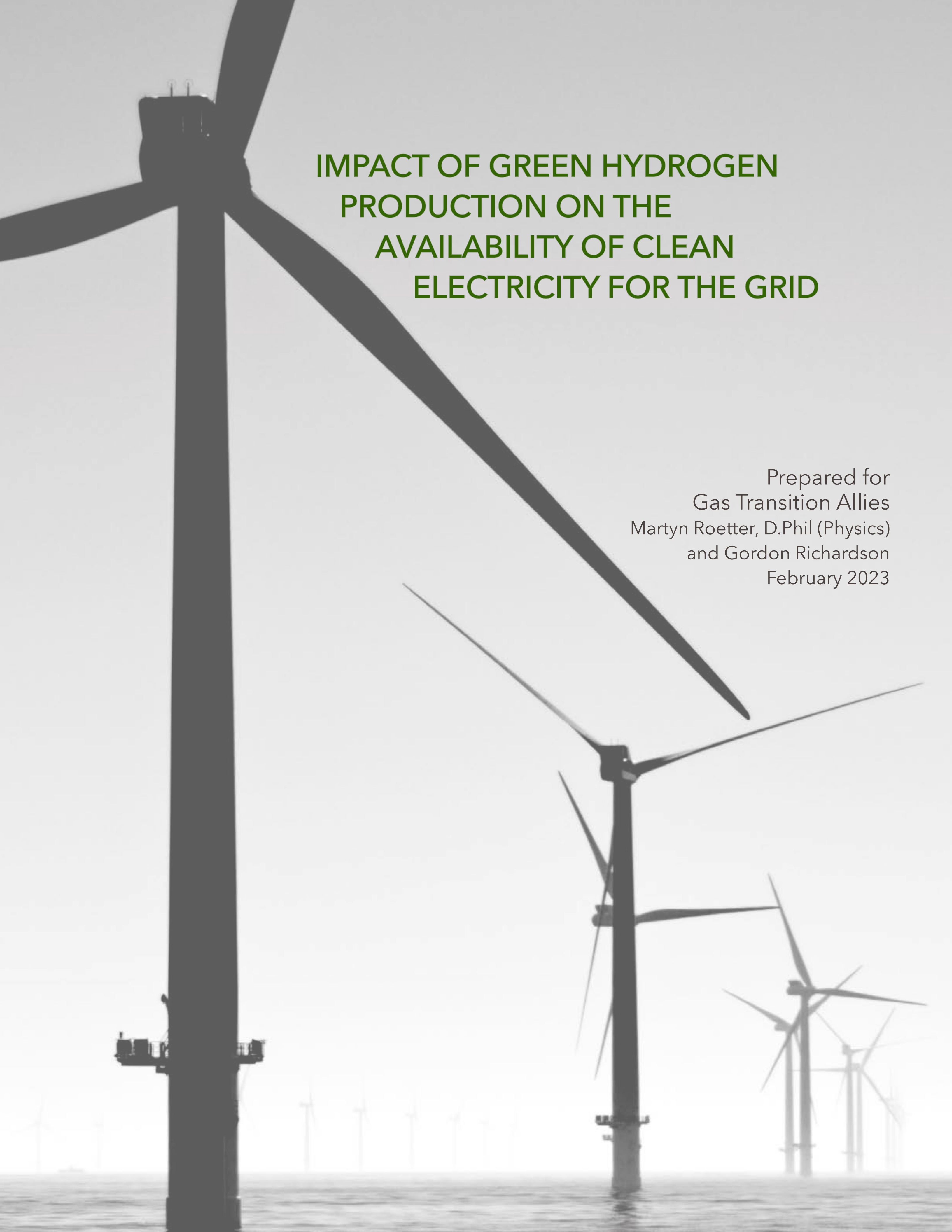

IMPACT OF GREEN HYDROGEN PRODUCTION ON THE AVAILABILITY OF CLEAN ELECTRICITY FOR THE GRID

Prepared for
Gas Transition Allies
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February 2023

Report prepared by Martyn Roetter and Gordon Richardson for Gas Transition Allies, a voluntary association. *Impact of Green Hydrogen Production on the Availability of Clean Electricity for the Grid* was written in their individual capacity and not as participants in Gas Transition Allies, nor on behalf of or with the endorsement of Gas Transition Allies or any participating organization.

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Please contact gastransitionallies@gmail.com with any questions or observations you may have.

Cover photo: Nicholas Doherty on Unsplash

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Executive Summary

Gas utilities in the Commonwealth of Massachusetts are proposing to use variable renewable energy sources, particularly wind power, to produce green hydrogen to replace various proportions of fossil methane (natural gas), now burned for heat in 1.3 million homes and hundreds of thousands of commercial buildings across the Commonwealth. In order to meet the goals of the Commonwealth's Climate Action Roadmap,[1] gas utilities or LDCs (local distribution companies)[2] intend to use green hydrogen and renewable natural gas (RNG), pumped through the gas distribution system, to achieve reductions in greenhouse gas (GHG) and other harmful emissions attributable to the building sector.

In this report, we estimate the increase in the demand for clean electricity that would result from using green hydrogen as a replacement for varying proportions of the methane currently burned in buildings in Massachusetts versus a similar calculation using the option of electric-powered heat pumps.

1 An Act Creating a Next-Generation Roadmap for Massachusetts Climate Policy, 2021. https://malegislature.gov/Laws/SessionLaws/Acts/2021/Chapter8 Accessed 1/11/2023

2 The LDCs' recommendations have been widely published and publicized—one extensive resource is available in their DPU's Docket 20-80 ("Future of Gas") filings, which are accessible at: Energy and Environmental Affairs, Department of Public Utilities, Docket Filings. https://eeaonline.eea.state.ma.us/DPU/Fileroom/dockets/bynumber/20-80 Accessed 1/11/2023

Key findings are:

- **Electric supply needs more than triple.** The supply of electricity needed to produce green hydrogen in quantities necessary to replace the natural gas currently used in buildings in Massachusetts is more than 3.4 times higher than electricity-powered heat pumps.

- **Electric demand rises.** Consequently, the total consumption of electricity in Massachusetts for all applications would increase to 2.7 times its current level if all methane in buildings were replaced by 100 percent hydrogen,[3] whereas the complete replacement of methane combustion systems by heat pumps would increase it to 1.5 times the present level.

- **More turbines required.** The capacity of offshore wind turbines needed to generate enough electricity to manufacture green hydrogen to replace 20 percent of methane burned in buildings is 3.9 GW (gigawatts), which exceeds the 3.2 GW of capacity predicted to be available for Massachusetts in 2030.[4]

- **Green grid delayed.** Blending hydrogen with methane to heat buildings will cannibalize the supply of clean electricity, diverting it from its primary targeted purpose of direct delivery to the electric grid and reducing GHG emissions from the electrification of buildings and vehicles.

DEFINITIONS

Green hydrogen is hydrogen produced by splitting water into hydrogen and oxygen using renewable clean electricity. This production method is considered non-polluting.

Fossil hydrogen (more commonly referred to as gray, blue, black, or brown hydrogen) or "dirty" hydrogen is used currently in applications such as fertilizer production and the refining of petroleum.

Renewable natural gas (RNG), also referred to as biomethane, has the same chemical composition as the fossil fuel natural gas or methane. RNG is produced today by biological processes from multiple sources, including livestock waste, landfills, wastewater sludge, food waste, and other organic waste operations, first as biogas. The biogas is then upgraded and purified to be fully interchangeable with natural gas in existing pipelines and gas appliances.

3 The combustion systems fueled by methane (boilers, furnaces, and appliances) would have to be modified or even replaced if hydrogen accounted for more than a minor proportion of the gas in a blend with methane. Jones, JS. Hydrogen blends over 5 percent may need infrastructure modifications—study. Smart Energy International. August 3, 2022. https://www.smart-energy.com/industry-sectors/energy-grid-management/hydrogen-blends-over-5-may-need-infrastructure-modifications-study/ Accessed 1/11/2023

4 The Commonwealth of Massachusetts. Massachusetts Clean Energy and Climate Plan for 2025 and 2030, 2022. https://www.mass.gov/doc/clean-energy-and-climate-plan-for-2025-and-2030/download Accessed 1/11/2023

The implications of these findings are sobering:

- Demand for clean electricity to produce green hydrogen will be competing with demand for electricity from existing as well as new applications, such as battery electric vehicles. Substantial increases in electricity consumption are expected from the increasing electrification of these applications, which include heating, transportation, and industrial decarbonization.
- To simultaneously decarbonize the electric grid and supply enough green hydrogen for home and commercial building heating will become impossible within any reasonable time frame up to and including 2050 and likely beyond, given the foreseeable scale and pace of the deployment of clean electricity generation, both planned and envisaged, which can realistically be expected due to the time involved in navigating permitting and siting processes, the delays likely to be encountered and the dramatic growth in generating capacity that will be required.
- Cannibalizing[5] a significant proportion of clean electricity for green hydrogen and diverting it from direct delivery to customers will threaten the imperative goal of achieving grid decarbonization in the power sector, which is critical for plans to reduce emissions in multiple sectors of the economy.
- If clean electricity is diverted to the production of green hydrogen, reductions in emissions attributable to electrification in the building sector (e.g. through heat pump installations) will be smaller and slower because such reductions are linked directly to the pace at which grid electricity becomes greener. For the same reason, targets for progressively reducing emissions will remain harder to achieve and potentially out of reach for the transport sector and industrial users despite their investments in electric solutions.
- Ensuring a reliable supply of green hydrogen is complicated by the unpredictability of wind and solar power availability. Hence uses of clean electricity generated by wind and solar power other than for decarbonization of the power grid and replenishment of energy storage systems during periods of surplus generation, to be drawn upon during periods of deficits in supply, such as for the production of green hydrogen, must be carefully evaluated and managed within an integrated energy planning process.

These findings justify consideration by policymakers of how much clean electricity accessible to the Commonwealth's electric grid can or should be diverted, and under what criteria and operating procedures, to produce green hydrogen rather than delivered directly to electricity users. Diversion of more than a minor proportion would imperil progress towards the goals of

5 The European Union is taking steps to manage the risk of cannibalization. Collins, L. *Green hydrogen production: Final proposal*' of EU Delegated Act calls for quarterly proof of dedicated renewables supply, Dec. 2, 2022. https://www.hydrogeninsight.com/policy/green-hydrogen-production-final-proposal-of-eu-delegated-act-calls-for-quarterly-proof-of-dedicated-renewables-supply/2-1-1365901 Accessed 1/11/2023

building a clean electric grid and hence reducing emissions generated in major sectors of the economy where electrification is required.

Green hydrogen can make useful contributions to the decarbonization of the economy in applications where the direct use of electricity is not feasible. Green hydrogen should be reserved for such applications and treated as a scarce resource, given the huge amount of clean electricity required to produce it.

The applications of green hydrogen should be prioritized according to an agreed-upon set of criteria, to direct its uses to where it will be most valuable. Heating buildings is not an appropriate use for green hydrogen due to the vast amount of electricity this use would demand and the much higher energy efficiency of heat pumps.

Introduction

The motivation for this paper was a dearth of analyses of how much renewable clean energy would be required to produce the green hydrogen inherent in the plans outlined by the gas utilities in the Commonwealth of Massachusetts to decarbonize the building sector. This paper focuses on the proposed use of green hydrogen for heating homes and commercial buildings and the need to consider the implications for clean electricity demand and therefore supply, which its production would entail.

At this stage, it is not clear how much hydrogen the gas utilities envisage delivering by 2050. The apparent plan of one major gas utility, National Grid, is to move from "natural gas" composed predominantly of methane to 100 percent supply of renewable natural gas (RNG, also composed predominantly of methane) and green hydrogen by 2050.[6] National Grid has also indicated that its 100 percent supply will be in the proportion of 20 percent hydrogen and 80 percent RNG.[7] The company has not specified the number or proportion of buildings that may still be using combustible gases for heating decades from now in this scenario.

6 Long-Range Resource and Requirements Plan of Boston Gas Company d/b/a National Grid or the Forecast Period 2022/23 to 2026/27, p.71: "…and gradual ramp-up of renewable natural gas and green hydrogen to 100 percent of supply by 2050." https://fileservice.eea.comacloud.net/FileService.Api/file/FileRoom/15699561, Accessed 1/11/2023

7 National Grid. Our clean energy vision: A fossil-free future for cleanly heating homes and businesses, April, 2022. https://www.nationalgrid.com/document/146251/download?utm_source=US+Newsroom+&utm_medium=-Press+Release+&utm_campaign=Fossil+Free Accessed 1/11/2023

It is also not clear how much combustible gas the gas utilities still plan to deliver through pipelines by mid-century and even later. Presumably National Grid anticipates that it will be a substantial amount given its plans to continue to invest billions of dollars in gas distribution infrastructure through GSEP (Gas System Enhancement Program) until 2044[8]. A large proportion of these investments will become multibillion dollar stranded assets well before the end of their useful lives, typically 50 years, if they are not delivering large revenue-generating flows to customers of the proposed 80/20 supply of RNG and green hydrogen in 2050 and subsequent years.

INTERRELATED ISSUES

Hydrogen production

Electricity generation

Gas transition

GREEN ELECTRICITY

Can be used directly to make the electricity grid green

Can be used in an electrolyzer to make hydrogen

Hydrogen as a Replacement for Natural Gas

It is generally assumed that green hydrogen is the only form of hydrogen to achieve significant reductions in carbon emissions[9]. Either dedicated renewable energy sources for green hydrogen production or substantial oversupplies of renewable energy that exceed demand for significant periods of time are required to produce green hydrogen at a scale sufficient to replace any significant proportion of methane consumption.

Wind energy is one of the most developed and cost-effective forms of renewable clean energy. Massachusetts foresees that its future grid will be largely supplied from offshore wind turbines. These turbines have significantly higher capacity factors[10] than onshore turbines and even more than solar panels. This analysis estimates the number of wind turbines necessary to power the electrolyzer stacks required to produce enough green hydrogen to deliver the thermal energy (heat) in buildings

8 National Grid. Calendar Year 2023 *Gas System Enhancement Plan*, October 31, 2022. See pages 16,17, and 36. https://fileservice.eea.comacloud.net/FileService.Api/file/FileRoom/15691907, Accessed 1/11/2023

9 Howarth, RW, Jacobson, MZ. *How green is blue hydrogen?* Energy Sci Eng. 2021; 9: 1676– 1687. https://doi.org/10.1002/ese3.956

10 The capacity factor of a source of electricity is the ratio of its actual electrical energy output over a given time period to the theoretical maximum electrical energy output over the same period, if operated continuously at full nameplate capacity.

that is now provided by burning methane. Both offshore and onshore turbines are considered, but separately and not in combination. The differences between the numbers and total capacity of these two types of wind turbines provide an idea of the sensitivity of the number and capacity of variable renewable energy (VRE), such as wind, solar, and hydropower installations required to satisfy a demand for specific amounts of electricity to the capacity factors and nameplate capacities (the maximum power output they can produce) of individual VRE sources.

DEFINITIONS

Green hydrogen is hydrogen produced by splitting water into hydrogen and oxygen using renewable clean electricity. This production method is considered non-polluting.

Fossil hydrogen (more commonly referred to as gray, blue, black, or brown hydrogen) or "dirty" hydrogen is used currently in applications such as fertilizer production and the refining of petroleum.

Renewable natural gas (RNG), also referred to as biomethane, has the same chemical composition as the fossil fuel natural gas or methane. RNG is produced today by biological processes from multiple sources, including livestock waste, landfills, wastewater sludge, food waste, and other organic waste operations, first as biogas. The biogas is then upgraded and purified to be fully interchangeable with natural gas in existing pipelines and gas appliances.

Assumptions and Limitations

The electricity consumption of the production of green hydrogen is calculated for two scenarios:

1. Replacement of 20 percent of the methane consumed in buildings by hydrogen
2. Complete replacement of methane by 100 percent hydrogen.

The first scenario, which will only reduce emissions by six to seven percent, corresponds to the maximum proportion of hydrogen that can be accommodated by the existing natural gas pipeline infrastructure and appliances. It is also consistent with the 80/20 mix of renewable methane and hydrogen envisioned by National Grid for 2050.

The second scenario reflects the fact that beyond a blend of 20 percent hydrogen, it would be necessary to switch the gas distribution grid directly and abruptly to

100 percent hydrogen supply[11], requiring the premature replacement of all existing natural gas boilers and appliances, at an enormous cost in addition to the costs of converting the grid and associated equipment such as compressors and meters to accommodate the different properties of hydrogen than methane.[12]

Utilities want to pipe hydrogen into homes and buildings as 20% hydrogen and 80% methane

The need for a one step jump from 20 percent to 100 percent hydrogen arises because, while increasing proportions of hydrogen in a blend with methane will result in continually increasing reductions in carbon dioxide emissions, these reductions remain relatively small even when the proportion of hydrogen by volume exceeds 50 percent (e.g., a reduction of 30 percent in a retrofitted gas turbine burning a blend with 60 percent hydrogen[13]), only reaching 100 percent reduction with 100 percent hydrogen.

As the proportion of hydrogen increases beyond 20 percent, it is unclear how much or how often parts of the gas infrastructure, appliances, or boilers would have to be retrofitted or replaced, since they vary widely by age and operating characteristics. Hence the scenario in which the proportion of hydrogen blended with methane would be steadily increased to achieve deep reductions in carbon emissions, compatible with the climate action plan targets, would be unpredictable to plan, with unmanageable financial and operational consequences for gas utilities and their customers.

For buildings currently using gas heating systems, similar calculations were made for switching from methane combustion systems to heat pumps. To be congruent with the hydrogen scenarios, calculations were made of the electricity needed to power heat pumps to replace 20 percent and 100 percent of current gas heating systems.

Heat pumps are 3.7 times more efficient than hydrogen boilers for heating buildings. Figure 1 shows a comparison between the end-to-end efficiency of two heating supply chains for buildings with the same input of clean electricity.

11 Fraunhofer Institute for Energy Economics and Energy System Technology. *Hydrogen in the Energy System of the Future: Focus on Heat in Buildings: A study on the use of hydrogen in the energy system of the future, with a special focus on heat in buildings*, May 2020. https://www.iee.fraunhofer.de/content/dam/iee/ energiesystemtechnik/en/documents/Studies-Reports/FraunhoferIEE_Study_H2_Heat_in_Buildings_final_EN_20200619.pdf Accessed 1/11/2023

12 Koestner, J. 6 *Things to Remember about Hydrogen vs Natural Gas, Power Engineers*, Power Engineering. August 12th, 2021. https://www.powereng.com/library/6-things-to-remember-about-hydrogen-vs-natural-gas Accessed 1/11/2023

13 Clark, K. *NYPA and EPRI release hydrogen blending test results*. Power Engineering. September 23, 2022. https://www.power-eng.com/hydrogen/118165/#gref Accessed 1/11/2023

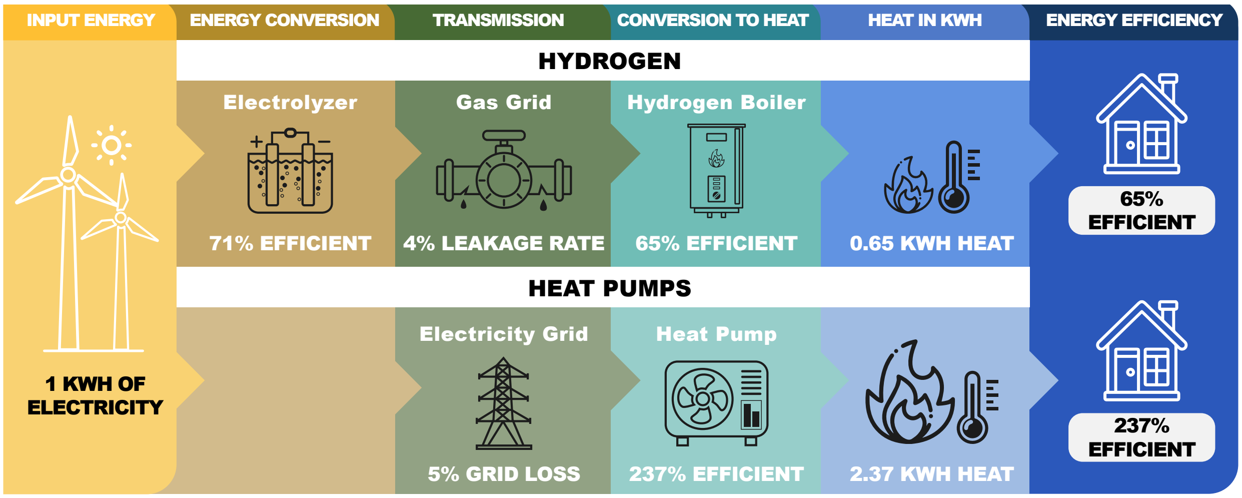


Figure 1. Efficiency of green hydrogen heat versus electric heat pumps

1. The top row shows electricity consumed by electrolyzers to produce green hydrogen, delivered via pipelines and burned in a boiler.
2. The bottom row shows electricity delivered directly to air source heat pumps

These efficiency differences are reflected in the amounts of wind power needed to heat buildings in the hydrogen and heat pump scenarios.

The calculations in this paper are based on several operating assumptions about the systems involved, as explained below.

Other analysts may wish to use different assumptions to perform sensitivity analyses or to carry out comparable calculations for jurisdictions other than Massachusetts, using parameters in the equations below that are relevant to their specific situations. Additionally, a few simplifying assumptions are made that err on the side of underestimating the electricity consumption of the production of green hydrogen.

EFFICIENCY

- It's efficient to use wind energy electricity with heat pumps.
- It's inefficient to use wind energy converted to hydrogen for combustion in a boiler or furnace.

Simplifying Assumptions

The simplifying assumptions made in this analysis are as follows:

1. Losses in the transportation and storage of hydrogen are ignored.
2. The change in lower heat value (LHV) of hydrogen under standard conditions (1 bar) due to pressure in the gas distribution network is negligible.
3. There are no losses in replacing methane with hydrogen in the pipeline transmission and distribution network.[14]
4. There are no transmission losses between the wind turbines that generate electricity and the electrolyzers producing green hydrogen, although a loss is assumed in the delivery of grid electricity to heat pumps in buildings.
5. No allowance is made for electricity required to provide and purify water for the electrolysis process.

The coefficient of performance of heat pumps used is based on air source heat pumps, which is a conservative estimate. Ground source heat pumps and networked ground source heat pumps have higher coefficients of performance. Their performance is also less sensitive to outside air temperatures because they transfer heat from more consistent temperatures below the surface of the earth. They consume less electricity to heat homes than air source heat pumps.

Therefore, the estimates presented in this paper of the amounts of clean electricity required to replace methane with hydrogen are conservative.

The proportion of households or residences in Massachusetts using natural gas is 51 percent.[15] If buildings that currently use another fuel, for example oil, switch to gas instead of heat pumps in the future, then the differences in electricity consumption between these alternative heating solutions calculated in this paper will become even more pronounced.

14 This assumption ignores the additional energy required for compression of hydrogen gas and the need to pump an additional volume of gas to deliver an equivalent amount of thermal energy because hydrogen has a lower energy density per unit volume.
Kurz, R., Lubomirsky, M., & Bainier, F. *Hydrogen in Pipelines: Impact of Hydrogen Transport in Natural Gas Pipelines*. Proceedings of the ASME Turbo Expo 2020: Turbomachinery Technical Conference and Exposition. Volume 9: Oil and Gas Applications; Organic Rankine Cycle Power Systems; Steam Turbine. Virtual, Online. September 21–25, 2020. V009T21A001. ASME. https://asmedigitalcollection.asme.org/GT/proceedings-abstract/GT2020/84201/V009T21A001/1095159

15 Massachusetts Department of Energy Resources. *How Massachusetts Households Heat Their Homes*. 2021. https://www.mass.gov/service-details/how-massachusetts-households-heat-their-homes Accessed 1/11/2023

Operating Assumptions

To calculate the numbers of wind turbines required to generate the electricity to produce green hydrogen in various scenarios we assume that[16]

- An average offshore wind turbine power nameplate capacity (PCoff) is 12 MW (megawatts) and a capacity factor (Foff) of 0.51, producing 53,611 MWh (megawatt hours) per year.
- An average onshore wind turbine power nameplate capacity (PCon) of 3.5 MW and a capacity factor (Fon) of 0.36 producing 11,038 MWh per year.

Limitations

This paper does not explore grid reliability or offer solutions for winter peak capacity issues under scenarios that envision significant building and transportation electrification. This paper also does not evaluate other criteria for evaluating the utility of hydrogen for heating buildings, including cost and efficiency, equity and environmental justice, polluting byproducts and health impacts, safety risks, and other regulatory questions. More information about those topics can be found in Appendix B. These questions still require consideration, but they are outside the scope of this paper.

Figure 2. Cold climate heat pump in Alaska

16 The assumed capacities of wind turbines are derived from: Office of Energy Efficiency and Renewable Energy. *2019 Wind Energy Data and Technology Trends*, 2020. https://www.energy.gov/eere/wind/2019-wind-energy-data-technology-trends and Office of Energy Efficiency and Renewable Energy. *Land-Based Wind Market Report: 2021 Edition*, August 2021. https://www.energy.gov/sites/default/files/2021-08/Land-Based%20Wind%20Market%20Report%202021%20Edition_Full%20Report_FINAL.pdf Accessed 1/11/2023; The capacity factors are derived from Center for Sustainable Systems, University of Michigan. *Wind Energy Factsheet. Pub. No. CSS07-09*, 2021. https://css.umich.edu/publications/factsheets/energy/wind-energy-factsheet#:~:text=The%20capacity%20factor%20of%20a,by%20its%20maximum%20power%20capability.&text=On%20land%2C%20capacity%20factors%20range%20from%200.26%20to%200.52.&text=The%20average%202019%20capacity%20factor,average%20capacity%20factor%20was%2035%25 Accessed 1/11/2023

Results of Calculations

This chapter summarizes the results of the calculations detailed in Appendix A.

Table 1 presents the results of calculations of the clean electricity that would be consumed for different amounts of green hydrogen production to replace all or a portion of the current consumption of natural gas in buildings in Massachusetts. These amounts are compared with the additional electricity that would be consumed if methane combustion systems were replaced by electric-powered air source heat pumps, fully and in the same partial proportions as hydrogen.

For context, the total consumption of electricity in Massachusetts in 2021 by all customers without any production of green hydrogen, as well as the planned procurements of offshore wind turbines, are presented as yardsticks against which the impact of green hydrogen's demands for clean electricity can be assessed.

Table 1. Replacement of Natural Gas in Massachusetts Buildings
Comparison of Wind Generated Electricity Consumption Between Green Hydrogen and Heat Pumps

Replacement Option for Methane and Proportion H_2	Electricity Consumption of Replacement (TWh)	Percent Increase in Electricity Consumption[A]	Total Offshore Wind Turbine Generation Capacity, (GW)[B]	Number of Offshore Wind Turbines[B]
100% Green H_2, all buildings	88.0	173%	19.7	1,643
100% Green H_2, residential only[C]	47.8	94.1%	10.7	892
20% green H_2, all buildings	17.6	34.6%	3.9	329
100% Heat Pumps, all buildings	25.9	51.0%	5.8	483
100% Heat Pumps, residential only[D]	14.1	27.7%	3.2	263
20% Heat Pumps, all buildings	5.2	10.2%	1.2	97

Table Notes:

A. Compared with the total 2021 consumption of electricity in Massachusetts of 50.8 TWh (terawatt hours) with no green hydrogen production; if all electricity consumed in the state in 2021 had been generated by wind turbines it would have absorbed the output of 16.1 GW (gigawatts) of onshore or 11.4 GW of offshore wind turbines with the same performance parameters as used in the table, or 4,603 onshore and 948 offshore turbines.

B. The numbers and total capacities of onshore and offshore wind turbines are calculated on the basis that the electricity to produce green hydrogen is generated entirely either by onshore or by offshore turbines; data for onshore turbines can be found in Appendix A.

C. This is a hypothetical, not a practical scenario, since many pipelines serve both residential and commercial buildings. It would not be feasible to segregate pipelines so that hydrogen is only delivered to residences.

D. This scenario is highly improbable since gas distribution pipelines that only generate revenues from commercial buildings in mixed use neighborhoods would not be economically viable.

Electricity consumption for either 20 percent or 100 percent replacement of natural gas in buildings currently heated with this gas is more than three times higher for green hydrogen than for heat pumps (Figure 2). This is a very conservative, low estimate of this ratio given our assumptions.

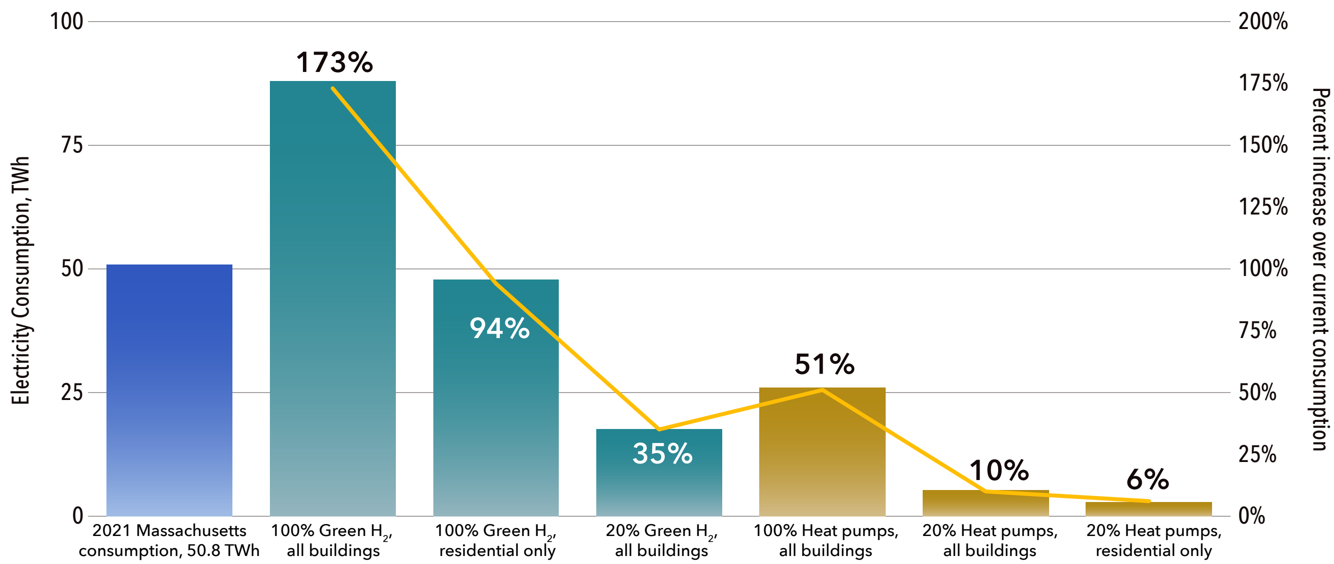


Figure 3. Electricity consumption (TWh) of green hydrogen and heat pumps with percent increase over current consumption

The capacities of the wind turbines needed to deliver electricity to produce enough green hydrogen or to supply heat pumps to replace methane can be compared with existing plans for offshore wind turbines for Massachusetts and for the Atlantic Northeast region:

- The predicted offshore wind capacity for Massachusetts is 3.2 GW (gigawatts) operating in 2030. This capacity represents procurements as of early 2023, out of the total offshore wind procurement target of 5.6 GW updated in 2021.[17] The pace of procurement of offshore wind capacity is not on track to meet its targets for decarbonizing the electric grid. Green hydrogen could push the plans to decarbonize the grid further off target.
- The regional goal for offshore wind capacity for the seven states from Massachusetts to Virginia in the Atlantic Northeast is 26.5 GW by 2035.[18]

17 The Commonwealth of Massachusetts. *Massachusetts Clean Energy and Climate Plan for 2025 and 2030*, 2022. https://www.mass.gov/doc/clean-energy-and-climate-plan-for-2025-and-2030/download Accessed 1/11/2023.

18 New York State Energy Research and Development Authority. *Offshore Wind. Leading a Regional IndustryCollaborating with Atlantic states and the federal government*, updated 2023. https://www.nyserda.ny.gov/All-Programs/Offshore-Wind/Focus-Areas/Leading-a-Regional-Industry Accessed 1/11/2023.

A recent presentation by the Massachusetts Executive Office of Energy and Environmental Affairs[19] finds that, based on electricity sector modeling, about 27 GW of solar and more than 20 GW of offshore wind power capacity will be needed in 2050 to meet the emission sublimit for the power sector. These numbers do not include supplying the additional large amounts of clean electricity needed to produce the quantities of green hydrogen for heating buildings being envisaged by the gas utilities.

Regarding the target for clean energy production by 2050, the Massachusetts 2050 Decarbonization Roadmap states:[20]

> *"Offshore wind and solar are the lowest cost low-carbon energy resources and will comprise the bulk of the Commonwealth's and the region's electricity generation in 2050; both must be deployed at scale (15–20 GW of each installed) in the Commonwealth over the next 30 years."*

The offshore wind generation capacity needed to produce enough green hydrogen for a 20 percent blend with methane exceeds all currently planned offshore wind capacity in Massachusetts by 2030 with only 7 percent emissions reductions at best. (see Figure 4).

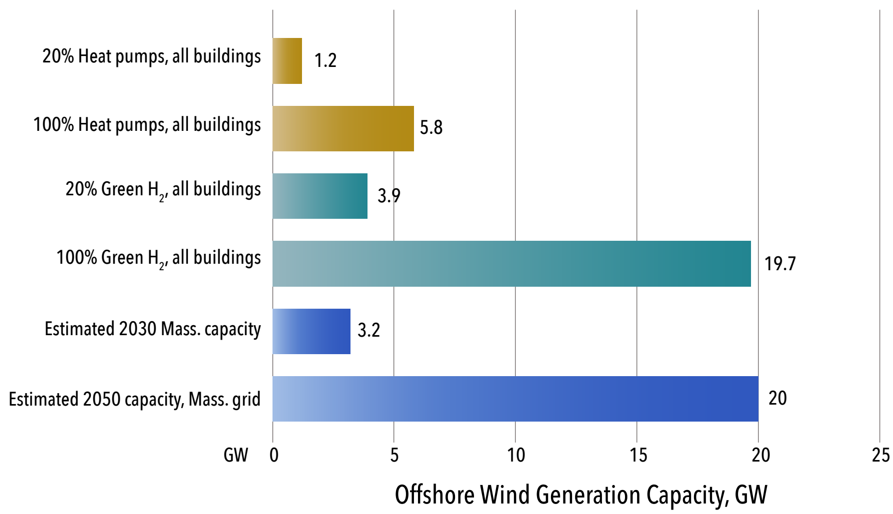


Figure 4. Offshore wind generation capacity (GW) needed to heat buildings with green hydrogen versus heat pumps

19 Massachusetts Executive Office of Energy and Environmental Affairs. *Clean Energy and Climate Plan for 2050 Limit, Sublimits, Goals, and Policies*, Public Hearings October 6, 7, and 11, 2022. https://www.mass.gov/doc/2050-cecppublic-hearingpresentationenglish/download Accessed 1/11/2023

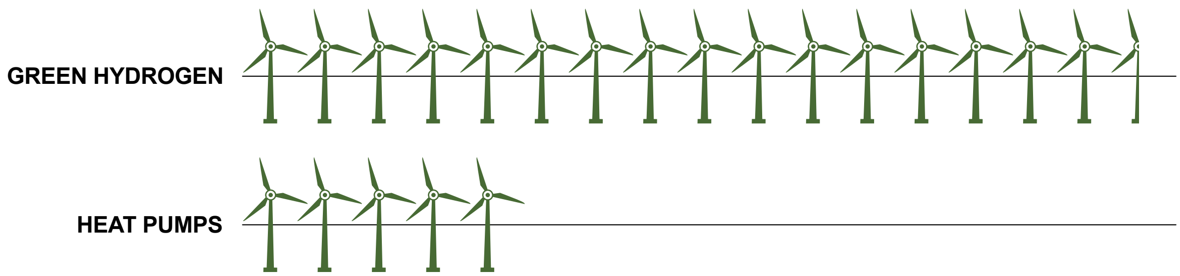
20 Massachusetts Executive Office of Energy and Environmental Affairs. *Massachusetts 2050 Decarbonization Roadmap, 2022*. https://www.mass.gov/doc/ma-decarbonization-roadmap-abridged-english/download Accessed 1/11/2023

Moreover, a 20 percent green hydrogen blend with methane by volume will only reduce greenhouse gases by at most 6–7 percent, not considering current rates of gas leakage in Massachusetts.[21] In contrast a similar amount of wind capacity could provide energy to around two-thirds of all buildings heated with natural gas that switch to heat pumps, resulting in more than a 50 percent reduction in greenhouse gases.[22]

Figure 5 illustrates how many more wind turbines are required to generate the electricity required to produce enough green hydrogen to heat all the buildings in Massachusetts that are currently using natural gas, compared to the electricity needed to power heat pumps with the same outcome.

GREEN HYDROGEN CONSUMES MORE THAN THREE TIMES THE OFFSHORE WIND CAPACITY AS HEAT PUMPS

Number of offshore wind turbines needed to cover heating demand in Massachusetts* where each wind turbine symbol = 100 offshore turbines and each turbine has a capacity of 12 MW



***Heating demand is based on Massachusetts 2021 demand in buildings currently heated by natural gas**

Figure 5. Wind demand for green hydrogen and heat pumps to replace natural gas in Massachusetts buildings.

21 Goldmeer, J. GE Gas Power, February 2019, *Power to Gas: Hydrogen for Power Generation*. https://www.ge.com/content/dam/ gepower/global/en_US/documents/fuel-flexibility/GEA33861%20 Power%20to%20Gas%20-%20 Hydrogen%20for%20Power%20 Generation.pdf Accessed 1/11/2023

22 Pistochini, T., Dichter, M., Chakraborty, S., Dichter, N., Aboud, A. *Greenhouse gas emission forecasts for electrification of space heating in residential homes in the US*, Energy Policy, Volume 163, 2022. https://doi.org/10.1016/j.enpol.2022.112813. Accessed 1/11/2023

Findings

Key findings from the calculations presented in Table 1 on page 16:

- The supply of electricity needed to produce green hydrogen in quantities necessary to replace the natural gas currently used in buildings in Massachusetts is more than 3.4 times higher than electricity-powered heat pumps. The difference in the capacity of the wind turbines needed to generate this electricity between the use of green hydrogen and heat pumps would be equally large.
- Consequently, the total consumption of electricity in Massachusetts for all applications would increase to 2.7 times its current level if all methane in buildings were replaced by 100 percent hydrogen,[23] whereas the complete replacement of methane combustion systems by heat pumps would increase it to 1.5 times the current level.
- The capacity of offshore wind turbines needed to generate enough electricity to manufacture green hydrogen to replace only 20 percent of methane burned in buildings is 3.9 GW, which exceeds the 3.2 GW of capacity predicted to be available for Massachusetts in 2030.[24] Note that 20 percent of the current gas supply is the maximum proportion of hydrogen in a blend of gases that would not require huge new investments in pipelines and associated equipment such as compressors and gas-fired home appliances.
- Blending hydrogen with methane to heat buildings will cannibalize the supply of clean electricity, diverting it from its primary targeted purpose of direct delivery to the electric grid and slowing anticipated emissions reductions from the electrification of buildings and vehicles.

FINDINGS

- Massachusetts has leased space offshore to produce up to 5.6 GW of electricity.
- We need 20 GW of offshore wind, plus 27 GW of solar for a clean grid by 2050.
- Making hydrogen for heating homes would consume huge amounts of clean electricity, forestalling a clean grid.
- We would need 3.4 times as much electricity to make hydrogen for heating as we would to transition to heat pumps.

23 The combustion systems fueled by methane (boilers, furnaces, and appliances) would have to be modified or replaced if hydrogen accounted for more than a minor proportion of the gas in a blend with methane. Jones, JS. *Hydrogen blends over 5 percent may need infrastructure modifications—study*. Smart Energy International. August 3, 2022. https://www.smart-energy.com/industry-sectors/energy-grid-management/hydrogen-blends-over-5-may-need-infrastructure-modifications-study/ Accessed 1/11/2023

24 The Commonwealth of Massachusetts. *Massachusetts Clean Energy and Climate Plan for 2025 and 2030*, 2022. https://www.mass.gov/doc/clean-energy-and-climate-plan-for-2025-and-2030/download Accessed 1/11/2023

IMPLICATIONS OF SMALL AMOUNTS OF GREEN HYDROGEN BLENDING ON RNG USE AND AVAILABILITY

It may be argued that it is possible to manage the increase in the consumption of clean electricity for producing green hydrogen by limiting the proportion of hydrogen included in the blend of gases by using mostly RNG, up to 80 percent according to National Grid.[25] However, there are compelling reasons to reject this alternative. First, the availability of RNG will be inadequate to fulfill this role if the blended gas is to serve a substantial proportion of all buildings currently served by natural gas. Analyses funded by the gas industry forecast that the maximum production of RNG achievable by 2040 in the U.S. would amount to less than 15 percent of the 2021 level of consumption of natural gas for all applications.[26] Moreover, while RNG may be somewhat less polluting than natural gas based on lifecycle accounting, it is still far from zero carbon. It would make more sense to reserve the limited quantities of available RNG for applications where there is no electric option. Heating buildings is not one of those applications.

In effect, gas utilities face a Hobson's choice for the future of combustible gases in buildings. This choice lies between blends with:

- A predominance of RNG ("fossil-free," but methane nevertheless) that would continue to leak methane into the atmosphere from leaky pipelines and perpetuate the harmful effects of the toxic byproducts generated by burning methane that are known to affect human health,[27] or
- A predominant proportion of green hydrogen that would increase the demand for clean electricity by impractically large or unattainable amounts, although it would reduce carbon dioxide emissions from buildings more substantially than if the gas includes a larger proportion of RNG.[28]

The first choice is a dead end from the emissions perspective, since the emissions levels resulting from gas blends with minority volumes of hydrogen will not meet the increasingly deep reductions prescribed over time, while the second choice with majority volumes of hydrogen is impossible to implement because of its requirement for huge amounts of clean electricity and replacement at vast expense of the gas ecosystem.

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25 The demands for electricity in the processes that convert biogas or purify it into biomethane to meet injection standards for the gas infrastructure have not been taken into consideration in calculations to estimate and compare the increase in demand for electricity of different proportions of hydrogen and fossil-free methane to replace fossil-formed methane compared to heat pumps.
Abd, AA., Othman, MR., Shamsudin, IK., Helwani, Z., Idris, I., *Biogas upgrading to natural gas pipeline quality using pressure swing adsorption for CO_2 separation over UiO-66: Experimental and dynamic modelling assessment*, Chemical Engineering Journal, Volume 453, Part 1, 2023, 139774, ISSN 1385-8947, https://doi.org/10.1016/j.cej.2022.139774

26 Feinstein, L. and de Place, E. *The Four Fatal Flaws of Renewable Natural Gas: Gas utilities are telling tall tales about RNG*. The Sightline Institute. March 9, 2021. https://www.sightline.org/2021/03/09/the-four-fatal-flaws-of-renewable-natural-gas/ Accessed 1/11/2023; American Gas Foundation. R*enewable Sources of Natural Gas: Supply and Emissions Reduction Assessment*, December 2019. https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf Accessed 1/11/2023

27 Michanowicz, MR, Dayalu, A., Nordgaard, CL, Buonocore, JJ, Fairchild, MW, Ackley, R., Schiff, JE, Liu, A., Phillips, NG, Schulman, A., Magavi, Z. and Spengler,JD. *Home is Where the Pipeline Ends: Characterization of Volatile Organic Compounds Present in Natural Gas at the Point of the Residential End User*. Environ. Sci. Technol. 2022, 56, 14, 10258–10268 https://pubs.acs.org/doi/10.1021/acs.est.1c08298

28 Clark, K. *NYPA and EPRI release hydrogen blending test results*. Power Engineering. September 23, 2022. https://www.power-eng.com/hydrogen/118165/#gref Accessed 1/11/2023

Discussion

The key findings in this paper raise the questions of how, when, and, even whether it will be possible to gain access to enough clean electricity to produce the green hydrogen needed to fulfill the gas utilities' plans for this gas, while also decarbonizing the grid.

The finding that burning hydrogen for heating would increase total demand for electricity by more than three times compared to the increase associated with heat pumps disproves the assertion that replacing methane with an electric option would increase total demand for electricity more than the proposed use of hydrogen for this purpose. The assertion[29] that use of hydrogen will reduce the total level of demand for electricity compared to a scenario in which buildings are increasingly electrified is mistaken. However, not only the error but also its magnitude become evident when the respective heating options and their requirements for electricity are analyzed along their entire respective energy supply chains.

The strong links between green hydrogen as a source of energy and the electricity required to produce it are one illustration of the imperative for integrated planning across all forms of energy, regardless of century-old silos, including the separate regulatory regimes for gas and electric utilities.

29 Stephen Woerner, President National Grid New England: "For those who would say green hydrogen requires daunting amounts of energy, it pales in comparison to what would be needed for a full-electrification scenario—where massive and costly upgrades would be necessary for the regional and local transmission and distribution grids," Woerner, S. *National Grid has a vision for fossil-free heat*, Commonwealth Magazine. July 21, 2022. https://commonwealthmagazine.org/opinion/national-grid-has-a-vision-for-fossil-free-heat/ Accessed 1/11/2023

Evaluation of Applications of Green Hydrogen

Total electricity consumption will predictably increase considerably in the Commonwealth, the nation, and globally, by 2050.[30] Under any circumstances, we face very daunting challenges and obstacles for the planning, permitting, and procuring of sufficient clean electricity generation in time to meet the demands of existing and new applications of electricity. These challenges may even intensify in the future, given the many delays in siting and permitting new utility-scale power generation installations and grid transmission infrastructure.

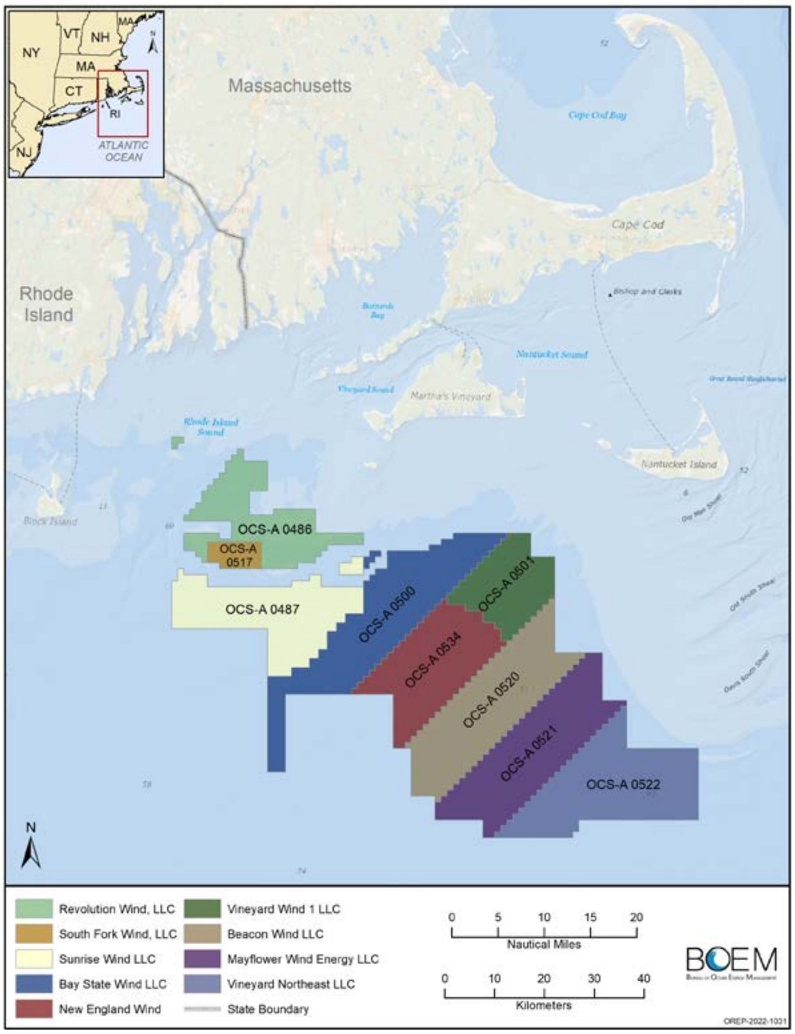

Figure 6. Massachusetts offshore lease area map
Note that Mayflower is now SouthCoast Wind. Source: Bureau of Ocean Energy Management

30 Massachusetts Executive Office of Energy and Environmental Affairs. *Massachusetts 2050 Decarbonization Roadmap*. https://www.mass.gov/doc/ma-decarbonization-roadmap-abridged-english/download Accessed 1/11/2023; U.S. Energy Information Administration. *Today in Energy: EIA projects less than a quarter of the world's electricity generated from coal by 2050*, January 22, 2020. https://www.eia.gov/todayinenergy/detail.php?id=42555 Accessed 1/11/2023

Hence, policymakers should favor options for energy solutions that minimize increases in demands for electricity unless there are other considerations that outweigh this considerable advantage. The findings of this paper strongly suggest that proposals to use green hydrogen for heating buildings are an extremely unwise choice because heat pumps are a more efficient option for heating buildings.

Blending green hydrogen with methane is unwise for many other reasons. Appendix B provides links to multiple independent analyses and reports that find serious objections to proposals for burning hydrogen in buildings to replace methane, including health impacts, safety risks, environmental justice concerns, costs, and greenhouse gas and air pollution emissions.

If the supply of clean electricity to produce green hydrogen is limited because of the imperative to decarbonize the grid, this gas should be treated as a scarce resource. Green hydrogen will only be able to satisfy a subset of its multiple proposed applications, which should therefore be prioritized according to a widely agreed-upon set of criteria.

One essential element for the objective evaluation of the relative merits of a proposed application of green hydrogen is an electricity budget that identifies the quantity and the sources of this electricity and does not impede decarbonization of the electric grid. To establish the relative values and priorities of proposed applications of green hydrogen, other criteria, such as the relative competitiveness (including but not limited to cost performance and contribution to reducing current greenhouse gas and other unwanted emissions) as well as the feasibility and availability of non-hydrogen options should be investigated.

The first priority should be to displace gray hydrogen, which accounts for two percent of global emissions.[31] The Department of Energy's[32] national goal of 10 million tonnes of green hydrogen in 2030 is the amount that would cover the replacement of today's uses of gray hydrogen. The 2050 goal to produce 50 million tonnes of green hydrogen in the U.S. would consume 2,150 TWh of clean electricity based on the same electrolyzer performance assumed earlier in this paper, which amounts to the daunting proportion of about 55 percent of total U.S. electricity consumption of 3,900 TWh in 2021.[33] The challenge of how to accommodate and coordinate concurrently the requirements of a decarbonized grid and the applications of green hydrogen where it can make valuable contributions to the decarbonization of selected sectors or subsectors of the economy is

31 Wood Mackenzie. *Green Hydrogen Production: Landscape, Projects and Costs*, October 2019. https://www.woodmac.com/news/editorial/the-future-for-green-hydrogen/ Accessed 1/11/2023

32 Department of Energy. *National Clean Hydrogen Strategy and Roadmap Draft*, September 2022. https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf Accessed 1/11/2023

33 U.S. Energy Information Administration. *Electricity explained: Use of electricity, May 3, 2022*. https://www.eia.gov/energyexplained/electricity/use-of-electricity.php Accessed 1/11/2023

a national issue.[34] Green hydrogen should only be expanded to new applications for which, unlike heating buildings, there is no feasible electric option. Arguably, this is the situation for some heavy and long-distance transport applications and for industrial processes that require high temperatures.

In the worst case, aggressive pursuit of the use of green hydrogen for heating buildings, as the gas utilities advocate, will not only impede decarbonization of the grid but may also frustrate or limit the availability of green hydrogen to meet the needs of other applications where it can uniquely or most competitively provide the greatest value. Figure 5 presents one perspective on where the most promising and valuable opportunities for green hydrogen may lie based on efficiency, cost, and availability of competing technologies. Domestic heating is found at the bottom of the ladder in row F; heat pumps for heating are an electric alternative that is far more efficient.

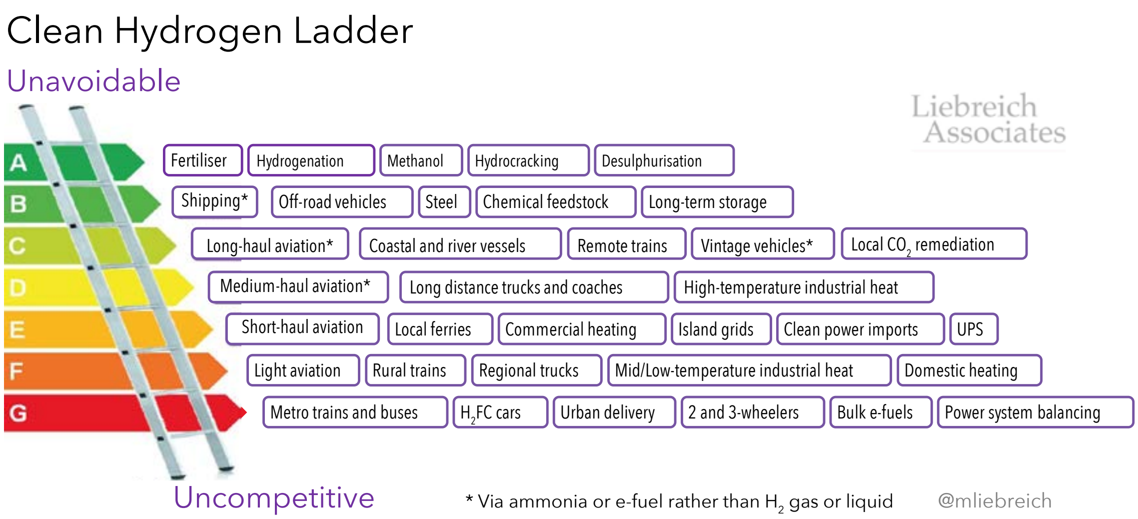

Figure 7. Technologies competing on the clean hydrogen ladder.
Source: Liebreich Associates[35]

34 The European Union is also alert to the importance of this issue and is trying to introduce rules to prevent the unreasonable cannibalization of clean electricity by producers of green hydrogen.
Kurmayor, MJ. *LEAK: Long-awaited EU rules on renewable hydrogen expected* 15 Dec. EURACTIV. Updated December 5, 2022. https://www.euractiv.com/section/energy/news/leak-long-awaited-eu-rules-on-renewable-hydrogen-expected-15-dec/ Accessed 1/11/2023

35 Naschert, C. *Hydrogen lobbying sets wrong priorities, says BloombergNEF founder*. S&P Global Market Intelligence. May 21, 2021. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/hydrogen-lobbying-sets-wrong-priorities-says-bloombergnef-founder-64534120 Accessed 1/11/2023

Green Hydrogen for Heating: A Predictable Dead End

Finally, the proposed use of green hydrogen with minor proportions in a blend with methane , such as 20 percent, will only produce very limited reductions in emissions.[36] These reductions will fall far short of the levels or emission sublimits that are being targeted.[37] If gas utilities embark along a path that requires the use of green hydrogen as a key strategy to reduce emissions, they will have to switch from a small amount (5–20 percent blend of hydrogen) to 100 percent green hydrogen at an enormous cost.

The quantities of green hydrogen required will become substantial, and the problem of accessing enough clean electricity to manufacture it, in the timescale needed, will become acute and foreseeably insurmountable. At some point, green hydrogen will have to increase to 100 percent to meet the goal of emissions reduction, and the gas utilities will inevitably have to cope with multiple highly problematic issues requiring substantial new investments in the gas distribution infrastructure and the gas-fired appliances of customers, who will be paying for both[38]. In addition, the distribution and burning of 100 percent hydrogen in large numbers of dispersed residential and commercial buildings raises serious concerns about safety, in contrast to the proven technologies and performance of heat pumps.

36 "Adding 10 percent green hydrogen in pipelines would only reduce CO_2 emissions by 5 percent, and a 50 percent mix of hydrogen would reduce them by 30 percent, because H_2 produces less energy when burned than methane." Neacsa, A.,Eparu, CN., Stoica, DB. *Hydrogen–Natural Gas Blending in Distribution Systems—An Energy, Economic, and Environmental Assessment*, Energies 2022, 15(17),6143; https://doi.org/10.3390/en15176143; Esposito, D., *Gas Utilities Are Promoting Hydrogen, But It Could Be A Dead End For Consumers And The Climate*, Forbes, March 29, 2022. https://www.forbes.com/sites/energyinnovation/2022/03/29/gas-utility-hydrogen-proposals-ignore-a-superior-decarbonization-pathway-electrification/?sh=4100314176a1 Accessed 1/11/2023

37 Massachusetts Executive Office of Energy and Environmental Affairs. *Massachusetts 2050 Decarbonization Roadmap*. https://www.mass.gov/doc/ma-decarbonization-roadmap-abridged-english/download Accessed 1/11/2023

38 Quintino FM, Nascimento N, Fernandes EC. *Aspects of Hydrogen and Biomethane Introduction in Natural Gas Infrastructure and Equipment*. Hydrogen. 2021; 2(3):301-318. https://doi.org/10.3390/hydrogen2030016

Conclusions

Proposals to blend green hydrogen with methane for heating buildings should be rejected because they will cannibalize clean electricity needed to decarbonize the grid.

Moreover, the resulting reductions in greenhouse gas and other undesirable emissions will be smaller than those achievable with the implementation of proven technologies, notably heat pumps. These reductions will be driven by the pace at which the grid is decarbonized. The pace of improvements in and the level of grid decarbonization will be maximized by ensuring that the outputs of existing and newly deployed variable renewable energy, like wind and solar, sources of clean electricity, such as wind and solar, are delivered directly to users over the grid and not diverted for less valuable purposes.

The findings presented in this paper demonstrate that progress in decarbonizing the grid will be much slower if the production of green hydrogen absorbs substantial amounts of clean electricity. Green hydrogen can make useful contributions to the decarbonization of the economy in some applications where the direct use of electricity is not feasible. Given that the production of green hydrogen demands a vast amount of clean electricity, it should be treated as a predictably scarce resource. The applications of green hydrogen should be prioritized according to an agreed-upon set of criteria, to direct its uses to where it will be most valuable. Heating buildings is not an appropriate use for green hydrogen due to the amount of electricity such a use would demand and the much greater energy efficiency of alternatives such as electric-powered heat pumps.

Policy Recommendations

Plans must be made as objectively as possible for transitioning to alternative thermal solutions for buildings and clean sources of energy to meet the needs of all sectors of the economy to decarbonize their operations. Such plans should reflect the interactions between energy supply chain options, as well as the individual merits and disadvantages of those options.

1. We recommend Acadia Center's RESPECT model for reforming the utility planning processes to ensure that utility investments and decision-making are aligned with state goals to address emissions reductions.[39]
2. Massachusetts needs a state-wide program for the progressive strategic retirement of the gas pipeline distribution infrastructure as a necessary plank in an integrated energy policy, to be completed by mid-century. This program should reduce gas demand to achieve the Commonwealth's goals for cutting emissions, incorporate equity and environmental justice, and redefine the roles of gas utilities so their financial interests will be successively decoupled from their current business model.
3. The uses of green hydrogen should be prioritized according to an agreed-upon set of criteria, and appropriate incentives should be applied to direct green hydrogen toward industries where emissions reductions could be maximized. Evaluation of uses should include an analysis of available alternatives, efficiency, cost, reliability, the air quality impacts, health and safety risks, and full life cycle greenhouse gas emissions, in addition to avoiding localized pollution in disadvantaged communities. Ideally development of these criteria should be established at the national level in a process that is independent of the gas industry and draws on expertise from multiple sources. Absent a national initiative, Massachusetts should consider undertaking the task itself in concert with other states.
4. State policy should prohibit blending of hydrogen with methane (natural and renewable) for distribution in Massachusetts for space and water heating and cooking.[40]

39 Boyd, A. and Tully, O. *RESPECT – Reforming Energy System Planning for Equity and Climate Transformation*. Acadia Center. November, 2021. https://acadiacenter.wpenginepowered.com/wp-content/uploads/2021/11/AC_RESPECT_Nov2021.pdf Accessed 1/17/2023

40 This recommendation regarding use of RNG and green hydrogen for heating is consistent with the recommendation from the Climate Action Council in New York State, where National Grid is also a major supplier of natural gas. *New York State Climate Action Council Scoping Plan, 2022,* New York State Climate Action Council. https://climate.ny.gov/resources/scoping-plan Accessed 1/11/2023; A member of this Climate Action Council, Professor Robert Howarth of Cornell University, explained the Council's recommendations in testimony he submitted to the Massachusetts Department of Public Utilities on January 4, 2023 in Docket 22-149, "RNG & green hydrogen should not be used for Heating" - https://fileservice.eea.comacloud.net/FileService.Api/file/FileRoom/16840893 Accessed 1/11/2023

Appendix A. Methods, Assumptions, and Calculations

The total generating capacity in gigawatts (GW) of VRE sources whose entire annual output would have to be dedicated to produce the amount of electricity in terawatt hours (TWh) necessary to produce green hydrogen can be calculated according to the equation:

$$GC=TWh/(8.760 \bullet F)\ GW \qquad [1]$$

where the number of hours in a year is 8,760 and F is the capacity factor of the VRE source.

In practice, no source of electrical energy can operate continuously throughout a year since, at a minimum, it will have to be taken offline for necessary maintenance and repairs. VRE sources, notably wind turbines and solar, have capacity factors well under 1, since the wind is too weak or too strong at various times for wind turbines to operate. Solar panels cannot operate at night, and their daylight output is limited under cloud cover. The capacity factors of these VRE sources also vary widely depending on their location. Generally offshore wind turbines have higher capacity factors than onshore systems, and both can achieve significantly higher capacity factors than solar, since there are times during the night as well as the day when wind conditions enable them to produce electricity.

Operating Assumptions

To calculate the numbers of wind turbines required to generate the electricity to produce green hydrogen in various scenarios we assume that[41]

- An average offshore wind turbine power nameplate capacity (PCoff) is 12 MW (megawatts) and a capacity factor (Foff) of 0.51, producing 53,611 MWh per year.
- An average onshore wind turbine power nameplate capacity (PCon) of 3.5 MW and a capacity factor (Fon) of 0.36 producing 11,038 MWh per year.

Estimates of Wind Turbine Capacities and Numbers to Produce Green Hydrogen

The numbers of wind turbines needed to generate the TWh of electricity necessary to produce a desired amount of green hydrogen can be calculated as follows.

The number of offshore turbines is:

$$N_{off} = TWh/(PC_{off} \text{ x } 8760 \text{ x } F_{off}) \qquad [2]$$

with a total capacity of:

$$GC_{off} = N_{off} \text{ x} PC_{off} \qquad [3]$$

The number of onshore turbines is:

$$N_{on} = TWh/(PC_{on} \text{ x } 8760 \text{ x } F_{on}) \qquad [4]$$

with a total capacity of:

$$GC_{on} = Non \text{ x } PC_{on} \qquad [5]$$

41 The assumed capacities of wind turbines are derived from: Office of Energy and Efficiency and Renewable Energy. *2019 Wind Energy Data & Technology Trends, 2020*. https://www.energy.gov/eere/wind/2019-wind-energy-data-technology-trends Accessed 1/11/2023; Office of Energy and Efficiency and Renewable Energy. *Land-Based Wind Market Report, 2021 Edition*. U.S Department of Energy, August 2021. https://www.energy.gov/sites/default/files/2021-08/Land-Based %20Wind %20Market %20Report %202021 %20Edition_Full %20Report_FINAL.pdf Accessed 1/11/2023; The capacity factors are derived from Center for Sustainable Systems, University of Michigan. 2021. *Wind Energy Factsheet. Pub. No. CSS07-09* https://css.umich.edu/publications/factsheets/energy/wind-energy-factsheet#:~:text=The %20capacity %20factor %20of %20a,by %20its %20maximum %20power %20capability.&text=On %20land %2C %20capacity %20factors %20range %20from %200.26 %20to %200.52.&text=The %20average %202019 %20capacity %20factor,average %20capacity %20factor %20was %2035 %25 Accessed 1/11/2023

Another critical operating assumption is the electricity input for the electrolyzers used to produce the green hydrogen. In the following calculations, electrolyzers requiring 43 kWh (kilowatt hours) per kg (kilogram) of hydrogen produced are assumed to become widely available in future.[42] Current electrolyzers require significantly more electricity to produce 1 kg of green hydrogen, about 50 kWh/kg, or up to over 70 kWh/kg depending on their type and size.[43]

Natural gas consumption in Massachusetts by sector for the year 2021 is shown in Table A–1.

Table A–1. Consumption of gas in the building sector in Massachusetts (2021)[44]

Sector	Million ft^3
Residential	122,812
Commercial	103,256
Residential + Commercial	226,068

The consumption of natural gas in buildings included in this table accounted for 59 percent of the total consumption of this gas in the Commonwealth. The generation of electricity by gas-fired turbines in power plants and the applications of this gas in industrial processes account for essentially all the remaining consumption.

The total amount of natural gas energy used in Massachusetts in 2021 for the residential sector is converted into Btu (British thermal units), using the average heat value of natural gas delivered to Massachusetts in 2021 as reported by the EIA. Using this value, 1,030 Btu/ft,[45] the total amount of natural gas energy (NGE) Massachusetts used in 2021 for the residential sector amounts to:

$$NGE_{res} = (1.030 \text{ x } 10^3) \text{ x } 1.22812 \text{ x } 10^{11} \text{ Btu} = 126.496 \text{ x } 10^{12} \text{ Btu} \qquad [6]$$

42 The most efficient electrolyzer announced as of Q1 2002 claims it will produce 1 kg of hydrogen per 41.5 kWh. Blain, Loz. *Record-breaking hydrogen electrolyzer claims 95 percent efficiency*. New Atlas. March 16, 2022. https://newatlas.com/energy/hysata-efficient-hydrogen-electrolysis/ Accessed 1/11/2023

43 Lazard. Lazard's *Levelized Cost Of Hydrogen Analysis*—Version 2.0, October, 2021. https://www.lazard.com/media/451895/lazards-levelized-cost-of-hydrogen-analysis-version-20-vf.pdf Accessed 1/11/23; Tashie-Lewis, BC. Nnabuife, SG. *Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy—A Technology Review*, Chemical Engineering Journal Advances, Volume 8, 2021, 100172, ISSN 2666-8211, https://doi.org/10.1016/j.ceja.2021.100172.

44 U.S. Energy Information Administration. *Natural Gas Consumption by End User: Massachusetts. 12/30/22.* https://www.eia.gov/dnav/ng/NG_CONS_SUM_DCU_SMA_A.htm Accessed 1/11/2023

45 U.S. Energy Information Administration. *Natural Gas: Heat Content of Natural Gas Consumed, 2022.* https://www.eia.gov/dnav/ng/ng_cons_heat_a_EPG0_VGTH_Btucf_a.htm Accessed 1/11/2023

The natural gas energy consumed in the building sector in the state including commercial as well as residential buildings amounts to:

$$NGE_{bldg.} = 1.030 \times 10^{3} \times 2.26068 \times 10^{11} \text{ Btu} = 232.850 \times 10^{12} \text{ Btu} \quad [7]$$

Table A2 presents the properties of hydrogen relevant to convert this amount of energy into the kilograms of hydrogen with the same energy content.

Table A–2. Properties of Hydrogen[46]

Properties of Hydrogen	Value
Lower Heating Value, LHV	290 Btu/ft^3
Density	2.55 grams/ft^3

The amount of natural gas energy in Btu is converted to kilograms of hydrogen kgH_2 for residential buildings using the LHV[47] and density of this gas, with the result:

$$kgH_{2res} = (126.496 \times 10^{12})/290] \times (2.55/1{,}000) = 1.1123 \times 10^{9} \text{ kg} \quad [8]$$

Thus, 1.1123 million tonnes (1 tonne = 1,000 kg) of hydrogen are needed to replace natural gas in the residential heating sector. The production of this amount of green hydrogen using electrolyzer stacks requiring 43 kWh per kg of hydrogen produced would consume the following amount of electricity (TWh)):

$$TWh_{res} = 43 \text{ kWh/kg} \times 1.1123 \times 109 \text{ kg} = 47.83 \text{ TWh}^{48} \quad [9]$$

The replacement of all the natural gas by green hydrogen in both residential and commercial buildings would require kilograms of hydrogen as follows:

46 The Lower Heating Value (LHV) of a fuel: The products of combustion contain the water vapor and the heat in the water vapor is not recovered, whereas in the Higher Heating Value (HHV) this heat is recovered by condensing the water vapor. The Engineering Toolbox. F*uels – Higher and Lower Calorific Values, 2023*. https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html. Accessed 1/11/2023

47 The LHV, rather than the higher heating value (HHV), is the appropriate heating value to use for the operation of gas appliances (e.g., water heaters, gas furnaces, gas ranges) that operate with an excess of air, so the water vapor produced does not condense but remains dissolved in the exhaust stream.
National Renewable Energy Laboratory. *Hydrogen Production: Fundamentals and Case Study Summaries*, Conference Paper, NREL/CP-550-47302, January 2010. https://www.nrel.gov/docs/fy10osti/47302.pdf Accessed 1/11/2023

48 For reference with currently available commercial electrolyzers producing one kg of hydrogen with 50-53 kWh of electricity this number would increase to between 56-60 TWh.
Enapter. AEM Electrolyser EL 4.0 Handbook, ELE40-DTS-COM02_rev04. https://handbook.enapter.com/electrolyser/el40/downloads/Enapter_Datasheet_EL40_EN.pdf Accessed 1/17/2023 Blain, L. Record-breaking hydrogen electrolyzer claims 95 percent efficiency. New Atlas. March 16, 2022. https://newatlas.com/energy/hysata-efficient-hydrogen-electrolysis/ Accessed 1/17/2023

$$kgH_{2bldg.} = (232.850 \times 10^{12})/290] \times (2.55/1{,}000) = 2.0475 \times 10^{9} \text{ kg} \quad [10]$$

Production of this amount of hydrogen would consume the following amount of electricity:

$$TWh_{bldg.} = 43 \text{ kWh/kg} \times 2.0475 \times 10^{9} \text{ kg} = 88.04 \text{ TWh} \quad [11]$$

With the capacity factors assumed above, an onshore wind turbine's annual energy output (WE_{on}) can be calculated as:

$$WE_{on} = 3.5 \text{ MW} \times 8760 \times 0.36 = 11{,}038 \text{ MWh or } 0.011038 \text{ TWh} \quad [12]$$

Similarly, the annual output of an offshore wind turbine (WE_{off}) with the operating parameters assumed earlier is:

$$WE_{off} = 12 \text{ MW} \times 8760 \times 0.51 = 0.05361 \text{ TWh} \quad [13]$$

Assuming no power transmission losses, the amount of electricity needed to power the electrolyzer stacks divided by the yearly energy output of the onshore and offshore wind turbines provides estimates of the number of wind turbines required (N_{on} and N_{off}) to produce enough green hydrogen to replace methane, assuming that this energy is generated entirely either only by onshore or only by offshore turbines.

To replace methane with green hydrogen in the residential sector, these numbers for onshore and offshore wind turbines amount to (numbers of turbines are rounded up to the next whole number):

N_{on} = 47.83 TWh/0.011037 TWh per onshore wind turbine = 4,334 wind turbines, a total generation capacity of 15.2 GW [14]

N_{0ff} = 47.83 TWh/0.05361 TWh per offshore wind turbine = 893 wind turbines a total generation capacity of 10.7 GW [15]

The total annual output of 4,344 onshore or 893 offshore wind turbines with total nameplate capacities of 15.2 GW and 10.7 GW respectively would be consumed to produce the amount of green hydrogen required to replace natural gas in the residential heating sector.

A similar calculation in which only 20 percent of the natural gas consumed in both residential and commercial buildings in Massachusetts is replaced by green hydrogen (consuming 17.61 TWh of clean electricity) would absorb the outputs of 1,596 onshore wind turbines (5.6 GW of capacity) and 329 offshore wind turbines (3.9 GW of capacity). Complete replacement of methane in both residential and commercial buildings by green hydrogen, consuming 88.04 TWh of electricity would absorb the entire output of 7,977 onshore (27.9 GW of capacity) and 1,643 offshore turbines (19.7 GW of capacity).

For reference, the predicted capacity of offshore wind turbines that will be supplying electricity in Massachusetts by 2030 is 3.2 GW.[49]

Requirements for clean electricity to produce green hydrogen to be blended with methane in proportion of 20 percent or to supply 100 percent green hydrogen can be compared with those for the electricity needed to power heat pumps[50] to deliver the same amount of thermal energy (heat) as is produced by burning this gas.

An Electric Option: Heat Pumps Versus Green Hydrogen

The equivalent thermal energy produced by gas-fired heating equipment in buildings is reduced by efficiency losses in boilers and other gas-fired systems, which are assumed to be 5 percent in this calculation. This loss, assuming new efficient equipment, is another input that produces conservative estimates of the ratio between the electricity consumption of green hydrogen to that of heat pumps for heating buildings. It overestimates the thermal energy heat pumps will have to generate, because most furnaces and boilers now operating in Massachusetts are less efficient than 95 percent. At 95 percent efficiency, the natural gas consumed in the building sector in Massachusetts will generate thermal energy (TE) of:

$$TE = 0.95 \text{ x } 232.859 \text{ x } 10^{12} \text{ BTU} = 221.21 \text{ x } 10^{12} \text{ BTU} \quad [16]$$

Assuming a power transmission loss over the grid to heat pumps of 5 percent[51], the electrical energy (EE) that would have to be generated so that a heat pump with an HSPF (heating seasonal performance factor) of 9, which produces 9,000 Btu per kWh of input, a realistic value for Massachusetts[52], would deliver this amount of heat is:

49 The Commonwealth of Massachusetts. *Massachusetts Clean Energy and Climate Plan for 2025 and 2030*, 2022. https://www.mass.gov/doc/clean-energy-and-climate-plan-for-2025-and-2030/download Accessed 1/11/2023

50 As of 2021 global installations of heat pumps amounted to some 190 million, including countries with cold climates such as Canada and Nordic countries: Norway (60 percent), Sweden (43 percent), Finland (41 percent), and Estonia (34 percent) have the greatest share of households with heat pumps. International Energy Association (IEA), *Heat Pumps, 2022*. https://www.iea.org/reports/heat-pumps Accessed 1/11/2023

51 This figure is slightly larger than the 4.5 percent loss calculated for Massachusetts from Table 10 in its State Electricity Profile for 2021. U.S. Energy Information Administration. *Massachusetts Electricity Profile 2021*, November 2022. https://www.eia.gov/electricity/state/massachusetts/ Accessed 1/11/2023

52 The Massachusetts Stretch code specifies air source heat pumps with a minimum HSPF of 10 and ground source heat pumps with a minimum seasonal heating coefficient of performance (COP) of 3.5. An HSPF of 10 translates to a COP of 2.93. An explanation of these two different ways of measuring the performance of a heat pump, and how to convert between them can be found in this citation. See 225 Cmr 23: *Massachusetts*

$$EE = TE/(0.95 \times 9000) \text{ kWh} = (221.21 \times 10^{12} /(0.95 \times 9000) \text{ kWh} = 25.87 \text{ TWh} \quad [17]$$

If heat pumps are installed to replace only 20 percent of the methane consumed in combustion systems in residential or in both residential and commercial buildings in the Commonwealth, the required amounts of electricity will be 2.81 TWh and 5.17 TWh respectively.

The total capacities and numbers of wind turbines whose output would have to be dedicated to generating the amounts of electricity for heat pumps to replace methane combustion systems in buildings fully or partially in the same proportions as green hydrogen replaces methane above can be calculated in the same way as for hydrogen.

Comparison of equations [11] and [17] shows that burning green hydrogen to replace methane in buildings would conservatively increase electricity consumption in the Commonwealth by 3.4 times (88.04/25.87), the increase attributable to heat pumps for the same purpose.

The results of the equations can be found in Table A–3.

Commercial Stretch Energy Code and Municipal Opt-In Specialized Code 2023, *Massachusetts Stretch Code and Specialized Code for Commercial buildings*, released 6/17/2022. https://www.mass.gov/doc/225-cmr-2200-commercial-specialized-stretch-energy-code-front-end-amendment-for-sos-june-16-2022/download?_ga=2.200907629.2113844588.1670088188-1627418680.1669421606 Accessed 1/11/2023,

Ather, SH. *How to Calculate Coefficient of Performance*. Sciencing. Updated September 26, 2019. https://sciencing.com/calculate-coefficient-performance-7583660.html Accessed 1/11/2023.

Table A–3. Replacement of Natural Gas in Massachusetts Buildings
Comparison of Demand for Wind-Generated Electricity Between Green Hydrogen and Heat Pump Options with Onshore Data

Replacement Option for Methane	Electricity Consumption of Replacement (TWh)	Percent Increase in Electricity Consumption[A]	Total Wind Turbine Generation Capacity, (GW)[B]		Number of Wind Turbines[B]	
Option and Proportion			Only Onshore	Only Offshore	Only Onshore	Only Offshore
100% Green H_2, all buildings	88.0	173 %	27.9	19.7	7,977	1,643
100% Green H_2, residential only[C]	47.8	94.1%	15.2	10.7	4,344	892
20% Green H_2, all buildings	17.6	34.6%	5.6	3.9	1,596	329
100% Heat Pumps, all buildings	25.9	51.0%	8.2	5.8	2,344	483
100% Heat Pumps, residential only[D]	14.1	27.7%	4.5	3.2	1,273	263
20% Heat Pumps, all buildings	5.2	10.2%	1.6	1.2	469	97

Table Notes:

A. Compared with the total 2021 consumption of electricity in Massachusetts of 50.8 TWh with no green hydrogen production; if all electricity consumed in the state in 2021 had been generated by wind turbines it would have absorbed the output of 16.1 GW of onshore or 11.4 GW of offshore wind turbines with the same performance parameters as used in the table, or 4,603 onshore and 948 offshore turbines.

B. The numbers and total capacities of onshore and offshore wind turbines are calculated on the basis that the electricity to produce green hydrogen is generated entirely either by onshore or by offshore turbines.

C. This scenario is hypothetical not practical since many pipelines serve both residential and commercial buildings. It would not be feasible to segregate pipelines so that green hydrogen is only delivered to residences.

D. This scenario is highly improbable since gas distribution pipelines which only generate revenues from commercial buildings in mixed use neighborhoods would not be economically viable.

Appendix B. Resources

Additional resources for evaluating the consequences of burning hydrogen for heating.

A. Costs and Efficiency

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3. Global Witness. *Heating homes with gas is expensive. Heating with hydrogen could cost double*, September 2022. https://www.globalwitness.org/en/campaigns/fossil-gas/heating-homes-gas-expensive-heating-hydrogen-could-cost-double/

4. Collins, L. Green hydrogen production: *Final proposal of EU Delegated Act calls for quarterly proof of dedicated renewables supply*, Hydrogeninsight Dec. 2, 2022. https://www.hydrogeninsight.com/policy/green-hydrogen-production-final-proposal-of-eu-delegated-act-calls-for-quarterly-proof-of-dedicated-renewables-supply/2-1-1365901

5. DNV. *Energy Transition Outlook: A global and regional forecast for 2050, 2022*. Updated 2023. https://www.dnv.com/energy-transition-outlook/download.html "Hydrogen is inefficient and expensive compared with direct electricity use but is essential for decarbonizing hard-to-abate sectors like high-heat processes in manufacturing, and maritime transport and aviation," p. 5.

B. Greenhouse Effects of Hydrogen and Byproducts of Burning Hydrogen in Air

1. Warwick, N., Griffiths, P., Keeble, J., Archibald, A., Pyle, J., and Shine, K., *Atmospheric implications of increased hydrogen use*. Department of Business, Energy and Industrial Strategy, United Kingdom April 2022. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067144/atmosphericimplications-of-increased-hydrogen-use.pdf
2. Clean Energy Group. *Hydrogen Hype in the Air*, December 14, 2020. https://www.cleanegroup.org/hydrogen-hype-in-the-air/
3. Hauglustaine, D., Paulot, F., Collins, W. et al. *Climate benefit of a future hydrogen economy.* Commun Earth Environ 3, 295, 2022. https://doi.org/10.1038/s43247-022-00626-z

C. Investments in Methane Pipeline Infrastructure to Accommodate Hydrogen

1. Raju, A. and Martinez-Morales, A. *Hydrogen Blending Impacts Study*, July 18, 2022. Prepared for the California Public Utilities Commission. docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M493/K760/493760600.PDF
2. Neacsa A., Eparu CN, Stoica DB. *Hydrogen–Natural Gas Blending in Distribution Systems—An Energy, Economic, and Environmental Assessment. Energies*. 2022; 15(17):6143. https://doi.org/10.3390/en15176143

D. Safety of Hydrogen in Domestic Environments

1. Collins, L. *Hydrogen in the home would be four times more dangerous than natural gas: Government Report*. RECHARGE News. August 2, 2021. https://www.rechargenews.com/energy-transition/hydrogen-in-the-home-would-be-four-times-more-dangerous-than-natural-gas-government-report/2-1-1047218
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4. HEET. *Eversource Gas breaks ground on first networked geothermal installation*, 2022. https://heet.org/2022/11/23/eversource-gas-breaks-ground-on-first-networked-geothermal-installation/.

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