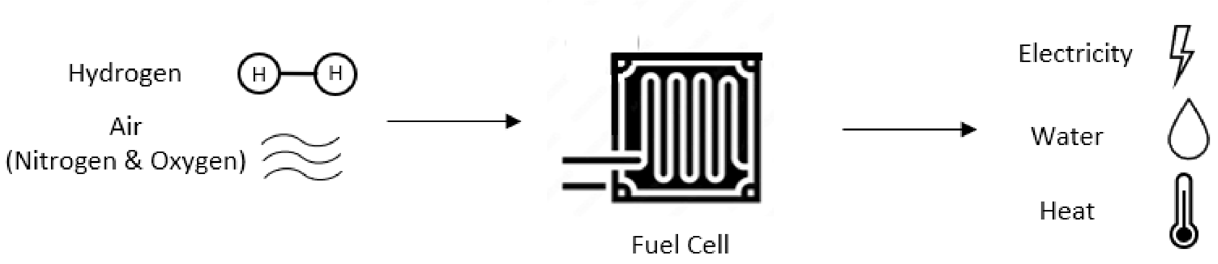
i. How Can Hydrogen be Used

Hydrogen can be used in three main ways: Processed in a fuel cell, burned through combustion, or used as a feedstock. Each of these ways to use hydrogen can be applied to various end uses across the transportation, industrial, power, and building sectors. The descriptions that follow summarize facts about how hydrogen can technically be used, but do not discuss potential societal preferences among the use options.

HYDROGEN PROCESSED IN FUEL CELLS

In a fuel cell, hydrogen and oxygen atoms are combined, producing water, electricity, and heat. There are many applications of hydrogen fuel cells across a range of sectors. In the transportation sector, hydrogen fuel cells can be used in cars, trucks, buses, ships, trains, planes, and off-road vehicles like forklifts. In the power sector, hydrogen fuel cells can be used in electricity generators, which can be used for off-grid power, back-up power, and grid balancing. Hydrogen can also be processed in combined heat and power systems to co-produce electricity and heat.

Figure 35- Hydrogen Conversion in a Fuel Cell

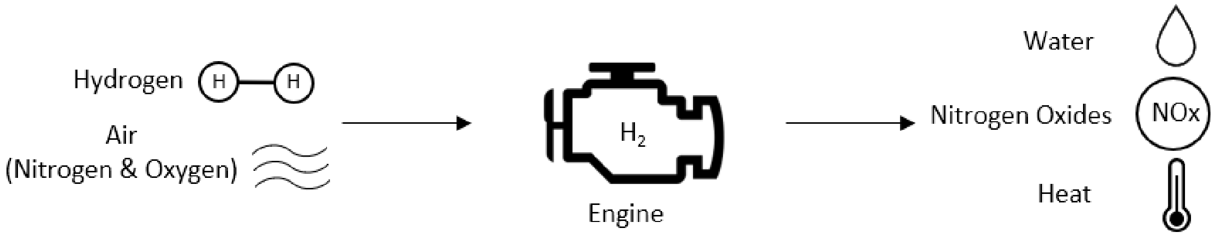


HYDROGEN BURNED IN COMBUSTION

Another way hydrogen can be used is through combustion. Hydrogen combustion is a chemical process that involves releasing energy from a hydrogen and air mixture. Hydrogen combustion, similar to fossil fuel combustion, creates polluting nitrogen oxides, or NOx, in varying concentrations depending on the conditions of combustion. NOx pollutants are harmful to respiratory systems and are therefore regulated by US state and federal governments.

Hydrogen combustion has a variety of potential applications. In industry, hydrogen can be combusted in furnaces to create high, medium, and low temperature heat. Hydrogen combustion can similarly be applied in the building sector to generate heat for homes and commercial spaces. In the transport sector, hydrogen combustion can be used to power engines across a variety of vehicles, including cars, trucks, ships and planes.

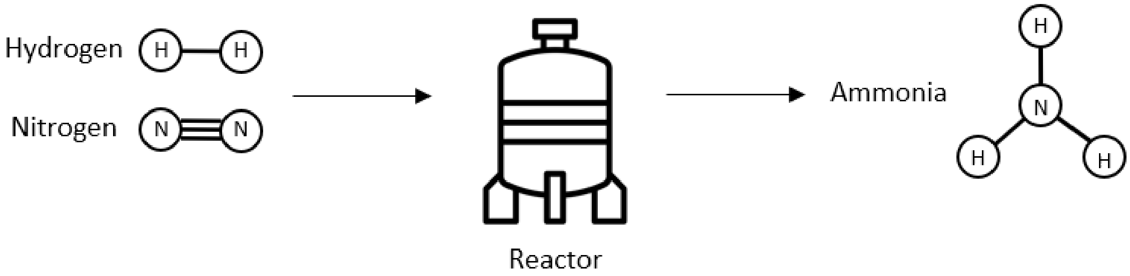
Figure 36- Hydrogen Burned in a Combustion Engine



HYDROGEN USED AS A FEEDSTOCK

The final major way that hydrogen can be used is as a raw material, or feedstock, for a variety of chemicals and fuels. While each fuel and chemical will have a different production process, typically hydrogen will be combined with another raw material through a chemical reaction that will produce one or more products. Some examples of products produced from hydrogen include but are not limited to ammonia, methanol, refining products, and sustainable aviation fuels.

Figure 37- Hydrogen Used as a Feedstock in Ammonia Production



ii. How is Hydrogen Made

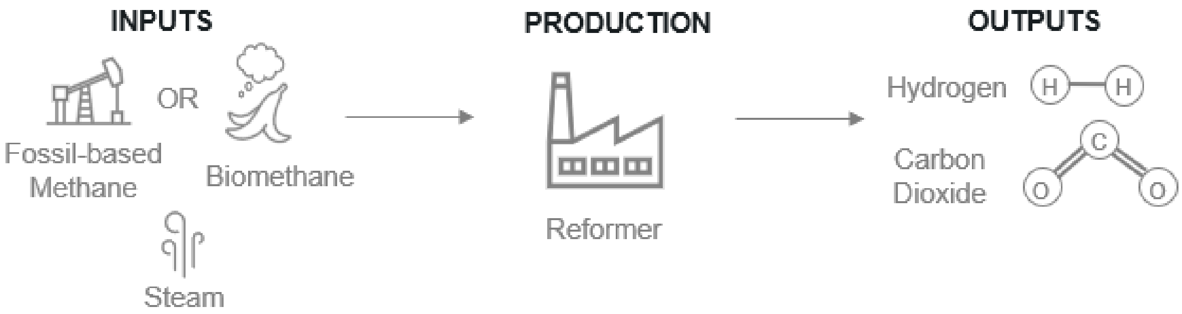
Although hydrogen is the most abundant element in the universe, it is not commonly found in its pure form needed for energy and feedstock use. Therefore, pure hydrogen must be produced. There are a variety of ways to produce hydrogen, which use different feedstocks and produce different by-products and levels of GHG emissions. Some of the most common production methods are described below.

A note on production method terminology and colors of hydrogen: As hydrogen began emerging as a fuel for the energy transition, industry stakeholders began to refer to the various types of hydrogen production methods by a designated color as a way to simplify discussions around hydrogen (e.g., saying 'blue hydrogen' instead of 'hydrogen produced by steam methane reforming with carbon capture). However, as the number of hydrogen production technologies grew, assigning a color to each production method became complicated and less standardized. Therefore, researchers and policymakers are starting to move away from using colors to categorize hydrogen. In this paper, DEEP uses the full production method name rather than its color, but in this appendix section, to provide full context, the commonly used color for each production method has been noted.

STEAM-METHANE REFORMING

Steam-methane reforming produces hydrogen through the reaction of high temperature steam with methane in a unit called a reformer. Though the most widely utilized methane source is fossil fuel-based natural gas, bio-based methane such as landfill gas may also be utilized. The outputs of this process are hydrogen and CO_2, making this a high GHG emission production process, especially when using fossil fuel-based natural gas as a feedstock. Not only are there CO_2 emissions associated with production, but there is the potential for upstream emissions due to methane leakage during methane extraction, transport, and use. However, if a bio-based methane feedstock is used, net GHG emissions from steam-methane reforming can be significantly reduced because any methane or CO_2 that is released during the hydrogen production process originally came from the atmosphere before it was part of the bio-based feedstock. Steam-methane reforming which uses fossil fuel-based natural gas is referred to as grey hydrogen in the hydrogen color coding scheme.

Figure 38- Hydrogen Produced via Steam Methane Reforming

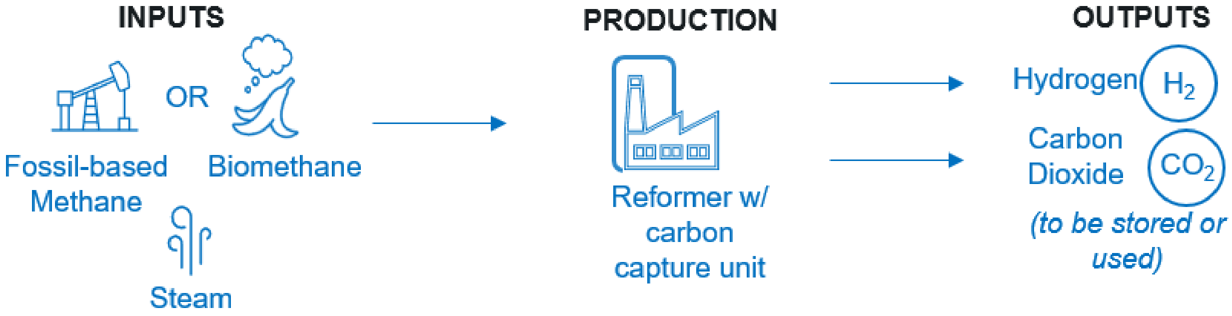


STEAM-METHANE REFORMING WITH CARBON CAPTURE

Carbon capture, utilization, and storage (CCUS) technologies can be applied in two locations in the steam-methane reforming process to reduce CO_2 emissions. The first and most common is downstream of the reformer where the CO_2 produced as a byproduct of the steam-methane reforming reaction is emitted. This is where the most highly concentrated CO_2 is produced and therefore is the easiest place to capture it. Some units also apply carbon capture to the outlet of the furnace that heats the steam methane reforming reaction. However, this is more cost intensive due to the lower concentration of CO_2.

In the CCUS process, not only are CO_2 emissions captured and not released to the atmosphere, but they are either used as an input to a different process that requires CO_2 or permanently stored. Storage may either be above-ground in tanks or below-ground in geologic reservoirs with the appropriate sealing capacity to prevent CO_2 leakage. Transport of the CO_2 to the storage or end use location requires equipment designed to prevent CO_2 leaks. Though carbon capture reduces CO_2 emissions, it cannot prevent the methane emissions associated with leaks from the natural gas inputs used for steam-methane reforming. The amount of CO_2 that can be recovered through CCUS technologies is approximately 60% from the reformer output and up to an additional 30% from the furnace, for a total potential capture rate of 90%[cxi]. The hydrogen produced from steam-methane reforming with CCUS is referred to as blue hydrogen in the hydrogen color coding scheme.

Figure 39- Hydrogen Produced via Steam Methane Reforming with Carbon Capture



ELECTROLYSIS

In electrolysis, electricity is used to split water into hydrogen and oxygen in a unit called an electrolyzer. The three electrolyzer technologies with the highest current potential for commercial growth are alkaline, proton exchange membrane (PEM), and solid oxide electrolyzer cell (SOEC) electrolyzers. Further detail on these electrolyzer types is provided in Table 48. The electricity used to power electrolysis can originate from the grid or dedicated renewable or nuclear sources specifically designated to supply electricity to a specific electrolysis plant. Electrolysis powered by renewable or nuclear sources has the potential to achieve net zero GHG emissions. Electrolysis utilizing grid electricity will have emissions associated with the grid mix of the particular geography. The color of the resulting hydrogen in the hydrogen color coding scheme is determined by the electricity source used in the electrolysis process: Green refers to hydrogen produced from electrolyzers using only renewable electricity, yellow for hydrogen produced from electrolyzers using grid electricity, and pink for hydrogen produced from electrolyzers nuclear electricity.

Figure 40- Hydrogen Produced via Electrolysis

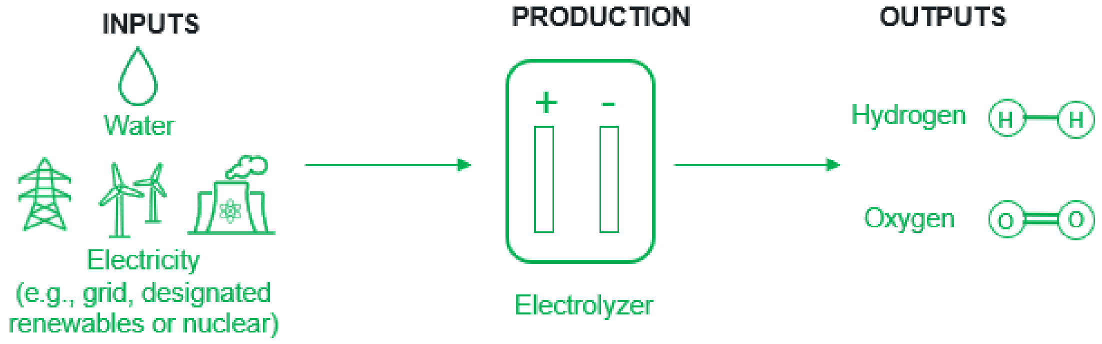


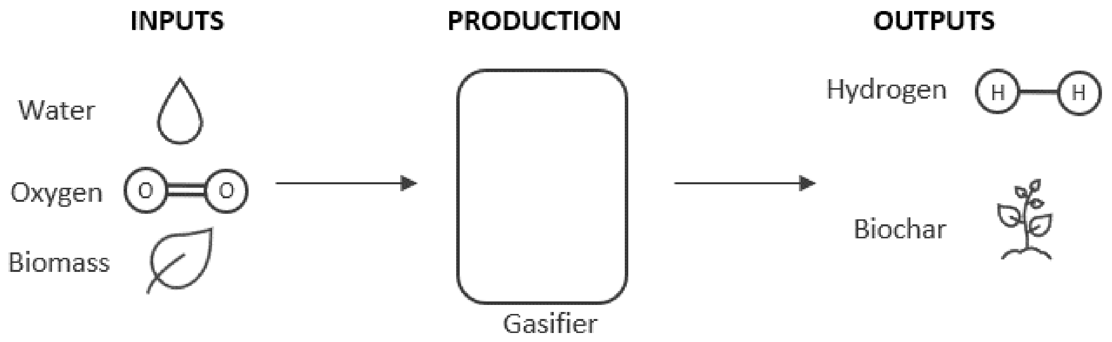
Table 48- Electrolyzer Technology Comparison

	Alkaline	Proton Exchange Membrane (PEM)	Solid Oxide Electrolyzer Cell (SOEC)
1. Maturity	Commercially viable (mature utilization in chlor-alkali and fertilizer industries)	Commercially viable (though low industry penetration)	Market demonstration phase
2. Scale of production	Optimal for large-scale hydrogen production (50 tons per day)	Large-scale hydrogen production (5 tons per day)	1 ton per day
3. Lifespan	Greatest lifespan	Similar lifespan to that of alkaline	Lifespan reduced because of high operating temperatures
4. Use of noble metals	Potential to minimize use of noble metals	Requires use of noble metals	Requires use of noble metals
5. Electrical system efficiency	73 - 75 %	65 - 67 %	Up to 99 % if external heat is provided
6. Compatibility with variable electricity	Requires stable electricity source	Optimal for variable renewable electricity sources	Potential compatibility with variable renewable energy sources
7. Cost	Lowest cost today	Almost as low cost as alkaline	Highest cost today, with anticipated future declines due to technological advancements

BIOMASS GASIFICATION

Biomass gasification produces hydrogen through the reaction and combustion of biomass with oxygen in a contained gasifier unit. This process produces hydrogen, CO_2, and biochar[6]. Though this process emits CO_2, it could achieve net-zero lifecycle emissions if the biomass used maintain an overall carbon balance. In other words, the carbon released is equivalent only to the carbon previously absorbed by the biogenic feedstock. Feedstock production, therefore, must not release CO_2 from carbon otherwise permanently stored. If the CO_2 product from this process is captured, utilized, and stored, gasification has the potential to be carbon negative. This process also requires heat, so to be a low or zero GHG emission process, the heat will need to be supplied by a low or zero GHG emission heat source, such as biomethane. There is not a consistent color used to describe hydrogen produced through biomass gasification.

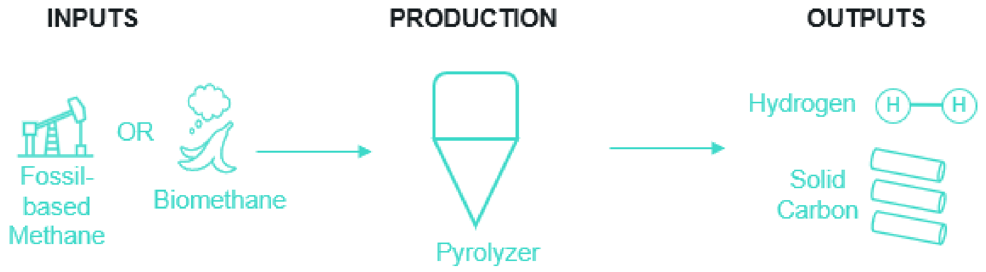
Figure 41- Hydrogen Produced via Biomass Gasification



METHANE PYROLYSIS

Methane pyrolysis is the production of hydrogen and solid carbon through the thermal decomposition of a methane source in a unit called a pyrolyzer. This process uses heat and the absence of oxygen to break down large molecules, methane, into smaller ones, such as hydrogen and carbon[3]. To be a low or zero GHG emission process, the heat will need to be supplied by a low or zero GHG emission heat source, such as biomethane. Given that this process uses methane as an input, there may be emissions associated with methane leakage during methane extraction, transport, and the production process. If the process uses biomethane, such as landfill gas, pyrolysis can achieve net-zero and even carbon negative because it takes CO_2 from the atmosphere and permanently stores it. Hydrogen produced through pyrolysis is turquoise in the hydrogen color coding scheme.

Figure 42- Hydrogen Produced via Methane Pyrolysis



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[6] Biochar is the charcoal remaining after the pyrolysis of biomass, commonly used in soil application to increase soil nutrients.

iii. Hydrogen Infrastructure

Hydrogen infrastructure is an important component of the hydrogen value chain that links hydrogen production with hydrogen use. When possible, it is often more cost efficient to produce hydrogen onsite directly where it is going to be used. Once the hydrogen is produced, it is stored until it is needed for an onsite hydrogen application, such as to provide electricity or heating.

HYDROGEN TRANSPORT

When onsite hydrogen production is not possible, hydrogen must be distributed to various end use locations. The optimal method of transporting hydrogen is dependent upon volume, distance, terrain, existing transport infrastructure, and end use. The most cost-effective transport methods will vary on a case-by-case basis. Generally, transport methods can be categorized into three groups that determine the infrastructure and equipment needed:

1. *Trucking:* When small volumes of hydrogen need to be transported short to medium distances, it usually makes sense to transport it via truck. Trucks outfitted to transport gaseous hydrogen optimize cost for the shortest distances below 250 miles. while trucks with the capacity to transport liquid hydrogen are optimal for distances greater than 250 miles [7]. While liquid trucking has a higher upfront capital cost than gaseous trucking, transport of hydrogen in liquid form is less expensive on a per kilogram basis for distances greater than 250 miles. Upon delivery, the hydrogen is often stored in a hydrogen storage tank.
2. *Pipelines:* When hydrogen needs to be transported in larger volumes (5 to 100 tonnes per day) for medium to long distances (up to 1,000 miles), pipelines are a good option. Pipelines provide economy of scale for transporting hydrogen. Existing natural gas pipelines may be repurposed to carry hydrogen if the material is compatible with hydrogen and the pipeline connections have been refitted to prevent the leakage of hydrogen, which is a smaller molecule than natural gas.
3. *Shipping:* For offsite hydrogen production, large end use volumes (greater than 100 tonnes per day), and distances greater than 1,000 miles, ship transport generally provides the lowest cost option where marine routes are available. Hydrogen may be transported in compressed form or chemically converted to a hydrogen carrier, such as ammonia, which is more optimal for marine handling and transport. Further information about hydrogen carriers is detailed next.

HYDROGEN CARRIERS

Hydrogen may be chemically converted to a hydrogen carrier, such as ammonia, in order to make transport or storage more cost effective. In gaseous form, hydrogen occupies relatively large volumes per unit of energy. Chemically converting hydrogen to a different chemical form for transport enables the hydrogen to be transported at smaller volumes per equivalent unit of energy. Though this chemical conversion process requires additional capital investment and energy, it can be financially optimal for operations with large transport distances and storage volumes.

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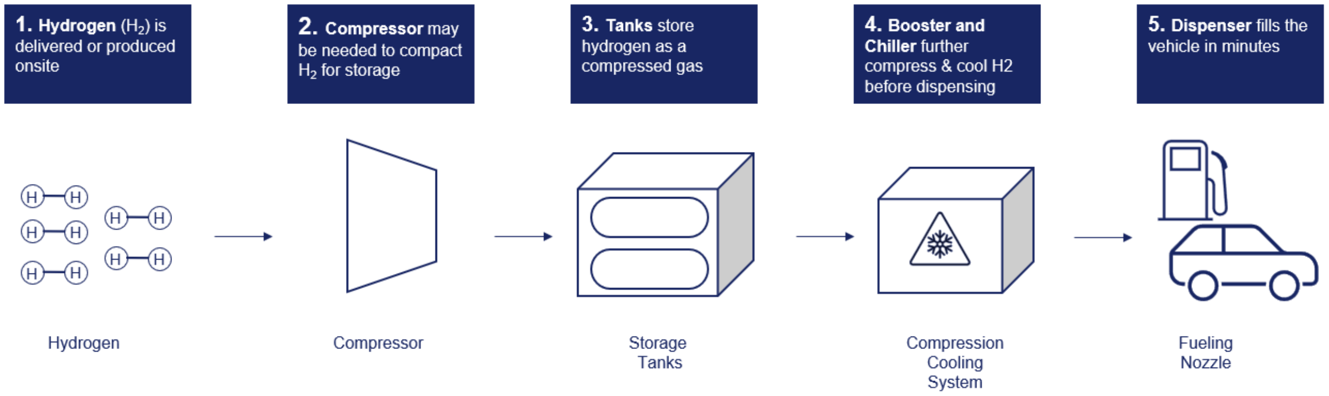
[7] Optimal transport methods for a specific distance and volume will vary based on the region. Projected optimal transport methods for a given distance and volume for Connecticut are noted in Figure 11.

HYDROGEN FUELING STATIONS

Hydrogen fueling stations are additional hydrogen infrastructure required specifically for transportation end uses. These stations, whether used to fill freight trucks, buses, passenger vehicles, or material handling equipment such as forklifts, resemble gasoline and diesel fueling stations. The primary difference is that the nozzle and storage equipment are designed to contain and safely distribute compressed hydrogen. Figure 43 provides a general overview of the fueling equipment and process.

Figure 43- Hydrogen Fueling Overview



B. Glossary

Table 49 - Glossary

Term	Definition
Byproduct	Secondary product derived from a production process, manufacturing or chemical reaction in addition to the primary product
Carbon capture, utilization, and storage (CCUS)	Process of capturing CO2 emissions and either using them to make products such as building materials (utilization) or permanently storing them (storage)
Carbon dioxide (CO_2)	A greenhouse gas produced through both natural processes and human activities that is contributing to climate change
Carbon dioxide equivalent (CO2e)	A metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential
Combustion	Chemical process in which a fuel reacts rapidly with oxygen to release energy
Contracts for differences	An agreement that stipulates when one party will pay the other party the difference between the current value of a product or asset and the value needed to incentivize investment in that product or asset
Electrification	The process of replacing technologies that use fossil fuels (coal, oil, gasoline, and natural gas) with technologies that use electricity as a source of energy
Electrolysis	Process that uses electricity to split water into hydrogen and oxygen
Electrolyzer	System that uses electricity to break water into hydrogen and oxygen in a process called electrolysis
Environmental Remediation	The removal of contaminants from water and soil
Feedstock	Raw material to supply or fuel a machine or industrial process
Fuel cell	Equipment that uses the chemical energy of hydrogen or other fuels to cleanly and efficiently produce electricity
Gasification	Process that converts organic or fossil-based carbonaceous materials at high temperatures in the presence of oxygen into synthetic gas, including but not limited to carbon monoxide, hydrogen, and CO2, and biochar
Global warming potential	A measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time relative to the emissions of 1 ton of CO2
Greenhouse Gas (GHG) Emissions	Compounds that trap heat or longwave radiation in the atmosphere
Grid Balancing	The act of ensuring that electricity consumption matches electricity production on an electrical grid at any moment
Hydrogen carrier	Molecules that hydrogen can be converted into for more efficient transport or storage
Levelized cost of hydrogen (LCOH)	The cost to produce, and when relevant, transport and store, a kilogram of hydrogen, evaluated over a 20-year period, taking into account all relevant discounted CAPEX, OPEX, and energy costs during that time period
Life cycle emissions	The aggregate quantity of greenhouse gas emissions associated with a specific material, from all stages of the materials life that have been included within the boundary as defined by the party at hand

Liquid Organic Hydrogen Carriers (LOHC)	A type of hydrogen carrier that can absorb and release hydrogen through chemical reactions
Low Carbon Fuel Standard (LCFS)	A policy that requires energy-related fuels to meet a certain GHG target within a specified jurisdiction and timeframe
Petroleum Refinery	An industrial manufacturing facility where crude oil is extracted and converted into more valuable goods, such as gasoline, jet fuel, and diesel
Pyrolysis	The thermal decomposition of materials at elevated temperatures in the absence of oxygen
Steam Methane Reforming	A process in which methane is heated with steam, usually with a catalyst, to produce a mixture of hydrogen and CO2
Sustainable Aviation Fuel (SAF)	A bio-based or synthetic fuel used to power aircraft that has similar properties to conventional fuel with a reduced carbon footprint
Technology Readiness Level (TRL)	A measure used by many entities to assess maturity of evolving technologies prior to incorporating that technology into a system
Total Cost of Ownership (TCO)	The total cost of ownership per unit of activity (e.g., mile traveled), evaluated over a 20-year time period, taking into account all relevant discounted CAPEX, OPEX, and energy costs during that time

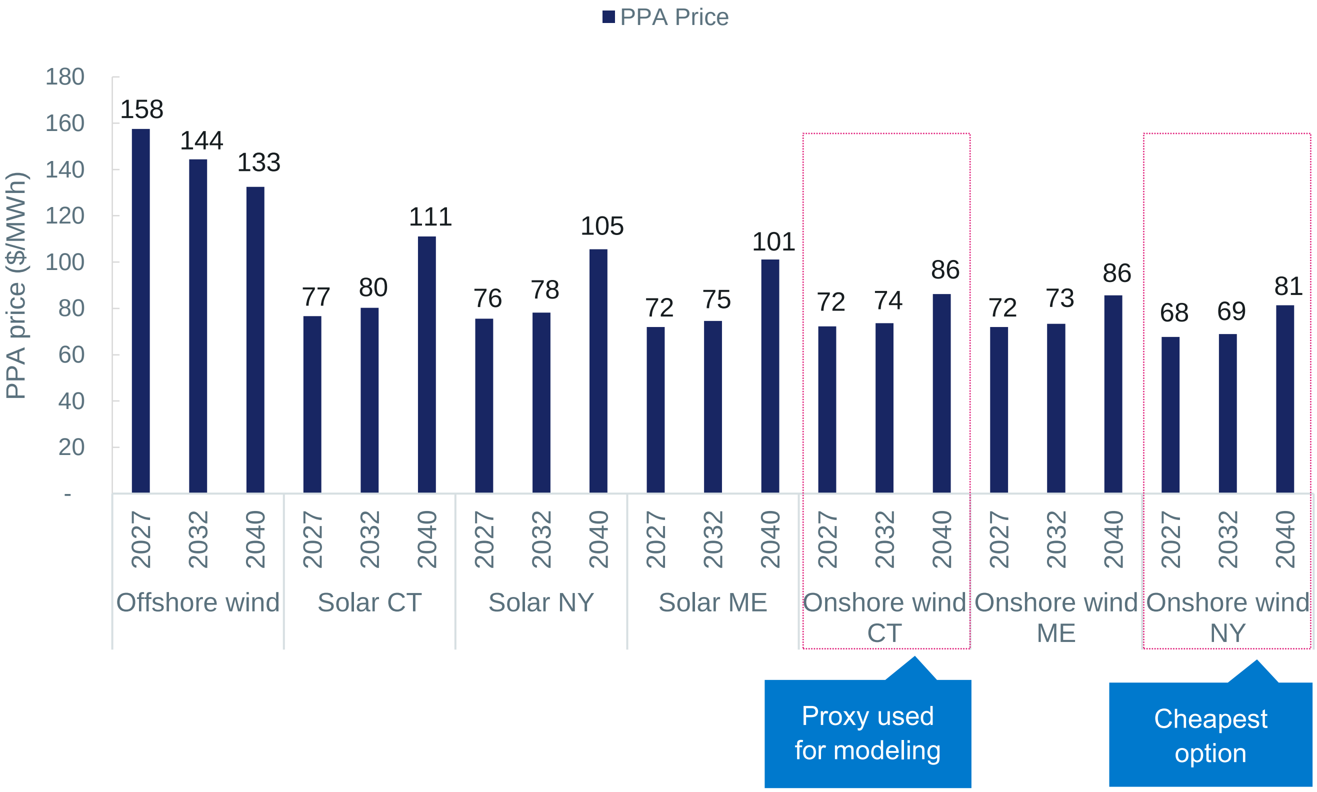
C. Methodology

i. Renewable Electricity Price Modeling

Renewable electricity PPA prices for solar PV, onshore wind, and offshore wind were forecasted for Connecticut, New York, and Maine and used as an input for the Levelized Cost of Hydrogen (LCOH) and Total Cost of Ownership (TCO) calculations for hydrogen end uses. For each electricity generation method, the generation equipment, electric infrastructure, engineering, design, construction, operations and maintenance, financing costs, developer overhead, developer margin, taxes and federal tax credits, and Open Access Transmission Tariffs were included. Solar PV and onshore wind also included cost of site control. All variables included expected variations over the three evaluated time periods of 2027, 2032, and 2040. For the federal tax credits, IRA renewable electricity credits are assumed to remain in place through 2040. PPA forecasts included a hybrid of physical and virtual PPA approaches, including a pricing model that considered developers' gross margin. Finally, high and low-price scenarios were calculated using Monte Carlo simulations.

Figure 44- Electricity PPA Prices by Generation Type and Regionshows how the costs modeled using this approach varied by state and generation method. As described in Section 2.A, onshore wind in Connecticut was selected as the proxy price for electricity to simplify the modeling, but a combination of generation methods would be used to power clean hydrogen production in Connecticut. The use of onshore wind as a modeling assumption is not a recommendation to pursue such a type of renewable energy source in the state.

Figure 44- Electricity PPA Prices by Generation Type and Region



The aim of the electricity modeling was to establish a justifiable, simple price devoid of speculations. A key uncertainty was the effect an unspecified mix of renewable electricity, utilized for hydrogen production, would have on the grid. This is because the integration of renewable electricity and hydrogen generation could either augment or reduce the grid's firming and balancing capabilities. The introduction of more renewables might pose challenges in balancing the grid due to their intermittent nature. Conversely, hydrogen production could offer an extra balancing mechanism if the plant's operations can be varied based on grid demand. Consequently, a hydrogen production facility powered by renewables would likely negotiate tailored rates with the local utility or PUC. In the absence of clarity on the directional impact these custom rates would have on firming, balancing, system capacity obligations, and local transportation costs, these costs were omitted from the analysis. While some renewable electricity price considerations are more pertinent to hydrogen production than to electric vehicle charging, the same renewable electricity pricing was applied across all models for consistency, to prevent any undue preference towards hydrogen. This approach is consistent with the approach used to calculate hydrogen production electricity prices in other studies, such as the U.S. DOE's National Clean Hydrogen Strategy and Roadmap, FCHEA's Roadmap to a US Hydrogen Economy, and Lazard's 2023 Levelized Cost of Energy+. The electricity rate used in the model does not reflect a target price, or energy supply strategy. It also does not suggest a policy recommendation to keep rates at that level or below to induce hydrogen production in the state of Connecticut. Market forces and other factors will determine the real, future rate that hydrogen producers pay for electricity.

ii. Hydrogen Production Techno-economic Analysis

For hydrogen production, the LCOH was obtained, considering the 45V tax credits, for three potential methods: methane pyrolysis, water electrolysis, and biomass gasification. The LCOH is the equivalent cost per kilogram of hydrogen that the project should be remunerated along its 20-year life cycle to obtain a project Net Present Value (NPV) equal to zero. For each production method, electricity prices, feedstock costs (water, renewable natural gas, and biomass), additional operational expenses, and components' costs were included. Variables included expected variations over the three evaluated time periods of 2027, 2032, and 2040, including anticipated technology improvements. To account for the potential economies of scale as the hydrogen economy evolves, for 2027, 2032, and 2040, the analysis considered 700, 4,000, and 6,000 kg per hour of production, respectively.

As a sensitivity on the LCOH, an analysis of the potential temporal matching requirement was added. This was executed through ENGIE Impact's internal optimizer Prosumer which minimizes the LCOH by adjusting equipment sizing variables such as hydrogen storage, electricity storage, electrolyzer size, and renewable electricity plant capacity, while adhering to specified temporality requirements as restrictions of this optimization for both monthly and hourly matching. The same general inputs are considered for both annual and hourly matching, with one exception: To reduce costs, hourly matching draws electricity from the grid for a small amount of hours each year, up to the carbon intensity limit of 0.45 kg CO2/ kg H2, ensuring it is still eligible for the 45 V production tax credit. The annual matching scenario, on the other hand, has a carbon intensity of zero, because it is able to match 100% of its annual renewable energy demand with PPAs that are additional to the existing renewable energy generation.

Finally, to compare the LCOH of hydrogen produced in CT with imported hydrogen, an internal high-level LCOH model from ENGIE Impact was utilized to obtain the LCOH for Texas, Utah, Nebraska, Vermont, and Virginia. Then, another internal model from ENGIE Impact was applied to estimate the transport cost from the different states to Connecticut, which varied depending on the state, with pipeline, trucking, and shipping options for its transport. For international imports, publicly available information[cxii] was used to obtain the LCOH and the same internal ENGIE Impact transport model was applied to estimate the cost of importing hydrogen to Connecticut, assuming maritime shipping as the transport method.

iii. Hydrogen Value Chain Infrastructure Techno-economic Analysis

In addition to the production cost, the LCOH also includes costs incurred when bringing the hydrogen molecules from the site of production to the end use location. To account for all the different steps of hydrogen transport and storage in between, ENGIE Impact utilized an internal model that assumes 40-bar storage at the site of production, five transport methods (pipeline, gaseous trucking, liquid trucking, train, and shipping), and when applicable, storage needed in between transport methods. Finally, different on-site storage systems (gaseous hydrogen, liquid hydrogen, and ammonia) are added based on what is most optimal for various end uses. When ammonia storage is used, the model includes the Haber-Bosch facilities and the ammonia cracker for the cases where ammonia is converted back to hydrogen.

iv. Hydrogen End Use Techno-economic Analysis

The third and last step of the techno-economic analysis consists of estimating the Total Cost of Ownership (TCO) for each end use. This financial estimate represents the complete cost of an asset through its entire life cycle. Therefore, the TCO accounts for the purchase price of an asset, or capital expenditure (CAPEX), plus the costs of operation (OPEX), representing the complete cost through its entire life cycle. For the CAPEX, more specifically, the analysis considered the initial investment cost, as well as reinvestments; only in the case of high-temperature heating is the CAPEX not included due to the case-by-case uncertainty. In relation to the OPEX, it is mainly wages. Finally, on the energy side, the analysis considered renewable electricity, e-methanol, e-ammonia, renewable natural gas, and hydrogen.

For this report, a 5% WACC was considered in all the end uses, and a 20-year project evaluation, with reinvestment if needed. With respect to federal incentives, the final TCO showed in the Affordability Lens section also includes the 45V tax credits, which go from $3/kg H2 until 2032 and then linearly decreases until 2041 to account for the declining proportion of hydrogen during that time period that is produced at facilities that would still be receiving the IRA credits.

v. Climate Energy Strategy Lens

Total addressable GHG emissions by end use

The total addressable GHG emissions for the majority of end uses were taken from the emissions associated with each end use in Connecticut's 2018 GHG inventory. A few end uses were calculated via alternative methods noted below:

- *Heavy-duty trucking:* Heavy-duty trucking emissions levels were calculated using the 2019 Freight Volume Summary data from TRANSEARCH noted in table 6.3 in Connecticut's Freight Plan Update published in December 2022, with a focus on trucks that go through the state of Connecticut.
- *Maritime:* This category includes bulk carriers, ferries, and tugboats. Since these must be evaluated separately instead of aggregating by maritime, different approaches were taken in each case. First, for bulk carriers, based on the total movement and type of goods, an average trip was estimated[cxiii], as well as a total fleet size of ships. Second, for the ferries, emissions were calculated based on the operation of the CT River Ferry (Chester - Hadlyme and Rocky Hill – Glastonbury), the Long Island Ferry (Bridgeport – Port Jefferson, and the three seasonal express. Finally, in the case of the tugboats, the number of tugboats and their operation was estimated based on the total goods moved in the main three ports, as well as a typical operation cycle for these ships.
- *Forklifts:* No detailed data was found for Connecticut forklift fleets, an estimation was carried out based on previous projects from ENGIE Impact, and the industry in the state.

Percent GHG emissions by end use

Percent GHG emissions reduction for each hydrogen end use were also calculated in multiple steps. First, the emissions associated with the end uses' fossil-based incumbent technology were calculated by using fossil fuel emissions factors from the EIA and multiplying by the standard efficiency of each activity (e.g., miles per gallon for heavy-duty trucking). Then, a similar calculation was performed for the hydrogen technology for two different carbon intensities: 2 kg CO2/kg of H2 (the upper limit of Connecticut's clean hydrogen definition), and for 0.45 kg CO2/ kg H2 (the upper end of the lowest carbon intensity tier for the 45V tax credit). Finally, the percent reduction in emissions was determined by calculating the emissions savings per unit of activity by swapping from the fossil-based incumbent technology to hydrogen, for each of the two hydrogen carbon intensity levels.

vi. Hydrogen Demand

Calculation of the total hydrogen demand was performed in three steps for each end use in each of the Base, High, and Low Hydrogen Scenarios. First, the total activity level for each end use was calculated (e.g., total miles per year in Connecticut). For most end uses, this activity level was calculated from the emissions associated with each activity from Connecticut's 2018 GHG inventory, with the exception of the three use cases noted in the emission section (heavy-duty trucking, maritime, and forklifts). Then, the activity level for each end use was multiplied by the volume of hydrogen needed for each activity level, yielding the maximum potential hydrogen demand for each end use. These coefficients were obtained from internal energy hydrogen models. Finally, the actual projected hydrogen demand was calculated by multiplying the potential maximum hydrogen demand for each end use by the anticipated hydrogen rate of adoption for each end use. As noted in the tables in Section 3.A:

Hydrogen Demand, the rate of adoption numbers were obtained from a mix of external sources, including the FCHEA US Hydrogen Roadmap, ATAG Waypoint 2050 Report, IRENA's Pathway to Decarbonize the Shipping Sector report, and internal ENGIE calculations.

vii. Total Capital Costs

The estimation of the total capital cost aimed to obtain the cumulative investment needed if the low-carbon hydrogen economy for CT develops as expected in the base case scenario. It was divided into three parts: renewable energy, hydrogen production, and end uses.

First, for the renewable energy cumulative investment, the total additional installed power per year was calculated based on the expected hydrogen demand curve. Then, the investment considered onshore wind energy, which also accounted for land, equipment, and energy transmission.

Second, the hydrogen adoption rate per end use results were used to estimate the expected size and investment for hydrogen production facilities. With this forecast of electrolyzers installed per year, the required investment is calculated following the year-by-year price decrease of electrolyzers and the constructed plants.

Finally, as the adoption rate per end use increases, so does the investment in related equipment needed through 2040. For instance, the investment in hydrogen trucks, and long-duration energy storage.

viii. Jobs Impact

Hydrogen jobs created

The first step in projecting the jobs created by hydrogen was to identify or calculate job multipliers for direct and indirect, production and infrastructure, and short-term and sustained jobs created per MW of hydrogen. In some cases, the jobs multipliers were pulled directly from external sources, such as the Economic Policy Institute. Job multipliers were also calculated by looking at jobs created from recent hydrogen production and pipeline projects, such as Monarch Energy's hydrogen project in Louisiana. Then the total projected hydrogen demand in MW for each time period in Connecticut was multiplied by the respective job multiplier to calculate the total projected short-term and sustained jobs that would be created in Connecticut from the scale up of hydrogen.

Fossil fuel jobs displaced

The first step in calculating the projected fossil fuel jobs displaced by hydrogen was to identify the volume of fossil fuels that could be displaced by hydrogen. These numbers were calculated by multiplying the current amount of petroleum and natural gas used for each end use by the hydrogen rate of adoption for each end use over each period. Next, we looked at the total petroleum and natural gas consumption in Connecticut and calculated the percentage of each fossil fuel type that would be displaced by hydrogen. Finally, we looked at the existing fossil fuel jobs noted in the 2022 US Energy & Employment Jobs Report for Connecticut, and calculated the projected jobs lost assuming that those jobs would be lost at the same percentages as fossil fuel would be reduced in Connecticut.

D. Overview of Previous Stakeholder Comments

In the context of the Comprehensive Energy Strategy (CES) process, on April 6, 2022, DEEP held a technical meeting seeking, among other things, stakeholders' input to inform a hydrogen strategy for Connecticut. DEEP received public comments during the meeting and through written comments submitted following the event. Through these comments, DEEP heard from a variety of stakeholders, including hydrogen-related industries in Connecticut such as fuel cell, electrolyzer, and transportation companies, regulated public utilities, public interest groups, and researchers.

Numerous stakeholders discussed hydrogen's potential to contribute to the state's energy, economic, and environmental goals. Most stakeholders identified environmental benefits as a reason to explore hydrogen, with potential caveats. From a climate perspective, many stakeholders noted hydrogen could help Connecticut better integrate and utilize renewable energy by providing long-duration energy storage of renewable electricity and dispatchable power for grid resiliency and reliability. The potential for hydrogen to help decarbonize sectors where electrification is infeasible was also valued by a variety of stakeholders. Some specific hydrogen end uses mentioned by stakeholders included using hydrogen to help decarbonize long-haul trucking, aviation, maritime shipping, and certain industries such as steel and ammonia production. Some stakeholders also supported using hydrogen in light- and medium-duty vehicles and residential and commercial buildings. However, other stakeholders opposed light- and medium-duty vehicle and residential and commercial building uses, arguing electrification would be more efficient. Some stakeholders also noted that hydrogen, if released into the air, is an indirect GHG with higher global warming potential than CO_2, and that lifecycle impacts from hydrogen production and leakage must be carefully quantified to understand its full climate impacts.

There was broad agreement to explore hydrogen produced from electrolysis of water, powered by renewable energy. Some stakeholders urged DEEP not to limit its focus to a particular production pathway or identified other pathways, such as electrolysis of water using nuclear energy or producing hydrogen from natural gas through steam-methane reformation, either with or without carbon capture and sequestration (CCS). Other stakeholders opposed producing hydrogen from fossil fuels and commented that, even with CCS, this would result in GHG emissions and be inconsistent with Connecticut's climate goals.

Several stakeholders commented on a future Connecticut hydrogen economy. Some argued that using hydrogen could be a cost-effective approach to decarbonizing existing energy systems. However, others noted that converting renewable electricity into hydrogen is less efficient and would be more expensive than using this electricity to power end uses directly, where feasible. Therefore, these stakeholders were skeptical that hydrogen would or should play a large role in decarbonization. Several stakeholders highlighted the potential economic benefits if Connecticut were to become a hydrogen innovation leader. These stakeholders voiced support for Connecticut's participation in the multistate regional hydrogen hub proposal to U.S. DOE and raised Connecticut's history of fuel cell innovation as a competitive advantage. Multiple stakeholders identified development of a skilled, technical workforce as necessary to pursue hydrogen, while noting that Connecticut has workers with many of the required skills, and that construction and deployment of hydrogen projects will be necessary to further develop this expertise. Other stakeholders emphasized the importance of supporting in-state manufacturers to ensure the economic benefits of a hydrogen economy accrue to Connecticut.

On the topic of factors impacting hydrogen's cost, some stakeholders stated that lower electricity costs will be needed to make hydrogen cost competitive. Others noted cost barriers in transporting and storing hydrogen and upgrading infrastructure and equipment to use hydrogen. Some argued that hydrogen's costs will come down through technological development and economies of scale and noted the importance of regulatory certainty and policy support through tax credits, carbon pricing, and other incentives, as well as support for research and development. Others urged caution and recommended a fuller accounting of costs before moving forward with plans to use hydrogen.

Stakeholders had differing perspectives on hydrogen infrastructure. Several noted that, to the extent existing natural gas pipelines and infrastructure are contemplated for hydrogen use, significant and costly upgrades or replacements would be required as hydrogen embrittles steel and iron pipes. Some raised concerns about the risk of hydrogen leaks from pipelines, the lack of suitable geologic formations for large-scale hydrogen storage, and the cost of replacing end use technologies, including appliances and equipment not designed to use hydrogen. Others viewed existing gas pipelines as assets that should be maintained and repurposed for hydrogen transportation and storage and argued that utilizing underground pipelines for hydrogen would provide cost and reliability benefits. Some stakeholders called for more research on the feasibility of using hydrogen in existing infrastructure. To the extent fossil fuel infrastructure is utilized for hydrogen, some stakeholders expressed concerns that this could also result in extending the use of fossil fuels and urged that there be clear and enforceable commitments to transition this infrastructure away from fossil fuels to fully renewable hydrogen.

In addition to climate impacts, stakeholders commented on the potential air quality impacts of using hydrogen. Some stakeholders argued for deploying hydrogen fuel cells, which emit little to no end use air pollution as alternatives to diesel generators and engines to improve local air quality. If hydrogen is used as a combustion fuel, however, some stakeholders raised concerns that air quality could be reduced as hydrogen combustion can produce NOx at higher levels than burning natural gas. Some stakeholders also cited water availability as another important consideration for hydrogen.

From an environmental justice perspective, some stakeholders argued hydrogen use and technologies could help reduce air pollution and GHG emissions in communities, provide jobs and economic development, and improve energy affordability and local grid resiliency. Other stakeholders expressed concerns about the potential siting of hydrogen infrastructure in communities that are already disproportionately burdened by industrial facilities and noted that, depending on the method of hydrogen production utilized, environmental burdens could increase in affected communities.[cxiv]

Several stakeholders commented on safety. Some raised concerns about hydrogen's high combustibility and explosion risks. Others pointed to existing safe uses of hydrogen, such as in fuel cell powered vehicles in New England. Some stakeholders argued that hydrogen is non-toxic, nonpoisonous, and environmentally benign; and downplayed combustion risks, including by noting that hydrogen gas dissipates quickly if released. Some stakeholders supporting wider hydrogen use argued for more public education of its safety benefits and pointed to existing safety codes and standards. Others commented that additional codes and standards, permitting requirements, training requirements, and operator qualifications are needed and urged DEEP to work closely with federal regulators and others on these issues.

All comments provided in the technical meeting or submitted in written form were considered for the development of this roadmap.

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