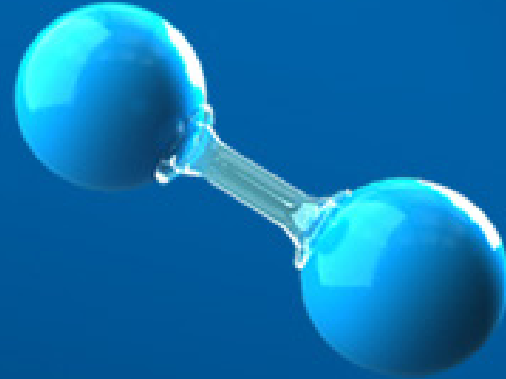


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# The Viability of Implementing Hydrogen in Massachusetts

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## Energy Storage

With the planned installments and reliance on gigawatts of new renewable power capacity (e.g., offshore wind and solar), there will be opportunities to store excess energy instead of curtailing power generation systems and a need for energy storage to respond to peak demands associated with renewable energy intermittency. **For large-scale reliance on renewable energy, energy storage must be integrated to balance and create a resilient electrical grid when either a lack or overabundance of renewable energy exists.**

Presently, lithium-ion batteries have been introduced in some utility-scale storage systems. Although they are appropriate in providing a cost-effective short-duration energy storage solution (typically a few hours), when considered for long-duration energy storage, lithium-ion batteries are generally not cost-effective due to their relatively short lifespan. When these batteries are used for stationary energy storage and need to last several decades, their state of health will decrease nonlinearly (including capacity fade and increase in internal resistance) [Kendall, Ambrose, 2020; Bazant, et al., 2021]. Another drawback to solely relying on lithium-ion batteries is the limited global resource of lithium. Lithium is a critical material and is expected to be subject to supply shortages in the future, even considering extensive recycling operations. It is estimated that the earth has approximately 26 million tons of lithium reserves. Even with an optimistic higher assessment that assumes potential extractable mineral deposits, there is an estimated 51 million tons of lithium reserves. The current demand for lithium is 0.16 million tons per year and by 2030, the annual demand for new lithium is expected to be 2 million tons per year [BloomerNEF; Greim, et al., 2020]. According to the International Energy Agency, in order to achieve the Paris climate goals, by 2040 lithium will need to be consumed at a rate 42 times higher than current levels [Bader, 2021]. **To electrify vehicles, electronics, and leverage energy storage in the electrical grid with the best policy scenario and recycling efforts, the balance of lithium demand and supply could extend only to about 2050, and the market will then begin to experience a large deficit that lasts for the remaining half of the century [Greim, et al., 2020]. Therefore, solely relying on lithium-ion batteries for energy storage is generally seen as not a viable long-term option.**

**The use of hydrogen can be an effective method for storing large amounts of energy for long periods of time (e.g., days or weeks) either as a gas, liquid, or in the form of ammonia. When coupled with fuel cells or gas turbine engines, hydrogen energy storage systems**

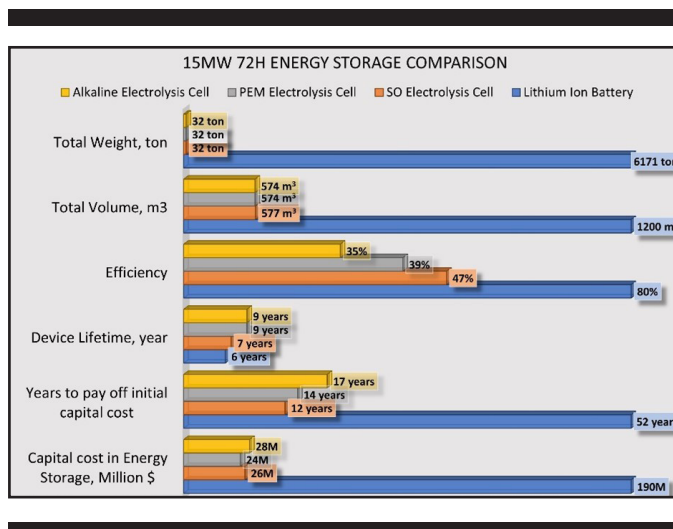


FIGURE 2 Techno-Economic Analysis performed at UMass Lowell comparing lithium-ion battery energy storage to a proposed hydrogen storage approach for a 15 MW turbine and a 3 day energy storage solution.

**can be used to provide a reliable backup energy source to address intermittency and ensure the energy grid is resilient to disruption.** Based on a preliminary techno-economic analysis conducted at UMass Lowell, which compared energy storage using lithium-ion batteries to a hydrogen storage/fuel cell system, the results indicate that for long-duration energy storage, hydrogen is more viable in terms of weight (1/193 times), volume (1/2 times), lifetime (3 times), and capital cost (1/7 times) than lithium-ion batteries (see Figure 2). However, some hydrogen production challenges need to be overcome due to the high costs of electrolyzers. Electrolyzer and fuel cell stack costs are still high due to limited production capability, small market share, and strict policy codes related to hydrogen generation and power-delivery devices. Furthermore, hydrogen storage and delivery capability with the existing infrastructure have not been demonstrated on a larger scale. If solutions to these challenges have been met, then hydrogen for energy storage will be able to meet cost targets and be cost competitive in the market. The overall near-term targets that have been set out by DOE are \$2/kg for hydrogen production and \$2/kg for delivery and dispensing for transportation applications [Satyapal, 2021]. Additional research needs to be performed in the following areas to decrease the cost and expand the hydrogen energy storage market: (1) technologies to reduce cost as well as to improve performance and reliability of fuel cell stacks and of storage and delivery methods; (2) harmonize codes and standards to address safety concerns; and (3) establish and safeguard a global supply chain and market, as well as workforce development.

## Thermal Heating

The thermal heating sector includes all home and commercial business, excluding agricultural and industrial activities. Implementing hydrogen into the thermal heating sector can provide opportunities to complement electrification by meeting energy demands during peak periods and periods of intermittent renewable energy production, thereby increasing resiliency. Currently, 52.3% of Massachusetts homeowners use a natural gas system for heating [EIA, 2021] and to meet the Commonwealth's zero-emission goals, most if not all of these natural gas homeowners would need to switch to either an all-electric system (e.g., heat pumps and resistive heating), decarbonized gas, a network geothermal system, or apply some other possible new technology such as carbon capture at a customer site. This switch will be costly and cause pushback by consumers especially for the sector of the population who are economically disadvantaged. Gas companies would also need to either repurpose or abandon the existing pipeline infrastructure. However, if increasing percentages of natural gas can be displaced by hydrogen, end-users could potentially keep their existing appliances (with some modifications or retrofits depending on the blend fraction) while also enabling the state to meet its zero-emission goal.

There are challenges with hydrogen implementation for the thermal heating sector that do need to be overcome in order to be commercially mature. A wholesale shift to change to a 100% pure hydrogen system, would require a significant investment in infrastructure and technology. A useful analogy is to think about gasoline and Diesel fuel. A vehicle operator cannot just simply put gasoline in a Diesel engine, or put Diesel in a gasoline vehicle. While they are both "fuels", their properties are different and so the hardware/technology must be designed appropriately to take advantage of the unique properties. The same can be said for hydrogen versus natural gas. While they are both fuels, they are not the same, and thus cannot be treated the same. However, much of the existing research on residential and industrial appliances has shown that low blend levels of hydrogen (i.e., less than 20%) can be tolerated without a significant change in performance. **Because hydrogen has a lower volumetric energy density than methane, volumetric blending of hydrogen with methane does not provide a linear reduction of carbon emissions per unit energy. For example, if methane is**

**blended with hydrogen at 5%, 20%, or 75% by volume, the carbon emission reductions per unit energy of the blended gas will be approximately 1.5%, 6%, and 50%, respectively [Goldmeer, 2019] (see Figure 3).**

Another potential challenge with using hydrogen in the thermal heating sector is hydrogen embrittlement of cast iron pipes and a lack of information and research done on how high blends and pure hydrogen in a

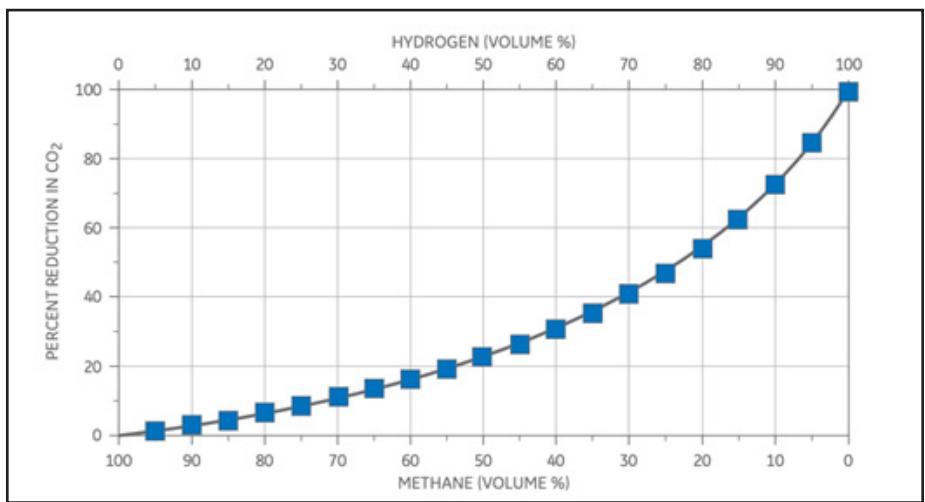


FIGURE 3 CO<sub>2</sub> Reduction with Respect to Hydrogen and Methane Blend Percentage [Goldmeer, 2019]

natural gas system will affect the end-user's appliances. Massachusetts has approximately 21,000 miles of main pipelines used for the transportation of natural gas from meter stations throughout the distribution system [Mass.gov, 2021]. The materials for main pipelines in Massachusetts vary depending on location and the distribution company and are made of either cast iron, steel, or a polyethylene plastic. There are approximately 7,928 miles of steel pipelines, 11,016 miles of plastic pipelines, and 2,809 miles of cast iron pipelines.

Depending on the pipeline's material, using hydrogen in either a pure form or a blend may cause embrittlement in pipelines. Polyethylene and lower-strength thicker wall steel pipelines are most compatible with hydrogen and have shown to be successful in large-scale pilot projects as well as with low blend ratios. Other forms of steel pipelines are still being studied in national laboratories and individual companies. Cast iron (commonly found in distribution systems in Massachusetts and the Northeast) has been shown to be unsuitable for hydrogen [Blanton, et al. 2021].

## Industrial Processes

Once the blended hydrogen is delivered to the end-user appliances, functionality will vary depending on the blend ratio. Research done by HyDeploy has shown that a 20% blend by volume of hydrogen in a natural gas system has worked in city-wide pilot projects and residential appliances can function effectively up to a 28% blend of hydrogen without issue [HyDeploy, 2021a]. However, this project is the largest hydrogen blending project to date and little to no research has been done on larger ratio blends of hydrogen. To ensure the safety of the end-user and their appliances, more testing must be done to understand the effects of blending higher percentages of hydrogen in the natural gas network as well as the impact on residential appliances (i.e., stoves, furnaces, and hot water heaters) (see Figure 4).

**For the hydrogen thermal heating sector to be successful, replacement of old and insufficient pipelines for hydrogen blending needs to be performed, more research needs to be done on higher blend ratios of hydrogen, and appliances may need to be redesigned or retrofitted to operate on hydrogen-natural gas blends or pure hydrogen.** When a pipeline becomes old or damaged and needs to be replaced, it will be more cost-effective to replace the old pipeline with a hydrogen compatible pipeline made of low strength carbon steel or polyethylene.

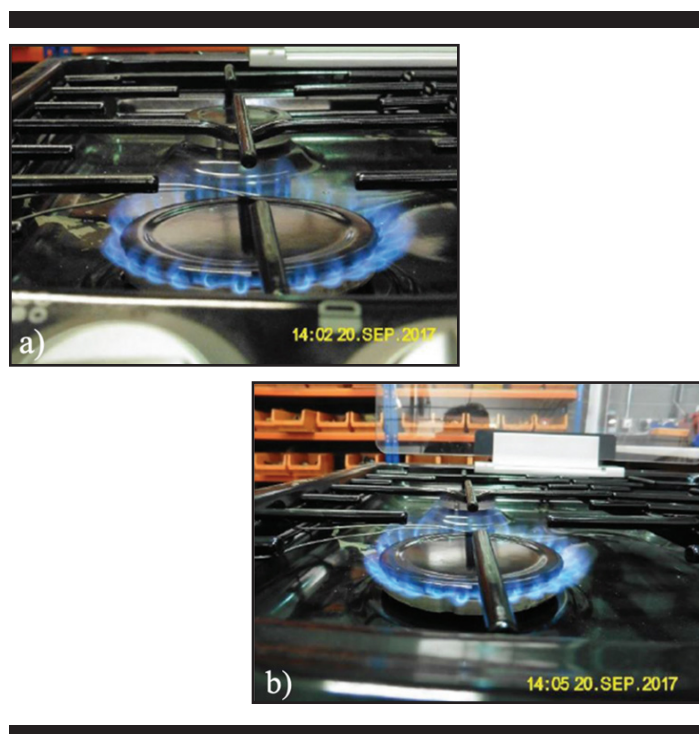


FIGURE 4 a) 100% Methane Flame; b) 28.4% Hydrogen Blend Flame [Issaac, 2019]



FIGURE 5 Hydrogen Based Steel Manufacturing [Collins, 2020]

Hydrogen for industrial processes provides opportunities for decarbonizing industries when a large amount of heat is needed. One example is steel manufacturing that would otherwise be hard to completely electrify (see Figure 5). Due to the processes used today to extract steel from iron ore, electricity cannot be used, instead, hydrogen is more viable as a replacement for coke (a derivative of coal) in the gasification processes used in industrial manufacturing. Using hydrogen in steel production only produces 0.056 tons of carbon dioxide for every ton of iron produced and represents 2.8% of the carbon emissions when compared to using coke [Vogl, et al., 2018].

The primary challenges for industrial processing (requiring heat generation) to replace fossil fuels (coal, oil, natural gas) are the capital cost required to convert existing equipment as well as the cost of the fuel used in the manufacturing process. **Currently, green hydrogen is more expensive for a given amount of energy compared to fossil fuels and there are no significant policies or incentives motivating companies to transition away from using fossil fuels.** For example, carbon credits can be implemented to incentivize low or no carbon-emitting industrial processes and help make hydrogen fuel for industrial methods cost competitive [Vogl, et al., 2018]. At the federal level there is a bill that has been introduced (not passed), the Clean H<sub>2</sub> Production Act, that would create production tax credits and investment tax credits for hydrogen [Congress.gov, 2021]

## Transportation

The transportation sector generates the largest share of greenhouse gas emissions within Massachusetts and represents a sizable opportunity for hydrogen utilization through fuel cell electric powertrains and traditional internal combustion engines. The transportation sector is composed of different applications including passenger vehicles, trucks, ships, and airplanes. Opportunities that hydrogen can bring to the transportation sector include fast refueling compared to battery electric vehicles (BEVs), zero nitrogen oxides (NOx) emissions (if used in fuel cell vehicles), a long-range driving alternative to BEVs, longer storage duration, and avoidance of CO2 emissions. Due to hydrogen’s high energy density, it allows for more energy to be stored per kilogram than other energy storage methods, including electric batteries.

The challenges in the transportation sector that hinder the adoption of hydrogen are the lack of infrastructure for refueling stations in Massachusetts and regulations that restrict the operation of hydrogen vehicles on some roadways (particularly tunnels). There are currently zero operating public hydrogen refueling stations and only two private hydrogen refueling stations in Massachusetts. When compared to electric charging stations, there is a drastic difference as significant expansion has been made in the last decade and there are 4,090 public and 299 private electric charging stations in Massachusetts [AFDC, 2021] (see Figure 6). Currently, hydrogen fuel purchases for new automobiles are subsidized by the auto manufacturers (e.g., Toyota Motor Corp.) by providing free hydrogen fill-ups, up to \$15,000 for new automobile purchases. The limited network of hydrogen fueling

stations in Massachusetts hinders the driving range for hydrogen-powered vehicles, preventing market penetration and causing relatively-high prices due to a lack of economy of scale.

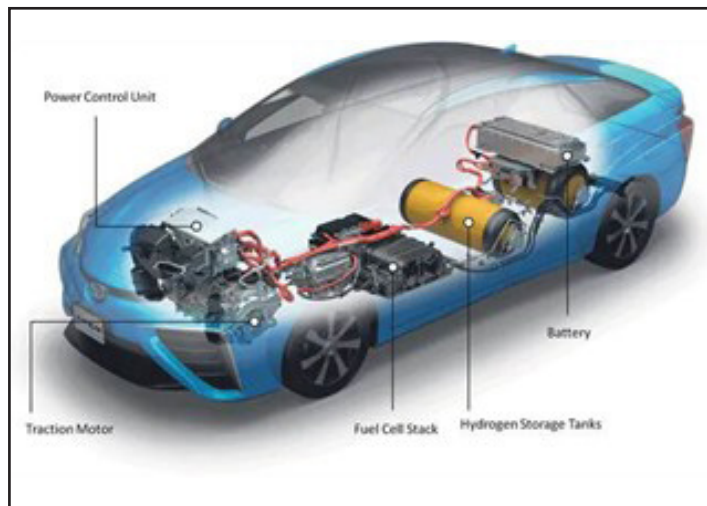


FIGURE 7 Internal Working of a Typical Fuel Cell Vehicle [Spiegel, 2019]

A convincing body of evidence in both California and internationally has revealed that hydrogen-based vehicles can be operated safely with cost competitiveness compared to gasoline or other fuels. Of the 11,674 hydrogen-powered automobiles operating in California, there have been no significant issues with fires for vehicles involved in accidents [CFCP, 2021].



FIGURE 6 Commercially Available Hydrogen Powered Automobil [Gardner, 2021]

In cold weather environments, as in Massachusetts’ winters, the driving range for battery electric vehicles is reduced. Several studies have reported that the average driving range for battery electric vehicles decreases by 41% depending on the temperature and driving conditions [Olsen, 2019; AAA, 2019; Delos Reyes, et al., 2016]. A Norwegian study tested common battery electric vehicles and their driving range in cold climates and found that there was an average decrease of 18.5% in driving range and vehicles took between 27 and 60 minutes to achieve an 80% charge under rapid charging conditions [Veihejelp, 2020]. In contrast, a hydrogen automobile can be refueled in approximately 3 minutes and its

driving range is not greatly affected by cold temperature operation (see Figure 7).

For a mid-sized city with 100,000 parking spaces and an average cost of \$1,200 per electric charger, the cost to electrify would be approximately \$120 million dollars, not including the wiring infrastructure cost required for electrical transmission. **It is not likely feasible for the vehicle transportation sector to be carbon neutral by relying solely on electric vehicles that utilize chemical batteries because of (1) the technical limitations of lithium-ion batteries operating in cold environments, (2) the inability for all drivers to have vehicles connected to charging stations at their homes throughout the night, and (3) a lack of suitability of using batteries for the trucking, shipping, and aviation sectors.** The path forward for increasing hydrogen in the transportation sector would be to increase the number of hydrogen fueling stations available to the public and address policies that hinder hydrogen transportation from further developing, such as restrictions for compressed hydrogen-powered vehicles traveling in tunnels in Massachusetts.

## Safety

Hydrogen as a fuel source and form of energy storage has brought up concerns with the public whether hydrogen is safe to use. This misconception has been perpetuated ever since the Hindenburg disaster in 1937. **Today the U.S. has 1,600 miles of existing hydrogen pipeline used in the Gulf Coast that has a track record of safety commensurate if not better than natural gas. Every year hydrogen is safely transported through these hydrogen pipelines to be used in petroleum refineries and chemical plants.**

Like many gasses, hydrogen is a colorless and odorless gas making it difficult to detect if a leak has occurred. Direct coloring agents may not be possible to add to hydrogen, but odorants can be added to provide a smell for hydrogen [HyDeploy, 2021b]. Sensors can also be installed to allow for fast and efficient detection of leaks without having to worry about seeing or smelling hydrogen. Other safety concerns regarding hydrogen include the wide ignition range of air concentrations from 4-74% [Carcassi, Fineschi, 2005] and the low energy ignition required

(0.019 mJ) [Kumamoto, et al., 2011] making hydrogen more likely to ignite in a wider range of scenarios than other combustible gases (e.g., natural gas). When stored in tanks or equipment, hydrogen is a safe fuel source and cannot be combusted unless there is a failure in the storage system. Safety codes and standards are put into place to minimize safety concerns and ensure the proper handling of hydrogen. Testing methods are also used to ensure the rigidity and verify the lifespan of these storage methods.

Testing has also been done on hydrogen igniting in enclosed spaces such as tunnels and it was found that no additional risk existed when compared to fuels like gasoline [LaFleur, et al., 2017]. For example, for a typical automobile, the energy available for combustion (~13 gallons of gasoline) is approximately 3 times higher than for a hydrogen vehicle (~4k kg of hydrogen). If a hydrogen fuel leak were to occur resulting from a crash, the hydrogen would disperse upward rapidly as opposed to gasoline that wets the vehicle or pavement and does not disperse quickly in an accident.

Emissions of NOx is a safety concern with the combustion of hydrogen because it is a byproduct of the combustion process in air. Combustion of hydrogen blended with natural gas increases NOx emissions by 92.81% for a 25% blend and upwards of 360% for a 75% blend [Cellek, Pinarbasi, 2018]. However, it is important to note that NOx emissions can be controlled and mitigated using certain techniques and modifications (e.g., by using a lean or lower fuel-to-air ratio). NOx is generated through combustion and the quantity of NOx is dependent on the flame temperature; by reducing the flame temperature, NOx emissions can be reduced [Menzies, 2019]. The flame temperature can be decreased by slowing down the rate of the fuel and air mixture. This leads to a lower flame temperature, therefore a reduction of NOx, and keeping the heat from the combustion process radiant, so the end-user does not experience any change when using the appliance [Menzies, 2019]. Water injection can also be used to reduce the hydrogen flame temperature and thereby reduce NOx for combustion in air. Other additions such as catalytic converters can be added to some appliances or furnaces to aid in the removal of NOx. European manufacturers have already started working on using these techniques and modifications and have found success in producing zero to low NOx emissions residential appliances [Sadler, et al., 2017].

## Greenhouse Gas Emissions

Gases that are responsible for trapping heat in the atmosphere are referred to as greenhouse gases (GHG). There are two primary concerns regarding the use of hydrogen and its effect on climate neutrality. The *first* is that NO<sub>x</sub> is generated during combustion of hydrogen and has a Global Warming Potential (GWP) 265–298 times that of CO<sub>2</sub> for a 100-year timescale and represents about 7% of the total greenhouse gas emissions. For reference the GWP of methane is 28–36 over 100 years [EPA, 2021]. However, a majority of NO<sub>x</sub> emission in the U.S. comes from agriculture (75%) and only about 5% comes from stationary combustion [Menzies, 2019] and can be mitigated by the emission control strategies previously mentioned. It's important to note that with a hydrogen-based system, carbon monoxide (CO) emission will also be avoided. This is very important as historically trade-offs are typically made in designing combustion systems for hydrocarbons, whereas trying to mitigate CO usually results in more NO<sub>x</sub>. But, if CO is not a concern, then there are multiple solutions that can be utilized to reduce NO<sub>x</sub>.

Another very important point is that NO<sub>x</sub> is a “catch-all” term that usually encompasses NO, NO<sub>2</sub>, and N<sub>2</sub>O when talking about combustion. The majority of emissions during hydrogen combustion are NO and NO<sub>2</sub>, not N<sub>2</sub>O, which is the worst NO<sub>x</sub> in terms of GWP. The combustion of hydrogen will raise NO<sub>x</sub> emissions by 20-40% compared to methane. However, if one compares the NO<sub>x</sub> emissions during the stationary combustion of methane, one can see that the effect of N<sub>2</sub>O is insignificant. Greenhouse gas emissions are reported in units of carbon dioxide equivalent (CO<sub>2</sub>e) by multiplying by their GWP by their emission factors [EPA, 2018]. During the combustion of natural gas, the CO<sub>2</sub>e for CO<sub>2</sub> is 53.06 kg CO<sub>2</sub>/mmBTU while the CO<sub>2</sub>e for N<sub>2</sub>O is 0.0298 kg N<sub>2</sub>O/mmBTU. This reveals that the resulting carbon dioxide emission has approximately 1780 times stronger effect on climate than the N<sub>2</sub>O gas emission for stationary combustion of natural gas. According to the reference [Thompson Academy, 2021], “Nitrous oxide (N<sub>2</sub>O) gas should not be confused with nitric oxide (NO) or nitrogen dioxide (NO<sub>2</sub>). Neither nitric oxide nor nitrogen dioxide are greenhouse gases, although they are important in the process of creation of tropospheric ozone (O<sub>3</sub>) which is a greenhouse gas.” The nitrogen oxides (NO + NO<sub>2</sub>) do not directly affect Earth's radiative balance, but they accelerate the generation of a direct GHG – tropospheric ozone. However, the impact on climate is difficult to directly quantify [Dentener, et al., 2001]. Lastly, it is important to mention **NO<sub>x</sub> is only generated in combustion processes when fuels (like hydrogen and natural gas) are burned in the presence of air. However, for applications that use a direct hydrogen**

**fuel cell (e.g., in automobiles and electricity generation), the only byproducts are water, heat, and electrical energy with zero NO<sub>x</sub> emissions.**

The *second* concern is that hydrogen itself (GWP of 5.8 over a 100-year timescale) is an indirect greenhouse gas that reacts in the atmosphere with tropospheric hydroxyl (OH) radicals and disrupts the distribution of methane in the ozone and thereby cause an increase in global warming. The release of hydrogen prolongs methane's atmospheric residence time, increasing its accumulation and greenhouse gas impact [Derwent, et al., 2006]. According to one study by Derwent et al., if a global hydrogen economy replaced the current fossil fuel-based energy system and exhibited a leakage rate of 1% or 10%, then it would decrease the climate impact to 0.6% or 6% of the current fossil fuel based system, respectively. Another more recent literature review on the atmospheric impacts of hydrogen from heating found that the most likely outcome is that hydrogen has a greenhouse gas effect that is small but not zero, and the global atmospheric impacts are likely to be small [Derwent, 2018]. Within the existing body of literature presented, there is significant uncertainty and additional research on this topic should be conducted. These findings emphasize the importance to ensure that leaks in hydrogen production, transportation, and utilization are minimized.

## Pipeline Transportation

Pipelines are the most cost-effective way to transport hydrogen compared to truck or rail. Although technical challenges remain on blending hydrogen with methane, solutions are being studied to identify how to increase the blending ratio while using the existing pipeline infrastructure [Melaina, et al. 2013]. Hydrogen has approximately one-third the heat value per unit volume compared to methane and so for the same pressure level, higher volumes of hydrogen need to be transported to deliver an equivalent amount of useable energy. This would require higher compression horsepower and will result in some additional energy losses compared to methane. The metering equipment used in gas distribution pipelines would also likely need modification based on the blend ratios [Blanton, et al. 2021].

Gas emissions via leaks in pipelines and other distribution equipment are also important when assessing the GHG



## Synthetic Fuels

emissions of the carrier fuel, whether it is methane or hydrogen [Abel, 2021]. Leaks are emitted via permeation through the pipe wall or through joints, fittings, and threads. For steel and ductile iron pipes, leakage mainly occurs through threads or mechanical joints and the volume leakage rate for hydrogen is about a factor of three higher than that for natural gas. For plastic pipes, permeation accounts for the majority of gas losses and are estimated to be about 4 to 5 times faster than for methane [Melaina, et al. 2013]. However, the leak rate depends on the blend percentage, pressure, and other factors. For example, in one study of a Dutch pipeline system, the experimentally estimated gas leakage rate was 0.0005% with a 17% hydrogen blend and considered to be insignificant [Haines, et al., 2003]. Because hydrogen is a smaller molecule than methane, hydrogen was thought to permeate through plastic pipelines more readily than methane, however, recent research has shown those leak rates are similar. Additionally, an application of a copper-based epoxy to thinly coat the steel pipe has been shown to successfully contain all hydrogen gas blends, and threaded pipe fittings to prevent hydrogen leaks [Mejia, et al., 2020]. Another study calculated that the yearly loss of hydrogen by leakage through polyethylene pipelines amount to approximately 0.0005–0.001 percent of the total transported volume [Klopffer, et al., 2015; Wassenaar, Micic, 2020].

One of the recommendations of a study performed by the Columbia University – Center on Global Energy Policy was to change the regulations on methane leak detection and repair the existing pipeline to be as low emission as possible, as well as accelerate the pace of cast-iron pipeline replacement [Blanton, et al. 2021]. These recommendations and others within their study are applicable to the Commonwealth of Massachusetts.



FIGURE 8 Example of a Synthetic Fuel [Morris, 2021]

Synthetic fuels are hydrocarbon fuels that are produced by chemically combining hydrogen with carbon sources such as CO<sub>2</sub> or biomass. Synthetic fuels can be created to emulate common fuels such as gasoline, diesel, methane, and kerosene (see Figure 8). The opportunities of using synthetic fuels over regular fuels is the use of CO<sub>2</sub> (e.g., from atmospheric sequestration) in the manufacturing process and its compatibility with existing distribution systems, fueling stations, and conversion technologies without significant modifications to existing infrastructure or equipment. By using CO<sub>2</sub> to produce synthetic fuels, it prevents additional CO<sub>2</sub> emissions in the atmosphere and helps in meeting net-zero emissions goals. For example, renewable or synthetic natural gas can be created by combining waste CO<sub>2</sub> from anaerobic digesters or power plants in MA with green hydrogen in a process referred to as methanation [Tsiotsias, et al., 2020]. Synthetic fuels can also be used in already existing refueling stations and combustion engines, which allow for a cost-effective transition to this carbon-neutral fuel.

Massachusetts currently lacks existing infrastructure dedicated to producing synthetic fuels and the green hydrogen necessary to make these fuels carbon neutral. The processing facilities to produce synthetic fuels are currently expensive and there are only a few test plants in operation. Massachusetts currently has no test plants for synthetic fuels or a large-scale infrastructure of green hydrogen to produce synthetic fuels. Massachusetts is currently not a leader in the production of conventional fossil fuels. However, in the future, with an established large offshore wind resource, the low cost generated electricity could potentially position the Commonwealth to be an early mover or leader in production of economically viable synthetic fuels.

The path forward for Massachusetts to produce synthetic fuels would need to include more research to be done on the production of synthetic fuels as well as the development of a synthetic fuel infrastructure and market. **Once more testing facilities have shown the benefits and challenges of synthetic fuels, then Massachusetts will be able to better assess if a synthetic fuel infrastructure would be beneficial for the Massachusetts economy.** Before an economically viable carbon-neutral synthetic fuel infrastructure is developed, a large-scale green hydrogen facility would first need to be created.

## Biomass: Including Bio-oil and Bio-gas

Biomass, including bio-oil and bio-gas can be used in steam reforming and water-gas shift processes to produce hydrogen. The opportunity with using biomass as a feedstock for hydrogen production is that biomass waste products are an available resource and can be used to sequester carbon dioxide from the atmosphere. It is estimated that up to 1 billion dry tons of sustainable biomass is available for energy generation use annually, which amounts to approximately 13-14 quadrillion Btu/year (in 2030) [DOE, 2021]. Biomass can also lead to an offset in carbon dioxide emissions because of the consumption of carbon dioxide in the production process of biomass (see Figure 9).

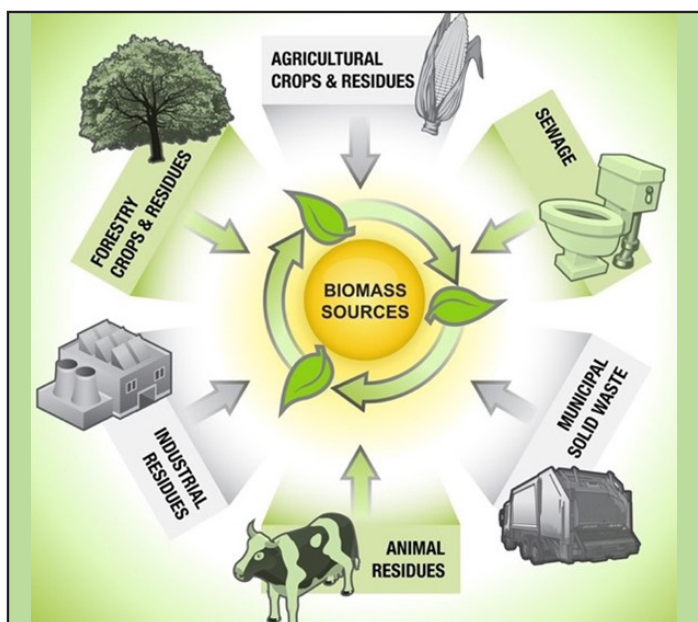


FIGURE 9 Sources of Biomass [Zafar, 2020]

**Currently, there are no biomass production sites in Massachusetts that are used for hydrogen generation and therefore is not currently part of the Massachusetts economy.** More research needs to be performed on the carbon offset and economic benefits for the Commonwealth. The challenges with reforming biomass include the cost of biomass-derived liquid, capital cost, and carbon emissions. Biomass-derived liquids are composed of larger molecules with more carbon atoms than natural gas and this makes them more difficult to separate and reform in the steam reforming process. Steam reforming processes for biomass have a high capital equipment cost as well as operation and maintenance cost. There are processes other than steam reforming that can produce hydrogen through biomass such as pyrolysis, but they are more costly and should be further researched and investigated before implementation.

## Ammonia/Fertilizer

Hydrogen can be produced and stored in the form of ammonia (NH<sub>3</sub>). The opportunity with ammonia for hydrogen storage is that it does constitute a practical, low-cost storage alternative, not requiring high pressure or cryogenic temperatures. Ammonia can be liquified at a pressure of 10 bars and contained at a temperature of -33°C. When compared to liquid hydrogen, liquefaction requires pressures of about 100 bars and containment at temperatures of -253°C or lower. This significant decrease in pressure and temperature allows for a less energy-intensive method to store and transport hydrogen (see Figure 10). Ammonia is an inhibitor for hydrogen embrittlement, meaning that ammonia can be safely transported through existing iron and steel natural gas pipelines.

The challenge with ammonia is the carbon-intensive processes currently used for its production. Today the common production of ammonia requires both the generation of hydrogen through steam methane reforming and nitrogen through air separation. Hydrogen and nitrogen are used as inputs to form ammonia in a catalyzed process at high temperature and pressure (i.e., the Haber-Bosch process). The use of green hydrogen in ammonia production is not currently economical. There still needs to be development in enhanced ammonia production before ammonia can be used at a large scale for green hydrogen storage or as an energy carrier. Currently, there are no ammonia or fertilizer production sites in Massachusetts and therefore it is not part of the state's economy. More research needs to be performed on the economic benefits of manufacturing ammonia or fertilizer and their carbon impact on the Commonwealth.



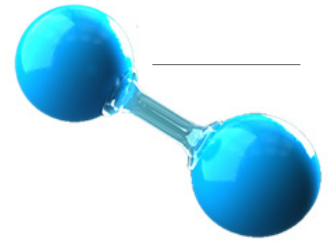
FIGURE 10 Example of Liquid Ammonia Storage [Simon, Taylor, 2021]

## The Vision and Next Steps for Hydrogen Integration

Further integration of green hydrogen into the Massachusetts economy enables a diversification of energy sources, supports market competition, affords greater energy resiliency, enables sector coupling, and minimizes changes of existing infrastructure to meet zero-emission goals. By diversifying Massachusetts' fuel sources, hydrogen integration allows for the promotion of consumer choice, market competitiveness, and enhanced grid reliability. Consumers will be able to choose a low carbon energy source that best fits their needs and what may be more suitable in their area or for their socioeconomic status. Sector coupling with hydrogen energy allows for an increased integration of energy end-use and multiple supply sectors [Travers, 2021; He, et al., 2021]. This allows for an increased efficiency and flexibility of a hydrogen economy, as well as working with electrification to reduce the cost of decarbonization [Nuffel, 2018]. For maximum carbon reduction, green hydrogen should be considered as a future potential fuel source as opposed to other forms (grey and blue hydrogen) that require the utilization of fossil fuels in their production or because carbon sequestration technologies are not presently effective for net-zero large-scale production. However, blending methane with green hydrogen may be considered as a transitional fuel until pipeline replacements are completed, the cost of green hydrogen is reduced, and the distribution infrastructure can accommodate 100% green hydrogen or carbon neutral synthetic fuels. The Massachusetts electrification efforts for commercial and residential heating and cooling (i.e., heat pumps) should initially be implemented in locations that currently rely solely on the dirtier fossil fuels (e.g., coal or oil) and do not have access to the natural gas infrastructure. **Direct use of renewable electricity for heat and power should be a first consideration, when possible and economical, rather than using renewable energy to generate fuel or for storage because of round trip efficiency losses.** Complete electrification may be difficult or impossible due to several factors such as intermittency, physical constraints, retrofitting limitations, transmission line augmentation, infrastructure replacement, permitting, public acceptance, and cost. Massachusetts' climate 2030 goals include electrifying 100,000 homes per year, but in 2020 only 461 homes made the switch revealing an extreme shortfall in electrification progress for a variety of reasons [Shankman, 2021]. In the end, to achieve widespread electrification and hydrogen production and distribution, the technology that will be embraced by consumers will be driven by cost per unit energy, performance, ease of implementation, capital expenditures required for retrofit and new energy infrastructure, and policy.

Challenges that a hydrogen economy will face includes producing green hydrogen at a cost competitive rate, incorporating the necessary infrastructure for safe utilization, addressing public acceptance, as well as adopting policies and creating incentives that enable hydrogen integration and consumption. Other countries and states (e.g., U.K. and NY) have already begun to explore the potential role of green hydrogen as part of a comprehensive decarbonization strategy [[NY.gov, 2021]. **In order to achieve carbon neutrality in Massachusetts, research and advancements need to be made in green hydrogen technology and further integration should be embraced. New policies and programs need to support the de-risking of large-scale commercial projects and pilot studies for technology and safety validation as well as public acceptance.** These may include state or federal tax credits and other subsidies, loan guarantee programs, and research funding. New carbon neutral energy standards and infrastructure (e.g., fueling stations) will generate demand, help reduce costs, and increase energy resiliency, enabling widespread use of hydrogen for the commercial, residential and transportation industries relevant to Massachusetts.

The Commonwealth of Massachusetts, the U.S., and the world are reaching an inflection point to address climate change and immediate action is necessary to transition to a world that does not rely on fossil fuels as its main energy source. Accomplishing this goal, in the short time necessary to make a difference, will require the planning and deployment of differing options, some of which are in initial or intermediate levels of development, but are anticipated to be realized in the near future or still face challenges with public perception and acceptance. For example, the vast renewable energy resource from offshore wind is expected to be available, but currently does not exist. Diversity, flexibility, and forward thinking will be necessary to make sure the Commonwealth's energy supply is resilient to disruption. Some of these technologies may be useful in more than one sector, others may not be. For practical reasons, there is no one size fits all approach that will transition all sectors quickly and efficiently. All options need to be evaluated and considered, and it is particularly important to continue research into those technologies that are still in their nascent stage. The use of hydrogen, in some applications that currently use fossil fuels, will reduce overall greenhouse gas emissions, and help contribute to meeting the Commonwealth's 2050 net-zero carbon goals, and if widely adopted, help reduce CO2 emissions globally. Challenges related to the use of hydrogen (e.g., cost, safety, public perception) can be overcome with proper and appropriate technological advancements, public awareness, and regulations.



## Recommendations

To make the use of hydrogen a reality, the Commonwealth should consider the following:

1

The development of an overall hydrogen policy that integrates the use of hydrogen to reduce the intensity of or eliminate the carbon of the fuels used in the thermal sector in Massachusetts.

2

A continuation of study of the advantages of green hydrogen within the transportation system (passenger, medium and heavy-duty vehicles, marine, rail, and aviation sectors) that would enable a cost-effective market and reduction in carbon footprint.

3

A re-evaluation of the policies in place that hinder hydrogen transportation from further development, such as traveling restrictions for compressed hydrogen-powered vehicles.

4

Continued research into the use of long-duration energy storage using hydrogen in partnership with the offshore wind industry and other renewable energy sources available to Massachusetts.

5

The establishment of an optional Pilot program implemented in participating gas local distribution companies' (LDCs) distribution systems for a blended mix of hydrogen with natural gas to reduce the amount of carbon for thermal delivery.

6

The alignment of the existing Gas System Enhancement Program (GSEP) with the net-zero reduction goals of the Commonwealth to make sure the pipeline system is as low emission as possible and ready for use when the expected green hydrogen resource becomes available to address the thermal needs. The GSEP should also incorporate hydrogen compatible design standards.

7

The creation of a renewable procurement standard for natural gas utilities and suppliers similar to the electric renewable portfolio standard (RPS) programs, allowing hydrogen to qualify for "thermal renewable energy credits" (TREC) that will encourage its use to further reduce the carbon footprint in the Commonwealth of Massachusetts.

# Appendices

Within the remainder report more details are provided on the following topics:

Appendix 1. Stakeholder Interviews

Appendix 2. Introduction to Hydrogen

Appendix 3. Hydrogen Production

Appendix 4. Conversion of Hydrogen to Energy

Appendix 5. Hydrogen Delivery and Storage

Appendix 6. Applications of Hydrogen

Appendix 7. Safety

Appendix 8. Cost Analysis

Appendix 9. Hydrogen Pathways for the Commonwealth of Massachusetts

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