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Hydrogen-Ready Appliances Assessment Report

This project was a specially-funded initiative with work sponsored by:

Prepared For NEEA:
Jeff Harris, Chief Transformation Officer
and
Peter Christeleit, Manager, Natural Gas Portfolio & Strategy

Prepared by:
Eli Font, Associate Director
Peter Kernan, Sr. Associate
Sarah Widder, Chief Services Officer

Cadeo Group
107 SE Washington Street #450
Portland, OR 97214

Northwest Energy Efficiency Alliance
PHONE
503-688-5400
EMAIL
info@neea.org

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In 2022, NEEA contracted with Cadeo Group to assess the current and future needs of natural gas appliances served by a blend of conventional methane and hydrogen. The attached report documents that assessment and provides recommendations for future actions to support efficient and safe use of hydrogen blended fuels in new and existing natural gas appliances. NEEA and Northwest stakeholders will take the findings from this report and determine appropriate next steps to address identified market barriers and opportunities for appliances in a market served by blended fuels in the future.

Context. The interest in hydrogen blended fuels is growing and is driven by several factors. Northwest natural gas utilities and policy makers are looking for ways to decarbonize the natural gas energy system. Reducing the amount of carbon embedded within the delivered fuel is one approach. Blending hydrogen with conventional methane can reduce carbon intensity of the delivered fuel if the hydrogen is produced in a way so that a net overall carbon emission reduction occurs.

The Northwest has abundant renewable energy resources in the form of hydroelectricity, wind energy and a growing solar energy resource. At times these renewable energy resources produce more energy than can be used by the energy system causing these resources to be curtailed and their energy production capability to go unused. The duration of these periods of curtailment is likely to grow as the electric power system adds more renewable resources to replace retired fossil-fueled power plants. Northwest renewable energy could be used to produce hydrogen without increasing carbon emissions which then can be used to de-carbonize the natural gas system and result in a net overall carbon emissions reduction. Interest in this concept is evident in that there are currently several projects planned for construction of hydrogen-production facilities in the Northwest within the next several years.

Hydrogen and Efficient Products. Blending hydrogen into the existing natural gas system raises questions regarding safety and efficiency in end-use appliances such as furnaces and water heaters. It also raises questions about aesthetics and consumer satisfaction in hearth products and cooking appliances.

As a market transformation organization NEEA works with manufacturers, distributors/retailers and contractors to increase market adoption of efficient natural gas appliances. New efficient natural gas products need to be capable of operating efficiently and safely under whatever fuel composition will be in place over the life of these appliances. Future efficient gas appliances may need to be tested, rated and labeled for use with blended fuels so that the market can be assured that these products are both safe and efficient, both now and in the future.

Northwest Energy Efficiency Alliance
700 NE Multnomah Street, Suite 1300, Portland, OR 97232
503.688.5400 | Fax 503.688.5447
neea.org | info@neea.org

Project description and results. NEEA hired Cadeo Group to assess the current industry knowledge and practices related to blending hydrogen into the natural gas system. As noted in the report, there is global interest and some limited experience with blends of hydrogen and methane ranging from a few percent up to 100%. There appears to be growing consensus that blends of up to 20% or perhaps even 30% are possible with little to no impact on current equipment. Higher fractions of hydrogen approaching 100% will likely require changes to equipment components and perhaps installation and maintenance practices.

The report also documents that there is currently no standardized testing, rating, or labeling program to enable differentiation of equipment manufactured for the North American market that is safe and efficient to operate with hydrogen blended fuels. From a market transformation perspective, this lack of a standardized program with these elements could represent a significant market barrier to the expanded use of hydrogen blended fuels.

The report also identifies unanswered questions about the long-term use of hydrogen blends on typical materials used in new natural gas appliances. Hydrogen is known to cause some metals and plastics to become brittle over time, increasing the risk of failure of parts made from these materials. It will be important to understand the implications of hydrogen blends over the lifetime of materials used in modern, high-efficiency equipment such as gas-fired heat pumps and condensing heating equipment. Uncertainty in long-term performance of appliances using hydrogen blends represents another market barrier for manufacturers who are designing and building the next generation of efficient gas equipment.

Next Steps. NEEA will be exploring next steps with funders to determine appropriate strategies to address the identified market barriers. Possible interventions could include engaging with organizations responsible for safety testing procedures, collaborating with California on a proposed labeling system, and exploring materials degradation with GTI and manufacturers. NEEA will also be looking to identify extra-regional partners that can help support the work as these barriers are not unique to the Northwest market but are in fact global issues to be addressed as hydrogen is increasingly identified as a decarbonization strategy worldwide.

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Abbreviations and Acronyms

AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ANSI	American National Standards Institute
Btu	British thermal unit
CEC	California Energy Commission
CFR	Code of Federal Regulations
Council	Northwest Power and Conservation Council
CSA	Canadian Standard Association
DOE	Department of Energy
GHG	Greenhouse gas
GTI	Gas Technology Institute
H_2	Hydrogen
HB	House Bill
HENG	Hydrogen enriched natural gas
kcal	Kilocalories
NEEA	Northwest Energy Efficiency Alliance
NFPA	National Fuel Protection Association
NO_x	Nitrogen Oxide
Nm^3	Normal cubic meters
NREL	National renewable Energy Laboratory
PAS	Publicly Available Specification
RBSA	Residential Building Stock Assessment
SB	Senate Bill
UCI	University of California, Irvine

Executive Summary

State policy targets on greenhouse gas emission reductions and other decarbonization initiatives are creating a movement toward low or zero-carbon gases and fuels. Given its versatility as an energy carrier and its potential for use in a broad range of applications, hydrogen is gaining in popularity, and natural gas providers are looking at integrating it into their networks. To better understand the impacts of blending hydrogen in the natural gas system on household appliances, Cadeo conducted a literature review and performed interviews with subject matter experts and market stakeholders.

Hydrogen integration initiatives are happening all over the world. In the United Kingdom, pilot programs are incorporating 20% hydrogen blends in natural gas in public networks, and in the Netherlands, pilots have replaced natural gas with 100% hydrogen. Utilities in the United States are currently testing up to 20% hydrogen blends within their training facilities, and the Gas Technology Institute conducted laboratory research that indicates that the water heaters and furnaces tested can maintain performance and safety with a 30% hydrogen blend in natural gas.

In general, the compilation of different studies indicates that there are limited performance impacts on existing appliances up to 20% hydrogen, and recent evidence suggests the value could be higher. However, there is an upper limit at which existing equipment can operate before appliance modifications are needed to burn 100% hydrogen. Frazer-Nash, an energy consultancy based in the United Kingdom, highlighted two components that will need replacement for 100% hydrogen:

1 | The existing atmospheric and partial premix burner design on all appliances.
2 | The ionization sensors commonly used on furnaces and water heaters.

In Europe, hydrogen-ready appliances are commercially available. These appliances can run immediately off blends up to 20%, and with the substitution of a minimum number of components in under an hour, they can run on 100% hydrogen.[1]

In Europe, standards for appliances include testing with a limit gas containing up to 23% hydrogen blend in natural gas. In the United States, the existing appliance safety and performance standards (American National Standards Institute/Canadian Standards Association Z21 series) do not cover hydrogen enriched natural gas (HENG), even as a limit gas.[2] To ensure safety and performance of end use appliances, standards and testing methods should be reviewed and expanded to include up to 20% HENG as a reference gas, as well as limit gases with higher concentration of hydrogen. The Canadian Standards Association Group's Technical

[1] HyLife, "Hy4Heat Hydrogen-Ready Wall-Mounted Gas Boilers," https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/616d78c680bd847c4efade9a/1634564294494/Bosch+HyLife+.pdf.

[2] Limit gases are gases described in appliance standards often used to test extreme variations in the characteristics of the gases.

Committees are currently reviewing the need to develop new standards or update existing ones (CSA/ANSI Z21) to include HENG.

The Northwest Energy Efficiency Alliance can support this market transformation by enabling the conversation with appliance manufacturers, encouraging the modification of test methods and standards and promoting their adoption, conducting focus groups with stakeholders to address barriers to ensure a safe development of this market, and supporting pilot projects and new research addressing the long-term impact of HENG on appliances.

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Section 1 Introduction

1.1 Drivers of the Hydrogen Market

State policy targets on greenhouse gas emission reductions and other decarbonization initiatives are creating a movement toward low or zero-carbon gases and fuels. Consequently, hydrogen is gaining popularity as the fuel to support the energy transition given its versatility as an energy carrier and its potential for use in a broad range of applications.

As part of the Energy Earthshots Initiative, which aims to accelerate the availability of more abundant, affordable, and reliable clean energy solutions, the US Department of Energy (DOE) set a goal to reduce the cost of clean hydrogen by 80% to $1 per kilogram in one decade.[3] the bipartisan Infrastructure Investment and Jobs Act then directed $9.5 billion to the DOE to develop three initiatives:

1 | A Regional Clean Hydrogen Hubs ($8 billion) to create jobs and expand use of clean hydrogen in the industrial sector.
2 | A Clean Hydrogen Electrolysis Program ($1 billion) to reduce the cost of hydrogen produced from clean electricity.
3 | A Clean Hydrogen Manufacturing and Recycling Initiatives ($500 million) to support a strong domestic supply chain.[4]

The Northwest Energy Efficiency Alliance (NEEA) also acknowledges a future role for hydrogen in the energy industry. NEEA recently published national and regional strategic planning briefing papers that explored macro-trends in the energy industry.[5] In these reports, NEEA acknowledged that green hydrogen will play an increasing role in the energy sector, including potential inclusion in existing gas distribution systems because of the increased pressure to reduce the greenhouse gas (GHG) emissions of natural gas. According to the report, whether hydrogen will serve residential buildings is unclear, though it is increasingly likely that hydrogen will serve some commercial and industrial end uses.

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[3] DOE (US Department of Energy), *Hydrogen Shot*, Hydrogen and Fuel Cell Technologies Office, https://www.energy.gov/eere/fuelcells/hydrogen-shot.

[4] DOE, "DOE Establishes Bipartisan Infrastructure Law's $9.5 Billion Clean Hydrogen Initiatives," *Energy.gov*, February 15, 2022, https://www.energy.gov/articles/doe-establishes-bipartisan-infrastructure-laws-95-billion-clean-hydrogen-initiatives.

[5] NEEA (Northwest Energy Efficiency Alliance), *Northwest Regional Trends*, NEEA Strategic Planning Briefing Paper, by Jason Eisdorfer (Portland, Oregon: NEEA), 11, https://neea.org/img/documents/NEEA-Strategic-Planning-Briefing-Paper-Northwest-Regional-Trends.pdf.

In regional energy planning, the Northwest Power and Conservation Council (the Council) also acknowledges a role for hydrogen in the 2021 Power Plan.[6] In particular, the Council sees hydrogen electrolyzers as an opportunity for the region to maximize use of inexpensive renewable electricity and store the energy in hydrogen for future consumption. This process adds time value to clean electricity to be flexibly consumed at a future time. However, beyond acknowledging the opportunity for production of hydrogen and some discussion of use in transportation and industry, the Council did not explicitly explore residential end uses of hydrogen in the 2021 Power Plan.

Policymaking is also an influencing factor within the Pacific Northwest. In recent legislative sessions, the State of Washington passed three bills focused on reducing GHG emissions associated with energy generation and use:

1 | The Clean Energy Transformation Act (Senate Bill [SB] 5116, 2019), which sets the target of 100% carbon-free electricity supply by 2045.
2 | The Climate Commitment Act (SB 5126, 2021), which caps and reduces GHG emissions from largest emitting sources and industries.
3 | The Clean Fuel Standard (House Bill [HB] 1091, 2021), which requires fuel suppliers to reduce the carbon intensity of transportation fuels by 20% (from 2017 levels) by 2038.

These legislative activities promote the development and use of hydrogen in the Northwest. Additionally, in the 2022 legislative session, Washington passed two bills specifically focused on promoting clean hydrogen: HB 1988, which includes tax deferrals for production of green, electrolytic hydrogen and SB 5910, which will accelerate the availability and use of renewable hydrogen in the state. The latter requires gas companies to file a notice, permitting, and safety standards to the Utilities and Transportation Commission when replacing natural gas with hydrogen to serve customers.

Washington is not acting alone on decarbonization policy. Oregon established the Clean Fuels Program in 2016 to help reduce the carbon intensity of transportation fuels by 10% by 2025 from 2015 levels. Reductions can be achieved by using lower carbon biofuels or switching to alternative fuels such as electricity, renewable natural gas, renewable propane, or renewable hydrogen.[7] More recently, Oregon established the Climate Protection Program[8] to reduce GHG emissions from large emitters in the state, regulating natural gas utilities under this program.

As a result of these increasing state regulations on GHG emission reductions, natural gas providers are looking at hydrogen gas integration in their networks as a strategy for decarbonization. To better understand the impacts of blending hydrogen in the natural gas

[6] The Council (Northwest Power and Conservation Council), *The 2021 Northwest Power Plan*, July 25, 2022, https://www.nwcouncil.org/fs/17680/2021powerplan_2022-3.pdf.
[7] Oregon DEQ (Department of Environmental Quality), "Clean Fuels Program Overview," *Oregon Clean Fuels Program*, July 25, 2022, https://www.oregon.gov/deq/ghgp/cfp/Pages/CFP-Overview.aspx.
[8] Oregon DEQ, "Climate Protection Program: Program Brief," July 25, 2022, https://www.oregon.gov/deq/ghgp/Documents/CPP-Overview.pdf.

system on household appliances, Cadeo conducted secondary research, as well as SMEs and stakeholder interviews. The research aimed to compile results of demonstration projects using hydrogen blends in household appliances, as well as identify gaps in knowledge and industry barriers around codes, standards, and test procedures. The following sections address hydrogen properties and considerations for its use on household appliances, list a variety of worldwide demonstration projects at the household level, review existing test methods and standards, and provide an assessment of the specific impacts on cook tops, ovens, furnaces, water heaters, hearths, and clothes dryers.

1.2 Hydrogen Properties that Differ from Natural Gas

Hydrogen (H_2) is the simplest and smallest molecule and the most abundant element in the universe.[9] Table 1 describes hydrogen molecule properties that makes it different from natural gas (or methane, the largest component in natural gas) and the potential consequences of those differences. A more comprehensive table of hydrogen properties versus other fossil fuels can be found in 0: Appendix A. Comparative Properties of Hydrogen and Other Fuels.

Table 1: Hydrogen Properties and Their Impact Relative to Natural Gas

Property	Description	Consequences/Impact
Wider flammable range	Flammable range for hydrogen is between 4% and 75% in air compared to 5% to 15% for natural gas.	Higher probability for combustion if exposed to an ignition source.
Less energy required to ignite	Under optimal combustion conditions (29% H_2 to air volume ratio), H_2 needs 0.02 megajoules to ignite, whereas natural gas ignition energy is 0.29 megajoules.	Higher probability of combustion if optimal combustion conditions occur. At low concentrations of hydrogen in air, the energy required to start combustion is similar to that of natural gas.
Lower vapor density	Hydrogen is 14 times lighter than the air, while methane is only two times lighter than air.	While in an open space this can provide a safety advantage, in a closed space H_2 will accumulate in high point, ceiling and roofs.

[9] ACS (American Chemical Society), "Hydrogen," *Molecule of the Week Archive*, July 25, 2022. https://www.acs.org/content/acs/en/molecule-of-the-week/archive/h/hydrogen.html.

Lower calorific value	A given amount of hydrogen has about one-third of the calorific value of the same amount of natural gas.	Greater amount of hydrogen (x3) is needed to deliver the same amount of energy as natural.
Higher flame temperature	Hydrogen flame temperature is approximately 200° Celsius higher than that of methane on air.	Consideration for material selection in exposed appliances.
Lighter flame color	Hydrogen burns with a pale blue flame that is nearly invisible in daylight, and the flames radiate little infrared heat.	Safety concerns, higher risk of injury.

Source: Data from W.F. Gale and T.C. Totemeier, eds., *Smithells Metals Reference Book* (Portsmouth, New Hampshire: Butterworth-Heinemann), 28, tables 28.25 and 28.31.

Natural gas interchangeability is the "ability to substitute one gaseous fuel for another in a combustion application without materially changing operational safety, efficiency, performance or materially increasing air pollutant emissions."[10] The most common metric to evaluate interchangeability of gaseous fuels is the Wobbe Index (WI). The WI is a ratio of a gas's higher heating output to the square root of its specific gravity.[11] Gases that have a similar WI are interchangeable due to the lack of discernible differences to the end user.

Despite the difference in hydrogen properties from that of natural gas, the WI for both gases are remarkably similar, ranging from 9,714 to 11,528 kilocalories (kcal) per normal cubic meter (Nm^3) for hydrogen and from 11,597 to 12,837 kcal/Nm^3 for natural gas.[12] In the case of blends, Marcogaz, the technical association of the European natural gas industry, published a technical report showing how increasing blends of hydrogen in natural gas has a small impact on the WI; however, the WI changes significantly other properties such as gross calorific value and density.[13]

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[10] FERC (Federal Energy Regulatory Commission), "Policy Statement on Provisions Governing Natural Gas Quality and Interchangeability in Interstate Natural Gas Pipeline Company Tariff," June 15, 2006, https://www.ferc.gov/sites/default/files/2020-04/G-1_29.pdf.

[11] CSA (Canadian Standards Association), *Appliance and Equipment Performance with Hydrogen-Enriched Natural Gases*, by C.J. Suchovsky, Lief Ericksen, Ted A. Williams, and Dragica Jeremic Nikolic, CSA Group, Standards Research: Toronto, 2021. https://www.csagroup.org/wp-content/uploads/CSA-Group-Research-Appliance-and-Equipment-Performance-with-Hydrogen-Enriched-Natural-Gases.pdf.

[12] Engineering ToolBox, "Fuel Gases – Wobbe Index," Engineering Toolbox, 2003, accessed July 25, 2022, https://www.engineeringtoolbox.com/wobbe-index-d_421.html.

[13] Marcogaz, "Impact of Hydrogen in Natural Gas on End-use Applications," Marcogaz, 2017, https://www.marcogaz.org/wp-content/uploads/2021/04/UTIL-GQ-17-29.pdf.

1.2.1 Safety Consideration of H2 Blends in Household Natural Gas Appliances

Though hydrogen is a nontoxic gas, the different properties of hydrogen can create safety hazards at the household level when used in gas appliances.

Natural gas is inherently odorless, but the industry adds sulfur-containing odorants, such as mercaptans, so end users can detect its presence and take necessary precautions should a leak occur. Hydrogen is also an odorless gas but due to its smaller size, the traditional odor molecules utilized in natural gas could not be carried with the gas.[14] It is worth noting that this is not a concern for low concentrations of hydrogen in natural gas. Nevertheless, a recent study has shown how two types of Sulphur-based odorants are compatible with 100% hydrogen gas allowing its identification at the 1% regulatory thresholds of gas in air by untrained participants in this study,[15] which solves for safety concerns in this respect. Additionally, existing gas-based appliances were originally designed to accommodate a larger molecule. Given the smaller size of hydrogen, leakages from material failure or improper connection increase the risk of combustion due to hydrogen higher flammability and lower ignition energy needed to combust. For the use of high concentration of hydrogen blend in natural gas or 100% hydrogen, the deployment of hydrogen sensors and properly designed ventilation systems are fundamental to prevent incidents.

Another safety consideration for the use of hydrogen in appliances is the light pale flame, almost invisible to the naked eye during daylight. The lack of visible flame can increase the risk of skin burns. This risk is exacerbated by the fact that hydrogen emits little infrared heat so the end user cannot be warned by the emanating heat when approaching the flame. Moreover, hydrogen flames emit substantial ultraviolet radiation, which can result in sunburn effects due to overexposure to the flame.[16] Flame color and the light resulting from it, are one of the major attractions of gas-fired heating systems, but the lack of a visible flame can create aesthetic concerns. Methods for coloring the hydrogen flame, which include inserting additives to the gas system at different entry points, have been published,[17] but nothing indicates that this has been developed beyond research purposes. Nevertheless, while the flame visual characteristics start

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[14] PNNL (Pacific Northwest National Laboratory), "Hydrogen Compared with Other Fuels," *Hydrogen Tools*, https://h2tools.org/hydrogen-compared-other-fuels.

[15] Mouli-Castillo, J. 2021. "A comparative study of odorants for gas escape detection of natural gas and hydrogen," in *International Journal of Hydrogen Energy,* Vol 46, Issue 27, 14881-14893 https://doi.org/10.1016/j.ijhydene.2021.01.211

[16] Ibid. https://h2tools.org/hydrogen-compared-other-fuels.

[17] Wayne Ernest Conrad, Method and Apparatus for Producing a Visible Hydrogen Flame, US patent 2012/0003593 A1, filed August 10, 2007, and issued January 5, 2012, https://patentimages.storage.googleapis.com/d8/4f/f1/f352c56b964b6d/US20120003593A1.pdf; John S. Fleming, and Arthur Morris Lister, Hydrogen-fueled Visual Flame Gas Fireplace, European patent WO1999/032832, filed December 21, 1998, and issued December 20, 2000, https://patentimages.storage.googleapis.com/49/3e/65/8cc689ed8f226d/EP1060350B1.pdf.

changing after around 50% hydrogen blend in natural gas,[18] the almost invisible flame only occurs under high concentrations of hydrogen in natural gas (above 80%) to 100% hydrogen. Therefore, risks of burns for not seeing the flame or aesthetic issues are not a concern for lower hydrogen blends in natural gas.

Last, hydrogen can produce embrittlement, which is the degradation of mechanical properties of materials, compromising their structural integrity. The hydrogen diffuses into a material, generating losses in tensile strength, ductility, and fracture toughness, and it also accelerates fatigue crack growth. Hydrogen embrittlement depends not only on the material properties (material strength, alloy composition, metallurgical features) but also on environmental variables and external stressors. For instance, for a given material, hydrogen embrittlement is more likely at near ambient temperature and higher hydrogen gas pressure, as well as when exposed to cyclic stress (instead of constant stress) and higher stress magnitudes.[19] As embrittlement is more common in high-pressure cycle exposure, gas appliances operating at atmospheric temperature should not be a concern.[20] Nevertheless, testing should be performed for all appliances using 100% hydrogen, especially in parts exposed to high temperature, the flame, and the circulation of hydrogen atoms.

With the increased regulatory pressure to reduce GHG emissions and the increased interest of gas companies in using hydrogen to this end, this report aims to conduct secondary research to understand the implications of introducing hydrogen blends in household gas appliances, as well as identify existing standards and test methods for hydrogen introduction in residential gas appliances, and the gaps that need to be addressed to ensure safe practices.

[18] Zhao, Y. 2019. "Investigation of visible light emission from hydrogen-air research flames", International Journal of Hydrogen Energy, 44(39) 22347-22354 https://doi.org/10.1016/j.ijhydene.2019.06.105

[19] PNNL, "Hydrogen Embrittlement," *Hydrogen Tools*, https://h2tools.org/bestpractices/hydrogen-embrittlement.

[20] Frazer-Nash Consultancy, *Appraisal of Domestic Hydrogen Appliances*, Department of Business, Energy & Industrial Strategy, FNC 55089/46433R, No. 1, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/699685/Hydrogen_Appliances-For_Publication-14-02-2018-PDF.pdf.

Section 2 Status of Hydrogen Introduction in Natural Gas Distribution Systems

This section describes the current status of blending hydrogen in natural gas networks in the United States and worldwide. More specifically, this section complies general findings from existing research and case studies on the impact of hydrogen enriched natural gas (HENG) on pipelines and appliances and the test methods and standards applicable to ensure efficiency, safety, and performance.

2.1 Hydrogen Blending in Pipelines and Appliances

The idea of mixing hydrogen with gas dates to the early and mid-1880s, where manufactured gas, produced from coal or petroleum products, typically contained between 30% to 50% hydrogen. This manufactured gas, also known as town gas, powered streetlights, commercial buildings, and households. The use of manufactured gas in the United States persisted until the 1950s when the last facility closed after natural gas displaced it.[21] The concept of a hydrogen economy was developed in the 1970s, with the objective of hydrogen replacing fossil fuels to reduce the spread of pollutants resulting from burning fossil fuels.[22] The renewed interest in hydrogen to decarbonize the gas system has led to new research on its impact on pipelines and appliances.

According to a National Renewable Energy Laboratory (NREL) study, supported by the Gas Technology Institute (GTI),[23] low concentrations of hydrogen blend (5% to 15% by volume) would be compatible with existing gas pipelines and end-use appliances in the United States. GTI found no major concerns pertaining to the integrity and durability of pipeline materials (low strength steel, iron, copper, and plastic) in the distribution system when operated under normal conditions. The NREL report highlight that several studies have been conducted for transmission pipelines given the higher pressures and the potentially susceptible steel material. Results show that up to 50% hydrogen can be carried with insignificant adaptations. Nevertheless, they recommend a detailed investigation on a case-by-case basis. For end uses, the maximum hydrogen blend amount that an appliance can take without affecting operations will depend on the composition of natural gas, the type of appliance (or combustion), and the age of the

[21] NREL (National Renewable Energy Library), *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues*, by M. W. Melania, O. Antonia, and M. Penev, DOE: Office of Energy Efficiency & Renewable Energy, NREL/TP-5600-51995, Washington, DC: Government Publishing Office, 2013, https://www.nrel.gov/docs/fy13osti/51995.pdf.
[22] J. O. Bockris, "The Hydrogen Economy," in *Environmental Chemistry*, Springer: Boston, 549–82, https://doi.org/10.1007/978-1-4615-6921-3_17.
[23] NREL, *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues*.

appliance. Once more, the amount blended without impacting operation will vary case-by-case, with well-serviced appliances capable of accepting higher hydrogen contents.

Marcogaz found similar results in their study. In 2017, a technical bulletin reported that mixtures of natural gas with up to 10% hydrogen can be operated in gas pipelines and appliances without significant integrity problems. In 2019, they announced that existing infrastructure and household appliances can accept up to 20% hydrogen without major modifications.[24]

2.2 Hydrogen Projects in Residential Sector by Country

All over the world, countries are developing pilot projects for introduction of hydrogen into natural gas systems. One of the most advanced nations in this area is the United Kingdom, with two of the largest electric utilities, National Grid and Scottish Gas Network, integrating hydrogen blends into their gas network to power not only industrial processes but also the residential sector. Nations like the Netherlands, Germany, and Australia are also participating in this transition. Hydrogen is gaining traction in the United States as the federal government supports hydrogen hubs and research and development funding, while a few states (like Hawaii, California, and New York) making progress on projects for hydrogen testing and blending in the natural gas systems.

2.2.1 United Kingdom

The United Kingdom has executed some of the most advanced efforts when it comes to blending hydrogen in the natural gas system and testing in the residential sector. The **Hy4Heat project**, financed by the UK government, had the mission to show that it was technically possible, safe, and convenient to replace methane with hydrogen for buildings and appliances. The project resulted in the development of hydrogen-ready appliances, safety assessment research, and hydrogen standards (discussed in Section Testing Metrics and Standards), which prepared the United Kingdom to pursue the next stage of hydrogen deployment: community trials.

A consortium partnership developed the **HyDeploy project**, which was the first project to demonstrate that injection of hydrogen into the natural gas system at 20% is safe and possible without requiring any changes to appliances. The first project from HyDeploy was at Keele University campus, which has its own dedicated gas network.[25] The project was structured in three phases:

1 | Securing regulatory permissions

[24] AHRI (Air-Conditioning, Heating, and Refrigeration Institute) *Assessment of Hydrogen Enriched Natural Gas*, by Paul A. Needley and Lukasz Peronski, AHRI Report No. 8024, Arlington, Virginia: AHRI. January 2021, https://ahrinet.org/App_Content/ahri/files/RESEARCH/Technical%20Results/AHRI-8024_Final%20Report.pdf

[25] HyDeploy, "Project Phases," HyDeploy, accessed July 25, 2022, https://hydeploy.co.uk/hydrogen/.

2 | Construction and preparation
3 | Trial

Phase 1 of the project was 18 months of laboratory work, network appliance testing, and risk analysis to ensure blending hydrogen at 20% would be safe in the Keele University gas system. Gas boilers, cookstoves, and hearths were tested during this period. The project obtained access to 95% of properties on campus and gathered evidence from the remaining ones. A gas safety test was conducted to ensure all appliances were safe and reliable. During safety testing, no appliances needed remedial work to operate on HENG. Operational performance and leakage testing was conducted on commercial boilers in the campus, which provided the same results, all appliances were safe to operate on 20% hydrogen blend. Additionally, a material analysis was conducted to ensure that all materials in the gas network that would be in contact with the blend would maintain operational integrity throughout the trial. Finally, a quantitative risk assessment for the Keele network was run with the aggregated results from Phase 1. The result of the assessment showed that the 20% hydrogen blend did not affect the safety of end users. Based on these results, the Health & Safety Executive (a UK government agency) granted an exemption to the hydrogen limit in Schedule 3 of the Gas Safety (Management) Regulations to allow up to 20% hydrogen to be blended into the Keele natural gas network.[26]

Phase 2 was the technical setup of three pieces of equipment:

1 | The electrolyzer
2 | A grid entry unit that would mix the hydrogen with the natural gas before injection
3 | Monitoring equipment to sample the gas mixture during the trial

This phase also included training operators involved in the trail phase on supplementary guidance for existing gas distribution procedures to account for the hydrogen effects.[27] Results showed no issues on the network with satisfactory rhinology,[28] well-controlled network composition, and no unusual issues on the network. Results provide evidence that the introduction of a up to a 20% hydrogen blend into the gas network can be done using business-as-usual procedures and protocols.[29]

[26] Tommy Isaac, "HyDeploy: The UK's First Hydrogen Blending Deployment Project," *Clean Energy*, 3, no. 2 (2019), 114–25, https://doi.org/10.1093/ce/zkz006.
[27] Ibid.
[28] Rhinology refers to odor intensity. In this case, a satisfactory rhinology means that no perceivable dilution in odor was observed due to hydrogen blend in natural gas system. Therefore, no impacts on the ability of the public to detect and report gas escapes would be expected.
[29] HyDeploy, HyDeploy Project: Gas Network Innovation Competition, Fourth Project Progress Report, December 2020, https://hydeploy.co.uk/app/uploads/2018/02/HYDEPLOY-FOURTH-OFGEM-PPR.pdf.

Phase 3 collected information on appliance performance through combustion temperature and flue gas checks on commercial and test boilers, as well as carbon monoxide alarm operation[30] and customer feedback. During testing, the appliances performed as expected with no carbon monoxide alarm issues and no adverse customer feedback.[31] The demonstration project finished in 2021, and end users reported noticing no difference while using the blend.[32]

After the success at Keele University campus, **HyDeploy2** launched in Winlaton in August 2021 and provides a 20% hydrogen blend via a closed public gas network. The small town of Winlaton consists of 668 homes, a church, a primary school and several small businesses.[33] For this project, a sample of 13 appliances that encompassed the design variability (age, burner design, etc.) within residential natural gas appliances were tested through modeling and physical experimentation.[34] The results showed that natural gas appliances are compatible with hydrogen blends (up to 20%) from a safety and performance perspective.[35]

Another critical result of the HyDeploy2 project was to provide evidence that HENG is suitable for transportation in cast iron mains and services. Suitability was assessed via two means:

1 | Material experimentation from pipeline extracts to obtain mechanical property test data.
2 | Computational models of crack and critical defects in pipelines to assess risks.

The first demonstration at Keele University campus had a distribution network predominantly comprised of polyethylene pipelines. The results at Winlaton suggest that a wider introduction of hydrogen blend gas is possible in existing metallic gas pipelines throughout the United Kingdom.[36] Currently, a countrywide program is replacing old iron gas pipes with polyethylene ones that are better suited to transport hydrogen and other green gases. Nevertheless, the gas network is composed of other materials that need further testing to ensure safety and support hydrogen blends throughout the system.[37]

2.2.2 Netherlands

The Netherlands has one of the most dense and sophisticated natural gas grids, including a dedicated hydrogen pipeline network of more than 1,000 kilometers connecting to industrial

[30] Tommy Isaac, "HyDeploy: The UK's First Hydrogen Blending Deployment Project." The carbon-monoxide sensor used in common detection instrumentation is an electrochemical cell that oxides the carbon monoxide and measures the rate of hydrogen-ion production. All relevant detectors underwent a rigorous regime of testing to ensure any implications resulting from the presence of hydrogen could be accounted for and incorporated into the detection instrument.
[31] Cadent, HyDeploy Project.
[32] HyDeploy, "Project Phases."
[33] Ibid.
[34] Some appliances were manufactured as early as 1976.
[35] HyDeploy2, HyDeploy2 Project: Gas Network Innovation Competition, Third Project Progress Report, December 2021, https://hydeploy.co.uk/app/uploads/2022/01/HYDEPLOY2-THIRD-OFGEM-PPR.pdf.
[36] Ibid.
[37] HyDeploy, "Producing Hydrogen," July 25, 2022, https://hydeploy.co.uk/about/technology/.

sites in Belgium and France. With the Netherlands ending most of its natural gas production in 2022, there are 15,000 kilometers of pipelines that may become stranded assets. Several pilot and demonstrations projects proved that with modest alterations the existing infrastructure can be used for hydrogen.[38] Gasunie, the state-owned gas company, is starting with large projects, converting 1,200 kilometers of pipelines to receive pure hydrogen by 2027[39] and driving an interest in other projects running on 100% on hydrogen.

The first **hydrogen-only boiler pilot project** started in June 2019 in Rozenburg, Rotterdam, with collaboration among different stakeholders including the City of Rotterdam, the gas operator Stedin Group, and the gas supplier GasTerra. Thermea Group developed the hydrogen boiler. This project proved the use of hydrogen for heating purposes and that the existing gas network was suitable for hydrogen transport.

Several other hydrogen pilot projects are currently underway in residential areas with the objective to replace natural gas with hydrogen using the existing infrastructure.[40] One of these projects is the **Hydrogen city project** (Stad Aardgasvrij), which aims to understand whether hydrogen can heat the buildings in the Stad aan 't Haringvliet neighborhood. Currently, hydrogen is being tested in one house and is stored in a container, reaching the house through the existing gas pipeline. The pipe was extensively tested for leaks, using nitrogen first and then hydrogen, proving that existing infrastructure was appropriate for transporting hydrogen. Three central boilers that run fully on hydrogen heat the house.[41] Nefit-Bosch developed and commercialized these central boilers, and they are hydrogen ready, which means they can operate on either natural gas or hydrogen.[42]

2.2.3 Australia

In May 2021, the largest hydrogen production site in Australia started injecting hydrogen gas into existing natural gas pipelines supplying hydrogen blends to more than 700 homes in the Hydrogen Park South Australia at the Tonsley Innovation District in Adelaide.[43] A 1.25-megawatt electrolyzer powered by wind and solar energy produces the hydrogen that is being blended at

[38] Netherlands Enterprise Agency, FME, and TKI New Gas, *Excelling in Hydrogen: Dutch Technology for a Climate-Neutral World*, NL Platform, April 2021, https://www.rvo.nl/sites/default/files/2021/03/Dutch%20solutions%20for%20a%20hydrogen%20economy.pdf.

[39] Vanessa Dezem, "What Does a Gas Country Do Without Gas? The Dutch Can Answer," Bloomberg News, January 19, 2022, https://www.bloomberg.com/news/articles/2022-01-20/the-netherlands-bets-on-hydrogen-after-natural-gas.

[40] A comprehensive list of these and other projects can be found here: https://www.topsectorenergie.nl/sites/default/files/uploads/TKI%20Gas/publicaties/Overview%20Hydrogen%20projects%20in%20the%20Netherlands%20versie%201mei2020.pdf.

[41] FuelCellsWork, "Netherlands: First Home in Stad Aan 'T Haringvliet Heated With Hydrogen," April 19, 2022, https://fuelcellsworks.com/news/netherlands-first-home-in-stad-aan-t-haringvliet-heated-with-hydrogen/.

[42] Nefit, "Cv-ketels," https://www.nefit-bosch.nl/producten/cv-ketels.

[43] Australian Gas Networks, "Hydrogen Park South Australia," accessed July 25, 2022, https://www.australiangasnetworks.com.au/hyp-sa.

about 5% in the Australian Gas Infrastructure Group distribution network.[44] This amount of blend does not affect the pipelines, which are made of polyethylene, nor household appliances. By law, any appliance sold in Australia must be tested according to the Australian Standards, which requires testing under varying gas compositions. One of these gas compositions contains 13% hydrogen.[45] Other projects targeting the residential sector are under development,[46] with one aiming to provide a 10% blend to more than 40,000 residential, commercial, and industrial customers in Wodonga, Victoria, and near Albury, New South Wales.[47]

2.2.4 Germany

In 2021, Avacon introduced the first admixture of hydrogen in the residential sector in Germany, with support from the German Technical and Scientific Association for Gas and Water, in its gas network in the Saxony-Anhalt region. The area sits in a medium-pressure distribution network pipeline of 35 kilometers in length servicing about 350 customers. The blend started at 10% and aims to reach 20%.[48] In the first stage of the project, all customer appliances were checked for safety and performance issues for compatibility with hydrogen. Almost 100% of tested appliances were suitable for the blend. Hydrogen-ready appliances replaced the few (four) unsuitable ones.[49] The project is underway and recently reached 15% hydrogen admixture into the gas system.

2.2.5 United States

The United States has an extensive gas network of about 3 million miles of natural gas pipelines and more than 1,600 miles of dedicated hydrogen pipeline.[50] At the federal level, the DOE has launched the HyBlend project, which aims to increase the potential of hydrogen and natural gas blends based by evaluating pipeline and hydrogen compatibility, analyzing life cycle emissions, and determining costs of hydrogen production and technology implementation.[51] Although this project is focused on pipeline analysis, the hydrogen blend limit will be determined by the

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[44] Sonali Paul, "Australia Starts Piping Hydrogen-gas Blend into Homes," *Reuters*, May 19, 2021, https://www.reuters.com/business/energy/australia-starts-piping-hydrogen-gas-blend-into-homes-2021-05-19/.

[45] Australian Gas Networks, "Hydrogen Park South Australia."

[46] Australian Gas Networks, "Hydrogen Park Gladstone," accessed July 25, 2022, https://www.agig.com.au/hydrogen-park-gladstone.

[47] Australian Gas Networks, "HyP Murray Valley New Hydrogen Blending Project," accessed July 25, 2022, https://www.agig.com.au/media-release---new-hydrogen-blending-project.

[48] Katharina Johannsen, "Avacon Tests 20 Percent Hydrogen in Gas Pipelines," *Energate Messenger*, March 23, 2022, https://www.energate-messenger.com/news/221135/avacon-tests-20-per-cent-hydrogen-in-gas-pipelines.

[49] Marvin Macke, "Twenty Percent Hydrogen in the German Gas Network for the First Time," *Eon.com*, October 28, 2021, https://www.eon.com/en/about-us/media/press-release/2021/20-percent-hydrogen-in-the-german-gas-network-for-the-first-time.html.

[50] DOE, "HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines," Hydrogen and Fuel Cell Technology Office, Office of Energy Efficiency and Renewable Energy, https://www.energy.gov/eere/fuelcells/hyblend-opportunities-hydrogen-blending-natural-gas-pipelines.

[51] Trip Johnson, "Hydrogen Blending," Fuel Cell and Hydrogen Energy Association, March 8, 2021, https://www.fchea.org/in-transition/2021/3/8/hydrogen-blending.

composition, design, and conditions of existing pipelines, as well as by end-use applications that utilize natural gas, such as household appliances, turbines, and industrial processes.[52]

GTI conducted research on the impacts of US natural gas appliances when operated with hydrogen blends of up to 30% by volume. Through laboratory testing and modeling, a series of short-term tests checked performance, efficiency, and emissions, among other factors. Results show that, in general, all appliances were able to tolerate the shift in gas composition without impacts in the combustion stability of burners and appliances and with efficiency varying only by 1% to 1.5% with the hydrogen blends tested.[53] A similar study funded by the California Energy Commission (CEC) showed that 5% to 10% of hydrogen by volume could be added to the natural gas system without affecting general operation of the nine tested appliances: cooktop burner, oven burner, gas fireplace, low-oxides-of-nitrogen storage water heater, tankless water heater, space heater, pool heater, outdoor grill, and laundry dryer.[54] Refer to Section 3 Hydrogen Use in Residential Appliances for detailed information by appliance type.

2.2.5.1 Hawaii

Hawai'i Gas has been blending hydrogen into their 1,100 miles of pipelines for many years. The existing network accommodates up to 15% hydrogen.[55] The company is leading research and pilot demonstration projects to increase the content of hydrogen in the pipelines to achieve the state's decarbonization goals.[56]

2.2.5.2 California

California has several ongoing hydrogen initiatives in different sectors. Regarding end-use appliances, the California Public Utilities Commission launched a grant funding opportunity (GFO-21-503 Examining the Effects of Hydrogen in End-Use Appliances for Large Commercial Buildings and Industrial Applications) in 2021 to develop a technical study to assess the impact of hydrogen and hydrogen blends in natural gas appliances in large commercial buildings and the industrial sector. In April 2022, the California Public Utilities Commission awarded GTI $1,770,000 to conduct this study.[57]

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[52] DOE, "HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines," Office of Energy Efficiency and Renewable Energy, https://www.energy.gov/sites/default/files/2021-08/hyblend-tech-summary.pdf.
[53] Paul Glanville, Alex Fridlyand, Brian Sutherland, Miroslaw Liszka, Yan Zhao, Luke Bingham, and Kris Jorgensen, "Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NO_x Emission and Operational Performance," *Energies* 15, no. 5: 1706. https://doi.org/10.3390/en15051706.
[54] California Energy Commission, *Implications of Increased Renewable Natural Gas on Appliance Emissions and Stability,* Energy Research and Development Division, October 2020, CEC-500-2020-070, https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2020-070.pdf.
[55] Hawai'i Gas, "Decarbonization and Energy Innovation," accessed July 25, 2022, https://www.hawaiigas.com/clean-energy/decarbonization.
[56] More information on this project doesn't seem to be publicly available at the time of this report.
[57] California Energy Commission, *Examining the Effects of Hydrogen in End-Use Appliances for Large Commercial Buildings and Industrial Applications*, Energy Research and Development, GFO-21-503, https://www.energy.ca.gov/solicitations/2021-09/gfo-21-503-examining-effects-hydrogen-end-use-appliances-large-commercial.

In 2021, the Southern California Gas Company (SoCalGas) started testing hydrogen blends to fuel a household and its appliances in its Engineering Analysis Center and Centralized Training Facility. Preliminary results show that natural gas appliances are compatible with up to a 20% hydrogen blend.[58] SoCalGas conducted a baseline testing of combustion characteristics, temperature through appliances and burner surface, and video of the flame (qualitative analysis). They found a light temperature increase in burner surface (20° Fahrenheit), which was well within the limits of melting points of different component materials, and slight changes to the flame color, but nothing impacting the performance of the appliances.[59] All appliances tested were legacy appliances available at their training facility. Additionally, in March 2022, SoCalGas initiated the Hydrogen Home project, which is a house to be built in Downey, California, in which natural gas with 20% hydrogen blend will power the water heater, clothes dryer, gas stove, fireplace, and grill.[60] The objective of this project is to prove the resiliency and reliability of a hydrogen microgrid, as the house will come with solar panels, batteries, electrolyzers, and fuel cells.

2.2.5.3 New York

In 2020, the New York State Energy Research and Development Authority awarded funding to test the impact of blending hydrogen into the existing gas network. National Grid and the Institute for Gas Innovation and Technology at Stony Brook University are working together to test pipeline materials to hydrogen exposure.[61] On December 2021, National Grid and the Town of Hempstead in Long Island announced a joint project, **HyGrid Project,** to expand the existing hydrogen facility, which was developed in 2009 to provide hydrogen for transportation, to inject hydrogen into the gas distribution system to power 800 homes.[62]

2.2.5.4 Oregon

In 2020, NW Natural started testing a 5% hydrogen blend in natural gas at the Sherwood Operations and Training Center. The aim was to evaluate the impact of HENG on the system and end-use equipment. In 2021, testing expanded to include additional end-use equipment performance on furnaces, fireplaces, and water heaters.[63] Results showed that gas flowed

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[58] SoCalGas (Southern California Gas Company), "SoCalGas Among First in the Nation to Test Hydrogen Blending in Real-World Infrastructure and Appliances in Closed Loop System," September 30, 2021, https://newsroom.socalgas.com/press-release/socalgas-among-first-in-the-nation-to-test-hydrogen-blending-in-real-world.

[59] SoCalGas Staff, zoom call with Eli Font and Peter Kernan of Cadeo Group, June 28, 2022.

[60] SoCalGas, "SoCalGas Begins Assembling Award-Winning H2 Hydrogen Home," March 2, 2022, https://newsroom.socalgas.com/press-release/socalgas-begins-assembling-award-winning-h2-hydrogen-home.

[61] National Grid, "Hydrogen Blending Research for a Net Zero Future," accessed July 25, 2022, https://www.nationalgrid.com/us/cop26/hydrogen-vision/stony-brook-case-study.

[62] National Grid, "One of the US' First Green Hydrogen Blending Projects Launches on Long Island," December 15, 2021, https://www.nationalgrid.com/stories/journey-to-net-zero-stories/hygrid-green-hydrogen-blending-project-launches.

[63] NW Natural, *OPUC Natural Gas Fact-Finding Workshop #3 – Modeling*, UM 2178, September 14, 2021, https://www.oregon.gov/puc/utilities/Documents/NGFF_WS3-NWNPresentation.pdf.

properly, there were no carbon monoxide alarms, and all appliances operated as expected, with normal flame and flame color presentation and no flashback. NW Natural did not perform additional tests like measuring nitrogen oxides (NO_x) and heat output, and all appliances at the training center are legacy equipment.[64]

2.2.5.5 Utah

Dominion Energy started testing 5% hydrogen blend in the natural gas system at the company's training academy to understand the impact of hydrogen in pipeline and appliances. Results show the 5% hydrogen blend has no impact in distribution system lines nor appliance performance.[65]

2.3 Testing Metrics and Standards

In general, there is a lack of internationally standardized testing methods and protocols to address HENG in pipelines and appliances.

In the **European Union**, the provision on certification on appliances falls under Regulation (EU) 2016/426, better known as Gas Appliances Regulation (GAR). The standard, EN 437 Test gases – Test pressures – Appliance categories, is commonly used to check conformity to GAR. Under this standard, a reference gas and limit gases are used to test for normal conditions and extreme variations in the characteristics of the gases. One of the limit gases, G222, contains 77% methane and 23% hydrogen, which provides a lower WI than the reference gas. As a result, all modern[66] gas appliances in the European Union market that are certified to GAR using EN 437 can operate under an admixture of 23% of hydrogen in natural gas.

Nevertheless, EN 437 does not cover all the additional risks generated by HENG.[67] Recommendations of the THyGA project[68] include identifying new tests and test conditions to assess those risks and defining new limit gases to cover the risk induced by higher concentrations of hydrogen in natural gas.[69]

Similarly, **Australia** standard AS/NZS 5263.0 Gas Appliances – General Requirements include tests with a limit gas containing 13% hydrogen and 87% methane. However, testing with this

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[64] NW Natural Staff, zoom call with Eli Font and Peter Kernan of Cadeo Group, June 28, 2022.
[65] Dominion Energy, "Dominion Energy Broadens Net Zero Commitments," February 11, 2022, https://news.dominionenergy.com/2022-02-11-Dominion-Energy-Broadens-Net-Zero-Commitments.
[66] The first edition of EN 437 standard dates from 1993, but many countries were already using these test gases several years before.
[67] THyGA (Testing Hydrogen admixture for Gas Applications), "Standardization & Certification WP4," Workshop, March 31, 2021, https://thyga-project.eu/wp-content/uploads/03_2021-03-31-THyGA-WP4-presentation-1.pdf.
[68] THyGA, "THyGA," accessed July 25, 2022, https://thyga-project.eu/.
[69] THyGA, *Overview of Current Standardization and Certification Framework and the Impact of H2NG Mixtures*, by Kris De Wit, Brussels, November 2020.

type of gas is limited to flame abnormality and ignition performance.[70] As is the case in Europe, additional testing would be necessary to cover other risks (such as integrity of materials and gas leakage among others) due to the increased concentration of hydrogen blends in natural gas appliances.

One of the outcomes of the Hy4Heat project in the **United Kingdom**, funded by the Department for Business, Energy and Industrial Strategy, is the British Standards Institution's Publicly Available Specification (PAS) 4444.[71] PAS 4444 is a guide for appliance manufacturers that addresses functionality, safety, installation, operating, and servicing requirement for hydrogen-fueled, dual-fueled, or converted appliances. This guide could be used as the basis for widescale standardization. Additionally, a hydrogen standard, the Reference Standard for Low Pressure Hydrogen Utilization, has been created for the purpose of the Hy4Heat project.[72] This standard is only applicable to 98% hydrogen gas, so it does not cover blends, but it does cover hydrogen installations in residential and small commercial premises downstream of the supplier's emergency control valve.

Through the HyDeploy project, a blend progression protocol (2 %, 5 %, 10 %, 12 %, 15 %, and 20 %) was designed and implemented to ensure safe management of hydrogen blends during the demonstration project and to prove that no detrimental effects would occur across the different blend levels to either pipelines or appliances.[73] The progression protocol included the following steps: compound operational review, combustion analysis, alarm review, network integrity review, rhinology testing and network compression checks.

North American–focused research conducted by Canadian Standard Association (CSA) on space heating and water heating appliances was based on the testing methods outlined in the binational CSA/American National Standards Institute (ANSI) Z21 series of standards. Appliances were tested for input rate, ignition and burner operating characteristics, combustion products properties, and gas leakage, using three gas mixtures: 100% methane, 5% hydrogen/methane blend, and 15% hydrogen/methane blend mixtures.[74] This research project established baseline characteristics and provided context for continued CSA engagements around hydrogen development in residential appliances. CSA Group's Technical Committees, which include relevant industry stakeholders such as utilities, regulators and manufacturers, among others, are currently reviewing the need to develop new standards or update existing ones (CSA/ANSI Z21) to include HENG. At the time of this report, there are no new standards under development for

[70] AGA, "2017 AGA Industry Forum - Gas in a CLIMATE OF CHANGE," AGA Newsflash, August 23, 2017, https://www.aga.asn.au/wp-content/uploads/2018/05/4-August-2017-NewsFlash.pdf.

[71] BEIS (Department for Business, Energy and Industrial Strategy), *Hydrogen-fired Gas Appliances*, April 30, 2020, https://shop.bsigroup.com/products/hydrogen-fired-gas-appliances-guide/standard.

[72] BEIS, *Work Package 2: IGEM Hydrogen Standards*, Hy4Heat, IGEM/H/1, Communication 1835, https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/615a359537180f62d8ace4a5/1633301910775/WP2+IGEM+Hydrogen+Standards+Report.pdf.

[73] HyDeploy, HyDeploy Project: Gas Network Innovation Competition, Fourth Project Progress Report.

[74] CSA, *Appliance and Equipment Performance with Hydrogen-Enriched Natural Gases*.

appliances and equipment, but the CSA Group committees are evaluating the gaps and needs regarding performance and safety of appliances operating using HENG.[75]

2.4 Summary

2.4.1 Hydrogen Testing in the Residential Sector

As hydrogen gains global traction as a decarbonization option, gas utilities and governments are looking into HENG potential to reduce carbon emissions from their operations and the building sector. Table 2 shows the maximum concentration of HENG tested at residential demonstration projects or training facilities by country. The results of these tests show no impacts on existing pipelines and appliance operation and safety—with the exclusion of the Netherlands, which is testing 100% hydrogen and using hydrogen boilers.

Table 2: Maximum Concentration of HENG Tested at Residential Demonstration Projects or Training Facilities per Country

Country	UK	Netherland	Australia	Germany	US
Hydrogen concentration	20%	100%	5%	15%	20%

In the United States, research performed at the laboratory level on appliance impact from operation with HENG shows that testing levels of hydrogen in blends keep increasing with time. As of now, the maximum limit was tested by GTI, indicating that all appliances tested (different types of water heaters and furnaces) can maintain performance and safety with 30% hydrogen blend in natural gas. Nevertheless, further research is needed to test a greater sample of appliances. Given the state of the current research, Cadeo recommends a case-by-case analysis in the service territory of the gas operator to evaluate appliance feasibility and impact. Remaining barriers are the lack of testing on a greater number of legacy or poorly maintained equipment and the long-term impact of operating natural gas appliances under HENG blends of varying concentrations.

2.4.2 Testing Methods and Standards

Though some appliance standards require testing with HENG as a limit gas, often the test methods are not comprehensive and focus only on ignition and burner combustion. In the United States, existing standards and testing methods for appliances (ANSI/CSA Z21 series) do not cover HENG, even as a limit gas. To ensure safety and performance of end-use appliances, standards and testing methods should be reviewed and expanded to include to include up to 20% HENG as a reference gas, as well as limit gases with higher concentration of hydrogen. This

[75] CSA Staff, CSA, zoom call with Eli Font and Peter Kernan of Cadeo Group, July 19, 2022.

could include expansion of existing standards to include HENG mixes and/or the development of new standards and testing protocols for higher blends, 100% hydrogen, or specific performance features. Results from interviews supports this finding, as stakeholders and SMEs claim that new test methods and standards addressing HENG would help the market move forward. Additionally, all interviewees call out the need for more studies on the impact of HENG in existing appliances and where modifications are needed. Some interviewees pointed out that long-term exposure of appliances to HENG should be evaluated to understand the long-term durability and effects of end-use products under different composition blends.

Section 3 Hydrogen Use in Residential Appliances

The purpose of this section is to explore key features of hydrogen use in residential appliances. In general, research indicates that product adjustments are necessary for 100% hydrogen, where several studies have shown little to no modification necessary to operate on blends of HENG up to varying percentages, with the maximum amount tested being 30%.

To better understand gas appliance operating capabilities with hydrogen, Cadeo researched equipment function, efficiency, standards, and test procedures associated with six residential gas-fired appliances:

- Cooktops
- Ovens
- Furnaces
- Water heaters
- Hearths
- Clothes dryers

Each of these appliances uses the combustion of natural gas to generate heat for a domestic use. This section reviews existing energy efficiency regulations and current standards and test procedures that apply to gas appliances. Then equipment function and aesthetic considerations are outlined for each of the six appliances. Following the review of individual equipment function and aesthetics, common qualities shared by each appliance type are explored. Section 3.4 Appliance Performance includes a review of appliance performance changes that occur with the addition of hydrogen. Section 3.5 Safety and Health Considerations discusses safety and health considerations. Section 3.6 Appliance Modification reviews necessary and anticipated modification to residential gas appliances operating on hydrogen blends versus 100% hydrogen.

3.1 Energy Efficiency Regulation

In the United States, the Energy Policy and Conservation Act requires the DOE to set energy efficiency standards for covered residential appliances.[76] These standards establish the minimum efficiency requirements of each product and the test procedures by which each is evaluated. Of the six residential appliances that Cadeo reviewed, only three have active energy conservation standards. Table 3 outlines which appliances have a current standard and what the third-party test procedure is based on.

[76] DOE, "Determinations and Coverage Rulemakings," Office of Energy Efficiency and Renewable Energy, accessed July 25, 2022, https://www.energy.gov/eere/buildings/determinations-and-coverage-rulemakings.

Table 3: Energy Conservation Standards and Test Procedures for Residential Gas Appliances

Appliance	Energy Conservation Standard	Test Procedure
Cooktops	No	N/A
Ovens	No	N/A
Furnaces	Yes	10 Code of Federal Regulations (CFR) part 430, Subpart B, Appendix N—Uniform Test Method for Measuring the Energy Consumption of Furnaces and Boilers
Water Heaters	Yes	10 CFR part 430, Subpart B, Appendix E—Uniform Test Method for Measuring the Energy Consumption of Water Heaters
Hearths	No	N/A
Clothes Dryers	Yes	10 CFR 430, Subpart B, Appendix D1—Uniform Test Method for Measuring the Energy Consumption of Clothes Dryers

The DOE establishes classes within each product type based on the fuel, the capacity of the equipment, and other performance-related features. Each of these classes receives their own efficiency standard and test procedures. For example, consumer furnaces have separate efficiency standards for furnaces that use gas, oil, or electricity. As a separate fuel, neither HENG nor 100% hydrogen is currently considered in DOE energy conservation standards. Therefore, gas appliances are not tested using hydrogen, meaning there is a lack of knowledge of whether a gas appliance operating on blends of hydrogen can meet the efficiency standards.

Researchers have explored efficiency impacts of residential appliances operating with HENG using existing standards and test procedures for natural gas appliances. In a study published in 2022, GTI recorded efficiency impacts of around 1% for blends of hydrogen ranging from 0% to 30% when operating common heating equipment in simulators and in the laboratory.[77] These results indicate that most equipment could continue to meet DOE energy conservation standards up to a 30% hydrogen blend.

[77] Paul Glanville et al., "Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance."

Beyond appliances meeting the energy conservation standard, there is a further consideration of HENG meeting the definition of natural gas based on heat content. The Code of Federal Regulations (CFR) defines natural gas as having a heating value of approximately 1,025 British thermal units (Btu) per cubic foot.[78] As long as a hydrogen blend does not materially impact the heat output, the appliance could still be considered a gas appliance in DOE's perspective, though hydrogen has about one-third the heat content of natural gas by volume. As a comparison point, the maximum amount of hydrogen blend acceptable under the energy content limits (proposed by each utility, i.e. 985 Btu/cubic foot for NW Natural, Cascade and Avista[79]) approved by the Oregon Public Utility Commission is 8.7%.[80] Any blend above 8.7% in the gas network would require a change in the current billing policy. DOE would need to consider appropriate heat content definitions for gas blends and pure hydrogen and may wish to issue guidance to clarify the coverage of hydrogen and mixed-fuel appliances to minimize confusion in the market.

3.2 Performance and Safety Standards

As mentioned in Section 2.3 Testing Metrics and Standards, North American standards of gas appliances follows the binational ANSI and CSA Z21 series. These standards outline the construction and performance of gas appliances. Test procedures within the Z21 series dictate the process by which the performance of the equipment is measured. Such procedures are typically referenced during the implementation of energy conservation standards under the Energy Policy and Conservation Act.

Table 4 identifies which set of Z21 standards apply to each type of equipment. For many, a year is appended to the end of the standard to indicate the most recent version adopted and approved by both ANSI and CSA.

[78] 10 CFR Appendix E to Subpart B of Part 430 - Uniform Test Method for Measuring the Energy Consumption of Water Heaters, https://www.law.cornell.edu/cfr/text/10/appendix-E_to_subpart_B_of_part_430.

[79] Avista heat content varies by system, Southern Oregon division value is 985 Btu/cubic foot, whereas Klamath Falls and La Grande and Baker are 1,065 and 1,055 Btu/cubic foot respectively. https://www.myavista.com/-/media/myavista/content-documents/our-rates-and-tariffs/or/or_02.pdf

[80] Gertrude Villaverde, "Hydrogen for Heat: Utilizing Hydrogen for Long-Term Energy Storage In Northern Climates," Honors College Thesis, (Oregon State University, 2019), https://ir.library.oregonstate.edu/concern/honors_college_theses/s4655n30w.

Table 4: Current ANSI/CSA Performance and Safety Standards for Gas Appliances

Gas Appliance	Standard
Cooktops	ANSI Z21.1/CSA 1.1-2016
Ovens	ANSI Z21.1/CSA 1.1-2016
Furnaces	CSA/ANSI Z21.47-21/CSA 2.3-2021
Water Heaters	ANSI Z21.10.1-2017/CSA 4.1-2017
Hearths	ANSI Z21.50-2007/CSA 2.22-2007
Clothes Dryers	ANSI Z21.5.2-2016 /CSA 7.2-2016

All appliances sold into US markets are certified under the current ANSI/CSA standard. The consumer-facing mark may be from a certifying body such as UL or CSA. Today, the Z21 series of standards does not consider blends of hydrogen, though there is a working group considering changes that would capture differences.

In a preliminary round of research, CSA explored the ability of residential furnaces, boilers, storage water heaters, and unvented space heaters to meet the safety and performance requirements for the respective Z21 standards. They used the Z21 performance parameter tests for ignition, burner operating characteristics, temperature rise, combustion, flue loss, and condensate measurement. The results demonstrated that no operability of critical safety issues occurred with blends of up to 15% hydrogen.[81]

3.3 Residential Gas Appliances

This section explores each of the residential gas appliances individually for their functionality and aesthetic consideration and how a shift from natural gas to HENG or 100% hydrogen would impact them. Other considerations relevant to appliance performance, health and safety, and modifications are reviewed in subsequent sections.

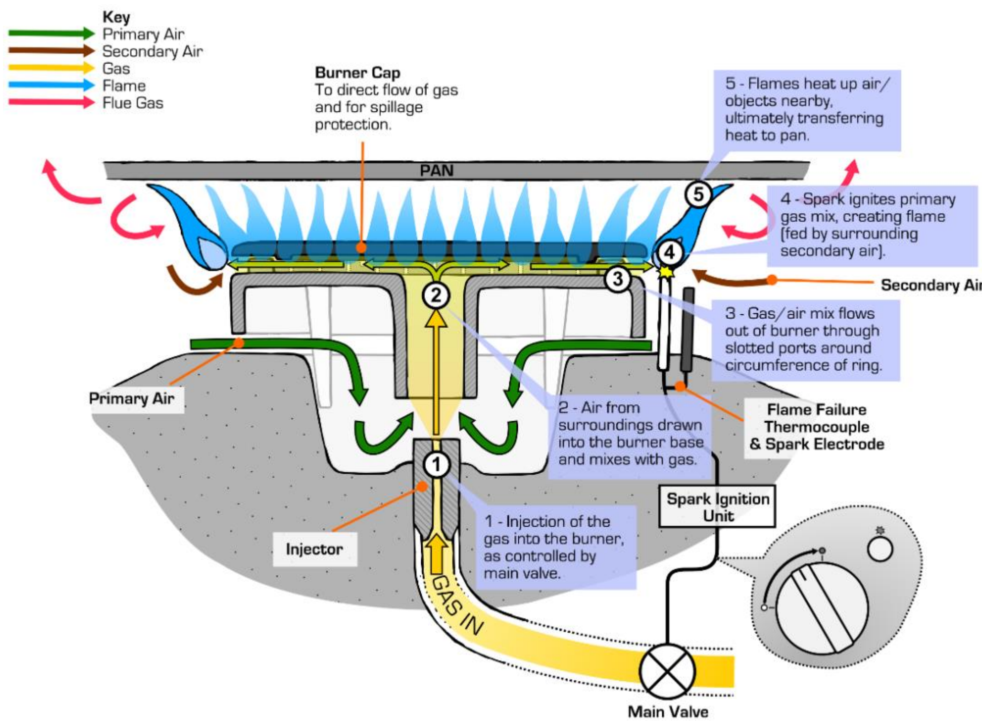
3.3.1 Cooktops

Cooktops are a common, end-use appliance that burn natural gas to provide heat for cooking. In the Northwest, NEEA's 2017 Residential Building Stock Assessment (RBSA) observed that 28% of single-family homes use gas cooktops.[82] Cooktops are therefore, an important appliance to

[81] CSA, *Appliance and Equipment Performance with Hydrogen-Enriched Natural Gases*.
[82] NEEA (Northwest Energy Efficiency Alliance), "Single-Family Homes Report," *Residential Building Stock Assessment II*, revised April 2019, *https://neea.org/img/uploads/Residential-Building-Stock-Assessment-II-Single-Family-Homes-Report-2016-2017.pdf*.

consider when studying hydrogen addition to the gas distribution system. Figure 1 depicts the key components outlining the operation of gas cooktops.

Figure 1: Schematic of a Residential Gas Cooktop



Source: Frazer-Nash Consultancy, *Appraisal of Domestic Hydrogen Appliances*, 12.

3.3.1.1 Equipment Function

Gas cooktops are a highly interactive appliance compared to a furnace or water heater, which are frequently located out of sight. This interaction is an influential factor in considering the operation of gas cooktops.

Gas cooktops have an incoming gas line that provides gas to an open-air burner. An air and gas mixture is routed through the burner to ports around a burner ring. An electronic spark igniter lights the air-gas mixture, and the flame surrounding the burner ring directly heats the pan and ambient air. Most cooktops are atmospherically vented, and thus the byproducts of combustion enter the living space unless separate ventilation removes them.

A 2019 study by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) found that cooktop performance was not significantly affected for blends of up to 15% hydrogen.[83] The

[83] Yan Zhao, Vincent McDonell, Scott Samuelsen, "Influence of Hydrogen Addition to Pipeline Natural Gas on the Combustion Performance of a Cooktop Burner," *International Journal of Hydrogen Energy*, 44, no. 23 (2019), 12239–12253, https://doi.org/10.1016/j.ijhydene.2019.03.100.https://www.sciencedirect.com/science/article/abs/pii/S0360319919311061

study examined more than 20 cooktop burners and used a representative self-aspirating burner like the one depicted in Figure 1. The study increased the percentage of hydrogen from 0% up to the maximum that could be attained without encountering operability issues. For the burner used, the limiting reagent to higher concentrations of hydrogen was flashback, which started occurring intermittently at 20% blends.

3.3.1.2 Aesthetics

Gas cooktops have received increased popularity in the Northwest. This is partially attributed to the real or perceived preference for cooking with gas because of the visual experience of a flame and the ability to modulate the heat output of the flame compared to an electric resistance burner. NEEA's recently published report on the Oregon residential specialty code established a baseline saturation of gas as the primary fuel in 82% of new construction.[84] It is assumed that because of the requirement of two gas appliances required in homes for builders to receive the line extension allowance, most new homes receiving gas furnaces also install a gas cooktop.

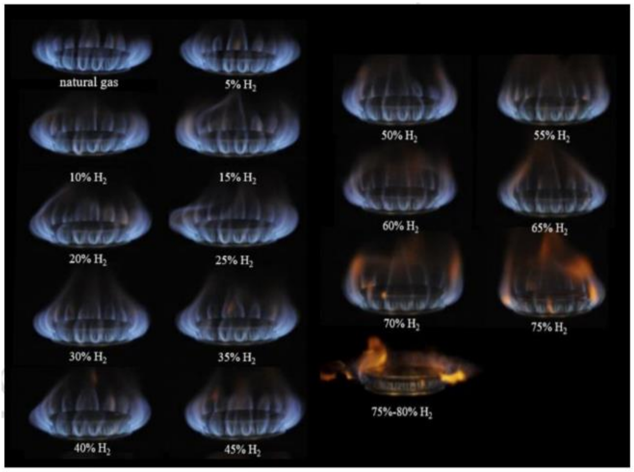
A 2019 study by GTI explored visual impacts to cooktop flames under blends of hydrogen varying in 5% increments from 0% hydrogen to around 80% hydrogen. Visual impacts to the flame were mostly imperceptible until around 50% hydrogen (see Figure 2). With unadjusted gas burners,[85] the flame showed increasing unsteadiness in high concentrations. Cooktops that burn 100% hydrogen require a different burner design, and there are additional safety concerns due to the hydrogen flame color being almost invisible to the naked eye during daytime and barely perceptible during nighttime.[86]

Figure 2: Gas Cooktop Flame Under Increasing Blends of HENG

[84] NEEA, Oregon Residential Specialty Code: 2005 Baseline and Code Roadmap to Achieve the 2030 Goal, by Henry Odum, Mark Frankel, and Paul Kintner, Seattle: NEEA.

[85] Unadjusted means that the burner is not altered to optimize for excess air with blends of hydrogen. An unadjusted burner is similar to how existing appliances installed in homes will operate.

[86] Yan Zhao, Vincent McDonell, Scott Samuelsen, "Influence of Hydrogen Addition to Pipeline Natural Gas on the Combustion Performance of a Cooktop Burner."



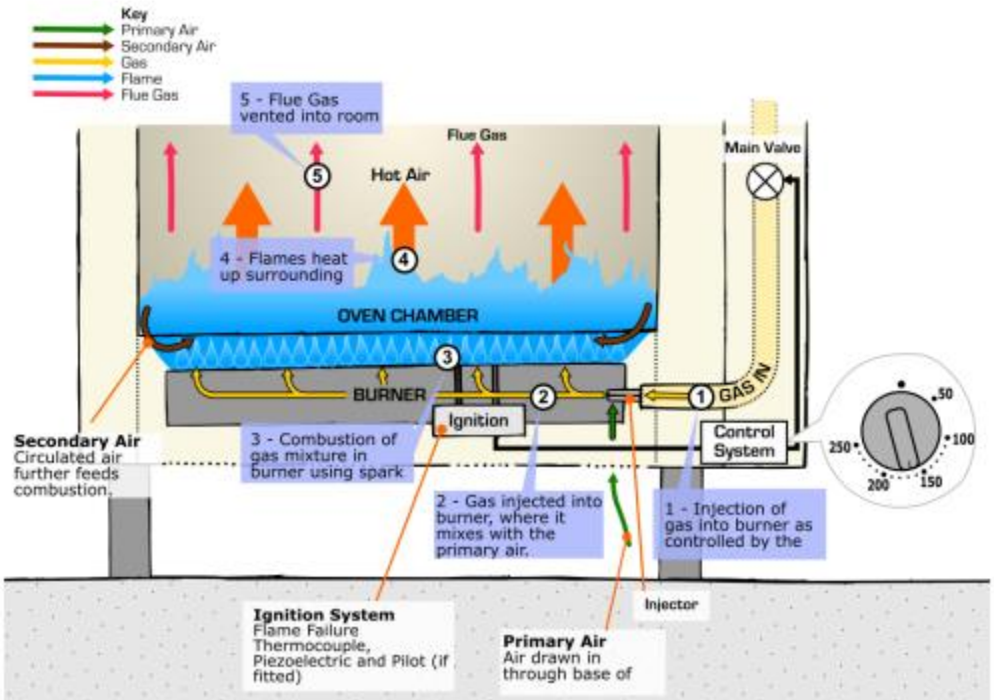
Source: Yan Zhao, Vincent McDonell, and Scott Samuelsen, "Influence of Hydrogen Addition to Pipeline Natural Gas on the Combustion Performance of a Cooktop Burner," *International Journal of Hydrogen Energy*, 44, 23 (2019) 12239-12253, https://doi.org/10.1016/j.ijhydene.2019.03.100.

3.3.2 Ovens

Similar to cooktops, gas ovens are a substantial part of the regional oven mix. NEEA's 2017 RBSA found that 19% of ovens in the region use natural gas, thus representing a smaller but still significant portion of the appliance mix than gas cooktops.[87] Figure 3 depicts the key components outlining the operation of a gas oven.

[87] NEEA, "Single-Family Homes Report."

Figure 3: Schematic of Residential Gas Oven



Source: Frazer-Nash Consultancy, *Appraisal of Domestic Hydrogen Appliances*, 13.

3.3.2.1 Equipment Function

Ovens operate via the injection of gas and primary combustion air into a linear cylindrical burner with ports along the length of the oven. An electronic spark triggers ignition, creating heat for the oven chamber. Flue gases are directed out and along the back of the oven and vented out the top into the room. This convective current helps circulate heated air within the oven. A thermoelectric sensor is typically the flame failure device mechanism, like a gas stove. In some cases, though more expensive, an ionization sensor, like those in gas furnaces, is used.

Gas ovens use a form of premix burner in which the gas is mixed with primary combustion air. This air-fuel mixture is then routed to burner ports along a linear tube. At this point the flame is ignited and introduced to secondary combustion air. These two air sources are intentionally designed to optimize for complete combustion of natural gas.

The University of California, Irvine (UCI) Combustion Laboratory conducted a study for the CEC that tested gas ovens for emissions and performance impacts of operating gas ovens with hydrogen blends. The study identified an upper limit of 30% hydrogen for the oven equipment tested.[88] Up to that point, there were no performance concerns. The study was inconclusive on NO_x emissions but observed an increase in unburned hydrocarbons and a reduction in carbon monoxide emissions.

[88] California Energy Commission, *Implications of Increased Renewable Natural Gas on Appliance Emissions and Stability*.

3.3.2.2 Aesthetics

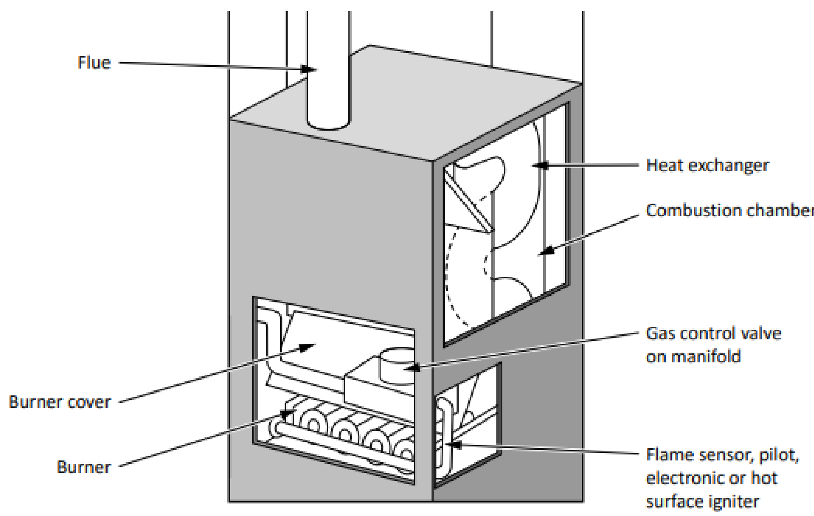
There are no aesthetic considerations for the operation of gas ovens as combustion typically occurs in a nonvisible location. The flame is concealed in a combustion chamber at the bottom of the oven. On the exterior, the gas pipe connection is typically concealed at the back of the oven and there are no other external indications that the appliance operates using gas. Gas ovens are commonly paired with gas cooktops in a range. However, it is also common to have dual fuel configurations with a gas cooktop and electric oven. Thus, a range with a gas cooktop increases the chances there is a gas oven but is not a guarantee.

3.3.3 Furnaces

Gas furnaces are important to consider for two fundamental reasons. First, they are the most common heating source in single-family residential buildings in the Northwest, at 56% of primary space heating.[89] Second, space heating is the top energy consumer in residential buildings. Therefore, the viability of hydrogen in residential buildings is contingent on the compatibility of hydrogen with furnaces.

This section explores appliance-specific considerations for residential gas furnaces. Figure 4 depicts the key components outlining the operation of gas furnaces.

Figure 4: Schematic of a Residential Gas Furnace



Source: CSA, *Appliance and Equipment Performance with Hydrogen-Enriched Natural Gases*, 8

3.3.3.1 Equipment Function

Gas furnaces operate via a gas pipe connected to the furnace. At the point of connection, a control valve attached to the manifold directs the gas from the valve to the gas burners. The burners are typically called "in-shot" burners, a form of partial premix burner similar to the burners on other appliances in this report. These in-shot burners involve premixing of primary

[89] NEEA, "Single-Family Homes Report."

combustion air before combustion. At the point of ignition, secondary air is added to ensure complete combustion.

Compared to cooktops and ovens, gas furnaces have additional infrastructure, namely a heat exchanger. The heat generated in the combustion chamber is transferred via a heat exchanger to separate air that is distributed to the household. Flue gases are sent to the exterior of the building via venting. It is important to highlight that there is no mixing of these volumes of air. The heat exchanger is responsible for extracting the heat from the combustion air and transferring it to separate, fresh air that is circulated within the building.

Additionally, it is increasingly common for furnaces in the Northwest to be condensing. This involves an additional heat exchanger where the exhaust gas is directed and cooled to the point where the gas condenses. The process of condensation releases the remaining heat in the flue gas, making the furnace more efficient, as that extra heat is now distributed to the building. The remaining byproducts of this process are water, which is commonly acidic, and some gaseous exhaust compounds, namely carbon dioxide. Condensing furnaces commonly require a condensate pump to manage the condensate liquid generated in the secondary heat exchanger.

The combustion of hydrogen compared to natural gas will produce more water per volume of gas burned. AHRI notes that 100% hydrogen produces 40% more water during combustion than natural gas, therefore a 20% hydrogen blend can be expected to result in 8% more moisture.[90]The condensate management system must be capable of handling the increased quantity of liquid produced by a HENG.

3.3.3.2 Aesthetics

There are no aesthetic concerns for furnaces, which are typically located in discrete locations such as closets, attics, basements, and garages.

3.3.4 Water Heaters

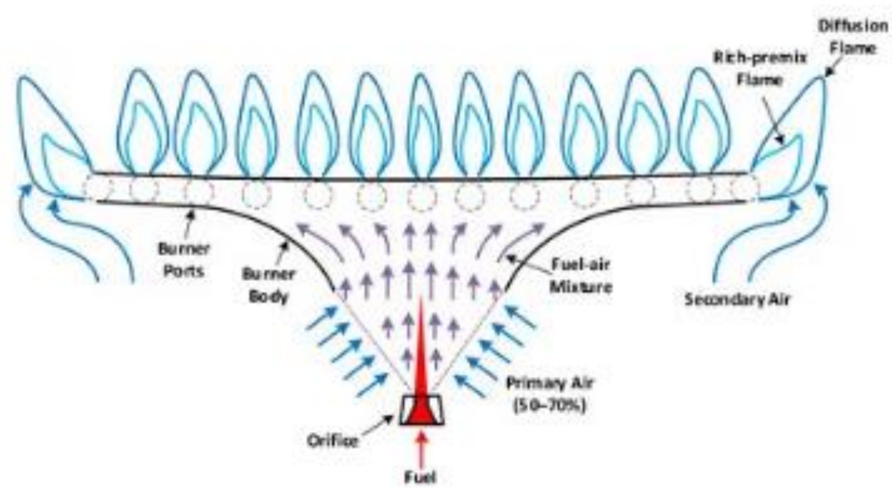
Gas water heaters are a significant regional consumer of energy. In NEEA's 2017 RBSA, gas water heaters represented 49% of single-family water heaters.[91] After space heating, water heating is the second-most consumptive energy end use in residential buildings. Therefore, the performance and compatibility of hydrogen with gas water heaters is important.

Figure 5 provides a reference image of a "pancake," partially premixed burner for a residential gas water heater.

[9090] AHRI, *Assessment of Hydrogen Enriched Natural Gas*, 50.

[91] NEEA, "Single-Family Homes Report."

Figure 5: Schematic of a Water Heater Burner



Source: Paul Glanville et al., "Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance."

3.3.4.1 Equipment Function

Water heaters operate similarly to furnaces in which burners produce heat that is exposed to a heat exchanger. In Figure 5, a pancake burner is shown. This burner type is common in water heaters and is a variety of partial premix burner with a different physical configuration from an in-shot burner. The general combustion principle is the same; fuel gas and primary air are mixed prior to the air-gas mixture being routed to the pancake burner ports. At the ports, the fuel is ignited and provided with secondary air to ensure complete combustion.

Similar to furnaces, water heaters also use a heat exchanger to transfer the heat from the flames into a physically separated medium. In the case of water heaters, the heat exchanger transfers the combustion heat to water. Figure 5 demonstrates one burner orientation for a residential tank water heater. Different burner designs may be used for on-demand gas water heaters and condensing gas water heaters.

Water heaters have been tested in multiple studies exploring performance and compatibility with hydrogen blends. Part of the focus on water heater testing is the prevalence of multiple burner types, including models meeting ultra-low NO_x emission requirements. A 2022 study found that burner surface temperature increased but did not have significant impact on burner performance parameter, up to 20% hydrogen.[92] The CSA study tested gas water heaters to the Z21 standard and found that the tested storage water heaters passed all performance and safety tests at both 5% and 15% blends of hydrogen.[93]

[92] Yan Zhao, Brendan Hickey, Shubham Srivastava, Valeriy Smirnov, and Vincent McDonell, "Decarbonized Combustion Performance of a Radiant Mesh Burner Operating on Pipeline Natural Gas Mixed with Hydrogen," *International Journal of Hydrogen Energy*, 47, Issue 42, (2022), 18551–18565, https://doi.org/10.1016/j.ijhydene.2022.04.003.
[93] CSA, *Appliance and Equipment Performance with Hydrogen-Enriched Natural Gases*.

Atmospherically vented gas water heaters are common in residential buildings in the Northwest and have additional performance considerations as outlined by AHRI. Due to hydrogen's increased moisture content, condensate forming on the metallic, type-B vent can drip back onto the burner causing hissing noises during operation and potentially leading to long-term performance issues related to the acidity of the condensate.[94] There may also be corrosion risk of the type-B venting material from prolonged exposure to a higher volume of acidic condensate.

3.3.4.2 Aesthetics

There are no aesthetic concerns. This equipment is typically located in a discrete area, such as a closet, basement, or garage.

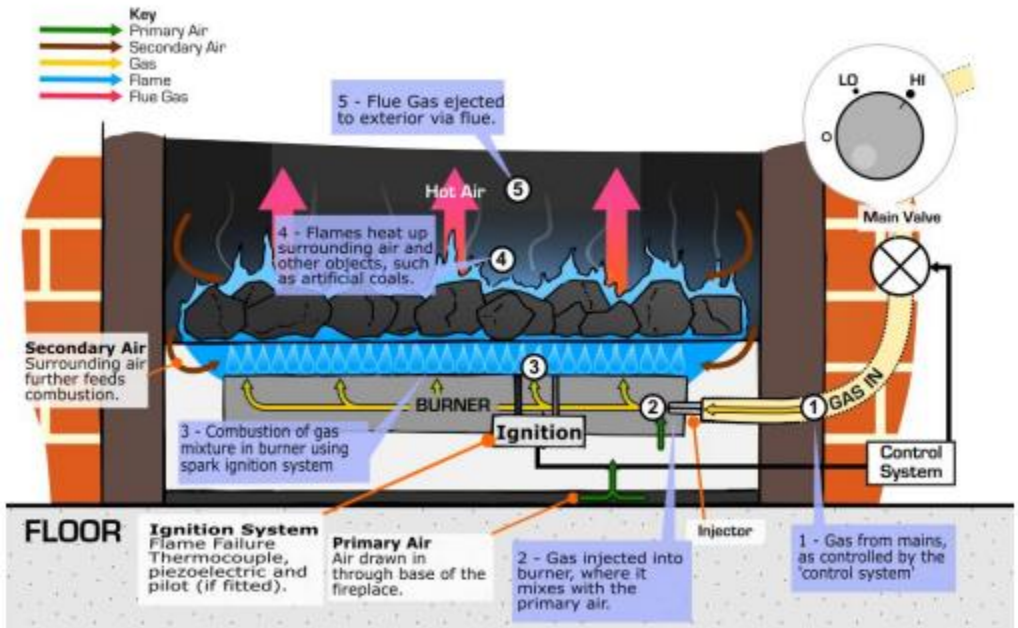
3.3.5 Hearths

Gas hearths are both a functional and aesthetic form of home heat in the Northwest. This intended use has impacts on both practical and technical considerations for use of hydrogen in gas hearths. American Gas Association predicts there are 40 million unvented gas-fired room heaters in the United States.[95]

This section explores appliance-specific considerations for residential gas hearths. Figure 6 depicts the key components outlining the operation of gas hearths.

[94] AHRI, *Assessment of Hydrogen Enriched Natural Gas*, 54.
[95] AHRI, "Hydrogen Enriched Natural Gas for Heating Products," March 18, 2021, video webinar, https://www.youtube.com/watch?v=SlwxqT56VBQ.

Figure 6: Schematic of a Residential Gas Hearth



Source: Frazer-Nash Consultancy, *Appraisal of Domestic Hydrogen Appliances*, 14.

3.3.5.1 Equipment Function

Gas hearths use a partial premix burner, typical of residential appliances. The common schematic is similar to a gas oven in which a cylindrical tube feeds premixed air and fuel to a number of ports, which is where ignition occurs in the presence of secondary air. The heat generated by combustion directly heats the physical space where it is located via convection of warmed air molecules. There is also radiant heat provided by physical objects heated via the flame. As in Figure 6, a flue may be present to direct flue gases to the exterior. However, there remain many unvented units in which, similar to a range or cooktop, flue gases are vented directly into the living space and should be appropriately managed for air quality purposes.

Gas hearths were tested by CSA per the Z21 performance and safety standards with both a 5% and a 15% hydrogen blend. Equipment operating on both blends passed the ignition performance or burner operating characteristics test. However, unlike the furnaces tested by CSA, the space heater had some instability issues and the flame extinguished consistently under an hour using the 15% blend.[96]

3.3.5.2 Aesthetics

A blue hydrogen flame may not have the same aesthetic quality generated by a more red, natural gas flame. In particular, this could be an aesthetic issue for 100% hydrogen hearths,

[96] CSA, *Appliance and Equipment Performance with Hydrogen-Enriched Natural Gases*, 19.

where there may be limited visual cues that the hearth is on during the daytime. However, this has not been a concern in pilots with up to 20% hydrogen (see Section 3.3.1 Cooktops).

3.3.6 Clothes Dryers

Clothes dryers are another appliance that can be powered by natural gas. As of NEEA's 2017 RBSA, only 7% of dryers in single-family homes were powered by natural gas.[97] Thus, they are a smaller portion of the regional mix, but their representation means it is important to consider appliance-level impacts in the instance of blending hydrogen into existing gas distribution.

3.3.6.1 Equipment Function

Gas dryers operate by burner, located within the cabinet of the dryer, which heats air that is supplied to the drum. A common burner type for gas clothes dryers is also a partially premixed burner, similar to the other appliances reviewed in this report.

Gas clothes dryers are a vented appliance where heat and moisture from drying of clothes are directed to the building exterior. One consideration for the use of hydrogen in clothes drying is the additional moisture content, which may impact the efficiency of removing moisture from clothes. A recent GTI study projected that a 5% addition of hydrogen did not have significant impact on the performance of the dryer.[98] Likely due to the smaller prevalence of gas clothes dryers and their comparatively small energy use, there are fewer studies that have looked closely at gas dryer operation with hydrogen.

3.3.6.2 Aesthetics

There are no aesthetic differences for dryer operation with hydrogen as the flame is not visible from the exterior of the appliance.

3.3.7 Distribution of Gas to Appliances

The network of pipes that transport hydrogen is also to considered for performance and construction impacts when mixing in hydrogen. The most important qualities related to pipelines are embrittlement and leakage. There are three levels of pipelines when thinking about the impacts of hydrogen:

1 | Transmission pipelines
2 | Distribution pipelines
3 | Household pipes

Each of these three levels has different considerations and separate standards. The NREL study mentioned in Section 2 Status of Hydrogen Introduction in Natural Gas Distribution Systems,

[97] NEEA, "Single-Family Homes Report."
[98] Paul Glanville et al., "Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance," 26.

determined that minimal changes to transmission pipelines are required for blends up to 50% hydrogen. Beyond this concentration, there is increased risk of both embrittlement and leakage.

On the distribution side, NREL concluded that there are increased considerations for gas distribution systems for multiple reasons, including their prevalence in densely populated areas and the materials commonly used in this section of the network. Densely populated areas are a concern where there may be high concentrations of hydrogen and a risk of detonation. The gas distribution contains considerably more piping than transmission systems due to many individual connections. This makes the system harder to maintain, and older piping systems may be more sensitive to embrittlement than the transmission system. Leaks into enclosed spaces are concerning with hydrogen since the fuel ignites easier and faster than natural gas, leading to higher risk of detonation in instances of hydrogen accumulation.[99] Nevertheless, in case of leakage, hydrogen dissipates faster than natural gas reducing the risk of detonation when operating with adequate ventilation systems.

The relevant standard for hydrogen pipelines is American Society of Mechanical Engineers B31.12 Hydrogen Pipelines and Piping Code—hydrogen piping design. This would be the applicable standard were utilities to convert portions of their distribution system to 100% hydrogen.

There are also building level and distribution level codes and standards that impact whether hydrogen can be added to the distribution system. The National Fuel Protection Association (NFPA) 54 – National Fuel Gas Code regulates gaseous fuels in buildings.[100] NFPA 54 provides minimum safety requirements for the design and installation of fuel gas piping systems in homes and other buildings.

3.4 Appliance Performance

Performance differences are similar across appliances and this section is intended to capture the considerations shared across each the six appliances. Most studies to date have established that existing equipment can operate using up to 20% hydrogen with no equipment modifications. However, above 20%, two critical performance impacts need to be considered: an increase in the amount of excess air during combustion, and increased production of condensate. Flashback and resultant flame instability is also a performance consideration but will be discussed in the health and safety section.

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[99] NFPA (National Fire Protection Association), *Natural Gas and Propane Fires, Explosions and Leaks: Estimates and Incident Descriptions*¸ by Marty Ahrens and Ben Evarts, October 2018, https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Hazardous-materials/osNaturalGasPropaneFires.ashx.

[100] NFPA, National Fuel Gas Code, NFPA 54, https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=54.

3.4.1.1 Increase in Excess Air during Combustion

The combustion of hydrogen requires less oxygen than burning the equivalent amount of natural gas. Therefore, residential appliances that are optimized for operation on natural gas alone, will see an increase in the amount of excess air when blends of hydrogen are introduced.

Impacts

- Combustion heats excess air, reducing the temperature of the flame, and subsequently reducing the appliance efficiency.[101] Based on recent GTI research, the effect on tested appliance efficiency is minimal, varying only 1 to 1.5% for a 30% hydrogen blend in natural gas.[102]
- Excess air cools the flame, inferring lower NO_x production.

3.4.1.2 Increased Production of Condensate in Combustion

Blending hydrogen into natural gas causes more condensate production because of the chemical oxidization. Burning pure hydrogen produces 40% more water vapor than burning methane.[103] Thus, a 20% hydrogen blend can be expected to produce 8% more water vapor, though variations will occur.

Impacts

- Condensate is acidic, which can cause corrosion of appliance components if not managed correctly.
- Additional condensate requires a management strategy, which is important in venting design and in exposure to equipment components.

3.5 Safety and Health Considerations

There are several health and safety factors that are unique to hydrogen to consider when adding hydrogen to natural gas.

3.5.1.1 Flashback

Flashback remains the primary safety concern for gas cooktops due to the wider flammability range and faster flame speed. Flashback is the quality in which a flame travels so quickly that it burns backward into the fuel line. The burner port velocity is the key factor that can enable or prevent flashback. That is, the speed at which gas is ejected from the line can prevent flashback if fast enough. If it is slower, the gas can flashback and burn fuel into the gas line.

Studies of existing gas equipment have attempted to understand the potential for flashback in gas appliances operating on HENG, because existing equipment is designed for natural gas,

[101] AHRI, *Assessment of Hydrogen Enriched Natural Gas*, 27.
[102] Glanville, P et all. "Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance", Energies 2022, 15(5), 1706; https://doi.org/10.3390/en15051706
[103] AHRI, *Assessment of Hydrogen Enriched Natural Gas*, 50.

which is less likely to flashback due to a slower flame speed and a narrower flammability range. Intermittent flashbacks during testing blends above 15% hydrogen were observed in AHRI's *Assessment of Hydrogen Enriched Natural Gas*, which led to a recommendation that 15% should be seen as a threshold.[104] However, other studies consider significantly higher values and there are different results on the maximum amount of hydrogen that can be burned in existing appliances without modification. In the GTI cooktop study, flashback was observed at 55% hydrogen in the presence of a pot on the burner.[105]

3.5.1.2 Fuel Accumulation and Detonation

Hydrogen is a small and buoyant molecule.. A key risk for both hydrogen and natural gas is that gaseous fuels can leak, accumulate, in an enclosed space, and then detonate. Hydrogen has both increased and diminished risk factors for this. On the one hand, because hydrogen is 14 times lighter than air, it is less likely to accumulate in houses or appliances than natural gas. On the other hand, because hydrogen is more flammable and easier and faster to ignite, there is a higher risk for detonation if it does accumulate. Though this is a low probability risk, the consequence could be great.

3.5.1.3 Visibility

Visibility was highlighted as an aesthetic consideration for appliances using high concentrations of hydrogen blends in natural gas or 100% hydrogen fuel, but it also presents a safety concern, specifically for gas cooktops and gas hearths where users expect to see a flame when the appliance is on. During the daytime, the pale blue flame of hydrogen has low visibility, meaning that a user could inadvertently leave a flame on. Alternatively, if a flame is present but not visible, it would pose a burning hazard. In addition to visual cues, hydrogen flames emit less infrared radiation, so people might not feel the heat of the flame until they are in contact with it. This reduces the sensory cue of the existence of a flame, which is a safety risk; however, 100% hydrogen cooktops can incorporate an indicator signaling that the flame is on, similarly to other "hot surface" indicators available in the market, thus minimizing safety risks.

3.5.1.4 Nitrogen Oxide

All combustion produces NO_x because of atmospheric nitrogen interacting with a hot flame. NO_x is a health hazard regulated in outdoor air by the Environmental Protection Agency. For this reason, many combustion appliances now build "Ultra Low-NO_x" versions of their appliances to produce fewer emissions. While continued research is needed, some studies have looked at the impact of burning hydrogen in gas appliances on NO_x production.

The initial studies of hydrogen in appliances have found decreased production of NO_x compared to natural gas. However, this quality is temperature sensitive and must be controlled for in appliance design and operation. The primary factor that leads to an increase in NO_x production is flame temperature. The hotter the flame, the more NO_x is produced. Since hydrogen burns

[104] AHRI, *Assessment of Hydrogen Enriched Natural Gas*.
[105] Yan Zhao, Vincent McDonell, and Scott Samuelsen, "Influence of Hydrogen Addition to Pipeline Natural Gas on the Combustion Performance of a Cooktop Burner," 8.

hotter than natural gas, there is the potential for an increase in NO_x production. However, as discussed in previous sections, burners optimized for use with natural gas produce more excess air when hydrogen is blended in. This extra air in the presence of the flame, reduces the temperature of the flame, thus reducing NO_x. AHRI 2021 recommends *not* adjusting appliances to optimize for excess air to maintain lower NO_x production.

The UCI Combustion Laboratory investigated NOx production from various appliances and published a table for the CEC which is included in Appendix B: NOx Production Impacts. A notable appliance design feature that can decrease NO_x is the proximity of the flame to solid surfaces. When flame temperature is reduced because of contact with a heat exchanger, less NO_x is produced. UCI tests found higher NO_x produced in an open hearth with unimpinged flame.

3.5.1.5 Flame Recognition

Selecting a flame recognition device is important for higher concentrations of HENG and 100% hydrogen. Natural gas furnaces commonly use ionization sensors to detect flames via the presence of ions from hydrocarbon combustion. With increasing concentrations of hydrogen and the subsequent reduction in hydrocarbons, ionization sensors cannot be used because the sensors will not detect a flame.[106] This results in a required part substitution in some appliances.

Other flame recognition devices found in appliances could also pose a safety concern. Another common flame recognition device for cooktops and ovens is called a thermoelectric flame failure device, which has a relatively slow reaction time before shutting off the flow of gas (typically 30 seconds or greater). For appliances that have enclosed volumes, such as ovens and hearths, unburnt gas could build up and pose a detonation hazard.[107]

3.6 Appliance Modification

Studies to date have consistently shown that residential gas appliances can operate using blends of hydrogen up to some given concentration of hydrogen to natural gas.

Frazer-Nash, an energy consultancy based in the United Kingdom, conducted a study[108] that highlighted two components that will not work on 100% hydrogen:

1 | The existing atmospheric and partial premix burner design on all appliances, which were discussed in the appliance-specific discussion.
2 | Ionization sensors commonly used on furnaces and water heaters.

In addition to these two specific changes, the literature contains some discussion of adjustments to flame temperature and potential long-term impacts of hydrogen use in appliances as requiring potential modification. A key takeaway from the consideration of appliance

[106] Frazer-Nash Consultancy, "Appraisal of Domestic Hydrogen Appliances," 14.
[107] Ibid.
[108] Ibid.

modification is that there is a ceiling to how much hydrogen can be used with existing appliances until component modifications or replacements are required. The exact level of hydrogen blending without appliance modification varies by appliance and report. However, to date most agree that at least 15% hydrogen is an acceptable level, with recent studies, such as GTI's report demonstrating minimal impacts up to 30% blends.[109]

In Europe, where hydrogen use in residential applications is more advanced, manufacturers are developing hydrogen-ready appliances. Such appliances can run immediately off blends up to 20% and can be converted to burn 100% hydrogen with the substitution of a minimum number of components in under an hour.[110]

3.6.1.1 Flame Temperature Modification

There are some design changes under consideration to optimize for the use of hydrogen blends. Since cooktops are atmospherically vented and combustion emissions directly enter the ambient environment, management of flue gases is important. Recent research has looked specifically at the production of NO_x during gas cooktop use. As noted in section 3.2, the tradeoff between flame temperature and excess air impacts NO_x production. Therefore, AHRI recommends not adjusting burner controls to optimize for excess air.[111] The result is that the reduced flame temperature reduces NO_x, though device operation time may be longer due to less heat output.

3.6.1.2 Burner Design Modification

For appliances to operate at higher concentrations of hydrogen, the burner design must eliminate the primary combustion air, and use a non-aerated burner. This means that the partial premix burner used in today's gas appliances is not compatible with 100% hydrogen. The main reason for incompatibility is the risk of flashback, when using hydrogen blends with partial premix burners.[112] Certain studies, such as AHRI 2021 have observed flashback at concentrations as low as 20%.[113] The non-aerated burner design enables more complete combustion of the hydrogen at a higher temperature, thereby increasing the thermal efficiency. However, Frazer-Nash cites the need for careful design to balance NO_x and flame temperature.

3.6.1.3 Ionization Sensors

As discussed in Section 3.5 Safety and Health Considerations, ionization sensors common in furnaces and water heaters will not be compatible with high concentrations of hydrogen, due to the lack of ions in carbon rectifying the flame. AHRI's *Assessment of Hydrogen Enriched Natural Gas* notes that ionization sensors work for hydrogen blends up to 30%, but beyond that point

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109 Paul Glanville et al., "Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NO_x Emission and Operational Performance."
110 HyLife, "Hy4Heat Hydrogen-Ready Wall-Mounted Gas Boilers."
111 AHRI, *Assessment of Hydrogen Enriched Natural Gas*, 36.
112 Frazer-Nash Consultancy, "Appraisal of Domestic Hydrogen Appliances," 21.
113 AHRI, *Assessment of Hydrogen Enriched Natural Gas*.

they require flame detection via an alternative method, likely heat sensing devices such as thermocouples or ultraviolet and infrared sensors.[114]

3.6.1.4 Long-term Impacts

During interviews, stakeholders and SMEs highlighted that the long-term impacts of hydrogen use in existing appliances remains an unknown in the research. Manufacturers of appliances subject their appliances to accelerated life cycle testing in which they attempt to mimic a product life cycle in a shorter period. To date, studies have not researched the long-term impacts of operating appliances with hydrogen or hydrogen blends.[115] This is a key area for future research because of hydrogen's physical qualities, such as embrittlement. In enclosed appliances such as furnaces, there is the potential for repeated, long-term exposure to hydrogen could expose certain welds to embrittlement. *Assessment of Hydrogen Enriched Natural Gas* notes that this leakage and embrittlement is a theoretical concern for now until further research is conducted.[116] For manufacturers, this will be a near-term research need.

3.7 Summary

Studies have found limited performance impacts on existing appliances up to 20% hydrogen, and recent evidence suggests the value could be higher. Table 5 summarizes the impacts on the reviewed appliances:

Table 5: Considerations for Hydrogen by Appliance

Appliance	Consideration					
	NO_x	Flashback	Aesthetics	Flame Recognition	Condensate Management	Fuel Accumulation
Cooktops	✓	✓	✓	✓		
Ovens	✓	✓		✓		✓
Furnaces	✓	✓		✓	✓	✓
Water Heaters	✓	✓				

[114] AHRI, *Assessment of Hydrogen Enriched Natural Gas*, 37.

[115] Hawai'i Gas has been integrating hydrogen in their Oahu pipelines since the inception of the SNG (synthetic natural gas) plant in 1974 (http://www.ililani.media/2022/02/hawaii-gas-fuel-mix-focuses-on-sng.html#:~:text=Hydrogen%20%E2%80%93%20Hydrogen%20has%20been%20part,in%20the%20production%20of%20SNG.). There are no publicly available reports or publications relating to long-term assessments of hydrogen use in natural gas appliances in the Oahu services area, as well as no reports on issues with this practice either.

[116] AHRI, *Assessment of Hydrogen Enriched Natural Gas*, 6.

Hearths	✓	✓	✓	✓		✓
Clothes Dryers	✓	✓		✓		✓

Even with limited impacts on low hydrogen blends, there is an upper limit at which existing equipment can operate before appliance modifications are needed to burn 100% hydrogen. The most significant modification is to the burner design, which must migrate from a partial premix burner, in which primary air is mixed with the gas prior to combustion, to a non-aerated burner. Non-aerated burners eliminate flashback risk associated with using hydrogen in partial premix burners. The second necessary modification is the flame recognition device. Ionization sensors do not recognize hydrogen flames due to the lack of hydrocarbon ions. Research also suggests that thermoelectric flame failure devices may not be best suited for hydrogen due to the slow reaction time—as much as 30 seconds—before shutting off the flow of gas. Research recommends specifically designed ultraviolet, infrared, or other heat sensing thermocouples as possible solutions.

Existing codes and standards for residential appliances do not consider hydrogen in their scope currently, yet there are ongoing discussions for the need to do so in the future. The DOE's energy conservation standards and test procedures are currently fuel-specific and apply to natural gas-fired appliances, as well as oil and propane. Appliances that use hydrogen are not covered by these regulations and DOE would need to expand their fuel type definitions and standards to cover appliances operating with HENG and 100% hydrogen. As mentioned in previous sections, the suite of safety and performance standards are the ANSI/CSA Z21 series, which are required for the sale of all appliances into the US market. During industry outreach, researchers identified a working group that started discussions to evaluate the need to update the Z21 standards for use with hydrogen blends.

Section 4 Conclusions and Recommendations

4.1 Conclusions

Blending hydrogen in gas pipelines is gaining interest of government agencies and gas utilities worldwide, with the United Kingdom leading the way. In the United States, a few gas utilities, especially those in states with ambitious climate commitments (California, New York, and Hawaii), are moving testing forward. Though natural gas and hydrogen molecule properties vary significantly, testing has shown no impact on appliance performance with up to 20% hydrogen blends. Furthermore, GTI research indicates that appliance tested (furnaces and water heaters) can maintain performance and safety with 30% hydrogen blend in natural gas. Studies in the US and Pacific Northwest in particular, similarly suggest that HENG blends up to 10 and20% are possible with existing appliances and infrastructure.[117]

However, findings from research studies suggests that there is a ceiling to how much hydrogen can be used with existing appliances until component modifications or replacements are required. Frazer-Nash highlighted two components that will need to be replaced for 100% hydrogen:

1 | The existing atmospheric and partial premix burner design on all appliances.
2 | The ionization sensors commonly used on furnaces and water heaters.

In Europe, hydrogen-ready appliances are commercially available. These appliances can run immediately off blends up to 20% and 100% hydrogen with the substitution of a minimum number of components in under an hour.[118] Additionally, higher content of hydrogen will require addressing other aesthetics and safety considerations. The hydrogen is almost impossible to see for the naked eye during daytime, which reduces aesthetic performance in the case of hearths and increases risk of burning in cooktops. There are research and development initiatives incorporating additives to make the hydrogen flame colored. Another area that needs research is the study of long-term impacts of HENG in residential appliances.

Standards in Europe and Australia include testing with HENG as a gas limit, covering a few of the test usually performed on the reference gas. Current standards and test methods for appliances in the United States (Z21 standards) fail to incorporate hydrogen blends, even as a limit gas. In the short term, standard-setting organizations should update these standards or develop new ones to ensure the safety, efficiency, and performance of household appliances when

[117] The different studies have tested different HENG blends (10% and 20%).
[118] HyLife, "Hy4Heat Hydrogen-Ready Wall-Mounted Gas Boilers."

functioning on HENG. In the long term, standards and test methods for 100% hydrogen appliances might be required.

4.2 Recommendations

There is no certainty about what a decarbonized future would look like. Currently, the market is seeing increased pressure toward electrification with distributed and large-scale deployment of low-cost renewable generation. But because the main goal is to reduce GHG emissions, the gas sector should also pursue decarbonization options such as injecting renewable natural gas, hydrogen, or other low-carbon fuels in its network. At this point in time, potential scenarios for the gas sector include:

1 | Varying percentage blends of hydrogen and low-carbon fuels.
2 | A 100% hydrogen system.

Hydrogen injection in natural gas pipelines is starting to materialize in the United States and worldwide. Given the different properties of these two gases, and the findings of this research, new appliances will need to adapt to this changing environment. Results of interviews indicate the need for easily convertible appliances that can work at varying blends and with minor modifications be 100% hydrogen ready. Interviewees highlighted the need for standards and test methods that provide confidence in appliance operations under certain HENG concentrations and identify concentrations at which appliance modifications are needed or higher hydrogen content should be avoided. Additionally, the lack of long-term research on HENG impact on appliances came up as a concern.

NEEA can support this market transformation by enabling the conversation with appliance manufacturers, encouraging the modification of test methods and standards and promoting their adoption, conducting focus groups with all stakeholders to address barriers to ensure a safe development of this market, and supporting pilot projects in the region and new research addressing the long-term impact on appliances.

Appendix A. Comparative Properties of Hydrogen and Other Fuels

Property	Units	Hydrogen	Methane	Propane	Methanol	Ethanol	Gasoline
Chemical Formula		H_2	CH_4	C_3H_8	CH_3OH	C_2H_5OH	C_xH_y (x = 4 - 12)
Molecular Weight [a, b]		2.02	16.04	44.1	32.04	46.07	100 - 105
Density, NTP [3, a, c]	kg/m³	0.0838	0.668	1.87	791	789	751
	lb/ft³	0.00523	0.0417	0.116	49.4	49.3	46.9
Viscosity, NTP [3, a, b]	g/cm-sec	8.81 E-5	1.10 E-4	8.012 E-5	9.18 E-3	0.0119	0.0037 - 0.0044
	lb/ft-sec	5.92 E-6	7.41 E-6	5.384 E-6	6.17 E-4	7.99 E-4	2.486 E-4 - 2.957 E-4
Normal Boiling Point [a, b]	°C	-253	-162	-42.1	64.5	78.5	27 - 225
	°F	-423	-259	-43.8	148	173.3	80 - 437
Vapor specific gravity, NTP [3, a, d]	air = 1	0.0696	0.555	1.55	N/A	N/A	3.66
Flash Point [b, d]	°C	<-253	-188	-104	11	13	-43
	°F	<-423	-306	-155	52	55	-45
Flammability Range in Air [c, b, d]	vol%	4.0 - 75.0	5.0 - 15.0	2.1 - 10.1	6.7 - 36.0	4.3 -19.0	1.4 - 7.6
Auto ignition temperature [b, d]	°C	585	540	490	385	423	230 - 480
	°F	1085	1003	914	723	793	450 - 900
Maximum flame velocity in air [2, c]	m/s	2.83	0.45	0.46	N/A	N/A	N/A
	ft/s	9.28	1.48	1.52			

Source: PNNL, "Comparative Properties of Hydrogen and Other Fuels," accessed July 25, 2022, https://h2tools.org/hyarc/hydrogen-data/comparative-properties-hydrogen-and-other-fuels.

Appendix B. NO_x Production Impacts

Table 6. Performance Summary of Appliance Burners

Appliance Burner		Natural gas + hydrogen	Natural gas + carbon dioxide (simulate biogas behavior)
Cooktop burner	Upper limit	20% (ignition); 55 (cooking); 75% (idle)	20% (ignition); 35% (cooking); 35% (idle)
	NO_x	-23.3% (0-50% H_2)	-51.4% (0–30% CO_2)
	CO	-14.0% (0-50% H_2)	+58.2% (0–30% CO_2)
	UHC	-74.2% (0-50% H_2)	+2128.4% (0–30% CO_2)
Oven burner	Upper limit	30%	15%
	NO_x	Variation within analyzer	-91.8% (0-10% CO_2)
	CO	-38.2% (0-25% H_2)	+113.8% (0-10% CO_2)
	UHC	+350.5% (0-25% H_2)	NA
Gas fireplace	Upper limit	100%	45%
	NO_x	+3966.4% (0-100% H_2)	-75.7% (0-40% CO_2)
	CO	-100% (0-100% H_2)	-99.9% (0-40% CO_2)
Low NO_x storage water heater	Upper limit	10%	15%
	NO_x	Variation within analyzer	-45.9% (0–10% CO_2)
	CO	+26.9% (0-5% H_2)	+334.4% (0–10% CO_2)
	UHC	-50.5% (0-5% H_2)	+159.3% (0–10% CO_2)
Tankless water heater (2 gal/min)	Upper limit	>20%	15%
	NO_x	-20.3% (0-20% H_2)	-44.8% (0–12% CO_2)
	CO	-9.7% (0-20% H_2)	+349.9% (0–12% CO_2)
	UHC	Variation within analyzer	+177.2% (0–12% CO_2)
Space heater	Upper limit	20% (ignition); 45% (operation)	10% (ignition); 30% (operation)
	NO_x	-4.2% (0-40% H_2)	-47.1% (0–25% CO_2)
	CO	-13.9% (0-40% H_2)	+897.8% (0–25% CO_2)
	UHC	Variation within analyzer	+193.9% (0–25% CO_2)
Pool heater	Upper limit	NA	20%
	NO_x	-95.6% (0–70% H_2)	-98.5% (0–15% CO_2)
	CO	+761.9% (0–70% H_2)	+2400% (0–15% CO_2)
Outdoor grill	Upper limit	> 40%	40%
	NO_x	+128.2% (0-40% H_2)	-~100% (0–35% CO_2)
	CO	-93.7% (0-40% H_2)	-77.5% (0–35% CO_2)
Laundry dryer	Upper limit	NA	15%
	NO_x	-61.9% (0-40% H_2)	-80.7% (0–10% CO_2)
	CO	-34.1% (0-40% H_2)	+118.1% (0–10% CO_2)

Source: California Energy Commission, Implications of Increased Renewable Natural Gas on Appliance Emissions and Stability, Table ES-1.