Decarbonizing Building Heat in Massachusetts

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Applied Economics Clinic

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Executive Summary

Eighty percent of Massachusetts households heat their homes with fossil fuels. In April 2020, Massachusetts' Governor Baker established a net zero greenhouse gas emissions target by 2050. In March 2021, the statewide emissions reduction target for 2030 was increased from 45 to 50 percent. To achieve these goals, Massachusetts' interim *Clean Energy and Climate Plan for 2030* and *2050 Decarbonization Roadmap* highlight the need to decarbonize the buildings sector using efficient electric heating technologies like electric heat pumps powered by renewable energy and, at the same time, lower the emissions in our electricity by increasing the share of renewable electric generation.

This Applied Economics Clinic white paper assesses the feasibility of green hydrogen, upgraded biogas (or "renewable" natural gas), and electric heat pumps as possible alternatives to fossil gas (see ES-Figure 1). AEC evaluated these alternatives in terms of price, feasibility, supply, and safety, and found that upgraded biogas and green hydrogen are infeasible, expensive, and unsafe strategies for decarbonization of building heating.

ES-Figure 1. Report card for heating fuel alternatives

	Fossil Gas **C**	Upgraded Biogas **D**	Green Hydrogen **F**	Electricity **A**
Emissions	**Poor** CO_2 from combustion and CH_4 from leaks	**Okay** CH_4 leaks and upstream emissions	**Okay** Indirect GHGs from H_2 & NO_X	**Good** Depends on fuel source, renewable share growing
Supply	**Very Good** Sufficient and consistent supply from fracking	**Poor** Limited local feedstocks	**Poor** Competes with other uses for renewable energy	**Very Good** Supply of renewable electricity expected to rise
Energy Bills	**Good** Currently low cost, vulnerable to price volatility	**Okay** 4 times more expensive than fossil gas today	**Poor** 6 times more expensive than fossil gas today	**Good** Using ground source heat pumps is cheaper than gas
Feasibility	**Poor** $16-$17B needed to stop distribution leaks	**Poor** $16-$17B needed to repair leaks; plus upgrades	**Poor** $16-$17B needed to repair leaks; plus upgrades	**Good** Widely available energy source (retrofits required)
Safety	**Poor** High risk of leaks and explosions	**Poor** High risk of leaks and explosions	**Poor** Increased risk of leaks and explosions	**Very Good** No risk of leaks or explosions

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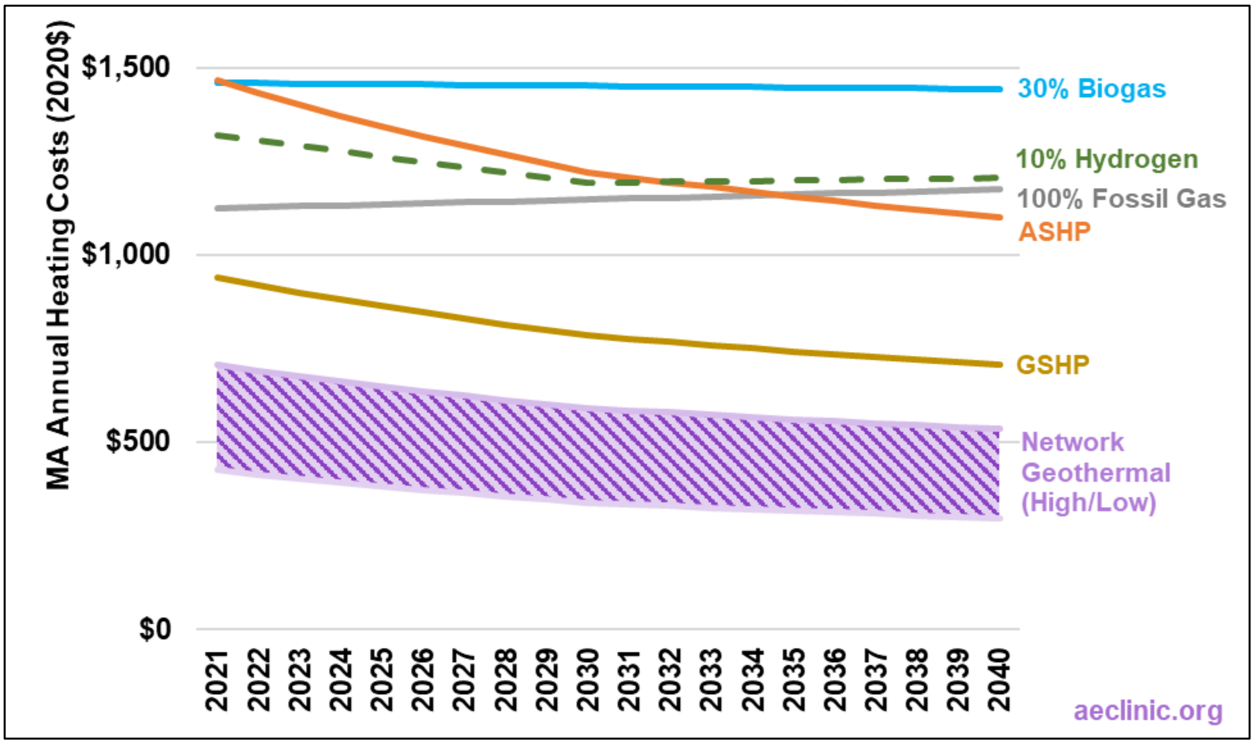
We also estimated annual home heating costs for an average Massachusetts home using different heating options (fossil gas, green hydrogen, upgraded biogas, and electric heating using heat pumps) and found that heating using fossil gas will be more expensive than heating with air-source heat pumps by the mid-2030s and is already more expensive than heating with ground-source heat pumps and networked geothermal systems (see ES-Figure 2). A fossil/biogas blend is more expensive than air-source heat pumps by 2023. Green hydrogen will not be feasible in Massachusetts until the 2040s, but if it were available today, a 10 percent blend of green hydrogen with fossil gas would be more expensive than heating with fossil gas, ground-source heat pumps, and networked geothermal but less expensive than biogas and ASHPs until the 2030s. Based on this review, building electrification using heat pumps is the best option for safe and cost-effective decarbonization due to increasing renewable energy sources and the feasibility of switching from fossil gas to electric heating.

ES-Figure 2. Annual residential heating costs in Massachusetts (average-sized home)



AEC's cost estimates include the conservative assumption that the number of gas customers remains constant over time in our fossil gas and gas blend scenarios. If instead, the number of gas customers falls due to building electrification, the remaining customers will need to shoulder more of the costs, resulting in higher rates and bills for those unable to electrify their heating.

Given the competing needs across sectors for these resources, safety concerns, and the declining cost of heat pumps, we question the feasibility of green hydrogen and upgraded biogas as options for building decarbonization in Massachusetts: These fuel substitutes emit greenhouse gases, cost more than either fossil gas or heating with electric heat pumps, and are less safe than a future that invests deeply in electrification.

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I. Decarbonizing Massachusetts' Home Heating

In April 2020, Massachusetts' Governor Baker issued a letter establishing a net zero[1] greenhouse gas emissions target by 2050.[2] In December 2020, the Commonwealth's Executive Office of Energy and Environmental Affairs released two reports: a study summarizing several potential pathways to net zero by 2050[3] and an interim *Clean Energy and Climate Plan* (CECP) for 2030.[4] Following the release of the interim 2030 CECP, the statewide emissions reduction target for 2030 was increased from 45 to 50 percent in March 2021.[5] Both reports highlight the need to decarbonize the buildings sector using efficient electric heating technologies like heat pumps powered by renewable energy. As our electric grid moves to renewables, emissions from electricity will decline, allowing us to meet our state's goal.

Electric resistance heating converts the flow of electricity directly into heat (e.g., baseboard heating and space heaters) with high efficiency losses.

Electric heat pumps use electricity to harness existing temperature differences, providing much more heating (or cooling) than the electricity expended.

Today, fossil fuels are the dominant heating source in Massachusetts—in 2019, 80 percent of Massachusetts households heated their homes with fossil fuels (see Figure 1 below). Only 17 percent of Massachusetts homes are heated with electricity; the vast majority of this electric heat is inefficient electric resistance heating. [6] Electric resistance heaters generally require 50 percent more electricity than heat pumps to produce the same amount of heat.[7] Using modern heat pumps instead would

[1] Defined as "A level of statewide greenhouse gas emissions that is equal in quantity to the amount of carbon dioxide or its equivalent that is removed from the atmosphere and stored annually by, or attributable to, the Commonwealth; provided, however, that in no event shall the level of emissions be greater than a level that is 85 percent below the 1990 level." See: Massachusetts Executive Office of Energy and Environmental Affairs (EEA) and The Cadmus Group. December 2020. "Massachusetts 2050 Decarbonization Roadmap." Available at: https://www.mass.gov/doc/ma-2050-decarbonization-roadmap/download. p. 7

[2] Commonwealth of Massachusetts. April 22, 2020. "Press Release: Baker-Polito Administration Issues Letter Establishing Net Zero Emissions Target." Available at: https://www.mass.gov/news/baker-polito-administration-issues-letter-establishing-net-zero-emissions-target.

[3] Executive Office of Energy and Environmental Affairs (EEA) and The Cadmus Group. December 2020. "Massachusetts 2050 Decarbonization Roadmap." Available at: https://www.mass.gov/doc/ma-2050-decarbonization-roadmap/download.

[4] EEA. December 2020. "Clean Energy and Climate Plan for 2030." Available at: https://www.mass.gov/doc/interim-clean-energy-and-climate-plan-for-2030-december-30-2020/download.

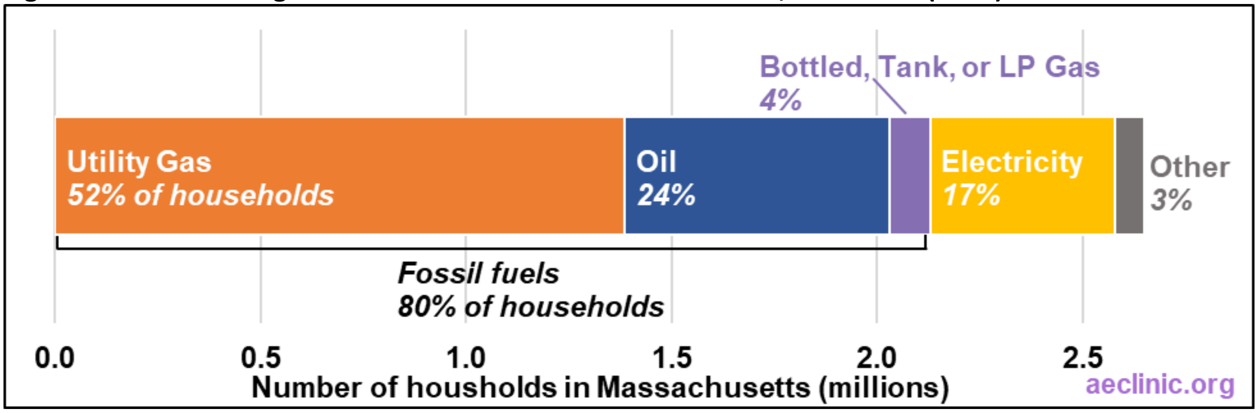
[5] Commonwealth of Massachusetts. 2021. "Massachusetts Clean Energy and Climate Plan for 2025 and 2030." Available at: https://www.mass.gov/info-details/massachusetts-clean-energy-and-climate-plan-for-2030#interim-clean-energy-and-climate-report-for-2030-.

[6] ISO New England. 2021. "Resource Mix." Available at: https://www.iso-ne.com/about/key-stats/resource-mix/.

[7] U.S. Department of Energy (DOE). n.d. "Electric Resistance Heating". Energy Saver. Available at: https://www.energy.gov/energysaver/electric-resistance-heating

radically reduce the amount of electricity needed for heating.

Figure 1. Home heating fuels used in Massachusetts households, in millions (2019)



Data source: U.S. Census Bureau. 2019. American Community Survey 1-Year Estimates [Table]. House Heating Fuel (Table ID: B25040). Available at: *https://data.census.gov/cedsci/table?q=heating%20fuels&g=0100000US_0400000US25&tid=ACSDT1Y2019.B25040&hidePreview=true*

The U.S. Energy Information Administration (EIA) expects fossil fuel consumption (gas and oil) in New England to remain about the same between 2020 and 2050 in all of its scenarios of the future economy. EIA's Reference case forecasts that New England will consume over 700 trillion metric British thermal units (or 700 million MMBtu) of oil/gas each year.[8] Approximately 500 million MMBtu of New England's fossil fuel consumption will be gas (see Figure 2 below). While oil consumption is expected to decline, gas consumption is expected to rise. It is worth noting that in its Reference forecast, EIA expects the consumption of oil and gas in New England in 2050 to be roughly equivalent to today's levels and for 30 percent of the consumption to be of higher-emitting oil. These expectations are the same in all of EIA's forecasts: There is no forecast made available by the Administration representing a future with electrification.

In June 2020, the Massachusetts Office of the Attorney General (AGO) filed a petition requesting that the Department of Public Utilities (DPU) assess the future of fossil gas in the Commonwealth given its commitment to net zero emissions by 2050.[9] In particular, the AGO asked DPU to investigate what industry, regulatory, and policy changes are needed to achieve the 2050 net zero mandate while also maintaining a safe and reliable gas system moving forward. In October 2020, DPU voted to open an investigation into the role of gas utilities with respect to the Commonwealth's 2050 climate goals in Docket No. 20-80.[10]

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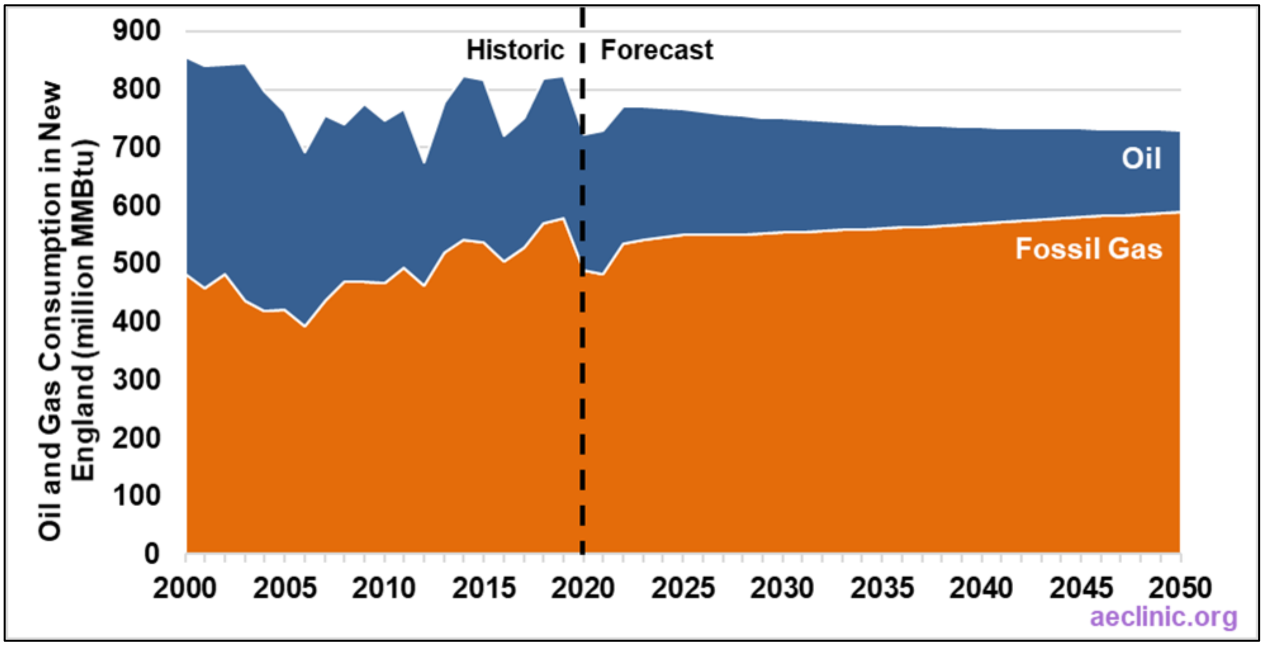
[8] U.S. EIA. Annual Energy Outlook 2021 [Table 2: Energy Consumption by Sector and Source]. Available at: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=2-AEO2021&cases=ref2021&sourcekey=0

[9] MA DPU Dkt. No. 20-80. Petition of the [AGO] "Requesting an Investigation into the impact on the continuing business operations of local gas distribution companies as the Commonwealth achieves its target 2050 climate goals."

[10] Ibid.

Figure 2. Gas and oil consumption in New England



Note: Oil and gas consumption from residential, industrial, and commercial sectors.
Data sources: (1) U.S. EIA. 2019. "Adjusted Sales of Distillate Fuel Oil by End Use". Available at: https://www.eia.gov/dnav/pet/pet_cons_821dsta_dcu_SMA_a.htm; (2) U.S. EIA. 2020. "Natural Gas Consumption by End Use". Available at: https://www.eia.gov/dnav/ng/ng_cons_sum_a_EPG0_vrs_mmcf_a.htm; (3) Growth rate: U.S. EIA. Annual Energy Outlook 2021 [Table 2: Energy Consumption by Sector and Source].

In Massachusetts and in New England as a whole, gas utilities have proposed several pathways for decarbonizing their gas supply in line with their respective states' emission reduction targets:

- Utilizing upgraded biogas[11] and green hydrogen fuels;
- Energy efficiency and demand response measures;
- District energy systems and steam production (e.g., network geothermal); and
- Infrastructure and equipment upgrades to reduce leaks and increase efficiency.[12]

This Applied Economics Clinic white paper assesses the suitability of biogas and green hydrogen as alternatives to fossil gas for heating in Massachusetts, including consideration of five areas of evaluation (see Table 1):

[11] Biogas is gas derived from biomass feedstocks like agricultural and municipal waste, forestry residues, or energy crops. To be used for pipeline injection or for vehicle fuel, biogas is "upgraded" to remove moisture, contaminants, and gases other than methane. For simplicity, we referred to this upgraded substance as "biogas" in this report.

[12] (1) The Cadmus Group, Arup, VEIC, Energy Futures Group, and Evolved Energy Research. 2020. *Buildings Sector Report: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study*. (2) National Grid. October 2, 2020. Our Plan: National Grid Net Zero by 2050. Available at: https://www.nationalgridus.com/media/pdfs/our-company/netzeroby2050plan.pdf; (3) Eversource. 2020. "Carbon Neutral by 2030". Available at: https://www.eversource.com/content/ct-c/about/sustainability/focus-areas/carbon-neutrality.

Table 1. Areas of evaluation for alternatives to fossil gas

	Areas of Evaluation
1	**Emissions:** emission reduction potential
2	**Supply:** ability of supply to meet demand
3	**Energy Bills:** cost relative to fossil gas
4	**Feasibility:** feasibility of injection into existing fossil gas infrastructure
5	**Safety:** potential safety concerns

There are pros and cons to each alternative to fossil gas for heating but across the five areas of evaluation identified above, it is evident that neither green hydrogen or biogas are viable candidates for decarbonizing the gas supply in Massachusetts. Our analysis finds that:

- Green hydrogen and most biogas produce emissions; and the gas distribution system will continue to leak greenhouse gases.
- There is not enough biogas to meet demand; and there are important uses for renewables other than making green hydrogen.
- Green hydrogen and biogas are both more expensive than fossil gas and electric heat pumps.

Section's II and III of this white paper examine the feasibility of biogas and green hydrogen as decarbonization strategies in Massachusetts. Section IV discusses renewable-derived electricity as an alternative resource to fossil gas for heating. Section V presents the average home heating cost in New England across different heating options. Lastly, Section VI, makes policy conclusions based on white paper findings.

II. Upgraded Biogas

Blending some percentage of biogas (also marketed as "renewable" natural gas)[13] into fossil gas as a decarbonization strategy is being explored by several gas utilities, including some in Massachusetts and elsewhere in New England. Biogas is derived from biomass feedstocks like agricultural and municipal waste, forestry residues, or energy crops. It can be produced through processes including anaerobic digestion or thermal gasification, and can be used for heating, electricity, and other industrial uses (see Table 2). To be used for pipeline injection or for vehicle fuel, biogas is treated to remove moisture, contaminants, and gases other than methane.[14] (We shorthand this "upgraded biogas" as just "biogas" throughout this white paper.)

Table 2. Biogas feedstock type by production process

Feedstock Type		Description
Anaerobic Digestion	**Landfill Gas**	Anaerobic digestion of organic waste produces a mixture of gases.
	Animal Manure	Manure from livestock, such as beef, dairy, swine, and poultry farms.
	Water Resource Recover Facilities	The processing of wastewater generated from residential, commercial, or industrial facilities produces a sewage sludge that can be used to create biogas.
	Food Waste	Residential and commercial food waste.
Thermal Gasification	**Agricultural residue**	Leaves, branches, stalks, and other unusable parts of crops leftover from harvesting.
	Forestry and forest product residue	Material generated from logging activities, forest and fire management, and milling.
	Energy Crops	Material, such as grasses, trees, and some crops, that are grown specifically to produce biogas.
	Municipal Solid Waste	Nonorganic material, such as plastics and construction debris, that would typically be landfilled.

Source: Stifle Equity Research. 2021. Energy & Power—Biofuels: Renewable Natural Gas. Stifel Equity Research. Available at: https://www.rngcoalition.com/data-resources-2. *p. 24*

Emissions

Biogas is often presented as an attractive alternative to fossil gas because under certain limited circumstances—over its entire lifecycle—it has the potential to release fewer greenhouse gas emissions than fossil fuels.[15] However, the pursuit of biogas as a decarbonization strategy comes with caveats. The

[13] The term "renewable" natural gas is misleading because not all biogas feedstocks are renewable resources.
[14] (1) U.S. EPA. July 2020. *An overview of renewable natural gas from biogas*. EPA 456-R-20-001. Available at: https://www.epa.gov/lmop/overview-renewable-natural-gas-biogas; (2) Gasper, R. and Searchinger, T. 2018. *The production and use of renewable natural gas as a climate strategy in the United States*. World Resources Institute (WRI). Available at: https://www.wri.org/research/production-and-use-waste-derived-renewable-natural-gas-climate-strategy-united-states
[15] U.S. EPA. July 2020. *An overview of renewable natural gas from biogas*. EPA 456-R-20-001.

extent of greenhouse gas emissions from biogas depends on the feedstock used (see Table 3, where positive values represented net emissions into the atmosphere and negative values represent net avoidance of emissions that would have otherwise occurred), how that feedstock would have otherwise been used, and the amount of methane leaked during biogas production, transport, and combustion. Methane emissions are much more potent than carbon dioxide (CO_2); their 20-year global warming potential is over 80 times that of CO_2. Therefore, substantial methane leaks from the biogas life cycle can negate any potential climate benefit.[16] In addition, using biogas to heat homes still produces harmful indoor and outdoor air pollution.[17]

Table 3. New England lifecycle greenhouse gas emissions by feedstock type, excluding local distribution system leaks

Feedstock Type	New England Lifecycle Greenhouse Gas Emissions (kg CO_2e/Btu)	
	LOW	HIGH
Landfill Gas	17	25
Animal Manure		
Dairy	-288	-279
Swine	-383	-373
Beef / Poultry	34	34
Water Resource Recovery Facilities	17	25
Food Waste	-92	-78
Agricultural Residue	24	52
Forestry and Forest Product Residue	24	52
Energy Crops	24	52
Municipal Solid Waste	24	52

Source: ICF. December 2019. Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment. An American Gas Foundation Study. p. 72. Available at: https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf

Based on New England's achievable biogas potential as reported by an ICF/WGL 2020 study,[18] combined emissions from all sources of biogas are expected to range from -61 to 36 kg of CO_2e per year. This range was obtained by multiplying the emissions factors shown in Table 3 above by New England biogas potential

[16] Gasper, R. and Searchinger, T. 2018.
[17] Saadat, S., Vespa, M., and Kresowik, M. 2020. *Rhetoric vs. reality: The myth of "renewable natural gas" for building decarbonization*. Earth Justice and Sierra Club. Available at: https://earthjustice.org/features/report-building-decarbonization
[18] ICF. March 2020. *Study on the Use of Biofuels (Renewable Natural Gas) in the Greater Washington, D.C. Metropolitan Area*. Prepared for Washington Gas Light Company. Available at: https://edocket.dcpsc.org/public/search/details/fc1142/597

as reported by the ICF/WGL 2020 study[19] under their "achievable" scenario (see Figure 3 below) and then taking the weighted average of the feedstock-specific greenhouse gas emissions.

Supply

Because of supply constraints, it is unlikely that utilities can rely on biogas alone to meet their decarbonization targets. Biogas is not available at the scale necessary to replace fossil gas.[20] Data on biogas supply in the United States is limited and subject to a lot of uncertainty given that current supply levels are extremely low. The U.S. Environmental Protection Agency (EPA) provides two databases that contain information about current biogas supply but they both have limitations:

Landfill Methane Outreach Program (LMOP) database.[21] LMOP was established by the EPA in 1994 as a voluntary program aiming to reduce or avoid methane emissions from landfills by converting emissions into usable biogas supplies.[22] LMOP contains information on the current biogas supply sourced from landfills. Though the LMOP database specifies if biogas is upgraded to pipeline quality gas, it has limited information because it only documents biogas from landfills and most entries lack actual gas volume data.

AgSTAR[23] Livestock Anaerobic Digester Database. Similar to LMOP, AgSTAR was established in 1994 and promotes the reduction of methane emissions and conversion to biogas, but it focuses on livestock waste rather than landfills. The Livestock Anaerobic Digester Database[24] provides information on biogas supplied from agricultural feedstocks. Unfortunately, many entries lack gas volume data and fail to specify if gas is pipeline quality.

Currently, landfill gas (which has positive net emissions) is one of the main sources of biogas but as of 2017 only 7 percent of captured landfill gas was processed to meet the standards necessary for use in transportation or injection into local pipeline networks.[25] The remainder—lower standard—biogas is used for onsite electricity and heating needs.[26]

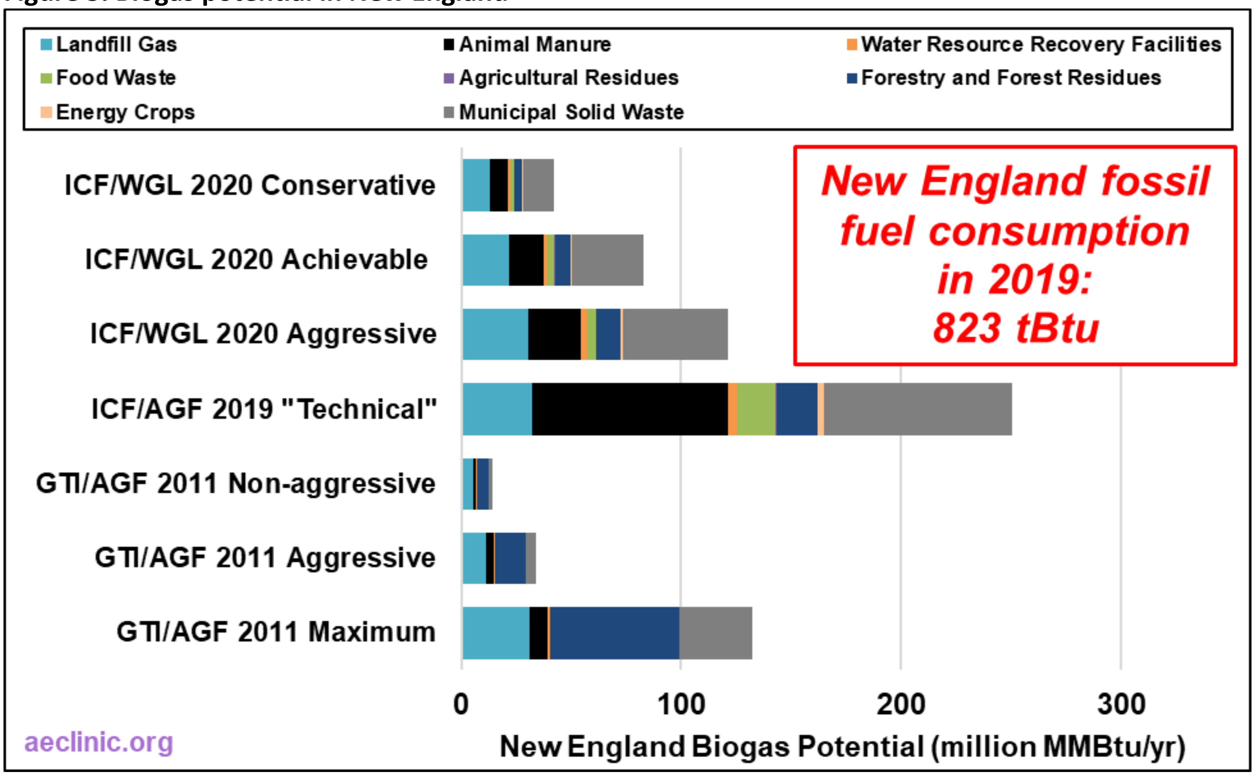
Outside of the limited information available on current biogas supply, several studies have attempted to project future biogas potential from different feedstocks both in New England (see Figure 3) and in the United States as a whole (see Figure 4). Across all studies and scenarios, New England landfill gas, animal manure, and municipal solid waste have the highest biogas potential, whereas summed up for the entire United States, energy crops and agricultural residues have the highest biogas potential. According to the

[19] Ibid.
[20] Ibid.
[21] U.S. EPA. n.d. "LMOP Landfill and Project Database." *Landfill Methane Outreach Program (LMOP)*. Available at: https://www.epa.gov/lmop/lmop-landfill-and-project-database
[22] U.S. EPA. 2017. *LMOP and Landfill Gas Energy in the United States*. Landfill Methane Outreach Program. Available at: https://www.epa.gov/sites/default/files/2017-06/documents/overview_lmop_lfg_us.pdf
[23] U.S. EPA. n.d. "What is EPA Doing: AgSTAR." *AgSTAR*. Available at: https://www.epa.gov/agstar/what-epa-doing-agstar
[24] U.S. EPA. n.d. "Livestock Anaerobic Digester Database." *AgSTAR.* Available at: https://www.epa.gov/agstar/livestock-anaerobic-digester-database
[25] Russell, P, Lowell, D, Jones, B. 2017, p. 2
[26] Ibid. p. 7

ICF/WGL 2020 study,[27] the projected achievable potential of biogas in New England is estimated at 83 million MMBtu/year, or about one-tenth of the supply needed to meet New England's total fossil fuel demand (see Figure 2 above). In the United States as a whole, the projected biogas achievable potential is about 3,835 million MMBtu, or one-fifth of total fossil fuel demand.

It is important to keep in mind that "technical" potential includes resources that are considered to be uneconomic (that is, they are physically possible but too costly to warrant their use). More reasonable estimates of biogas supply are only a fraction of the "technical potential."

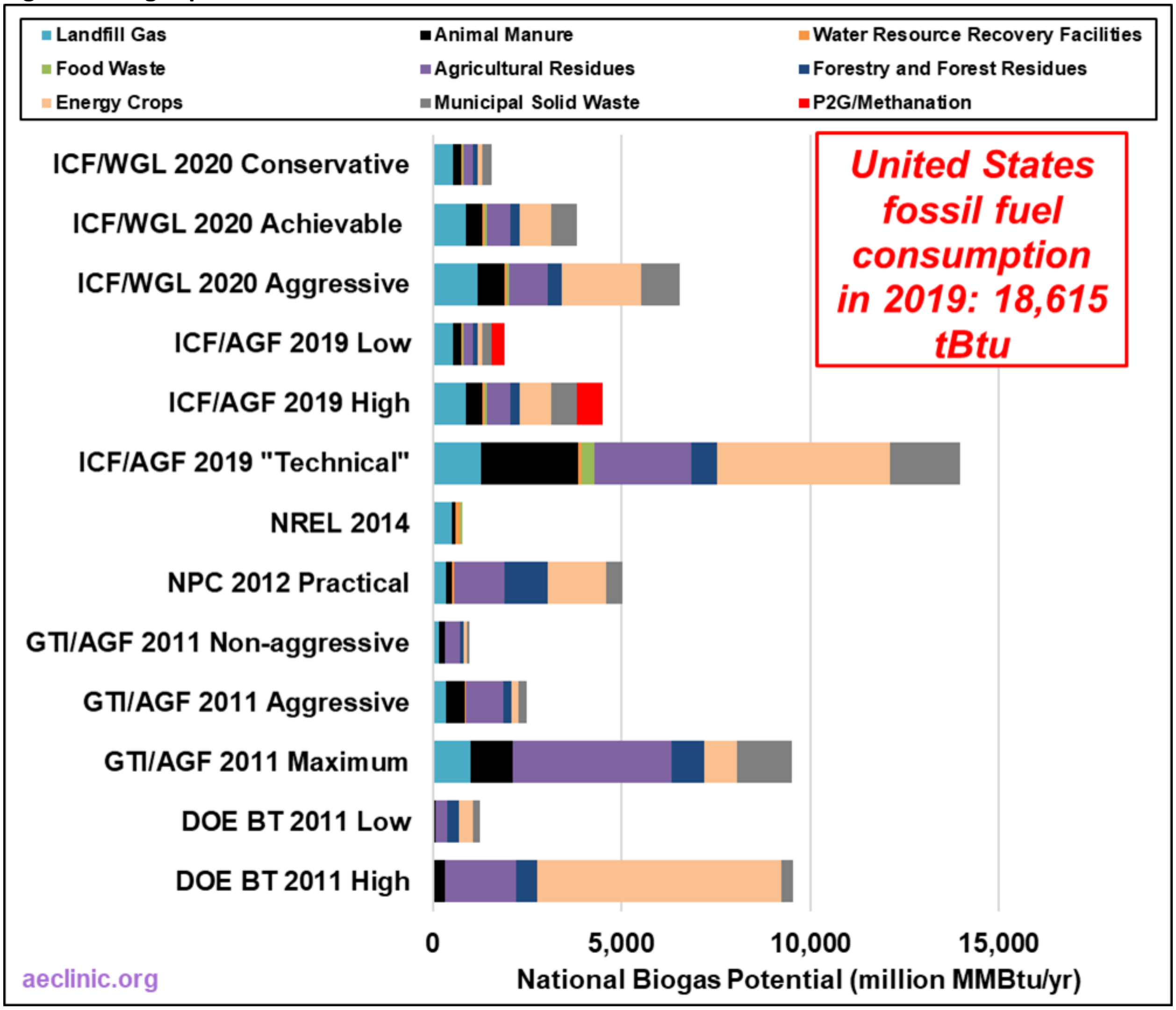
Figure 3. Biogas potential in New England



Note: Biogas here refers to biogas that is upgraded for pipeline injection
Data source: (1) See Table 4 in Appendix A: Biogas resources; (2) U.S. EIA. 2021. "Adjusted Sales of Distillate Fuel Oil by End Use". Available at: https://www.eia.gov/dnav/pet/pet_cons_821dsta_dcu_SMA_a.htm; (3) U.S. EIA. 2021. "Natural Gas Consumption by End Use". Available at: https://www.eia.gov/dnav/ng/ng_cons_sum_a_EPG0_vrs_mmcf_a.htm

[27] Ibid.

Figure 4. Biogas potential in the United States



Note: Biogas here refers to biogas that is upgraded for pipeline injection
Data source: (1) See Table 4 in Appendix A: Biogas resources; (2) U.S. EIA. 2021. "Adjusted Sales of Distillate Fuel Oil by End Use". Available at: https://www.eia.gov/dnav/pet/pet_cons_821dsta_dcu_SMA_a.htm; (3) U.S. EIA. 2021. "Natural Gas Consumption by End Use". Available at: https://www.eia.gov/dnav/ng/ng_cons_sum_a_EPG0_vrs_mmcf_a.htm

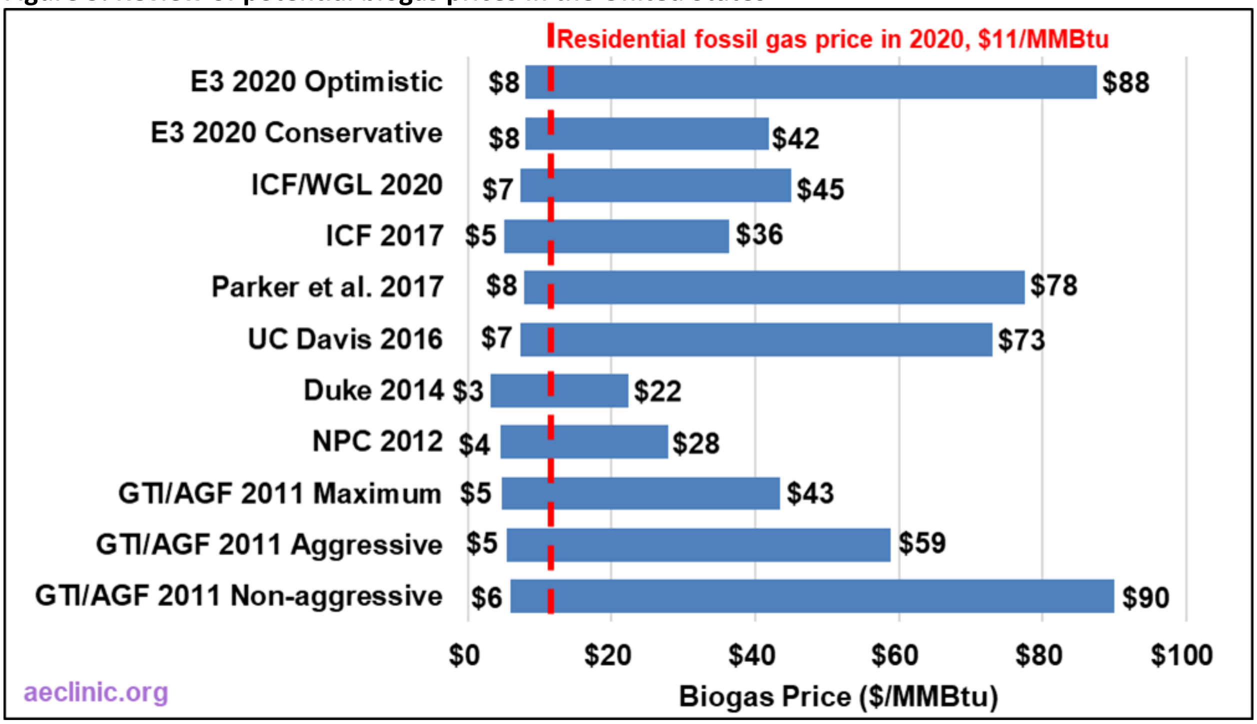
Energy Bills

In addition, biogas is likely to cost several times more than fossil gas per unit of energy. Currently, the capital and operating costs of capturing and treating biogas, coupled with the relatively low price of fossil gas, prevent its widespread production. Moreover, while injecting biogas into pipelines could allow a wide distribution, this method would have extensive costs (due to the extensive planning, interconnection costs, infrastructure expansion, and equipment upgrades needed) that are not included in the biogas price estimates that are available in the literature.[28] Furthermore, $15.5-$16.6 billion would still be needed to

[28] (1) U.S. EPA. July 2020.*An overview of renewable natural gas from biogas*. EPA 456-R-20-001; (2) Gasper, R. and

replace Massachusetts' leaky pipes regardless of how much biogas is mixed into fossil gas supplies.[29] (Note that in an electrification scenario, this investment leads to stranded assets.) A review of recent sources reveals a range of potential biogas prices from about $3 per MMBtu to $90 per MMBtu (see Figure 5). Because biogas demand is at least 3 times higher than biogas supply in New England (see Figure 3 above), all biogas resources would be needed, even the most expensive ones. In this supplier's market, the price of biogas can be expected to reach the higher end of the range of price projections, approaching $90 per MMBtu.

Figure 5. Review of potential biogas prices in the United States



Note: Residential fossil gas price is the U.S. price provided by EIA. The gas price used in Section V is derived from Massachusetts' utility-specific gas rates. Biogas here refers to biogas that is upgraded for pipeline injection
Data source: (1) See Table 4 in Appendix A: Biogas resources.(2) U.S. EIA. 2020. "Natural Gas Prices." Available at: *https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm*

Feasibility

The lack of availability and high cost of biogas is compounded by the inefficiency of biogas production. The magnitude of this inefficiency depends on: (1) the size of the biogas system; (2) the biomass feedstock; (3) the end-use, and; (4) distance traveled.[30] For example, 15 to 25 percent of biogas produced from landfill

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Searchinger, T. 2018. (3) Dyer et al. 2021. "The Feasibility of Renewable Natural Gas in New Jersey." Sustainability, 12, 1618. https://doi.org/10.3390/su13041618

[29] Castigliego, J. R., Stasio, T., Stanton, L. 2020. *Fixing Massachusetts' Leaky Pipes: When Will It Be Paid Off?* Applied Economics Clinic. Available at: https://aeclinic.org/publicationpages/fixing-massachusetts-leaky-pipes-when-will-it-be-paid-off

[30] Pöschl, M., Ward, S., and Owende, P. 2010. "Evaluation of energy efficiency of various biogas production and

gas collection systems is lost.[31]

Safety

The local safety issues related to biogas apply to all forms of methane: Biogas is not more or less safe than fossil gas. Key concerns include: the risk of fire or explosion in and around homes, schools, and businesses;[32] detrimental effects from poor indoor air quality;[33] and environmental effects near leak sites, including tree mortality.[34]

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utilization pathways." *Applied Energy*, 87, 3305-3321. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0306261910001790

[31] Gasper, R. and Searchinger, T. 2018.

[32] (1) Campbell, R. 2020. *Structure Fires in Schools*. National Fire Protection Association. Available at: https://www.nfpa.org/News-and-Research/Data-research-and-tools/Building-and-Life-Safety/Structure-fires-in-schools; (2) Glick D., Plautz, J. 2018. "The rising risks of the West's latest gas boom." High Country News. Available at: https://www.hcn.org/issues/50.18/energy-industry-how-site-workers-and-firefighters-responding-to-a-2017-natural-gas-explosion-in-windsor-colorado-narrowly-avoided-disaster

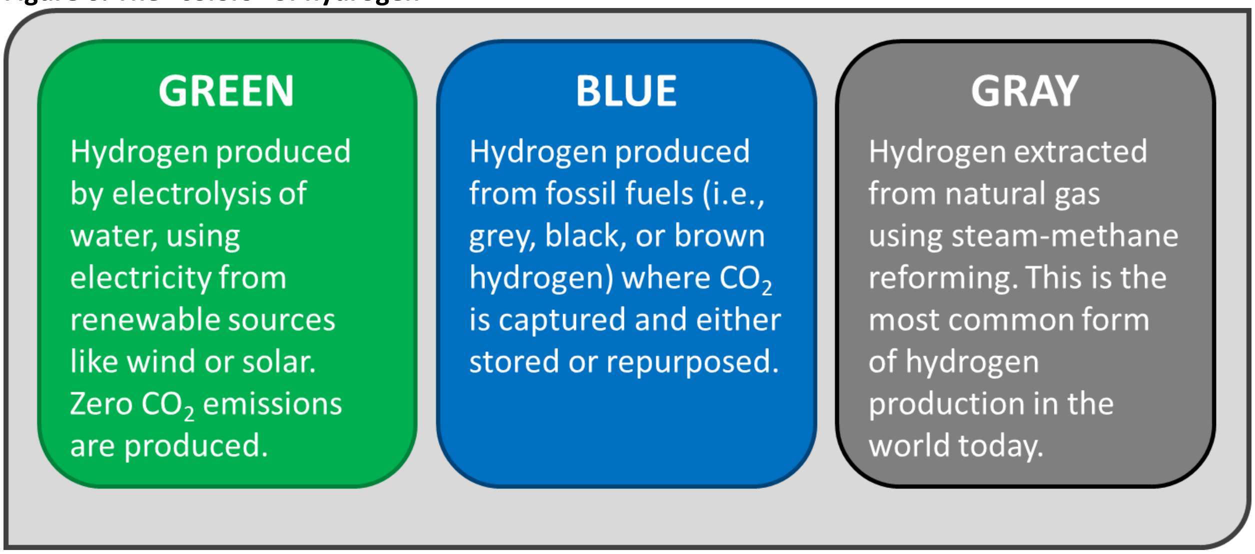
[33] U.S. EPA. n.d. "Introduction to Indoor Air Quality." Available at: https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality#:~:text=Immediate%20Effects,-Some%20health%20effects&text=These%20include%20irritation%20of%20the,if%20it%20can%20be%20identified

[34] (1) Gas Leaks Allies. n.d. Gas Leaks Kill Trees. Available at: https://www.wellesleyma.gov/DocumentCenter/View/9596/Gas-Leaks-Kill-Trees-PDF#:~:text=Gas%20leaks%20have%20killed%20street,cost%20taxpayers%20millions%20of%20dollars; (2) Schollaert, C., Ackley, R. C., DeSantis, A., Polka, E., and Scammell, M. K. 2020. "Natural gas leaks and tree death: A first-look case-control study of urban trees in Chelsea, MA USA." *Environmental Pollution, 263(A)*. Available at: https://doi.org/10.1016/j.envpol.2020.114464 ; (3) Storrow, B. May 5, 2020. "Methane Leaks Erase Some of the Climate Benefits of Natural Gas." Scientific American. Available at: https://www.scientificamerican.com/article/methane-leaks-erase-some-of-the-climate-benefits-of-natural-gas/

III. Green hydrogen

Hydrogen is an energy carrier that is produced from an energy source through electrolysis, steam methane reformation, or gasification. It can be used on site at the time of production or stored for later use.[35] There are several types or “colors” of hydrogen,[36] distinguished by the energy source and process used to produce it (see Figure 6).

Figure 6. The "colors" of hydrogen



Source: The North American Council for Freight Efficiency. 2020. Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors. Available at: https://nacfe.org/emerging-technology/electric-trucks-2/making-sense-of-heavy-duty-hydrogen-fuel-cell-tractors/

Emissions

While the combustion of hydrogen itself releases no emissions, the energy source and process used to produce it can generate substantial emissions. Gray hydrogen, the most common form of hydrogen production today, is made from fossil gas using a method called “steam-methane reforming”.[37] The production of gray hydrogen from fossil fuels generates 10 to 19 metric tons of CO_2 emissions per metric ton of hydrogen. Like gray hydrogen, blue hydrogen is produced from fossil fuels (e.g., fossil gas or coal) using steam-methane reforming, but CO_2 emissions produced in the process are either captured or repurposed rather than released.[38] In contrast, green hydrogen is produced from the electrolysis of water

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[35] DOE. Office of Energy Efficiency and Renewable Energy (EERE). February 21, 2017. *Hydrogen: A Clean, Flexible Energy Carrier*.. Available at: https://www.energy.gov/eere/articles/hydrogen-clean-flexible-energy-carrier

[36] For information on additional “colors” (or types) of hydrogen see: Castigliego, J. R. and Stasio, T. 2021. “The “Colors” of Hydrogen [Blog]. Applied Economics Clinic. Available at: https://aeclinic.org/aec-blog/2021/6/24/the-colors-of-hydrogen?rq=hydrogen

[37] North American Council for Freight Efficiency. December 2020. *Making Sense Of Heavy-duty Hydrogen Fuel Cell Tractors*. Available at: https://nacfe.org/emerging-technology/electric-trucks-2/making-sense-of-heavy-duty-hydrogen-fuel-cell-tractors/

[38] Ibid.

using electricity generated exclusively by renewable sources like wind and solar.[39] Green hydrogen is the only type of hydrogen potentially able to approach the state's net zero emissions mandate because it is sourced from renewable energy sources; it is the only type of hydrogen examined in this paper.

That being said, green hydrogen is not a zero-emissions fuel. Its combustion releases nitrogen oxides (NO_x)—a harmful air pollutant that causes respiratory and other serious health issues.[40] Moreover, since hydrogen is the smallest molecule, it is even more likely to leak from existing pipelines than fossil gas.[41] Researchers estimate that about 10 percent of hydrogen produced will leak during production, storage, and transport.[42] Both NO_x and hydrogen itself are "indirect greenhouse gases"—that is, these gases form ozone when released into the atmosphere. Ozone is greenhouse gas and harmful air pollutant with a 20-year global warming potential 62 to 69 times greater than CO_2.[43]

Supply

Globally, green hydrogen production is limited to demonstration projects.[44] Moreover, the use of green hydrogen to decarbonize heating may not be the most efficient use of the renewable energy needed to create it. According to the International Renewable Energy Agency's (IRENA) guide to green hydrogen policy making, direct electrification using renewable energy is the fastest and most cost-effective solution to decarbonizing the energy supply.[45] The most efficient use of green hydrogen may be in the most hard-to-decarbonize sectors. For example, a marginal abatement cost curve for hydrogen created by BloombergNEF reveals that the transportation (e.g. trucks and ships) and manufacturing sectors (e.g. steel, cement, and glass production) are the least expensive uses of hydrogen for sectoral emissions reduction in comparison to the gas power generation or shipping sectors; in contrast, space and water heating is identified as the most expensive uses of hydrogen to reduce emissions.[46] Moreover, IRENA identifies residential heating as the lowest priority of hydrogen applications, with chemicals and refineries being the

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[39] Ibid.

[40] Milford, L., Mullendore, S., Ramanan, A. 2020. "Hydrogen Hype in the Air" [Blog]. Clean Energy Group. Available at: https://www.cleanegroup.org/hydrogen-hype-in-the-air/; (2) Forster, P. et. al. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University. Press, Cambridge, United Kingdom and New York, NY, USA. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf

[41] Parfomak, PW. March 2, 2021. *Pipeline Transportation of Hydrogen: Regulation, Research, and Policy*. Congressional Research Service. R46700. p. 3. Available at: https://crsreports.congress.gov/product/pdf/R/R46700

[42] NaTrompme, T. K., Shia, R.-L., Allen, M., Eiler, J. M. & Yung, Y. L. 2003. "Potential environmental impact of a hydrogen economy on the stratosphere." *Science, 300,* 1740 – 1742. https://doi.org/10.1126%2Fscience.1085169

[43] Forster, P. et. al. 2018.; 2) J.M.K.C. Donev et al. 2021. "Energy Education - Greenhouse gas." Available at: https://energyeducation.ca/encyclopedia/Greenhouse_gas.

[44] IRENA. 2020. Green Hydrogen Guide to Policymaking. p. 14; (6) U.S. EIA. 2020. "Natural Gas Prices." Available at: https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm

[45] IRENA. 2020. p. 26.

[46] BloombergNEF. 2020. *Hydrogen Economy Outlook*. Available at: https://assets.bbhub.io/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

top priority.[47] For building decarbonization, electrification (e.g., switching out gas and oil furnaces for air-source heat pumps) is more efficient and cost-effective than green hydrogen pipeline injection.[48]

Energy Bills

Several economic barriers raise additional questions regarding green hydrogen development. Green hydrogen production expenses (for both alkaline water and polymer electrolyte membranes) are between 2 and 3 times higher than for its gray counterpart.[49] This high cost is largely due to a complete lack of dedicated hydrogen production infrastructure and substantial energy losses (that is, highly inefficient production processes), both of which could be corrected with investments that have not been made yet.[50]

Green hydrogen is also more costly than fossil gas. A review of recent literature from U.S. and international sources reveals that, where available globally, the price of green hydrogen is significantly more expensive than fossil gas today. Global prices for green hydrogen range from $18 per MMBtu to $59 per MMBtu today (see Figure 7) dropping to between $9 to $24 per MMBtu in 2030 and $6 to $17 per MMBtu in 2050 (see Figure 8); hydrogen injection before 2040—the midpoint between the available price estimates—is unlikely in Massachusetts. (For comparison, U.S. EIA reports the average 2020 residential price of fossil gas as $11 per MMBtu.[51])

Our presentation of the effect of green hydrogen injection on energy bills is purely for illustration and comparison. Two distinct limitations make the injection of an amount of hydrogen into Massachusetts gas distribution systems unlikely –if not impossible—in the near future:

1. Our review found no commercial-scale sources of hydrogen in the United States.
2. Safe injection of hydrogen into the Commonwealth's existing gas pipelines cannot occur until 2040, the date by which utilities' expect to complete their ongoing repair efforts to aging and leak-prone pipes[52] at a cost of $15.5-$16.6 billion.[53]

Moreover, hydrogen is more likely to leak through pipeline imperfections and will degrade common pipeline materials, especially if injected at more than 20 percent of total gas volume.[54] Hydrogen is also less dense than gas, meaning larger, more costly pipelines or additional compressor stations would be needed to achieve the same volume of energy delivery.[55] The production of green hydrogen is also

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[47] IRENA. 2022. *Geopolitics of the Energy Transformation: The Hydrogen Factor*. Available at: https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen

[48] (1) BloombergNEF. 2020. *Hydrogen Economy Outlook*; (2) Ibid.

[49] 1) Anouti, Y., Raed K, Shihab E, and Ramzi H. 2020. 2) International Renewable Energy Agency. 2020. *Green Hydrogen: A Guide to Policy Making*. p. 14, 17. Available at: https://www.irena.org/publications/2020/Nov/Green-hydrogen

[50] Ibid.

[51] U.S.EIA. 2020. "Natural Gas Prices." Available at: https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm

[52] Castigliego, J. R., Stasio, T., Stanton, L. 2020. *Fixing Massachusetts' Leaky Pipes: When Will It Be Paid Off?*

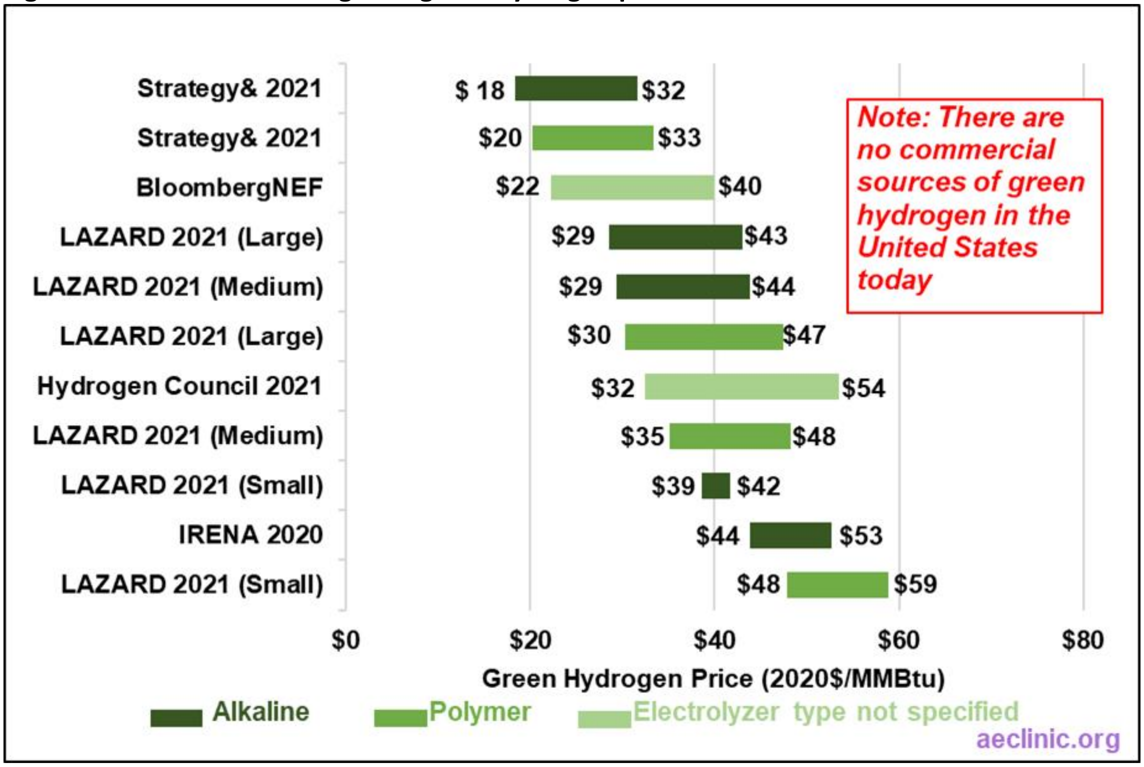
[53] Ibid.

[54] Parfomak, PW. March 2, 2021. p. 3.

[55] (1) Ibid; (2) Abbas, A. J., Hassani, H., Burby, M. and John, I. J. 2021. "An Investigation into the Volumetric Flow Rate

inefficient, with 30 to 35 percent of energy lost during electrolysis.[56]

Figure 7. Review of current global green hydrogen price estimates

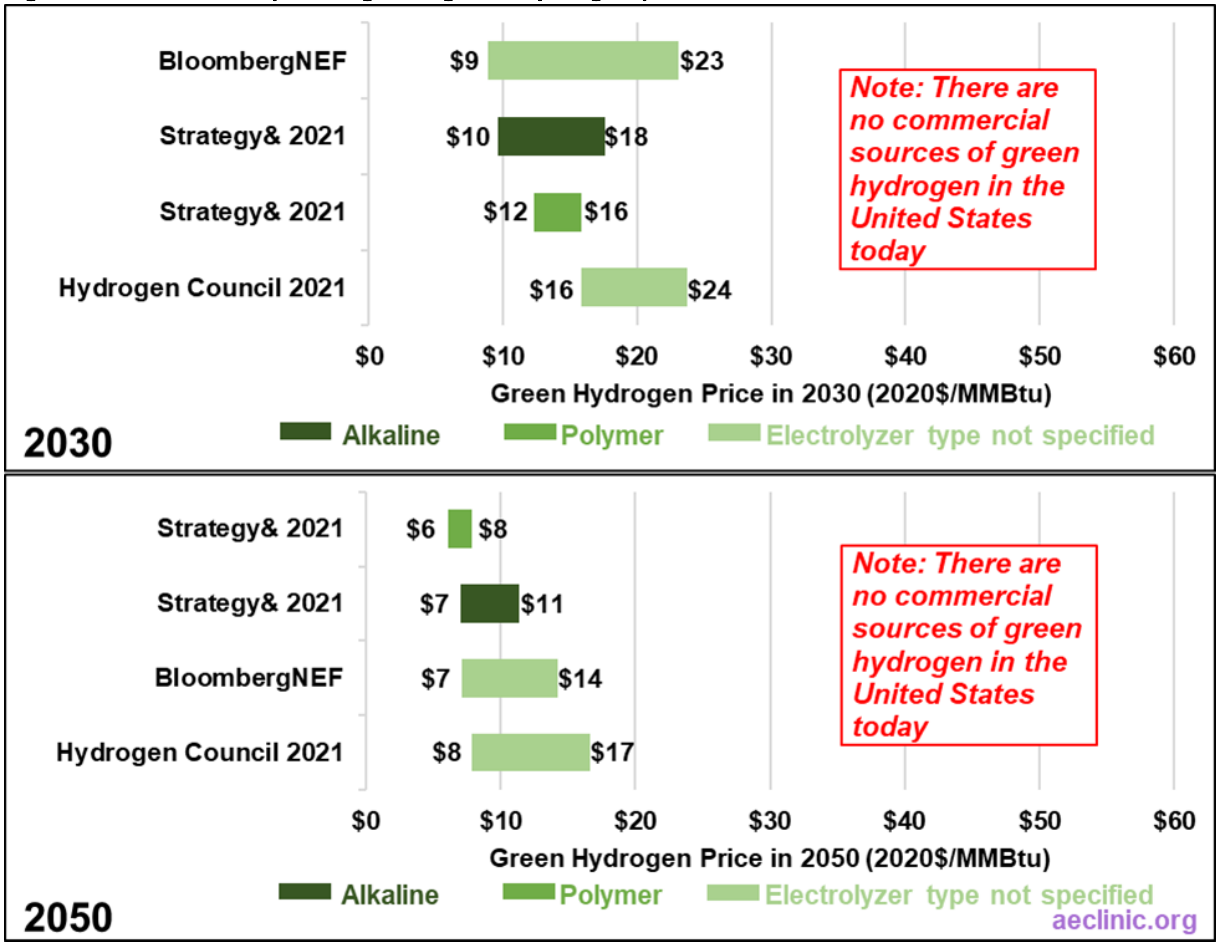


Note: "Alkaline" and "Polymer" refer to alkaline water and polymer electrolyte membrane electrolyzers, respectively. Data sources: (1) Anouti, Y., Kombargi R., Elborai S., and Hage, R. 2020. "The Dawn of Green Hydrogen". Strategy&; (2) BloombergNEF. Hydrogen Economy Outlook. 2020. (3) LAZARD. 2021. LAZARD's Levelized Cost of Hydrogen-Version 2.0. p.12; (4) Hydrogen Council. 2021. Hydrogen decarbonization pathways: Potential supply scenarios. (5) IRENA. 2020. Green Hydrogen Guide to Policymaking. p. 14; (6) U.S. EIA. 2020. "Natural Gas Prices." Available at: https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm

Requirement of Hydrogen Transportation in Existing Natural Gas Pipelines and Its Safety Implications." *Gases, 1,* 156-179. https://doi.org/10.3390/gases1040013

[56] (1) International Renewable Energy Agency. 2020. p. 14, 17. (2) Saadat, S. and Gerson, S. 2021.

Figure 8. Review of expected global green hydrogen prices in 2030 and 2050



Note: "Alkaline" and "Polymer" refer to alkaline water and polymer electrolyte membrane electrolyzers, respectively.
Sources: (1) Anouti, Y., Kombargi R., Elborai S., and Hage, R. 2020. "The Dawn of Green Hydrogen". Strategy&; (2) BloombergNEF. 2020. Hydrogen Economy Outlook. (3) Hydrogen Council. 2021. Hydrogen decarbonization pathways: Potential supply scenarios;(4) U.S. EIA. 2020. "Natural Gas Prices." Available at: https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm

Feasibility

There are three major electrolysis technologies that can be used to produce green hydrogen: (1) alkaline water; (2) polymer electrolyte membranes, and; (3) solid oxide electrolyzer cells.[57] Alkaline water is the most common and cheapest technology used to produce green hydrogen, while polymer electrolyte membrane is less common and more expensive but produces higher quality hydrogen with a lower concentration of contaminants.[58] Electrolyzer membrane technology is still in development but its

[57] Anouti, Y., Raed K, Shihab E, and Ramzi H. 2020. *The Dawn of Green Hydrogen*. Strategy &. Available at: https://www.strategyand.pwc.com/m1/en/reports/2020/the-dawn-of-green-hydrogen/the-dawn-of-green-hydrogen.pdf
[58] 1) Ibid.

proponents claim that it will produce green hydrogen at a higher efficiency rate.[59]

Until then, the production of green hydrogen is inefficient: 30 to 35 percent of energy used to produce green hydrogen is lost during electrolysis.[60] According to the Regulatory Assistance Project, it takes about five times more wind or solar to heat a home using green hydrogen compared to heating with heat pumps.[61] That being said, there may be a potential opportunity for green hydrogen production and storage using excess wind or solar that otherwise would have been lost; more analysis is needed to determine the best use of that excess energy.[62] Given the safety concerns with hydrogen (see above), siting hydrogen production and storage facilities may be challenging.[63]

Hydrogen, the smallest of all molecules, is hard to contain and more likely to leak from existing pipelines than methane (fossil gas or biogas).[64] There are also serious technical barriers to green hydrogen deployment starting with the infrastructure needed to transport hydrogen.[65] Hydrogen embrittles metals, making catastrophic breaks more likely in existing pipelines, such as the unprotected steel pipes[66] that currently make up 16 percent of the gas pipes under Massachusetts' streets.[67] Analysis from the Congressional Research Service assert that no more than a 20 percent hydrogen blend can be injected safely into existing pipeline systems before major upgrades are required.[68] According to a National Renewable Energy Laboratory (NREL) study, hydrogen blended into the gas distribution system should be limited to 15 percent of total gas volume (85 percent methane content).[69]

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[59] Hauch, A. et al. October 9, 2020. *Recent advances in solid oxide cell technology for electrolysis*. Science. Vol 370, Issue 6513. Available at: https://www.science.org/doi/10.1126/science.aba6118

[60] International Renewable Energy Agency (IRENA). 2020. *Green Hydrogen A Guide to Policy Making*. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_hydrogen_policy_2020.pdf. p. 13

[61] Rosenow, J. September 30, 2020. "Heating homes with hydrogen: Are we being sold a pup?" [Blog]. Regulatory Assistance Project. Available at: https://www.raponline.org/blog/heating-homes-with-hydrogen-are-we-being-sold-a-pup/

[62] International Renewable Energy Agency (IRENA). 2020. *Green Hydrogen A Guide to Policy Making*. p.28

[63] U.S. DOE. No date. Hydrogen Program Codes and Standards. Available at: https://www.hydrogen.energy.gov/codes_standards.html

[64] Mejia AH, et al. March 2020. *Hydrogen leaks at the same rate as natural gas in typical low-pressure gas infrastructure*. International Journal of Hydrogen Energy. Volume 45, Issue 15. Available at: https://www.sciencedirect.com/science/article/pii/S0360319919347275

[65] Ibid.

[66] Parfomak, PW. March 2, 2021. Pipeline Transportation of Hydrogen: Regulation, Research, and Policy. Congressional Research Service. p. 3.

[67] The Commonwealth of Massachusetts. December 30, 2020. *Report on the Prevalence of Natural Gas Leaks*. D.P.U. 20-GLR-01. P.16. Available at: https://fileservice.eea.comacloud.net/FileService.Api/file/FileRoom/13083938

[68] Parfomak, PW. March 2, 2021. Pipeline Transportation of Hydrogen: Regulation, Research, and Policy. Congressional Research Service. p. 3.

[69] 1) Melaina, MW. et al. March 2013. *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues*. NREL. p. 31. Available at: https://www.nrel.gov/docs/fy13osti/51995.pdf; 2) Jaworski, J., et al. June 11, 2020. *Study of the Effect of Addition of Hydrogen to Natural Gas on Diaphragm Gas Meters*. Energies. Available at: https://www.mdpi.com/1996-1073/13/11/3006

Safety

Industry sources suggest that without equipment upgrades, there is a risk of explosions or “unplanned ignition” at higher concentrations of hydrogen.[70] While safety codes exist for both fossil gas and for hydrogen separately, there are no safety codes for a fossil gas and hydrogen blend.[71] According to the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (DOE EERE), the United States and the Netherlands are working together on the “harmonization of safety, codes and standards in emerging areas like hydrogen and natural gas blending.”[72]

[70] St. John, J. November 30, 2020. “Green Hydrogen in Natural Gas Pipelines: Decarbonization Solution or Pipe Dream?” Greentech Media. Available at: https://www.greentechmedia.com/articles/read/green-hydrogen-in-natural-gas-pipelines-decarbonization-solution-or-pipe-dream

[71] (1) U.S. DOE EERE. n.d. “H2IQ Hour: Overview of Federal Regulations for Hydrogen Technologies in the United States: Text Version.” Available at: https://www.energy.gov/eere/fuelcells/h2iq-hour-overview-federal-regulations-hydrogen-technologies-united-states-text; (2) Gibbs, K. E., and Ramadevanahalli, A. P. 2021. “Considerations For Transporting a Blended Hydrogen Stream in Interstate Natural Gas Pipelines.” Available at: https://www.morganlewis.com/pubs/2021/06/considerations-for-transporting-a-blended-hydrogen-stream-in-interstate-natural-gas-pipelines

[72] U.S. DOE EERE. 2020. “Collaboration Between the United States and the Netherlands Focuses on Hydrogen Technology.” Available at: https://www.energy.gov/eere/articles/collaboration-between-united-states-and-netherlands-focuses-hydrogen-technology

IV. Electric Heat Pumps

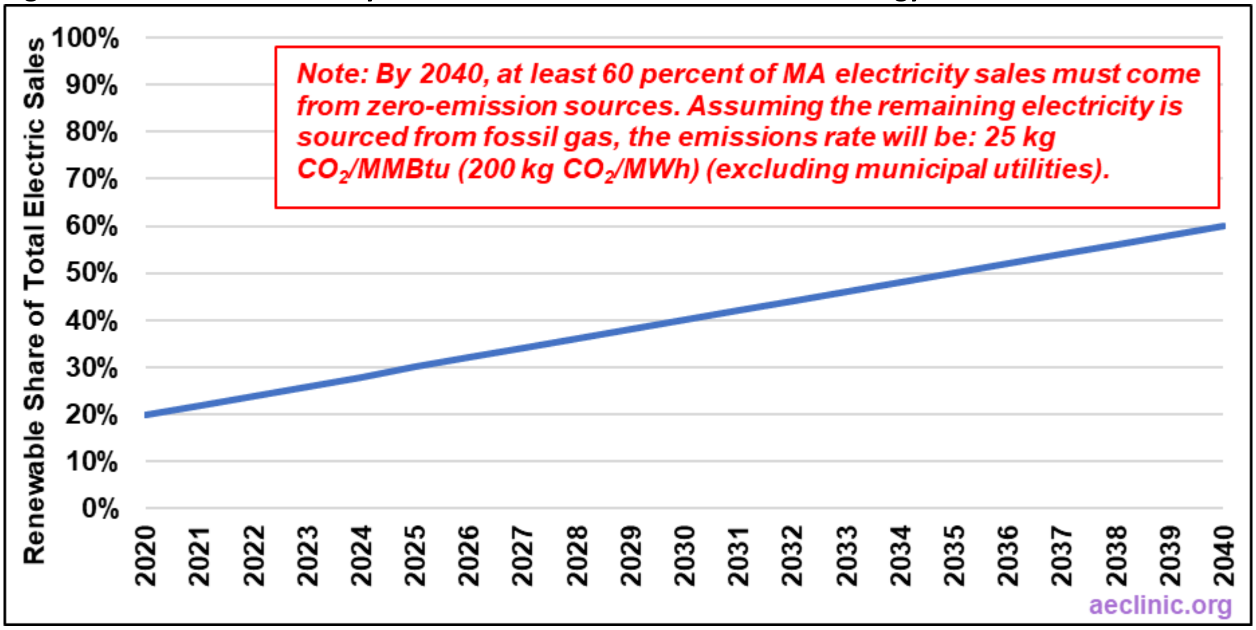
A third decarbonization alternative is the replacement of existing fossil fuel heating equipment with high efficiency electric heat pumps. Heat pumps use ground, water, and ambient air temperatures—combined with a small amount of electricity—to provide buildings with efficient space and water heating and cooling. For each unit of energy used, heat pumps can move three or more units of heat into or out of a building.[73]

Emissions

The emission rate of greenhouse gases from electric generation depends on the energy source used to produce it. New England's current electric mix is dominated by fossil gas and nuclear, comprising 52 percent and 27 percent of total generation. respectively.[74] To forecast Massachusetts grid emissions rates for 2040 we assume that the grid resource mix would gradually transition towards clean, renewable energy sources (e.g., solar, wind, etc.) driven by current Clean Energy Standard (CES)[75] obligations. For Massachusetts, these obligations require at least 60 percent of the Commonwealth's electricity sales in 2040 to come from zero-emission sources (see Figure 9 below). The Commonwealth's municipal utilities—12 percent of Massachusetts' electric sales in 2020[76]—are not required to meet the renewable energy targets set out by the RPS or CES. Taking municipal utilities into account results in a CES obligation of roughly 53 percent.

[73] M.J. Bradley & Associates, LLC. 2019. *Life Cycle Analysis of the Northeast Supply Enhancement Project*. Available at: https://www.mjbradley.com/sites/default/files/MJBA_NESE_LCA_06112019.pdf
[74] ISO-NE. 2020. "Resource Mix."
[75] MA DEP 310 CMR 7.00. *7.75 Clean Energy Standard*. Available at: https://www.mass.gov/doc/310-cmr-700-air-pollution-control-regulations/download
[76] U.S. EIA. 2021. "Annual Electric Power Industry Report, Form EIA-861 detailed data files." Available at: https://www.eia.gov/electricity/data/eia861/

Figure 9. Renewable electricity sales under the Massachusetts Clean Energy Standard



Source: (1) MA DEP 310 CMR 7.00. 7.75 Clean Energy Standard. Available at: https://www.mass.gov/doc/310-cmr-700-air-pollution-control-regulations/download. (2) U.S. EIA. 2021. "Form EIA-923 detailed data with previous form data (EIA-906/920)." Available at: https://www.eia.gov/electricity/data/eia923/; (3) U.S. EIA. 2021. "Annual Electric Power Industry Report, Form EIA-861 detailed data files." Available at: https://www.eia.gov/electricity/data/eia861/; (4) U.S. EPA. April 2021. Emission Factors for Greenhouse Gas Inventories. EPA Center for Corporate Climate Leadership. Available at: https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_apr2021.pdf

To estimate the emissions rate for electricity in Massachusetts, we assume all non-renewable generation (47 percent) is provided by gas-fired generators such that the annual grid emissions rate in 2040 is equal to the individual emissions rate for gas (53.1 kg CO2/MMBtu)[77] multiplied by 47 percent resulting in a 2040 emissions rate of 24.8 kg CO2/MMBtu. To account for the efficiency of an air-source heat pump we then divide the 2040 emissions rate by a COP of 4.2[78] to result in an emissions rate of 5.9 kg CO2/MMBtu. In contrast the emissions rate for a new gas furnace (with an efficiency of 95 percent[79]) is 55.9 kg CO2/MMBtu; almost ten times that of an air-source heat pump in 2040. Given the hypothetical nature of incorporating green hydrogen and biogas into the existing gas supply, we are unable to estimate the emissions rate for heating with these potential technologies at this time.

In line with the CES, the *Massachusetts 2050 Decarbonization Roadmap* anticipates a more than doubling of zero-emission electric capacity over the next 30 years, mostly from New England wind and solar.[80]

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[77] U.S. EPA. April 2021. *Emission Factors for Greenhouse Gas Inventories*. EPA Center for Corporate Climate Leadership. Available at: https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_apr2021.pdf

[78] Jadun, P. et al. 2017. *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050*. National Renewable Energy Laboratory. Available at: https://www.nrel.gov/docs/fy18osti/70485.pdf. p.54

[79] M.J. Bradley & Associates, LLC. 2019. *Life Cycle Analysis of the Northeast Supply Enhancement Project*. Available at: https://www.mjbradley.com/sites/default/files/MJBA_NESE_LCA_06112019.pdf

[80] MA EOEEA. 2020. *Massachusetts 2050 Decarbonization Roadmap*. Available at: https://www.mass.gov/info-details/ma-decarbonization-roadmap

Moreover, over 80 percent of proposed (as of February 2022) generating resources in New England are solar and wind, amounting to almost 20,000 MW of new clean energy.[81] This movement to zero-emission electric generation in Massachusetts means that the emissions of any electric appliance decrease every year while emission rates from gas furnaces stay constant.

The number of heat pumps installed in Massachusetts homes is expected to rise dramatically. According to a 2020 report on the buildings sector prepared for the Massachusetts Executive Office of Energy and Environmental Affairs, heat pumps will need to be installed in 100,000 homes per year for the next 25 to 30 years to meet the Commonwealth's climate targets.[82]

Tens of thousands of Massachusetts residents have converted their existing fossil gas or oil heating systems over to electric air-source heat pumps. By 2019, the Massachusetts Clean Energy Center (MassCEC) Whole-Home Air-Source Heat Pump Pilot program (which is no longer accepting applications) had provided heat pump rebates to over 20,000 homes (see Figure 10). Similarly, over 500 ground-source heat pumps have been installed through the now-concluded MassCEC commercial ground-source heat pump program (see Figure 11). While promising, these numbers fall short of Massachusetts' home electrification goals.[83] Massachusetts Department of Energy Resources 2018 *Comprehensive Energy Plan* presents three future scenarios of heat pump adoption which correspond to 2, 20, and 29 percent of Massachusetts homes—which is about 52,000, 533,000, and 766,000 homes respectively—heating with heat pumps by 2030.[84]

To ramp up electrification efforts, MassCEC now has a new set of incentives for both whole-home and partial-home air- or ground-source heat pumps; for example, customers can receive up to $15,000 back for installing a high-efficiency ground-source heat pump.[85]

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[81] ISO-NE. 2021. Regional Electricity Outlook. Available at: https://www.iso-ne.com/about/regional-electricity-outlook/

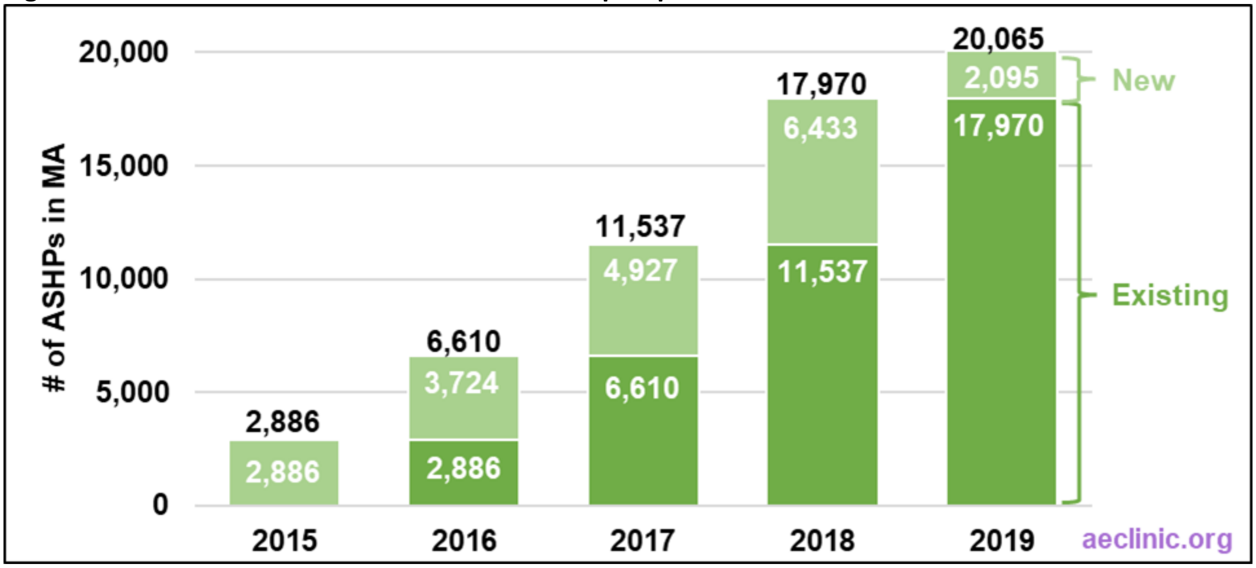
[82] The Cadmus Group, Arup, VEIC, Energy Futures Group, and Evolved Energy Research. 2020. *Buildings Sector Report: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study*. Prepared for the Commonwealth of Massachusetts.

[83] Stasio, T. 2021. "Massachusetts' Electrification Progress is Falling Short" [Blog]. Available at: https://aeclinic.org/aec-blog/2021/8/25/massachusetts-electrification-progress-is-falling-short

[84] (1) Massachusetts Department of Energy Resources. 2018. *Massachusetts Comprehensive Energy Plan*. Available at: https://www.mass.gov/files/documents/2019/01/10/CEP%20Report-%20Final%2001102019.pdf. p. 87, 97, 123; (2) U.S. Census Bureau. 2019. American Community Survey 1-Year Estimates [Table]. House Heating Fuel (Table ID: B25040).

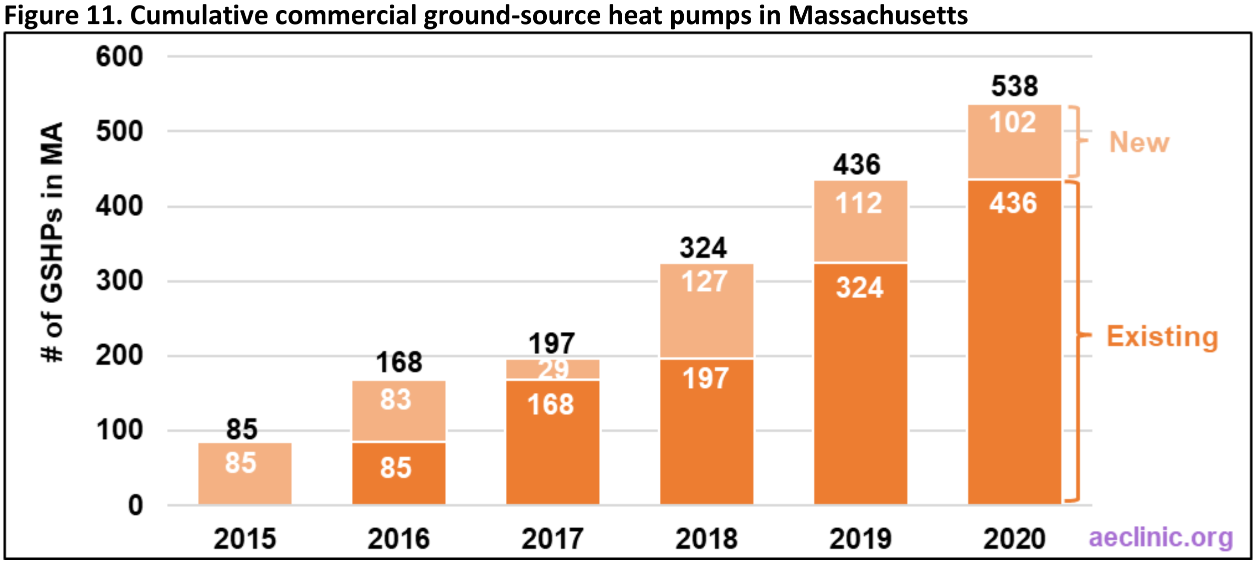
[85] MassCEC. 2022. "Heat Pump Rebates." Available at: https://www.masssave.com/en/saving/residential-rebates/heat-pump?gclid=CjwKCAiAg6yRBhBNEiwAeVyL0GRMOa33Nt4b7nYZGO4kG5hWXYyO0OrQ08ExQvotNYAxGzlKOfiFnBoC8SMQAvD_BwE

Figure 10. Cumulative residential air-source heat pumps in Massachusetts



Source: MassCEC. 2019. Air-Source Heat Pump Residential Projects Database. Available at: https://www.masscec.com/public-records-requests

Figure 11. Cumulative commercial ground-source heat pumps in Massachusetts



Source: MassCEC. 2020. Residential and Small-Scale Ground-Source Heat Pumps Database. Available at: https://www.masscec.com/ground-source-heat-pumps

Possible way forward

One possible path forward is a system of networked ground-source heat pumps[86] that can be installed, owned and operated by a local gas utility. Networked geothermal can be used for both heating and cooling and, because it is powered by electricity, releases fewer emissions than fossil gas. Network geothermal has an efficiency of 600 to 800 percent, meaning that for each unit of energy used, network geothermal can

[86] For example, see HEET's GeoGrid model: HEET. n.d. "The GeoGrid." Available at: https://heet.org/geogrid/

move 6 to 8 units of heat into or out of a building.[87] According to a forthcoming Energy+Environmental Economics report, of the eight pathways analyzed networked geothermal is the second most affordable decarbonization pathway, behind low electrification efforts.[88] Both Eversource[89] and National Grid[90] were approved in 2020 and 2021 respectively to install demonstration installations of networked geothermal in Massachusetts.

[87] Castigliego, J. R., Alisalad, S., Stasio, T., and Stanton, E. A. 2021. *Inflection Point: When Heating with Gas Cost More*. Applied Economics Clinic White Paper, AEC-2021-01-WP-01. Available at: https://aeclinic.org/publicationpages/2021/01/13/inflection-point-when-heating-with-gas-costs-more

[88] Energy+Environmental Economics and Scott Madden Management Consultants. Forthcoming March 2022. *The Role of Gas Distribution Companies in Achieving the Commonwealth's Climate Goals*.
the Commonwealth's Climate Goals.

[89] (1) Eversource. No date. "Geothermal Pilot Program for Eastern Massachusetts". Available at: https://www.eversource.com/content/ema-c/business/save-money-energy/explore-alternatives/geothermal-pilot-program; (2) Eversource. 2022. "Eversource and the City of Framingham Set to Launch Environmentally Friendly Geothermal Project." Available at: https://www.eversource.com/content/wma/residential/about/our-company/news-room/massachusetts/newspost?Group=massachusetts&Post=eversource-and-the-city-of-framingham-set-to-launch-environmentally-friendly-geothermal-project

[90] Gilvarg, C. December 16, 2021. "Department of Public Utilities Approves National Grid Geothermal Demonstration Project". MA DPU. Available at: https://www.mass.gov/news/department-of-public-utilities-approves-national-grid-geothermal-demonstration-project

V. Annual Home Heating Costs

To better understand the impact of the costs of different heating options on Massachusetts households, AEC compared household annual heating costs for fossil gas, biogas, hydrogen, combinations of these three fuels, and electric heat pumps. (The injection of hydrogen into Massachusetts pipelines appears to be infeasible before 2040; scenarios using hydrogen are presented here only for the purpose of allowing cost comparisons.) The cost estimates presented here include only energy bills (not equipment purchases) and only heating (not cooling, which would increase cost savings of heat pumps). These annual energy cost estimates are a useful measure for understanding households ongoing costs and impacts on renters. Equipment costs are also important but are strongly impacted by policy choices regarding rebates and other incentives.

AEC's cost estimates include a conservative assumption that has the impact of reducing the costs of future fossil gas and fossil gas blend options for heating. We assume that the number of gas customers remains constant over time in our fossil gas and gas blend scenarios. If instead, the number of gas customers falls—a likely outcome of Massachusetts' decarbonization goal of adding about a million new heat pump customers by 2050[91]— the remaining customers will need to shoulder more of the costs, resulting in higher rates and bills for those unable to electrify their heating. As a result, the home heating costs for fossil gas and fossil gas blends shown throughout this section are likely underestimated. Researchers at the Energy Institute at Haas find that, on average, a 20 percent decrease in U.S. residential gas customers would increase bills by about $40 per year for remaining gas customers. The relationship between lost gas customers and gas bills is not linear; with a 40 percent reduction in customers, bills for remaining gas customers would rise $115 per year.[92] In Massachusetts, bill increases would likely be higher due to the gas system replacements required as part of utility's gas system enhancement plans (GSEP). The cost to replace and repair Massachusetts gas infrastructure would be passed on to remaining customers; In a 2020 policy brief, AEC found that a realistic customer decline (i.e., the number of customers declines to zero by 2050 based on assumed electrification of space and water heating) would result in a $28-$30 per month GSEP charge compared to the $5 monthly GSEP charge today.[93]

If the Commonwealth were to pursue a decarbonization pathway which relied on electrification of the buildings sector, without policies aimed at enhancing energy equity, low-income households who cannot afford to switch their heating systems will most likely bear the brunt of rising gas rates.[94]Assuming no change in current rate components other than the gas supply price, this report finds that heating an

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[91] The Cadmus Group, Arup, VEIC, Energy Futures Group, and Evolved Energy Research. 2020. *Buildings Sector Report: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study*. Prepared for the Commonwealth of Massachusetts.

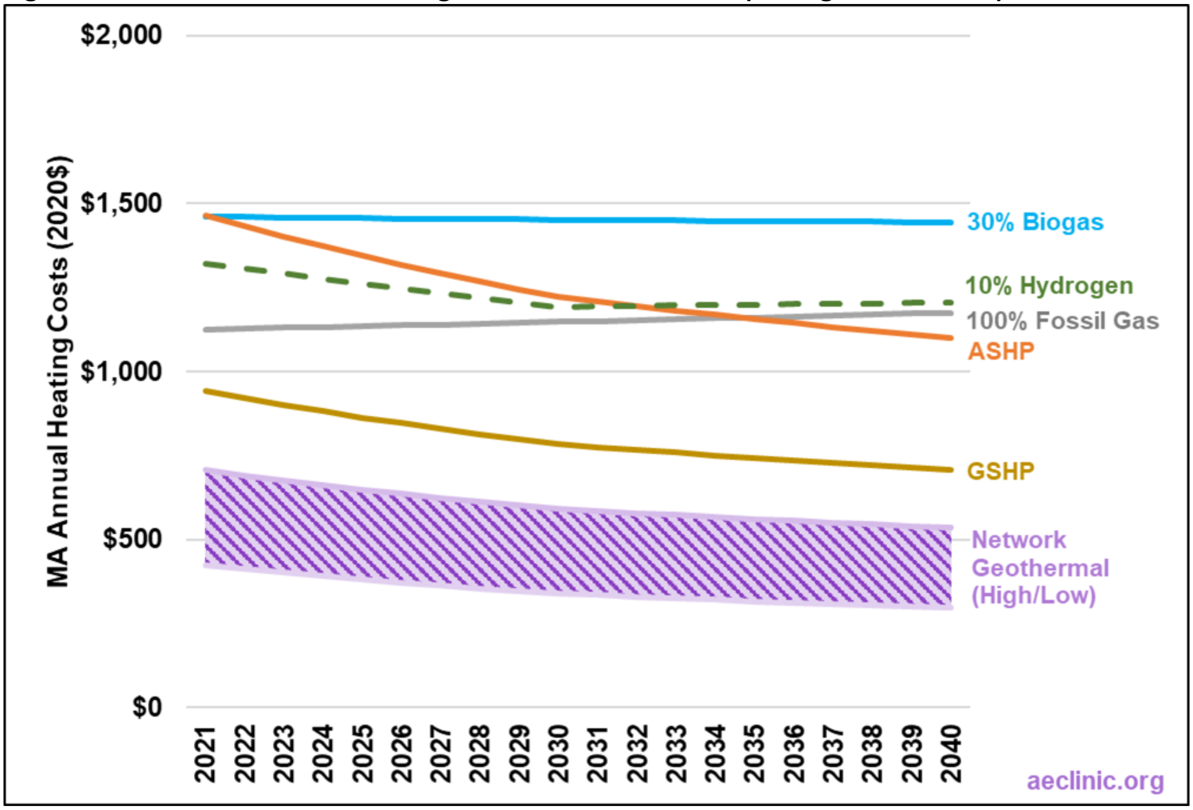
[92] Davis, L. W., and Hausman, C. January 2022. *Who will pay for legacy utility costs?* Energy Institute at Haas White Paper, WP 317R. Available at: https://haas.berkeley.edu/wp-content/uploads/WP317.pdf

[93] Castigliego, J. R., Stasio, T., Stanton, L. 2020. *Fixing Massachusetts' Leaky Pipes: When Will It Be Paid Off?*

[94] For more information about equitable electrification, see: Stasio, T., Woods, B., Castigliego, J. R., and Stanton, E.A. 2021. Equity Assessment of Electrification Incentives in the District of Columbia, Applied Economics Clinic. Prepared on behalf of Office of People's Counsel for the District of Columbia. Available at: https://aeclinic.org/publicationpages/2021/12/6/equity-assessment-of-electrificatio-incentives-in-the-district-of-columbia

average-sized home[95] in Massachusetts using fossil gas will be more expensive than heating with air-source heat pumps by the mid-2030s and is already more expensive than heating with ground-source heat pumps and networked geothermal systems (see Figure 12).

Figure 12. Annual residential heating costs in Massachusetts (average-sized home)



Note: For more information on how these costs were calculated see Appendix B: Methodology and Assumptions.

Assuming there is enough supply, a 30 percent blend of biogas with fossil gas is the most expensive home heating option from 2022 onwards. If it were available today, a 10 percent blend of green hydrogen with fossil gas would be more expensive than heating with fossil gas, ground-source heat pumps, and networked geothermal but less expensive than biogas and ASHPs; however, there is no current source for green hydrogen in Massachusetts and no way to transport or store it. In addition, green hydrogen cannot be safely injected into the Commonwealth's existing leak-prone gas infrastructure until 2040 when the leak prone distribution system is entirely replaced. After 2040, the annual heating cost of a 10 percent hydrogen/fossil gas blend would range from $1,320 today to $1,210 in 2040.

Throughout our 2021 to 2040 analysis period networked geothermal (or "district heating") systems have the lowest energy bills. (Note that these results update our analysis from January 2021[96] using the most

[95] The average-sized home in New England requires 59 million Btus (abbreviated "MMBtu") of heat each year, regardless of the energy source that produces the heat. Source: U.S. EIA. May 2018. 2015 RECS Survey Data [Table CE6.1]. Available at: https://www.eia.gov/consumption/residential/data/2015/c&e/pdf/ce6.1.pdf

[96] Castigliego, J. R., Alisalad, S., Stasio, T., and Stanton, E. A. 2021. *Inflection Point: When Heating with Gas Cost More*.

recent gas and electric utility rate information.)

The remainder of this section explores the hypothetical cost of heating using biogas and green hydrogen blended with fossil gas. Substantial technical and supply availability barriers prevent these energy sources from being viable alternatives to electric heat pumps today or in the near future. Importantly, the prices assumed here do not include the costs associated with overcoming the significant technical barriers to injecting biogas and/or green hydrogen into the Commonwealth's existing fossil gas infrastructure discussed in Sections II and III above.

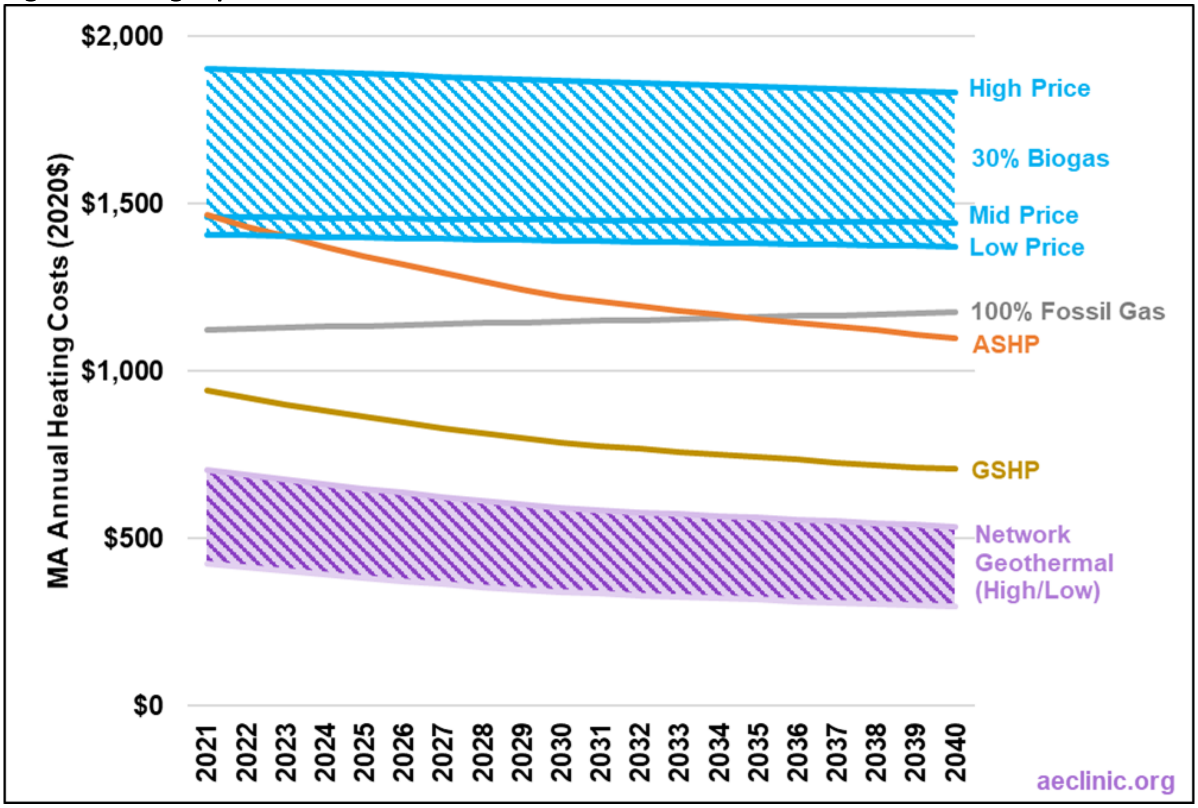
In addition to a 30 percent biogas blend, we considered several other biomass concentrations.[97] All in all, the cost to heat the average home in Massachusetts is substantially more expensive using biogas. The higher the biogas share of the total gas volume, the higher the total annual consumer energy bills. In 2025: each additional 10 percent of biogas mixed into fossil gas adds another $107 to the average-sized home's annual heating costs.

Using the 30 percent biogas/70 percent fossil gas blend, potential home heating costs range from $1,407 to $1,903 in 2021 (see Figure 13). The low-, mid-, and high-biogas price projections correspond to different price scenarios for biogas, based on our review of recent sources discussed in Section II above. Again, regardless of the price projection used, the biogas/fossil gas blend is more expensive than fossil gas, heat pumps, or networked geothermal. Because the supply of biogas is limited, it is reasonable to expect that biogas prices would likely be closer to the high-biogas price shown here rather than the low- or mid-biogas price.

Applied Economics Clinic White Paper, AEC-2021-01-WP-01. Available at: https://aeclinic.org/publicationpages/2021/01/13/inflection-point-when-heating-with-gas-costs-more

[97] See Biogas prices and scenarios in Appendix B: Assumptions and Methodology for more information.

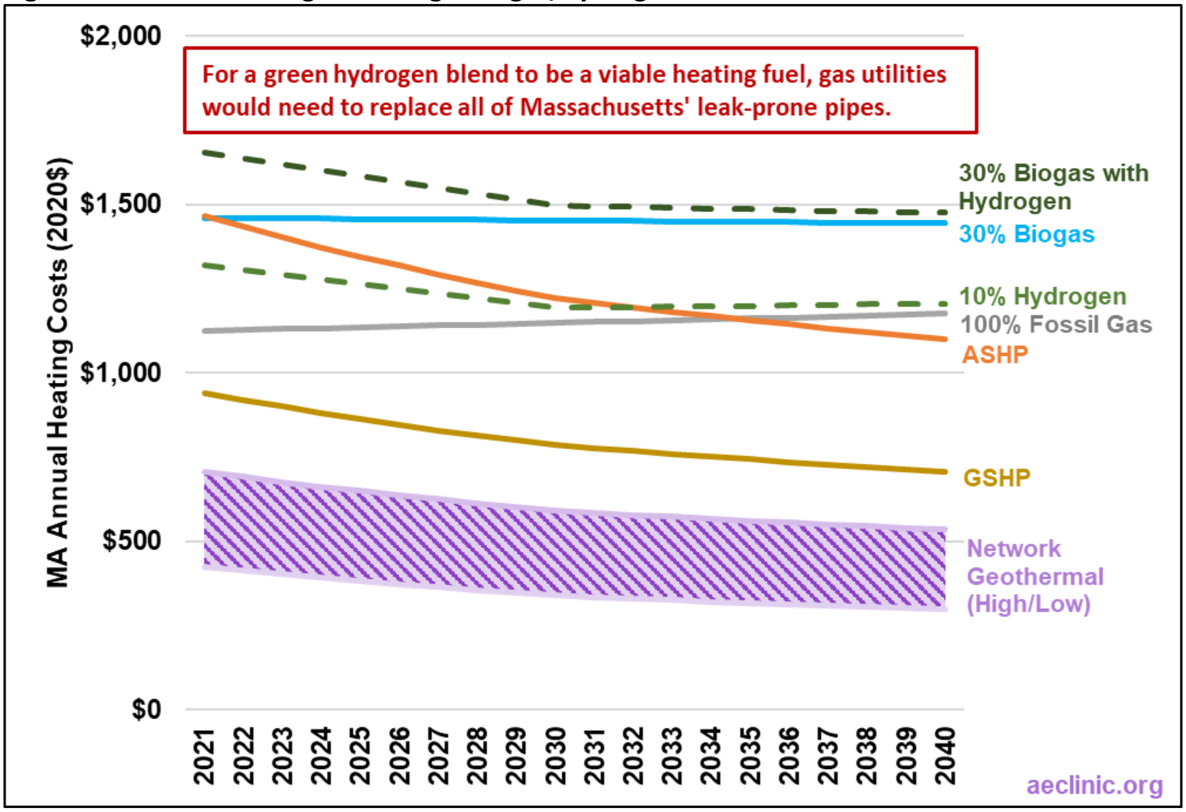
Figure 13. Biogas price scenarios



Note: For more information on how these costs were calculated see Appendix B: Methodology and Assumptions.

Using a 30 percent biogas/10 percent hydrogen/60 percent fossil gas blend to heat Massachusetts homes is more expensive than fossil gas alone, heat pumps, and networked geothermal both now and in the future (see Figure 14).

Figure 14. Annual heating cost using a biogas/hydrogen blend



Note: For more information on how these costs were calculated see Appendix B: Methodology and Assumptions.

Overall, relying on biogas and/or green hydrogen would result in higher home heating costs for Massachusetts residents. Both alternative fuels sources also emit greenhouse gases, drawing into question their utility in plans to meet Massachusetts' net zero mandate. Across all scenarios, heating with biogas and green hydrogen is more expensive than heating with fossil gas alone. Moreover, the cost to heat the average home using ground-source heat pumps or networked geothermal is already cheaper than fossil gas and heating with air-source heating pumps will be cheaper than fossil gas in the near future.

VI. Policy Conclusions

Massachusetts is running out of time to implement reforms capable of halving greenhouse gas emissions by 2030 and reaching net zero emissions by 2050. Heating buildings is a major source of emissions that will require a new, forward-looking approach to successfully decarbonize. This white paper compares three prevalent policy ideas for decarbonizing the buildings sector. Two of these proposals (blending fossil gas with upgraded biogas and green hydrogen) change the fuel used (partially replacing fossil gas) but would continue to rely primarily on a fossil gas mixture with very serious health and safety risks. Moreover, the high investment cost of replacing and/or repairing Massachusetts' aging gas infrastructure would not be paid off during this century under current repayment schedules.[98] With such a long timeline for paying off these costs, it is a distinct possibility that gas infrastructure investments will end up unpaid, or stranded, as the Commonwealth moves away from fossil fuels. A third proposal involves a larger conceptual change: relying our existing network of electric lines to power several different types of highly efficient electric heat pumps for both heating and cooling.

Our analysis shows that—compared to distribution of biogas and hydrogen via pipelines—building electrification (1) provides strong emission reductions which grow stronger over time as our electric grid moves to more renewables, (2) has more reliable sources of energy supply, (3) costs customers less (immediately if delivered through networked geothermal and soon if delivered through air source heat pumps), (4) is less likely to result in potential stranded assets, and (5) lacks any major safety concern (see Figure 15).

[98] Castigliego, J. R., Stasio, T., Stanton, L. 2020. *Fixing Massachusetts' Leaky Pipes: When Will It Be Paid Off?*

Figure 15. Report card for heating fuel alternatives

	Fossil Gas **C**	Upgraded Biogas **D**	Green Hydrogen **F**	Electricity **A**
Emissions	**Poor** CO_2 from combustion and CH_4 from leaks	**Okay** CH_4 leaks and upstream emissions	**Okay** Indirect GHGs from H_2 & NO_X	**Good** Depends on fuel source, renewable share growing
Supply	**Very Good** Sufficient and consistent supply from fracking	**Poor** Limited local feedstocks	**Poor** Competes with other uses for renewable energy	**Very Good** Supply of renewable electricity expected to rise
Energy Bills	**Good** Currently low cost, vulnerable to price volatility	**Okay** 4 times more expensive than fossil gas today	**Poor** 6 times more expensive than fossil gas today	**Good** Using ground source heat pumps is cheaper than gas
Feasibility	**Poor** $16-$17B needed to stop distribution leaks	**Poor** $16-$17B needed to repair leaks; plus upgrades	**Poor** $16-$17B needed to repair leaks; plus upgrades	**Good** Widely available energy source (retrofits required)
Safety	**Poor** High risk of leaks and explosions	**Poor** High risk of leaks and explosions	**Poor** Increased risk of leaks and explosions	**Very Good** No risk of leaks or explosions

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For proponents of the use of biogas and hydrogen in reducing emissions in the Massachusetts building sector: The viability of these energy sources as large-scale solutions for the Commonwealth is at best an open question. The use, cost, and emissions of electric heat pumps are well studied, well understood, and involve few uncertainties. In contrast, if biogas and hydrogen are put forward as part of a decarbonization plan these questions must be addressed:

- What are the life-cycle CO_2 and non-CO_2 emissions of the specific (not generic) substances and processes that will be used to produce and transport this biogas and/or hydrogen?
- Is there a guaranteed supply of the biogas and/or hydrogen proposed for inclusions? Have contracts been signed guaranteeing this supply?
- What is the delivered (into the Massachusetts distribution system) price of this biogas and/or hydrogen?
- What specific upgrades will be needed to Massachusetts transmission, distribution, and heating infrastructure to allow the introduction of what specific shares of biogas and/or hydrogen? How long would these upgrades take? Are there bids offering quotes for this work?

- What analysis has been performed regarding health and safety risks associated with introducing biogas and/or hydrogen into the Massachusetts gas distribution system?

Without detailed answers to questions like these, switching to biogas and hydrogen in Massachusetts gas distribution and heating systems is more of a theory than a plan.

Appendix A: Biogas resources

Table 4. List of reviewed biogas studies

Study	Source
E3 2020	Aas, D. et al. April 2020. *The Challenge of Retail Gas in California's Low-Carbon Future* . Prepared for California Energy Commission. CEC-500-2019-055-F. Available at: https://ww2.energy.ca.gov/2019publications/CEC-500-2019-055/index.html
ICF/WGL 2020	ICF. March 2020. *Study on the Use of Biofuels (Renewable Natural Gas) in the Greater Washington, D.C. Metropolitan Area* . Prepared for Washington Gas Light Company. Available at: https://edocket.dcpsc.org/public/search/details/fc1142/597
ICF/AGF 2019	American Gas Foundation. December 2019. *Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment* . Prepared by ICF. Available at: https://www.gasfoundation.org/2019/12/18/renewable-sources-of-natural-gas/
Parker et al. 2017	Parker, N. et al. 2017. "Renewable natural gas in California: An assessment of the technical and economic potential." Energy Policy 111, 235-245. Available at: https://doi.org/10.1016/j.enpol.2017.09.034.
UC Davis 2016	Jaffe, A. et al. June 2016. *The Feasibility of Renewable Natural Gas as a Large-Scale, Low Carbon Substitute* . UC Davis Institute of Transportation Studies. UCD-ITS-RR-16-20. Available at: https://steps.ucdavis.edu/wp-content/uploads/2017/05/2016-UCD-ITS-RR-16-20.pdf.
NREL 2014	Saur, G., Milbrandt, A. July 2014. *Renewable Hydrogen Potential from Biogas in the United States* . National Renewable Energy Laboratory (NREL). Available at: https://www.nrel.gov/docs/fy14osti/60283.pdf
Duke 2014	Murray et. al. February 2014. *Biogas in the United States: An Assessment of Market Potential in a Carbon-Constrained Future* . Nicholas Institute for Environmental Policy Solutions, Duke University. Available at: https://nicholasinstitute.duke.edu/content/biogas-united-states-assessment-market-potential-carbon-constrained-future.
NPC 2012	Hamberg, K., et. al. March 2012. *Renewable natural gas for transportation: an overview of the feedstock capacity, economics, and GHG emission reduction benefits of RNG as a low-carbon fuel. Topic Paper #22* . A White Paper for the National Petroleum Council – Future Transportation Fuels Study. Available at: https://www.npc.org/FTF_Topic_papers/22-RNG.pdf
GTI/AGF 2011	American Gas Foundation. September 2011. *The potential for renewable gas: biogas derived from biomass feedstocks and upgraded to pipeline quality* . Prepared by the Gas Technology Institute. Available at: https://www.eesi.org/files/agf-renewable-gas-assessment-report-110901.pdf
DOE BT 2011	Sheehy, P. and Rosenfeld, J. 2017. *Design Principles for a Renewable Gas Standard* . ICF. Available at: https://static1.squarespace.com/static/53a09c47e4b050b5ad5bf4f5/t/5a56701dec212d1888aa212a/1515614239606/ICF_WhitePaper_Design_Principles.pdf **Note:** The DOE BT study (including the most recent update) did not estimate yields of RNG. The focus of the study is on the feedstock rather than the finished fuel. ICF used conversion efficiencies from the UC Davis work to estimate the tBtu of finished fuel (in this case, RNG) based on the feedstock potential reported in the DOE BT study.

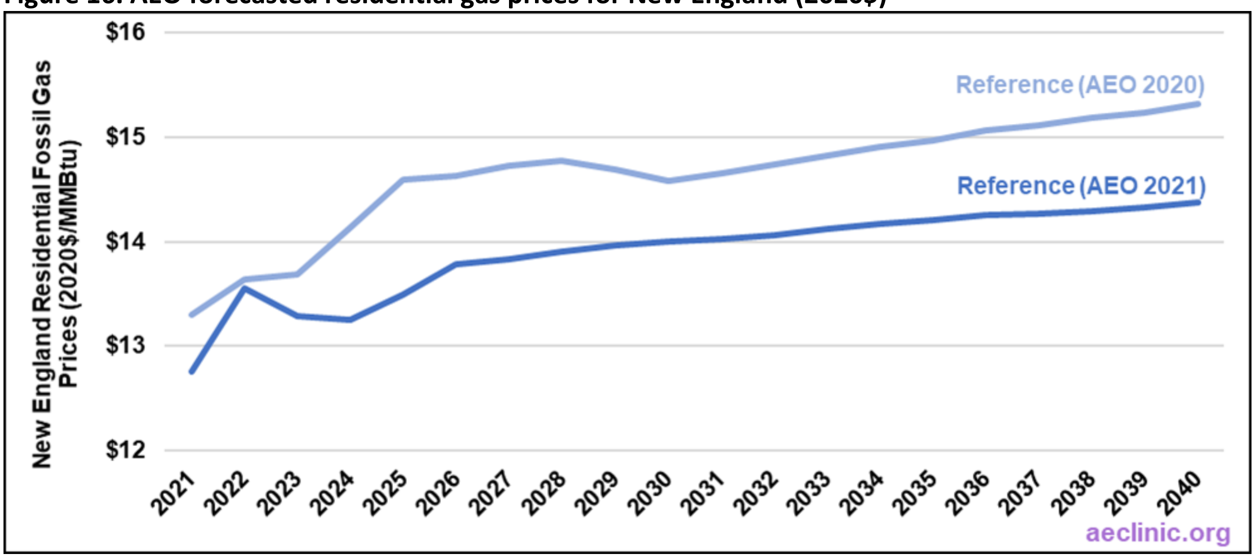
Appendix B: Assumptions and Methodology

To estimate the cost of heating the average home in Massachusetts using the various heating fuels and technologies, AEC adopted the same methodology used in our January 2021 white paper, *Inflection Point: When Heating with Gas Costs More*[99] updated to incorporate the most recent gas and electric rate and sales data.[100] AEC compared heating costs on a $ per MMBtu basis and then scaled these rates to the annual heating costs for an average-sized New England home with a heating requirement of 59 MMBtu.[101] The cost to customers includes all fixed and variable costs that residential customers would pay on their monthly gas and electric bill. The analysis was conducted over the period 2021 to 2040.

Gas and electric prices

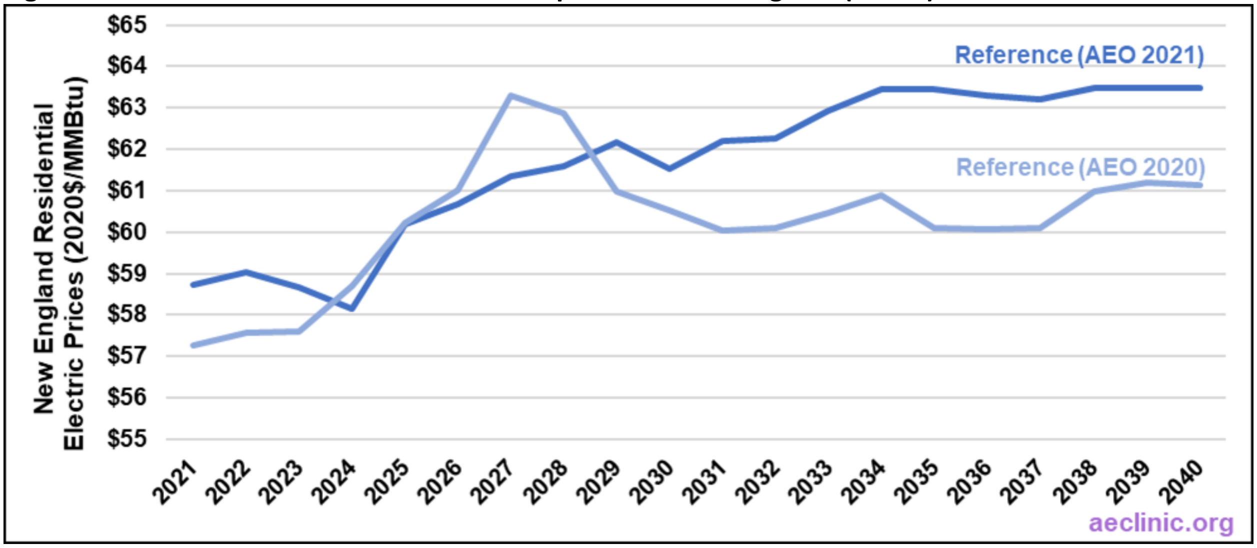
Annual growth rates in residential gas and electric prices are calculated using price forecasts from the U.S. EIA 2021 Annual Energy Outlook (AEO) Reference case (see Figure 16 and Figure 17). The annual average growth rate in the New England residential gas and electric price from 2021 to 2040 is 0.6 percent and 0.4 percent respectively. The annual average fossil gas price growth rate is lower than it was based on the previous years' AEO projection (see Figure 16); the opposite is true for the electric price (see Figure 17).

Figure 16. AEO forecasted residential gas prices for New England (2020$)



[99] Castigliego, J. R., Alisalad, S., Stasio, T., and Stanton, E. A. 2021.
[100] See Appendix C: Utility-specific resources for gas and electric rates for a full list of utility-specific resources.
[101] U.S. EIA. May 2018. 2015 RECS Survey Data [Table CE6.1]. Available at: https://www.eia.gov/consumption/residential/data/2015/c&e/pdf/ce6.1.pdf

Figure 17. AEO forecasted residential electric prices for New England (2020$)



Gas and electric rates

Gas and electric rates for 2021 are based on the most recent service and delivery rates for each Massachusetts' gas and electric utility.[102] Compared to the rates used in AEC's January 2021 white paper, *Inflection Point: When Heating with Gas Costs More,*[103] both gas and electric rates have increased, but electric rates have increased by more. Gas and electric rates are composed of several charges and adjustment factors measured in $ per them for gas and $ per kWh for electricity.

Gas rates for 2021 are based on the most recent service and delivery rates for each Massachusetts' gas utility and include the following charges and adjustment factors:[104]

- Fixed Monthly Customer Charge (converted from a fixed monthly charge to an inferred $ per therm charge by dividing the equivalent annual customer charge by the U.S. EIA's 2020 annual residential gas sales[105] in therms for each utility)
- Distribution Charge ($ per therm)
- Revenue Decoupling Adjustment Factor (RDAF, $ per therm)
- Local Distribution Adjustment Factor (LDAF, $ per therm)
- Gas System Enhancement Adjustment Factor (GSEAF, $ per therm)

[102] See Appendix C: Utility-specific resources for gas and electric rates for a full list of utility-specific resources.
[103] Castigliego, J. R., Alisalad, S., Stasio, T., and Stanton, E. A. 2021.
[104] Charges and adjustment factors are sourced from utility-specific documentation. See Appendix C: Utility-specific resources for gas and electric rates.
[105] U.S. EIA. *EIA Natural Gas Annual Respondent Query System*. 2020. Available at: https://www.eia.gov/naturalgas/ngqs/#?year1=2020&year2=2020&company=Name

- Gas Adjustment Factor (GAF, $ per therm)

Electric rates for 2020 are based on the most recent service and delivery rates for each of Massachusetts' electric utilities, which include the following charges and adjustment factors:[106]

- Fixed Monthly Customer Charge (converted from a fixed monthly charge to an inferred $ per kWh charge by dividing the equivalent annual customer charge by the U.S. EIA's annual residential electric sales[107] in kWh for 2020 for each utility)
- Basic Service Charge ($ per kWh)
- Distribution Charge ($ per kWh)
- Transition Charge ($ per kWh)
- Transmission Charge ($ per kWh)
- Energy Efficiency Charge ($ per kWh)
- Renewable Resource Charge ($ per kWh)
- Distributed Solar Charge ($ per kWh)
- Among other charges and adjustment factors

For more information on electric rates and the calculation of home heating costs for air-source and ground-source heat pumps, see AEC's January 2021 white paper, *Inflection Point: When Heating with Gas Costs More.*[108]

Biogas prices and scenarios

Customers do not currently heat their homes using biogas. Therefore, AEC conducted a review of the price of biogas from recent sources (see Figure 5 above). Based on this review, AEC assumes three biogas price scenarios: "Low," "Mid," and "High" (see Figure 18). The "Low" price range starts with $18 per MMBtu in 2021 and decreases to $18 per MMBtu in 2040 based on ICF's marginal cost curve for biogas for Washington Gas Light Company.[109] The "Mid" price range starts with $25 per MMBtu in 2021 and decreases to $22 per MMBtu in 2040 based on ICF's 2025, 2032 and 2040 marginal cost curves for biogas for the District of Columbia.[110] Lastly, the "High" price range starts with $50 per MMBtu and decreases to $44 per MMBtu in 2040 representing a reasonable estimate of a high biogas price based on our review of recent sources which includes prices ranging from $8 per MMBtu to $90 per MMBtu (see Figure 5 above).

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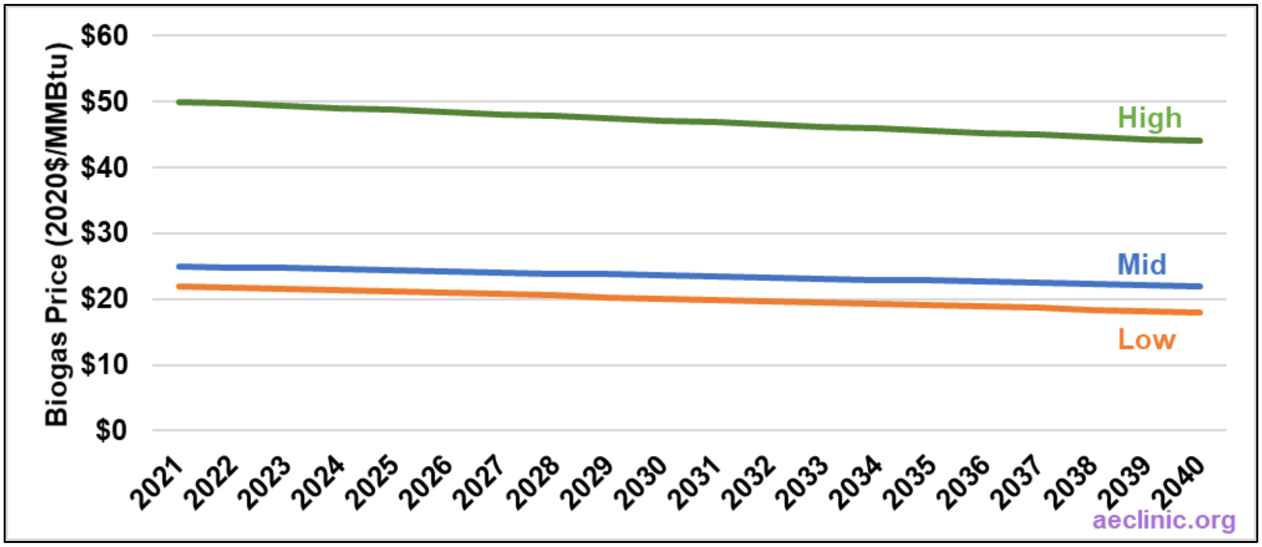
[106] Charges and adjustment factors are sourced from utility-specific documentation. See Appendix C: Utility-specific resources for gas and electric rates.
[107] U.S. EIA. 2020. "Sales_Ult_Cust_2020". EIA-861 Annual Survey Data. Available at: https://www.eia.gov/electricity/data/eia861/
[108] Castigliego, J. R., Alisalad, S., Stasio, T., and Stanton, E. A. 2021.
[109] ICF. March 2020. *Study on the Use of Biofuels (Renewable Natural Gas) in the Greater Washington, D.C. Metropolitan Area [Figure 14]*.
[110] Ibid. [Figure 13]

A linear price projection is used to interpolate the biogas price in between 2021 and 2040 for each of the scenarios.

Figure 18. Biogas price projections (2020$)



AEC then considers five blends of fossil gas and biogas:

- 100% Fossil Gas
- 70% Fossil Gas/30% Biogas
- 50% Fossil Gas/50% Biogas
- 25% Fossil Gas/75% Biogas
- 100% Biogas

To calculate the average cost of a heating a home using fossil gas, biogas, or any of the blends identified above, we estimated the average home heating cost of each of these fuel sources based on their respective prices and the average New England residential heat requirement. The fossil gas price is a weighted average of Massachusetts' gas utilities gas rates. As was mentioned above, these rates are composed of several charges and adjustment factors, measured in $ per therm. These components are explained detail in Appendix B of our January 2021 white paper, *Inflection Point: When Heating with Gas Costs More*.[111] Using the appropriate efficiency rate for a new gas furnace (95 percent)[112] and the U.S. EIA's conversion factor (10 therms per MMBtu)[113], these utility-specific gas charges and adjustment factors were converted from $ per therm to the more universal measure of $ per MMBtu.

The cost of electricity used in residential gas furnace operations was also included in total customer

[111] Castigliego, J. R., Alisalad, S., Stasio, T., and Stanton, E. A. 2021. Appendix B: Methodology and Assumptions.
[112] M.J. Bradley & Associates, LLC. 2019. *Life Cycle Analysis of the Northeast Supply Enhancement Project*.
[113] U.S. EIA. Last Updated June 3, 2020. "Units and calculators explained". Available at: https://www.eia.gov/energyexplained/units-and-calculators/energy-conversion-calculators.php

charges. This cost was calculated by multiplying by the U.S. EIA's typical electric consumption for a gas furnace (322 kWh per year)[114] by the weighted average of variable residential electric charges ($0.24 per kWh) and then dividing that product by the U.S. EIA's 2020 annual residential gas sales[115] in MMBtu for each utility.

The biogas price is calculated using a similar methodology as the fossil gas price. However, one component of the fossil gas price, the price of fossil gas supply (also known as the gas adjustment factor), is replaced with each of the estimated biogas prices from Figure 18 above.

To calculate a total price in $ per MMBtu, for each fossil gas/biogas blend scenario, each price is multiplied by its portion, or share, of the blend. Massachusetts average annual heating cost is the total price is multiplied by the New England heating requirement for an average home (59 MMBtu).[116]

Green hydrogen prices

Like biogas, green hydrogen blended with fossil gas is not currently used to heat homes. To estimate the price of green hydrogen, AEC conducted a review of various sources (see Figure 7 and Figure 8 above). Based on this review, AEC assumes three price benchmarks for green hydrogen:

- $39 per MMBtu in 2021 (the mid-point for medium systems today according to LAZARD's 2021 study)[117]
- $14 per MMBtu in 2030 (the mid-point between alkaline and polymer electrolyzers in 2030 according to Strategy&'s 2021 study)[118]
- $12 per MMBtu in 2040 (based on the mid-point between alkaline and polymer electrolyzers in 2050 according to Strategy&'s 2021 study[119])[120]

A linear price projection is used to interpolate the years between these benchmarks (see Figure 19).

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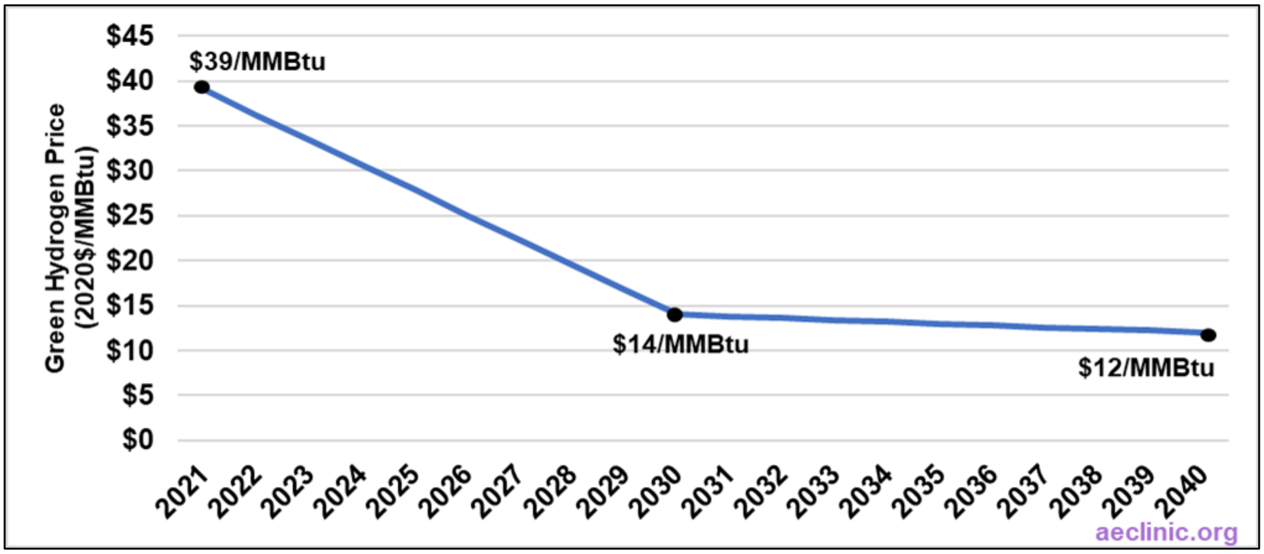
[114] U.S. EIA. 2018. Technology Forecast Updates - Residential and Commercial Building Technologies - Reference Case. p. 8. Available at: https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf.
[115] U.S. EIA. EIA Natural Gas Annual Respondent Query System. 2020.
[116] U.S. EIA. May 2018. 2015 RECS Survey Data [Table CE6.1].
[117] LAZARD. 2021. *LAZARD's Levelized Cost of Hydrogen-Version 2.0*. p.12;
[118] Anouti, Y., Kombargi R., Elborai S., and Hage, R. 2020.
[119] Anouti, Y., Kombargi R., Elborai S., and Hage, R. 2020.
[120] The mid-point price in 2050 is $9, assuming a linear price decrease from 2030 to 2040, the projected price in 2040 is $12.

Figure 19. Green hydrogen price projection



AEC then considers a blend of fossil gas (60 percent), biogas (30 percent), and green hydrogen (10 percent). Due to technical and infrastructure-related constraints (see Section III), we assume that green hydrogen is injected into existing fossil gas pipelines comprising 10 percent of total gas volume.

To calculate the average cost of a heating a home using green hydrogen or any of the blends identified above, we estimated the average home heating cost of green hydrogen using its price and the average New England residential heat requirement. The green hydrogen price is calculated using a similar methodology as the biogas price discussed above; the price of fossil gas supply is replaced with the estimate green hydrogen price from Figure 19 above.

The total price, in $ per MMBtu, for the fossil gas/biogas/green hydrogen blend scenario, is calculated by multiplying each price by its share of the blend. The green hydrogen price is multiplied by 0.10, because it is assumed to comprise 10 percent of the blend. The Massachusetts average annual heating cost is the total price is multiplied by the New England heating requirement for an average home (59 MMBtu).[121]

Appendix C: Utility-specific resources for gas and electric rates

Gas Rates and Information

Base Rate Charges and Adjustment Factors

- Eversource. May 2021. "2021 Summary of Eastern Massachusetts Gas Rates". 06-Domestic Heating. Available at: https://www.eversource.com/content/docs/default-source/rates-tariffs/summary-rates-gas.pdf
- Boston Gas. 1 November 2020. "Approved Rates for Massachusetts". R-3 Residential

[121] U.S. EIA. May 2018. 2015 RECS Survey Data [Table CE6.1].

Heating. Available at: https://gasrates.nationalgridus.com/ne/Web%20Boston%201120%20v2.pdf

- Colonial Gas. 1 May 2021. "Approved Rates for Massachusetts". R-3 Residential Heating. https://gasrates.nationalgridus.com/ne/Web%20Colonial%201120%20v2.pdf
- Columbia Gas. February 2021. *Winter Rates*. Tariff Rates R&T 3. Available at: https://www.columbiagasma.com/our-company/about-us/regulatory-information
- Eversource. May 2021. "2021 Summary of Eastern Massachusetts Gas Rates". 06-Domestic Heating. Available at: https://www.eversource.com/content/docs/default-source/rates-tariffs/summary-rates-gas.pdf
- Liberty Utilities. Effective February 1, 2021. "Sales Service Rates - Peak". Available at: https://massachusetts.libertyutilities.com/uploads/Feb%201%20-%20Sales%20Service%20Rates%20-%20Peak.pdf
- Unitil. May 2021. *Summary of Gas Rates*. R3 Residential Heat Rate. Available at: https://unitil.com/energy-for-residents/gas-information/tariffs
- Massachusetts Department of Public Utilities (MA DPU). April 2021. *2020/2021 Peak Gas Adjustment Factors*. Available at: https://www.mass.gov/doc/gaf-historical-data-workbook-1999-2019/download

Gas System Enhancement Adjustment Factors (GSEAFs)

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