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ROLE OF COMBUSTION-BASED BUILDING EQUIPMENT IN DECARBONIZATION

Final Report

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Role of Combustion-based Building Equipment in Decarbonization

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Executive Summary

In North America, natural gas is the predominant fuel providing space heating and hot water in residential and commercial buildings, used in 85 million homes and businesses served by 5.4 million km distribution network capable of delivering >600 GW of energy. A portfolio of technologies are needed for the built environment to address the approximately 1,000 Mt CO_2e/year of GHG emissions from these furnaces, boilers, water heaters, infrared heaters, and other equipment, while retaining the energy storage and delivery function of the gas grid. This study provides an overview of technology pathways for building GHG emissions reductions, with a focus on options for combustion equipment manufacturers. Specifically, this report provides (a) a technical review of GHG emission reduction technology pathways for combustion equipment in buildings, (b) an estimated technical potential of these technologies, (c) a summary of the pertinent industry projects and, if relevant, emerging standards, and (d) outstanding technology needs and barriers for further development and investigation.

For technologies and innovations to decarbonize North American buildings that continue use of delivered fuels, there are three major categories of solutions. These solutions can be applied in sequence or tandem, in retrofit and in new construction, with the potential to significantly reduce GHG emissions overall (>80%) with *existing technologies and infrastructure.*

- ***Advanced Conservation Measures (ACM):*** These are foundational solutions to reduce thermal loads while maintaining comfort. Measures reduce heating and cooling loads *broadly* year-over-year (e.g. building envelope improvements) or *temporally* with load shifting advantageously decouple energy supply and demand, including load shifting controls and energy storage. For ACM we examine the potential for *Thermal Energy Storage (TES)*, as integral to heating equipment with latent, thermochemical, or other solutions.
- ***Innovative Mechanical Solutions (IMS):*** These are unitary or distributed mechanical HVAC and water heating technologies with non-incremental improvements in efficiency, often through heat pump technologies in part ("hybrid") or whole. Solutions that can prioritize on-site or delivered renewable energies or ensure system resiliency also apply. For IMS we examine three solutions overall, two heat pump-based pathways a) *Hybrid Heat Pumps (HHP)* combining electrically-driven heat pumps with fuel-fired heating for flexibility and peak demand management and b) *Fuel-fired Heat Pumps (FFHPs)* for maximum efficiency with fuel-fired heating, and improved system efficiency and resiliency with *Micro-Combined Heat and Power (mCHP).* In practice, these solutions are often mutually exclusive.
- ***Upstream and Downstream Decarbonization (UDD):*** For fuel-fired technologies, further emission reductions are feasible by (a) accepting decarbonized fuels, including low/zero hydrogen and/or hydrocarbons (e.g. biomethane) and (b) mitigating emissions directly from equipment, both CO_2 and CH_4. For UDD, this study examines three solutions including those concerning adopting *Low/Zero Carbon Fuels (LCF)*, implementing *Distributed Carbon Capture (DCC),* and efforts to *Mitigate Methane Emissions (MME)*.

From this in-depth review of pathways as applied by manufacturers of combustion-based building heating equipment, a summary of the synthesis is provided in the table below. Of these seven decarbonization pathways for heating equipment, deployed *in addition* to energy conservation/efficiency measures, the decarbonization of delivered fuel use was demonstrated using *existing technologies and infrastructure*. Overall, it remains critical that delivered energies continue to decarbonize (electricity/fuels), and certain pathways can provide flexibility between grids as this unfolds (ex: mCHP, HHP). Beyond the supply-side, the role of the utility is also critical, supporting technology adoption and market awareness through case studies, programs, market transformation. Other themes across pathways include the need for: modernization of safety and performance standards, improved value proposition for system-wide benefits (e.g. grid services, system resilience), expansion of new markets (e.g. CH_4 / CO_2 credits), and mechanisms to increase customer safety and awareness (e.g. "H_2 ready" equipment). Through collaboration, the heating equipment industry can drive the decarbonization of their customers.

Table: Summary of Key Findings from Technology Pathways Reviewed

Tech. Pathway	GHG Reduction[1] Near	GHG Reduction[1] Long	Key Benefits	Tech. Maturity
ACM: TES	15%-30%	>30%	Added resiliency and grid services, improve thermal performance, cost/GHG optimization with grids	10+ market players and most at demo-scale, equipment-integrated solutions are emerging for heating and cooling
IMS: mCHP	30%-50%	<50%		Large diversity of core tech., size, applications (30+), but market is small
IMS: FFHPs	40%-50%	>50%	Max. efficiency for fuel-fired heating, low/zero-GWP, cold-climate ready	~20 market players, wide range of mature/emerging technologies globally, emerging market in NA
IMS: HHPs	~20%	>>20%	Peak energy demand mgmt.., system flexibility, can optimize against cost, GHG, comfort	Most mature pathway, many products available across equip. categories, market is increasing globally
UDD: LCFs	<100% (net)	<100%	Full decarbonization is feasible on net or absolute basis, compatible with all other pathways	Supply is in scale-up phase, "drop-in" biofuels available increasingly, for H_2-based fuels scaling up underway but knowledge gaps on compatibility with existing equip. & infrastructure remain
UDD: DCC	~20%	>>20%	Retrofit potential for larger combustion equip., add'l revenue possible via credits/CO_2 off-takers	Limited number of emerging tech. in pilot/demo phase, regulatory drivers and CO_2 markets are evolving rapidly
UDD: MME	High level of uncertainty		Further reduction in climate impact, increased attention on utility customer CH_4 emissions	Mechanism/mitigation of CH_4 emissions from equipment well understood, research is ongoing to define baseline, test methods, and sampling protocols

1 Estimates are approximate compared to standard combustion baseline, some depend on current/future GHG intensity of electricity grid and/or availability of low/zero-carbon fuels. For LCFs – short term emissions on net basis primarily via "drop-in" biofuels and long term on absolute basis with H_2-based & synfuels. For mCHP – it is important to note that emissions benefits *decrease* as the electricity grid decarbonizes, while for HHPs it is the opposite. For MME - studies show order of magnitude range of estimated methane emissions for baseline.

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List of Acronyms

ACM	Advanced conservation measures
AFUE	Annual fuel utilization efficiency
AHJ	Authority Having Jurisdiction
AHU	Air handling unit
ASHP	Air-source heat pump
bioLPG	Bio-liquid petroleum gas
CARB-DG	California Air Resources Board Distributed Generation Certification
CCHP	Cold-climate heat pump
CH_4	Methane
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Coefficient of Performance
DCC	Distributed carbon capture
DER	Distributed energy resource
DHW	Domestic hot water
EIA	U.S. Energy Information Administration
FFHP	Fuel-fired heat pump
GAHP	Gas-fired absorption heat pump
GHG	Greenhouse gas emissions
GHGI	Greenhouse Gas Inventory (U.S. EPA)
GHPWH	Gas-fired heat pump water heaters
GWP	Global warming potential
H_2	Hydrogen
HHP	Hybrid heat pump
HVAC	Heating, ventilation, air-conditioning
IC	Internal combustion
IES	Integrated energy system
IMS	Innovative mechanical solutions

IPCC	Intergovernmental Panel on Climate Change
LCFs	Low-carbon fuels
mCHP	Micro combined heat & power
MME	Mitigating utility customer methane emissions
Mt	Megatonne
NEEA	Northwest Energy Efficiency Alliance
NORA	National Oilheat Research Alliance
NO_X	Oxides of nitrogen
OAT	Outdoor air temperature
PCM	Phase change material
PPA	Power purchase agreement
PRCI	Pipeline Research Council International
PV	Photovoltaic
RD&D	Research, development, and demonstration
RNG	Renewable natural gas
RTU	Rooftop unit
RWT	Return water temperature
rDME	Renewable dimethyl ether
SOFC	Solid oxide fuel cells
TC	Thermochemical
TWH	Tankless water heater
UDD	Upstream and downstream decarbonization
UEF	Uniform energy factor
VRF	Variable refrigerant flow

1. The Role of Combustion-based Building Equipment in Decarbonization

In North America, natural gas is the predominant fuel for providing space heating and hot water to residential and commercial buildings, used in the majority of homes and businesses. For these buildings, the distribution and delivery of fuels to buildings is a mega-scale form of seasonal energy storage, delivering greater than 600 GW of energy during the winter, often in the form of heating from natural gas storage supplies built up over periods of 6-8 months [Liss, 2022]. The scale of this network is significant: for the U.S. and Canada combined, this distribution system serves 85 million homes and businesses with a network spanning 5.4 million km [EIA, 2021 and CGA, 2021]. As efforts increase to reduce the impact of buildings on the environment, the greater than 1,000 Mt CO_2e/year emitted from this fuel consumption should be mitigated to meet decarbonization and/or greenhouse gas (GHG) emission reduction targets [LLNL, 2021].

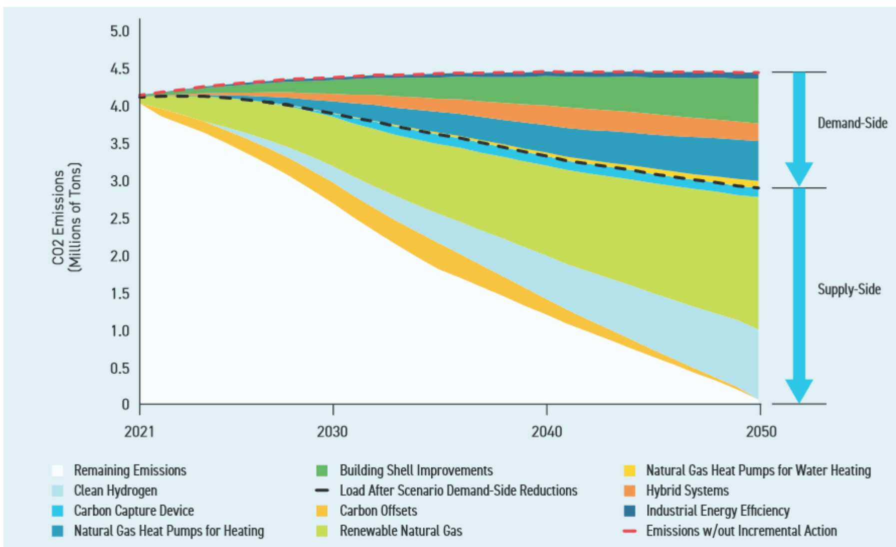


Figure 1: "Balanced Approach" Net Zero Scenario – Oregon-based Utility [Northwest Natural, 2021]

Building on traditional energy efficiency and conservation measures, which remain the pillars of any climate mitigation and decarbonization scheme (e.g., developing and deploying condensing efficiency (>90%) equipment), there are many emerging pathways to reduce CO_2e emissions from buildings served by combustion equipment. These pathways, focused on GHG emission reductions, must also be balanced with concerns around end user comfort, cost-effectiveness, and the resilience of these energy systems. Candidate technology types include those that reduce the GHG impact of combustion technologies through the use of low/zero carbon fuels and those that improve the efficiency or functionality of the combustion equipment, such as integrated thermal energy storage. Recent studies have outlined how regional and national governments and utilities can meet aggressive emission reduction goals, typically net-zero by 2050 or earlier. Pertinent to combustion equipment, there are many recent and notable studies, such as those by the American Gas Association [AGA, 2022] and by numerous individual utilities [National Grid, 2022 and Northwest Natural, 2021], where multiple technology pathways are projected to contribute collectively to meet these goals (see Figure 1). In the example below from Northwest Natural, many technologies on the demand side (e.g., fuel-fired heat pumps) and supply side (e.g., renewable natural gas (RNG)/biomethane) are needed to reach net zero.

Introduction

The aggressive goals and targets to decarbonize North American buildings by 2050 or sooner must be met with a portfolio of solutions, as a "silver bullet" does not exist. The diversity of the building stock requires a portfolio of solutions to address the variations in construction, design, and use of electrically-driven or fuel-fired equipment across climate zones, building code jurisdiction, and socioeconomic strata. This building stock includes everything from detached single-family houses to high-rise multifamily buildings to complex medical and industrial facilities. Concerning new construction versus existing buildings, 79% of U.S. housing units were built before 2000 with a broad distribution in vintage. In a recent study, the lifespan of a U.S. residential building was estimated at 130 years [Ianchenko, 2020], while U.S. commercial buildings are commonly modeled with a median lifetime of 50-65 years [EIA, 2022]. Thus, one can assume that most of the building stock in 2050 exists today, including a disproportionate fraction of buildings in colder climates that use fuels for heating.

This study provides an overview of technology pathways for GHG building emissions reductions, with a focus on options for combustion equipment manufacturers. Specifically, this report provides (a) a technical review of GHG emission reduction technology pathways for combustion equipment in buildings, (b) an estimated technical potential of these technologies, (c) a summary of the pertinent industry projects and, if relevant, emerging standards, and (d) outstanding technology needs and barriers for further development and investigation.

Emission Reduction Technology Pathways

For technologies and innovations to decarbonize North American buildings that would continue use of delivered fuels, both in retrofit and in new construction, the authors envision solutions in three major categories, generally to be applied in sequence or tandem:

- ***Advanced Conservation Measures:*** These are foundational solutions that serve to reduce overall thermal loads through technologies and other solutions to maintain thermal comfort with reduced heating, ventilation, air-conditioning (HVAC), and water heating equipment output. These measures can reduce heating and cooling loads *broadly* through a net reduction in loads year-over-year. Measures can include improving building thermal envelopes, more effective ventilation, or improving the efficiency of heat distribution within the building, or *temporally* with temporary shifts of HVAC loads to advantageously decouple thermal energy supply and demand, including advanced controls (e.g., load shifting controls) and thermal energy storage solutions.
- ***Innovative Mechanical Solutions:*** This broad category includes unitary or distributed mechanical HVAC and water heating technologies that represent non-incremental improvements in energy efficiency, and inherently deliver GHG emissions reductions, compared to conventional equipment. This includes advanced electrically-driven and thermally-driven heat pump technologies, yielding significant improvements in efficiency for buildings currently served by delivered electricity or fuels. Also included are advanced hybrid technologies that incorporate both fuel-fired and electrically-driven components, and can therefore operate in either or both modes, depending on conditions locally, regionally, or using delivered energy sources. Mechanical solutions that can prioritize on-site renewable

energies also apply. To improve the economics of these innovative mechanical solutions, it is often advantageous to employ advanced conservation measures first to avoid over-sizing equipment.

- ***Upstream and Downstream Decarbonization:*** For fuel-fired thermal technologies, further GHG emission reductions are feasible by (a) accepting decarbonized fuels, including hydrogen (H_2), renewable and synthetic natural gas, and other hydrocarbons (e.g., renewable dimethyl ether [rDME]), and (b) by applying methods of carbon capture. While the latter is unconventional in the building sector, demonstrations of thermal technologies compatible with blended or pure decarbonized fuels are underway, outlining *at least* a mid-term pathway to accelerating the commodity market for these decarbonized fuels, or *at most* a long-term cost-effective pathway for deep decarbonization.

While relative contributions to each category of solutions will depend on numerous specifics—not only the building itself but the GHG content of delivered fuels and electricity—this decarbonization "stack" can meet aggressive GHG reductions in aggregate. As shown in Figure 2, for a given thermal load (e.g., space and water heating) to reduce its GHG impact by 80% by 2030, the building can first employ conservation measures that reduce thermal demand by 30%, with common solutions including foam insulation and air sealing, water-efficient fixtures, and smart thermostat controls. At this point, the building may be considered "heat pump ready", where a correctly-sized heat pump serving this reduced demand can be 40% smaller than the baseline. As one option, an efficient thermally-driven heat pump would reduce GHG emissions by 50%. Finally, if the building is served by a utility with a 40% decarbonized fuel blend such as natural gas blended with green H_2 or RNG, an overall 80% reduction over baseline is achieved with **existing technologies and infrastructure**.

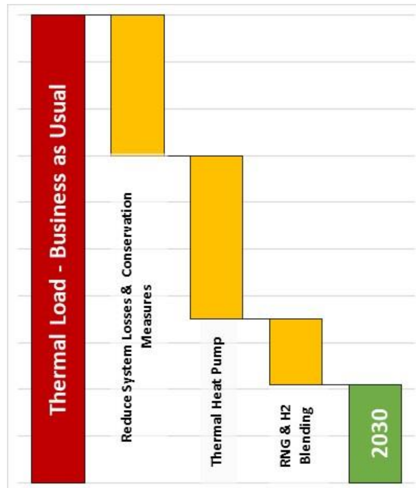


Figure 2: Illustration of GHG Emission Reduction "Stack"

When considering full or partial electrification as a decarbonization alternative, it is important to note that electricity production is currently responsible for 32% of U.S. GHG emissions. Until the electricity grid is decarbonized, shifting to near-zero GHG emissions using these thermal technologies can provide viable GHG emission reduction pathways in new construction and retrofit. Other benefits include having the inherent resiliency of the gas grid and mitigating any significant local or regional increase in peak energy demand.

Scoping of the Study

On scoping this technology survey and review, the authors investigated the following technology pathways for standard combustion equipment (water heaters, boilers, furnaces, infrared heaters):

Advanced Conservation Measures:

- **Thermal Energy Storage:** Thermal energy storage solutions for integration with combustion equipment beyond storing sensible heat.

Innovative Mechanical Solutions:

- **Micro Combined Heat & Power (mCHP):** Where existing grid constraints or interruptions are challenges, mCHP (<50 kWe) can play a role in decarbonization, including provisions for "self-powered" heating equipment.
- **Fuel-fired Heat Pumps (FFHP):** Sorption, vapor compression, and thermal compression-type solutions.
- **Hybrid Heat Pumps:** Integration of electrically-driven heat pumps with combustion-type heating equipment, for staged or simultaneous operation.

Upstream and Downstream Decarbonization:

- **Low/Zero Carbon Fuels:** Combustion equipment compatibility with non-fossil fuels, both blended and 100%, including hydrogen, synthetic/renewable methane, and renewable propane.
- **Distributed Carbon Capture:** Point source (post-combustion) and integrated carbon capture (pre-combustion).
- **Mitigating Utility Customer Methane Emissions:** Methods to quantify and mitigate fugitive methane emissions from combustion equipment.

These technology pathways will be explored, focusing on combustion equipment, with the following bounding conditions:

- U.S. and Canada market applications only, for residential and light commercial-sized factory-built equipment, generally less than 293 kW (<1,000 kBtu/h[2]) input in size and judged to be mass-market applications.
- Technology pathways that are commercially available or are judged to be within 3-5 years of commercialization.
- Applications for potable water heating, hydronic heating, and forced-air heating will be considered, that may fit into one of three categories:
    - Represent an add-on/replacement component *within* the conventional equipment, such as high-hydrogen (>30% H_2 by vol.) blend tolerant combustion components.
    - Replace the conventional equipment in whole, such as a fuel-fired heat pump water heater.
    - Be installed or implemented with conventional equipment, such as a point-source carbon capture device.
- GHG emission reductions will focus on CO_2; however, impact on other so-called short-lived climate pollutants will be considered, specifically refrigerants and methane.

2 Note that at times in this report, IP units are stated rather than SI as default reflecting nature of product definitions and/or R&D efforts cited.

Review Synthesis and Conclusions

Initially and as a disclaimer, this is not a study that seeks to quantify aggregate approaches to GHG emission reductions, inclusive of scenario modeling and complex treatment of energy grid dynamics regionally and over time. There are numerous recent studies that achieve this analysis (with varying degrees of treating the technology pathways described), including notable studies with a utility-focus [AGA, 2022; National Grid, 2022; Northwest Natural, 2021], a regional-focus [e21 Initiative, 2021], and a national-focus [LCRI, 2022]. Rather this is a technology survey with the primary goal of reviewing seven potential decarbonization technology pathways for combustion-based heating equipment. The synthesis and conclusions offered in this section reflect the data and information collected in subsequent sections and the engineering judgement of the authors, but do not reflect the outcome of original decarbonization pathways simulation or other integrated modeling approach. Such an integrated quantitative analysis of the potential pathways outlined in this study, for water heaters, furnaces, boilers, and infrared heaters, would support further prioritization and GHG emission reduction quantification, and would constitute a worthwhile follow-on exercise.

These technology pathways have similarities within groupings. As noted, for heating equipment end users, these three pathway groupings **are not mutually exclusive**. Multiple pathways can be combined in sum or over time to achieve decarbonization goals and, in the case of *Upstream and Downstream Decarbonization*, options within a grouping can be combined as well.

- *Advanced Conservation Measures* (ACM), which seek to reduce or optimize overall thermal loads, are less applicable to heating equipment manufacturers than other pathway groupings. ACMs tend to be applied at the building energy system level (e.g., advanced thermal insulation) and serve to decarbonize heating equipment indirectly via load reduction rather than directly, via technology implementation. The exception is Thermal Energy Storage (TES), which has benefits of providing grid balancing/services or improving thermal system functionality and performance. Examples of the latter include prioritization of low carbon energy inputs or reducing system cycling losses. Optimizing energy time-of-use consumption tends to be an electrically-focused pathway, given the inherent energy storage of delivered fuels, however, shifts in regulatory and market dynamics are evolving such that TES can provide decarbonization options for combustion-based heating equipment as well. Given that the primary means of heating energy storage is sensible (hot water), TES is most applicable to water heating and boilers (all sizes), may be applied in HVAC, and is compatible with other pathways.
- *Innovative Mechanical Solutions* (IMS), where the core technology for converting delivered energy to thermal comfort is often fundamentally altered, may be most applicable to heating equipment manufacturers because it has direct bearing on the product design and performance. Three technology pathways are reviewed, which concern approaches to (1) integrated energy system design in mCHP or (2) adoption of heat pump technology through partial electrification, hybrid heat pumps (HHPs), or (3) emerging thermally-driven cycles as FFHPs. Given that these three technology groupings each may represent non-incremental investments above the conventional combustion equipment and often serve similar functions (e.g., heat pump cycles), they are commonly mutually exclusive. As an example, it is

unlikely that a mass-market residential boiler will be developed to employ both FFHP and HHP technologies.

In terms of near-term GHG emission reductions, all three approaches offer approximately 20%-50% GHG reductions over conventional combustion equipment baselines, but dynamics vary. For mCHP, GHG emission savings come from preferential distributed generation versus a power grid with high GHG-intensity. Thus, GHG reduction benefits decline with a lower emission power grid. The reverse is true for HHPs, where GHG emission savings come from preferential use of a lower GHG-intensity power grid as a primary input. Thus, GHG reduction benefits increase with a lower emission power grid. For FFHPs, the decarbonization of the power grid is important but will not comparably impact GHG reductions as much, where savings derived from the greater fuel-fired efficiency. Subsequently noted, all IMS pathways benefit from and are compatible with upstream and downstream decarbonization. Similarly, TES can be beneficially applied to mCHP, FFHPs, and HHPs alike.

Conversely, some IMS approaches provide improved end user resiliency and require fewer modifications to distribution of utilities (both customer and utility-owned) than others. mCHP provides high end user resiliency but adds complexity through system integration. FFHPs often are suitable for direct retrofits with conventional heating equipment but may have increased power demand relative to replacement equipment.[3] HHPs can provide inherent resiliency and flexibility but performance is a strong function of operating controls. For all pathways discussed, it is important to note that peak energy demand impacts are frequently less than the alternatives (e.g., full electrification).

- *Upstream and Downstream Decarbonization* (UDD) pathways are important for heating equipment manufacturers for two primary reasons: (a) collectively or individually they can represent pathways to full decarbonization of heating and (b) heating equipment modifications may be necessary to accommodate new requirements concerning the nature of fuels consumed, presence of emission collection, or methane emission limitations. It is important to note that all UDD pathways can be combined a) with other pathways and b) with each other for overall decarbonization. The UDD pathways are also mutually reinforcing, in that each emerging pathway resolving technical, market, and regulatory barriers can support that maturation of others.

  One UDD pathway is low/(zero) carbon fuels (LCFs), which like low/zero carbon electricity can represent a potential for complete decarbonization of a thermal load. In the pathway review, a range of LCFs are considered, broadly in two groups: (a) biogenically or synthetically produced hydrocarbons, which provide net GHG emission reductions, with direct emissions offset in part or whole, and commonly represent “drop-in” replacements for conventional fossil fuels (e.g., biomethane, bioLPG [bio liquid propane gas]) and (b) hydrogen-based fuels, either delivered as hydrogen or blended with hydrocarbon-based fuels. These are frequently not “drop-in” replacements, however, research, development, and

3 For example, residential gas heat pump water heaters will require power while the majority of storage-type gas water heaters do not.

demonstration (RD&D) is accelerating to accommodate them, and they do provide overall emission reductions depending on the GHG-intensity of the hydrogen.

A second UDD pathway is Distributed Carbon Capture (DCC), which is an emerging pathway where direct or indirect carbon pricing is applicable, with scaled-down solutions from power and industrial sectors currently in development or demonstration for post-combustion CO_2 capture. As a nascent technology, DCC for larger combustion equipment may accelerate due to the fast-evolving regulatory framework for carbon pricing, along with the incentive and carbon utilization markets.

Finally, mitigating utility customer Methane Emissions (MME) is an emerging topic rather than technology pathway, with accelerating efforts to better understand the contribution of methane emissions downstream of the utility meter. While research is underway to both quantify specific equipment emissions and develop sampling methodologies to handle these highly transient emissions, it is possible that heating equipment manufacturers will (a) quantify equipment emissions (either voluntarily or because they are required to do do) or (b) provide product designs and/or customer best practices to mitigate methane emissions. Industry guidance and testing protocols are not yet developed for heating equipment and remain a key barrier. For this reason, decarbonization potentials in this study do not reflect the contribution from methane emissions. Future approaches to regulate methane emissions from equipment may mirror those previously established for criteria air pollutants (e.g., carbon monoxide (CO), oxides of nitrogen [NO_x]).

The following tables summarize the primary technology pathways by product category, benefits and emission reduction potential, and recommendations. Finally, throughout the review, the importance of industry collaboration with utilities, regulators, and other stakeholders is robustly emphasized. This includes the modernization of existing performance and safety standards, and creation of new standards where necessary, support for RD&D of emerging decarbonization technologies, and engagement with the overall market transformation process, inclusive of design and implementation of new structures (e.g., methane emission mitigation programs) and the development of new markets (e.g., distributed carbon sequestration and utilization).

Table 1: Primary Pathways by Product Category

Product Category		Max. Efficiency Rating[4]	Primary Pathways
Residential	Water Heater	0.90 UEF (Storage) 0.96 UEF (Instantaneous)	ACM: TES; IMS: mCHP, FFHPs; UDD: LCFs, MME
	Warm-air Furnace	99.0 % AFUE	IMS: FFHPs, HHPs; UDD: LCFs, MME
	Boiler	96.0% AFUE (Water) 83.4% AFUE (Steam)	ACM: TES; IMS: mCHP, FFHPs, HHPs; UDD: LCFs, MME
Commercial (Non-residential)	Water Heater	97% TE (Storage) 99% TE (Instantaneous)	ACM: TES; IMS: mCHP, FFHPs, HHPs; UDD: LCFs, DCC, MME
	Warm-air Furnace	>90% TE[5]	IMS: FFHPs, HHPs; UDD: LCFs, MME
	Boiler	99.4% AFUE (Water) 84.2% TE (Steam)	ACM: TES; IMS: mCHP, FFHPs, HHPs; UDD: LCFs, DCC, MME
	Infrared Heater	Up to 96% TE[6]	UDD: LCFs, MME, TES[6]

4 Maximum efficiencies based on AHRI Certification Directory, inclusive of inactive equipment
5 "Condensing RTUs" are commonly rated as industrial-type air heating equipment, thus value is based on recent studies of this category: http://betterbricks.org/uploads/resources/CRTU_pilotSummaryReport_3.23.20.pdf
6 Upper limit based on personal communication, George File (SRP Group). Thermal energy storage can benefit infrared heating at a building-integrated level, as discussed in the TES section.

Table 2: Summary of Technology Pathways

	Technology Pathway	Potential GHG Reduction*	Key Benefits	Technical and Market Maturity
Advanced Conservation Measure: Primary GHG reductions by load reduction or optimization relative to delivered energies	Thermal Energy Storage	15% to 30% in near term, >30% potential in long term**	Adds system potential to provide grid balancing/services, improve thermal system functionality and performance.	While building-integrated TES can benefit from efficient combustion technologies (e.g. IR heating), this pathway focused on equipment-integrated TES. Several solutions at TRL ≥7 for heating or cooling, with more emerging. Range of technologies and materials by ~10 market players, though limited applications are well-defined by RD&D for heating equipment, with market applications limited to specific use cases (e.g., ice storage for chilling).
Innovative Mechanical Solutions: Primary GHG reductions by improvements in equipment or system efficiency	Micro-Combined Heat & Power	30% to 50% in near term**, reduced potential in long term***	With distributed generation, mCHP provides partial or overall heating system resiliency with GHG and cost arbitrage versus electricity grid.	Large diversity of technology size, type, and applications served by ~30 market players, with the majority at or beyond initial system prototyping and on to pre-production demos or commercial availability. Despite favorable economics in range of applications, immature market lacks well-defined value propositions and alignment with applicable incentives/standards.
	Fuel-fired Heat Pumps	40% to 50% demonstrated, with greater potential from emerging technologies	In addition to maximum heating efficiencies with delivered fuels, most FFHPs use low/zero-GWP refrigerants, eliminate indoor combustion and associated issues, and provide superior cold-climate performance relative to alternative heat pump technologies.	Across three primary technology types (e.g., sorption) ~20 market players, a wide range of technologies either developing via U.S./Canadian partnerships or converting to North American market from Asia or UK/EU products. Several products available at light-commercial scale and above, multiple emerging in 2-3 years for residential applications, all buoyed by range of emerging utility and government incentives.
	Hybrid Heat Pumps	Up to 20%**, with increased potential in long term	Inherent heating system flexibility and peak energy demand management, for end user and grid management alike, with opportunity for optimization against multiple metrics (OpEx, GHG, comfort).	The most mature of pathways discussed, with hybrid or "dual fuel" products available across range of product categories, however, value proposition remains a challenge, with system redundancy requiring product optimization and both standards and incentives to better recognize GHG benefits.

	Technology Pathway	Potential GHG Reduction*	Key Benefits	Technical and Market Maturity
Upstream and Downstream Decarbonization: Primary GHG reductions by use of decarbonized fuels or direct mitigation of GHG emissions	Low/Zero-Carbon Fuels	Up to 100% feasible on net emission basis (e.g., biomethane, bioLPG) in near term, up to 100% overall with hydrogen in long term****	Full decarbonization of heating feasible on net emission basis with existing equipment and infrastructure ("drop-in" hydrocarbons) and technically feasible to do same on absolute basis with modified or replaced equipment and infrastructure; key overall pathway for large thermal demands (e.g., "difficult to electrify").	On supply-side, emerging low-carbon/zero-carbon fuels are in scale-up phase in North America, with "drop-in" fuels available today (blended or 100%) and demonstrations of emerging fuels (e.g., hydrogen) underway in range of utility trials. On demand-side, limited research continues on equipment impacts of "drop-in" fuels and significant RD&D needed to understand impacts of and technologies to support consuming emerging fuels (e.g., hydrogen).
	Carbon Capture	Appx. 20% in near term, with increased potential in long term	As add-on to combustion equipment, benefits for retrofit potential are strong, and ability to scale-up to large equipment is favorable. While associated handling and disposition of captured carbon present new logistical challenges, potential for additional revenues via credits/incentives and carbon utilization markets is improving.	Technical and market maturity for utility customer carbon capture is developing; where several technologies undergo experimental or field-based demonstrations, technology development and value proposition definition for carbon capture is in process. Both regulatory drivers (e.g., carbon pricing) and markets for carbon utilization are evolving rapidly.
	Mitigating Methane Emissions	High uncertainty with GHG reduction potential across heating equipment*****	With increased emphasis on methane emissions in GHG inventories and reductions by energy industry, it is imperative to better quantify and mitigate equipment emissions.	Not a technology per se, research is maturing to better define emissions across equipment categories, improved methods of experimental/field-based assessments, and emerging efforts on mitigation.

*Approximately compared to standard combustion baseline // **Depending on GHG intensity of electricity grid // ***Near-term savings derive from GHG arbitrage against fossil grid generation; long-term savings diminish as electricity grid reduces GHG intensity // **** 100% hydrogen heating proven feasible through demonstration, but it is not available at large scale in the near term // ***** Studies show order of magnitude range of estimated methane emissions

Table 3: Summary of Recommendations

Technology Pathway		Role of Utility	Role of Manufacturer
Advanced Conservation Measure: Primary GHG reductions by load reduction or optimization relative to delivered energies	Thermal Energy Storage	Support definition of use cases through RD&D and value proposition through innovative rate structures and peak demand management schemes, support emerging industry standard development.	Support technology development and integration with heating equipment, understand and characterize system resiliency value proposition for customers; where applicable, support development of emerging industry standards.
Innovative Mechanical Solutions: Primary GHG reductions by improvements in equipment or system efficiency	Micro-Combined Heat & Power		
	Fuel-fired Heat Pumps	Continue and accelerate market transformation initiatives, including development and implementation of FFHP-focused programs, support RD&D where needed, and expand to include workforce training.	Support technology and product development for range of heating equipment applications; where applicable, support updating of industry standards and guidance concerning system specification, installation, and operation.
	Hybrid Heat Pumps	Support development of new or updated industry standards to recognize efficiency and GHG benefits, develop and implement programs to incentivize for the same, with grid-connected features where beneficial.	Support development of new or updated industry standards to recognize efficiency and GHG benefits, optimize existing or develop new products to enhance efficiency, emission, and flexibility benefits.
Upstream and Downstream Decarbonization: Primary GHG reductions by use of decarbonized fuels or direct mitigation of GHG emissions	Low/Zero-Carbon Fuels	Driving the supply-side decarbonization, it is imperative for utility-coordinated efforts during scale-up to develop or update pertinent standards, lead harmonization of system gas quality where needed, perform necessary system-wide RD&D (e.g., gas variability studies), and aid in defining and improving value proposition.	Support RD&D concerning impacts on existing or current equipment designs, product development for range of fuel tolerance (e.g., blended vs. hydrogen-fired), and support or lead definition of updated product certification/labeling schemes (e.g., "H2 ready").
	Carbon Capture	Lead RD&D efforts to better define technology and use cases, support coordination with regulatory and industry stakeholders on recognition of decarbonization benefits and integration with prospective carbon utilization markets.	Support RD&D efforts to better define and resolve technology, installation, and operational barriers, while supporting refinement of value proposition with stakeholders, inclusive of both sequestration and utilization, and support development of industry standards.
	Mitigating Methane Emissions	Support RD&D to quantify equipment methane emissions, develop sampling/testing protocols, and develop mitigation strategies for heating equipment.	Support RD&D to define equipment methane emissions, sampling/testing protocols, and product modifications/designs to reduce emissions.

References for Introductory Section

- American Gas Association (AGA), 2022. Net-Zero Emissions Opportunities for Gas Utilities, Report prepared for the AGA by ICF, link: https://www.aga.org/globalassets/research--insights/reports/aga-net-zero-emissions-opportunities-for-gas-utilities.pdf
- Canadian Gas Association (CGA). Available online: https://www.cga.ca/natural-gas-statistics/
- e21 Initiative, 2021. Decarbonizing Minnesota's Natural Gas End Uses. Report prepared jointly by Great Plains Institute and Center for Energy and Environment, link: https://e21initiative.org/wp-content/uploads/2021/07/Decarbonizing-NG-End-Uses-Stakeholder-Process-Summary.pdf
- Energy Information Administration (EIA), United States Department of Energy, 2022.
- Ianchenko, A., Simonen, K., Barnes, C. 2020. Residential Building Lifespan and Community Turnover, Journal of Architectural Engineering, Vol 26, Issue 3.
- Lawrence Livermore National Laboratory (LLNL). Carbon Flow Charts. Available online: https://flowcharts.llnl.gov/commodities/carbon
- Liss, W. 2022. Long-Duration Utility-Scale Energy Storage, Report Prepared by GTI Energy, link: https://www.gti.energy/wp-content/uploads/2022/02/GTI-Energy-Storage-White-Paper-Ver5-02-2022-FNL.pdf
- Low-Carbon Resources Initiative, 2022. Net-Zero 2050: U.S. Economy-Wide Deep Decarbonization Scenario Analysis, link: https://lcri-netzero.epri.com/
- National Grid, 2022. Our Clean Energy Vision – A Fossil-Free Future for Cleanly Heating Homes and Businesses, link: https://www.nationalgrid.com/document/146251/download
- Northwest Natural, 2021. Vision 2050: Destination Zero, link: https://www.nwnatural.com/about-us/the-company/destination-zero
- U.S. Energy Information Administration (EIA). Available online: https://www.eia.gov/energyexplained/natural-gas/natural-gas-pipelines.php

2. Thermal Energy Storage

Summary of Technology Pathway

Thermal Energy Storage (TES) is playing a vital role in various applications and market sectors. Material properties can be exploited for TES through physical mechanisms (sensible heat or latent heat) or chemical reactions (i.e., thermochemical energy storage, or "TCES"). Physical mechanisms are further classified into sensible energy storage systems and latent heat systems as shown in Figure 3. Thermal energy storage achieved by modulating the system temperature is termed as sensible heat storage. Therefore, the effectiveness of sensible heat storage platforms depends on the specific heat capacity of the energy storage material. Sensible storage systems typically use rocks, ground (i.e., soil), or molten salt as the storage medium.

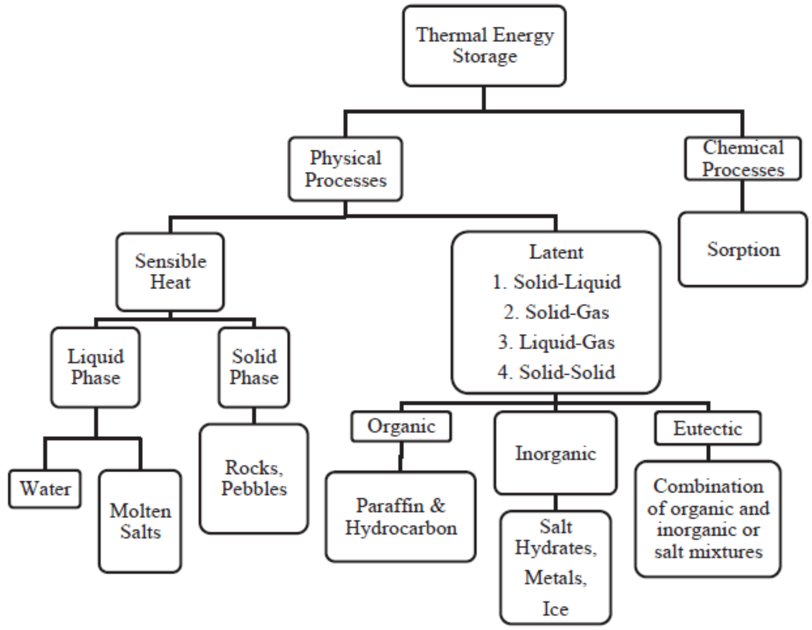


Figure 3: Classification of TES Materials

The energy storage in latent heat thermal energy storage system (LHTESS) is achieved by realizing phase transformation from solid to liquid or liquid to vapor, which typically occurs at quasi-isothermal conditions. The latent storage medium can also be classified as phase change materials (PCMs), where the major proportion of the total stored thermal energy is in the form of latent heat. In addition, PCMs can be classified as organic and inorganic. Often, inorganic PCMs are realized in the form of eutectic mixtures that enable quasi-isothermal operation. The different types of PCMs that are available commercially can be primarily classified as organic, inorganic, and eutectic [Abhat 1983; Dinçer and Rosen 2010; Kumar and Banerjee 2018].

Covalent bonding is typically encountered in organic PCMs. Organic PCMs are sourced from agricultural/food processing and hydrocarbon processing industries (e.g., oil, wax, fatty acids, etc.). Therefore, these materials are inexpensive, provide ease of implementation in thermal applications, usually have low environmental footprint in the applications, and are available abundantly from natural sources (e.g., from oil and gas explorations worldwide as well as beeswax harvesting, alcohol derivatives, and fatty acids). Hence historically speaking, they are one of the most widely used among commercially available PCMs. The chemical composition of organic PCMs includes paraffin [C_nH_{2n+2}] and fatty acids [$CH_3(CH_2)_{2n}(COOH)$], where n is an integer. The most commonly used paraffin-based PCMs are typically straight chain n-alkanes. The melting temperature range and the latent heat capacity of this material class depend on the length of the polymer chain. Non-paraffin PCMs consist of esters, fatty acids, alcohols, and glycols. Non-paraffin based PCMs are typically classified based on their latent heat and melting temperature.

Ionic bonding is typically encountered in the chemical composition analyses of inorganic PCMs. Typical examples of inorganic PCMs include various types of metals, salts, and salt hydrates. Typically, alkali metal salts are used as commercial inorganic PCMs. The anions in these salts and salt hydrates consist of oxides, hydroxides, chlorides, chlorates, citrates, carbonates, sulfates, and nitrates. Inorganic PCMs confer applicability over a wider range of temperatures and higher values of volumetric energy storage capacities, as well as higher values of thermal conductivity, compared to that of the organic PCMs. This accrues primarily from the higher density values of inorganic PCMs (compared to that of organic PCMs). Typically, in salt hydrates, the solid-liquid phase transformation (i.e., melting and solidification) occurs reversibly by the dehydration and hydration process, respectively. The melting point of various salt hydrates varies from 5 to 130 °C. Above an operating point of 150 °C, different types of anhydrous salts can be used as PCMs (rather than the salt hydrates). Other categories of inorganic PCMs include metals and metal eutectics that have low melting points. Eutectic PCMs are composed of two or more constituent materials in a specific ratio that confer the unique property of melting and freezing congruently thus providing the appearance of a single melting point (or solidification point).

Chemical heat storage is based on reversible chemical reactions with high reaction enthalpy with negligible heat loss. Charging/discharging could be varied by controlling the reactant concentrations. These reactions can be either chemical or physical. The main limits are related to the very slow reaction kinetics, due to the high energy associated with the process, as well as heat and mass transfer diffusion resistance within the material. Physical reactions are typical sorption reaction, where a refrigerant (e.g., ammonia, water) reacts with a sorbent, which can be either a liquid (e.g., water; ionic liquid; etc.) or solid (e.g., calcium oxide, magnesium nitrate; etc.). Physical reactions are generally needing lower charging temperature (i.e., 70-150°C) and is characterized by lower reaction enthalpies compared to the chemical reactions. Chemical reactions are typically a process that involves rearrangement of the molecular or ionic structure to form new compound. An example of a reversible chemical reaction is a hydration reaction of magnesium oxide and water at an operating temperature of 250°C.

Recent energy consumption survey data show that energy consumption by building sectors consisting of residential and commercial buildings is increasing considerably (Berry 2018). The majority of the energy consumption in buildings provides thermal comfort, such as HVAC systems. Therefore, the role of TES is to resolve the time-scale mismatch between supply and demand, efficiency, sizing, and utilization of renewable energy to develop high-efficient and low-carbon energy systems in the building environment. Figure 4 illustrates possible TES technologies that can be integrated with various applications in building, industry, solar, and power generation. Latent and thermochemical (sorption and reaction) technologies could aid in decarbonizing combustion-based building equipment.

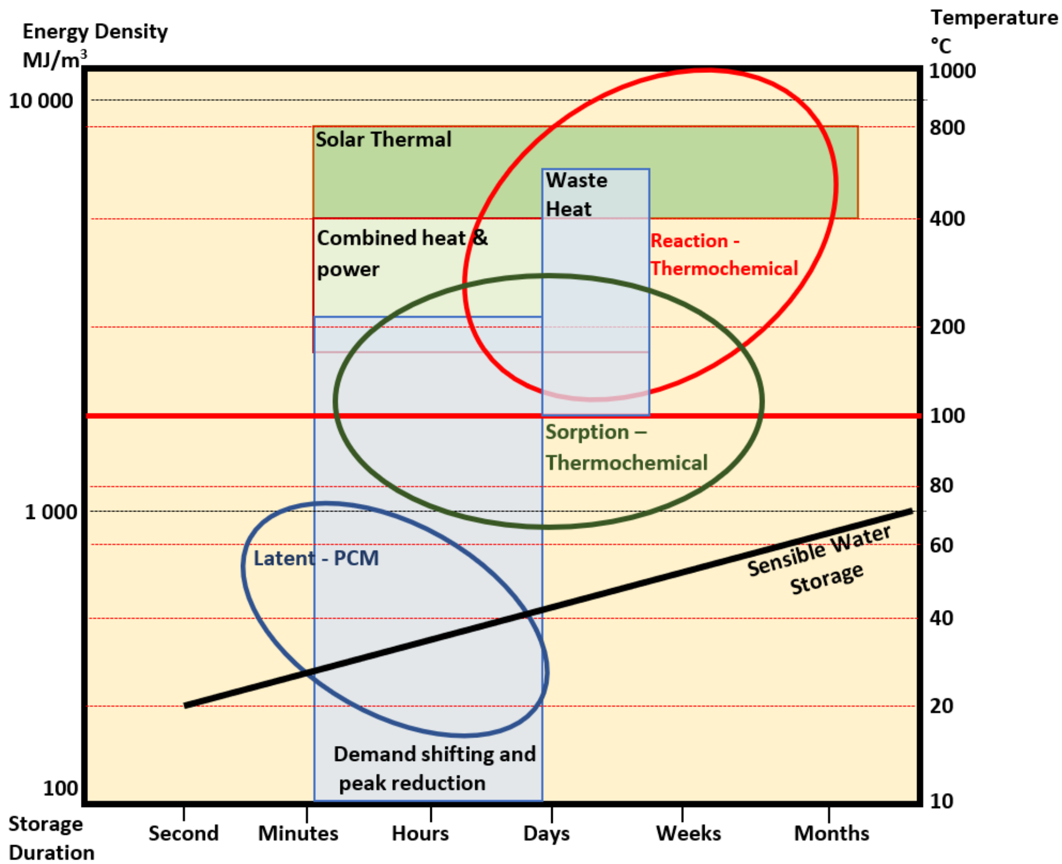


Figure 4: Summary of Thermal Storage Technology Based on Storage Duration, Density, Temperature, and Application

As sensible storage is widely well-known and characterized, this technology survey will focus on TES technologies beyond sensible storage. Recent studies have shown that latent storage (i.e., phase change materials, or PCMs) are price comparable to sensible water-based storage coupled with an indirect storage tank [Hirschey, 2021]. Table 4 lists the various applications of thermal energy storage technology and their technology readiness level (TRL) for the decarbonization of buildings for cooling, heating, and combined power heat and power generation. As summarized in the table below, most of the TES manufacturers, developers, and start-ups (MFR) focus on decarbonizing buildings through electrification. Multiple studies have shown that TES is a potential low-cost technology to help electrify the heating and cooling loads in building sectors [Odukomaiya, 2021; Rahimpour, 2017; and Arteconi, 2019]. As highlighted, integration of PCM in envelopes and thermochemical (TC) storage in mCHP are the only state-of-art technologies currently available or being researched that *could be* integrated with combustion-based building equipment. However, there are no market products that fall into these categories.

Table 4: Summarizing State-of-the-Art TES Technologies in Building Applications

Process	Storage	App	Building	Site Energy	Req. Equip	TRL	MFR
Cooling	Ice	• Peak Shift • Efficiency	Comm.	Elec	Chillers	8	MFR A-D
	Latent		Res./ Light Comm.		HP RTU	5	MFR E
	Latent	• Peak Shift • Efficiency • Sizing	Res.		HP	5	MFR F
Heating	Latent	• Peak Shift • Efficiency	Res. Light Comm.	Elec / Gas	Envelope	7	MFR G
	Latent	• Peak Shift • Efficiency • Sizing	Res. Light Comm.	Elec	HP	8	MFR H
	Latent	• Supp. heat • Sizing	Res.	Elec	None	6	MFR I
	Latent	• Peak Shift • Efficiency	Res. Comm.	Elec	None	6	MFR J
	TC	• LDS • Peak Storage	Res. Comm.	Solar Thermal	DHW	<4	Acad.
CHP	Latent / TC	• LDS • Load Balance	Comm.	Gas	mCHP	<2	Acad.

Demand response and peak load shifting needs are familiar features in the electricity market. Therefore, most of the research and development for TES is focused on technologies to aid the shifting of peak loads in buildings as low-cost alternatives to electric batteries. Demand response and peak load shifting are far less common in the natural gas pipeline and delivery market; hence, researchers and industries have not considered TES in combustion-based building equipment. The inset figure summarizes the current utilization of TES for heat applications as per International Renewable Energy Agency [IRENA, 2020].

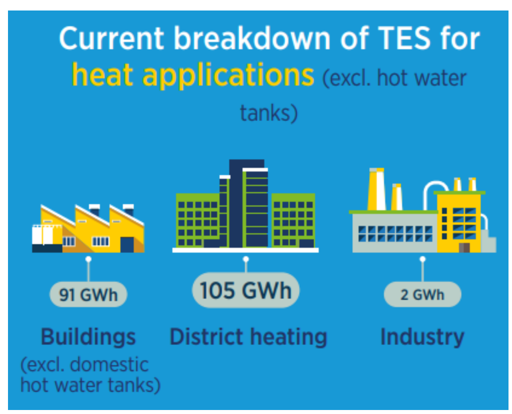


Figure 5: Illustration of TES in Heating Sector [IRENA, 2020]

The potential benefits of integrating TES into combustion-based equipment are (1) sizing and (2) efficiency when coupled with a FFHP or mCHP system. As a means of efficiently storing and distributing energy from space and water heating equipment, while integrating with existing sensible energy storage (e.g., hot water), TES technologies are commonly charged/discharged with liquid media (e.g. water loops) and hence are most suitable for hydronic-based systems, including boilers, water-delivery heat pumps, and via integration, water heating. TES integration with forced-air distribution and air-delivery heating equipment is feasible, but less common in this assessment for the equipment types considered (e.g., furnaces) and are not widely applicable to infrared heaters.

As noted previously, TES solutions are a form of *Advanced Conservation Measures*, which serve to better match or otherwise modulate the supply of thermal energy to the demand. In broad terms, the benefits TES offers can fall into one or more of the following categories:

- Grid Balancing/Services: For customer-side (or "behind" the meter) energy storage, TES systems can de-couple the timing of consuming delivered energy from serving thermal loads. With heating equipment, for example, the customer can prioritize purchasing low-carbon energy or optimize for energy time-of-use, which can result in favorable rates and avoided demand charges.[7] For a utility that has incentivized customer participation in demand response/grid-connected programs, TES can provide load smoothing, shifting, or otherwise avoiding energy grid capacity constraints or relying on higher-emitting variable generation.
- System Design - Coupling Low-Carbon Energy with Demand: Where renewable energy and/or waste heat is available, it is often challenging to couple these variable and intermittent supplies with thermal demands met by space and water heating equipment. TES can, again, de-couple supply from demand and act as a buffer, often with reduced losses versus conventional means (e.g., hot water). As shown in the example in Figure 6, TES can be readily integrated with existing heating equipment in a hydronic heating system arrangement to maximize low-carbon energy use while satisfying thermal demands with a "thermal battery". As a system, TES provides a basis to serve one or more loads with multiple and variable inputs, such as heat supplied by a mCHP system.

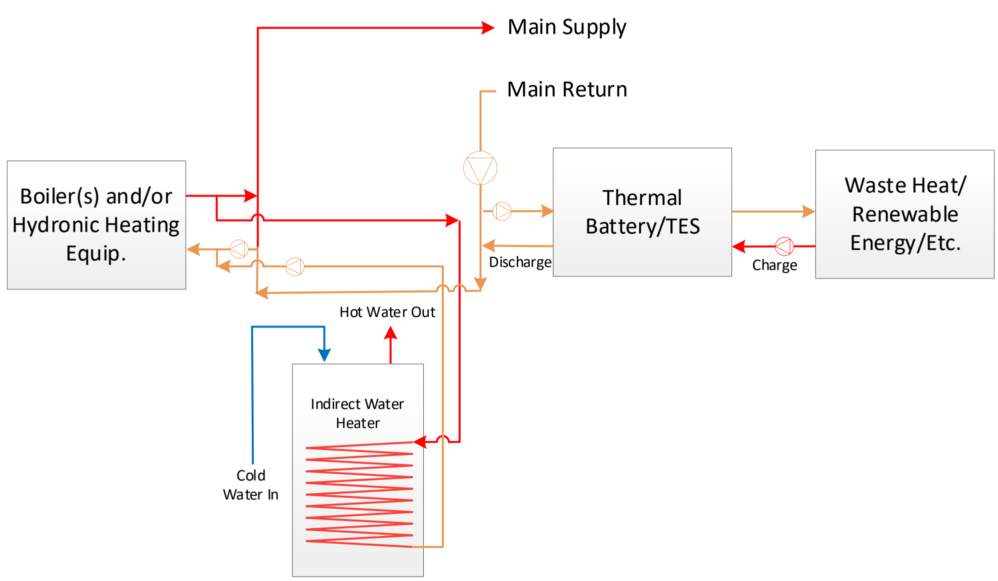


Figure 6: Conceptual Representation of TES Integrated with Hydronic Heating System

7 Certainly time-of-use rates and demand charges are common for electricity grids today, wherein hybrid-type heating equipment or systems can participate.

- System Design - De-coupling Intermittent Demands from Heating Inputs: TES can similarly de-couple differing and intermittent demands from a single heating input. A simple example is a combined space and water heating system, wherein a hybrid or FFHP will favor fewer, longer duration cycles to serve intermittent and "peaky" hot water demands and more constant but less "peaky" space heating loads. TES can de-couple these aggregate demands to assure optimal cycling operation of the heat pump system.

For the examples above, TES does not provide energy conservation in the traditional sense, by reducing thermal demands in total. Rather it mitigates or modulates thermal demands to drive overall GHG emission reductions through optimal mechanical equipment performance, prioritization of low carbon energies, and providing energy grid balancing/services on the customer-side. Individually or collectively, it is challenging to estimate the GHG emission reduction potential from these types of TES applications. Although this technology pathway for heating is accelerating, it is still limited. Nonetheless, 14% to 30% reductions have been noted in some cases [Xu, 2021 and GTI Energy estimates].

Overview of Technology, R&D, and Industry Status

As scoped in this study, this section looks at TES from an equipment integration point of view and does not cover the technology solutions or research associated with integrating TES with building envelopes. This area of TES research and development is robust, which interested readers are encouraged to refer to overall reviews [Mumme, 2020; Odukomaiya, 2021; Rathore, 2022] and descriptions of emerging technologies and approaches [Paranjothi, 2021; Kishore, 2020]. This is not to say that building-integrated TES cannot benefit from efficient combustion-based technologies, such as the potential energy efficiency benefits of efficient infrared heating with high thermal mass structures versus alternatives with high outdoor air exchange, which can have an estimated 30% energy savings relative to conventional warm-air heat distribution systems per consultation with an infrared heating industry expert[8]. As noted previously, there is rather limited technology development in applying TES directly with combustion-based building equipment. Thus, the following discussion focuses on *prospective* areas of development that are at an early stage, as an augmentation of either FFHPs or mCHP, which will be considered separately in later sections (as *Innovative Mechanical Solutions*). Certainly, there are system-level approaches to TES where energy storage can benefit system performance or enable integration with certain loads (e.g., potable hot water), such as indirect storage tanks can do now, however, this extends into application engineering which is beyond the scope of this study.

Integration of TES with Fuel-Fired Heat Pumps

FFHPs are an emerging class of efficient heating equipment. They are commonly Air-Water Heat Pumps that operate at an efficiency higher than 100% by upgrading the ambient heat via a refrigeration cycle. Unlike the most common direct-expansion type air-source heat pumps, FFHPs can offer the advantage of coupling space and domestic hot water (DHW) with a single system. This approach of combined space and water heating, or combi system, helps offset the equipment and installation costs by offering a shared operation at greater delivered efficiency

8 Personal communication, George File, R&D Manager, SRP Group (2023).

than gas-fired water heaters, burners, and boilers. Here, the application of TES as directly integrated with FFHPs is explored.

Over the years, the operation and installation of combi systems has been well understood, but some significant drawbacks have impacted the performance of FFHPs, which include:

Challenges:

1) FFHPs generally have increased thermal mass that requires bringing the system components up to the operating temperature, this can take a few minutes Therefore, the performance degrades with short cycling or without heat recovery. This is further amplified with large loop volumes. These losses are estimated to be ~25% [LaFleur, 2022]. This short-cycling effect is magnified during DHW recovery because FFHPs are oversized for DHW operation. A study has shown that a larger tank with a high heat transfer area doubles the performance [LaFleur, 2022].
2) Studies have shown that FFHP performance can be improved with a lower return water temperature (RWT). Therefore, maintaining a lower RWT (~95˚F) increases the performance by 10-30% [Garrabrant, 2016]. In actual application, maintaining a low RWT with DHW and possibly forced-air systems is challenging.
3) Most FFHPs have integrated outdoor temperature reset curves. This strategy mainly focuses on adjusting the target supply temperature to maintain occupant thermal comfort. Therefore, the system is designed to operate at 100% capacity during cold conditions with lower performance. With limited thermal energy storage, the system cannot take advantage of the daily diurnal temperature with its outdoor temperature reset curve.
4) Most FFHPs are sized based on standard approaches for peak load requirements. Therefore, FFHPs are oversized for most heating-degree days, possibly operating at short cycles.
5) Most FFHPs prioritize DHW because DHW load will likely be satisfied more quickly. But with the current installation, the fuel-fired absorption heat pump (GAHP) cannot simultaneously provide space heating and DHW.

A solution under development to address the drawbacks mentioned above is the integration of FFHPs with stratified latent TES, as illustrated in Figure 7, with the FFHP as a GAHP, whether for residential or non-residential applications. In this concept, the FFHP is integrated with a stratified TES storage by replacing the indirect storage tank commonly found in the combi system.

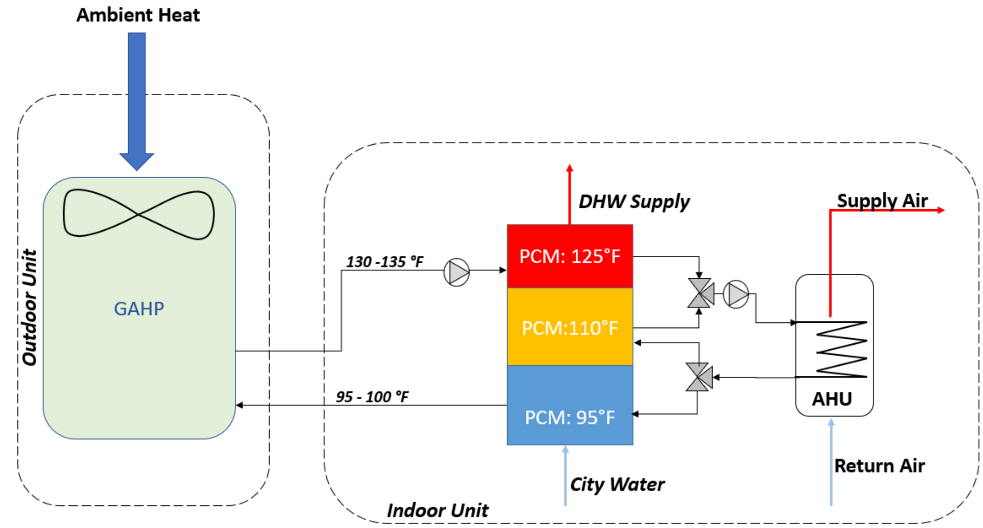


Figure 7: Potential Integration of Latent TES with GAHPs

For this system concept, the benefits of stratified latent TES storage, which could also translate to similar benefits for other hydronic-type systems (e.g., boiler-based), are as follows:

- As per MFR H, the latent TES shortage can store 3 times more energy with the same footprint as an indirect storage tank. With less than a 20% increment in cost compared to an 80-gallon indirect storage tank.
- Reduced standby tank heat losses. MFR H has reported a 50% reduction in annual standby losses compared to a 55-gallon storage tank.
- Unlike stratified water storage, stratified latent TES is not impacted by the flow rate on the charge and discharge side due to its physical stratification.
- Unlike sensible storage, latent TES storage works at a nearly isothermal conditions, and storage capacity is not a function of tank temperature.

However, there are some possible additional benefits of integration with FFHPs specifically, which include the following (also potentially applicable to other hydronic-type systems):

- Reduce FFHPs' short cycle needs with increased storage capacity with a similar footprint, as the FFHP only needs to charge the latent TES storage when the minimum required energy is depreciated.
- Reduce standby tank heat losses, avoiding an oversized tank for combi operation common for water-based systems.
- Maintain a constant favorable RWT with physical stratification.
- Take advantage of the daily diurnal temperature by charging the storage at favorable ambient conditions and/or when delivered energy has a lower cost or lower GHG-intensity.
- Operate the FFHPs at a favorable modulation rate while providing the required thermal comfort.
- Size the FFHP for lower peak load operation with the added TES thermal capacitance.

- Retain the ability to provide simultaneous space heating and DHW.

Integration of Latent TES with Micro-Combined Heat and Power

Technically, mCHP units such as micro gas turbines, gas engines, and solid oxide fuel cells (SOFC) are quite well developed, as discussed in detail in a later section. However, the operation of mCHP systems is inherently challenging due to the simultaneous generation of heat and power while meeting uneven electric and heating loads. Conventional control strategies for mCHP attempt to meet either the heat or electricity load, but not both. Heat-led control is the most commonly utilized control strategy, known as thermostat control [Hawkes, 2007]. A study has shown that heat-load control may cause an influx of electricity. When supplied to the grid, this can skew supply and demand and harm utilities [Peacock, 2007]. Alternatively, mCHP systems can be operated with electricity-led control, but in this method, any available waste is rejected. Utilizing a mCHP in this manner can lower overall system efficiency [Shaneb, 2010]. Thus, neither strategy can leverage mCHP's full potential. Recent studies have shown that operating mCHP systems integrated with TES with electricity-led controls is cheaper than heat-led controls with battery storage [Bird, 2020; Barbieri, 2012; Nuytten, 2013]. Most of these studies focused on modeling and experimental work with hot water sensible storage tanks [Bianchi, 2013]. There are already multiple manufacturers in this field. There are only a few studies on integrating latent or thermochemical storage with mCHP [Nuytten, 2013 and Wen, 2023]. These studies mainly focus on modeling and academic laboratory work for material and system-level development. Table 5 summarizes the outcomes of current work on integrating thermochemical storage with mCHP.

Technology Pathway Outlook

For combined space and water heating systems, as summarized, integration of a latent TES system with FFHP could be a potential pathway for increasing the market adoption of combustion-based equipment for space and water heating, or of hydronic applications. This is applicable for water heaters, boilers, and furnaces alike, and for residential and non-residential buildings. This integration could provide energy savings and GHG reduction of 15% - 30% [GTI Energy estimates]. As highlighted in Table 5, latent TES systems are well-known and widely available in the market. Lack of knowledge and awareness of latent TES systems and their benefit among combustion-based appliance manufacturers and gas utilities is the most significant barrier to the wider adoption of this technology. Future supports are needed to evaluate and bring this potential technology application to the market and prove out its benefits in controlled and uncontrolled conditions.

For mCHP applications, as summarized by several studies, integrating mCHP with latent or thermochemical energy storage would enhance the system's overall performance. The majority of these studies are focused on modeling and laboratory-scale development. Future support is needed to bring this technology to market through large-scale evaluations.

For both latent and thermochemical energy storage, the use cases are not widely proven in experimental or field studies and require further research for optimization and the development of best practices for integration with space and water heating equipment.

Table 5: Recent Studies on Integrating TES with mCHP

Storage	Research Focus	Outcome	Organization
Latent Storage [Nuytten, 2013]	Modeling/Experimental	Improved the storage capacity by 30% and extended the storage duration by 48 hours compared to sensible storage.	EnergyVille, Belgium
Thermochemical Storage [Fopah-Lele, 2015]	Material and lab Scale thermochemical reactor design for mCHP	Developed a new $SrBr_2$ hydration material with a regeneration temperature of 105˚C and increased cyclic stability with a storage efficiency of 77% with 65kWh of storage capacity.	Leuphana University of Lüneburg, Germany
Latent Storage [Baniasadi, 2017]	Modeling work of coupling latent storage with SOFC	The modeling work showed that latent storage was not suitable for SOFC from exergy and exergoeconomic points of view. Therefore, the design of latent storage tank shall be optimized to obtain lower exergy destruction cost rate.	University of Isfahan, Iran
Short- and Long-Term Storage	Experimental and field work on micro-CHP integrated with heat pump and with a short or long-term shortage	Ongoing work	University of Twente, Netherlands
Long-term geothermal energy storage	Integrating geothermal energy storage to manage load imbalance and coupled with a heat pump for district energy	Ongoing work	GSS integrated energy

References for TES Section

- Abhat, A. 1983. "Low Temperature Latent Heat Thermal Energy Storage: Heat Storage Materials." Solar Energy 30(4): 313–32.
- A.D. Hawkes & M.A. Leach. Cost-effective operating strategy for residential micro-combined heat and power. Energy 32, (2007).
- A.D. Peacock & M. Newborough. Controlling micro-CHP systems to modulate electrical load profiles. Energy 32, 1093–1103 (2007).
- Arteconi, A., Mugnini, A. & Polonara, F. Energy flexible buildings: A methodology for rating the flexibility performance of buildings with electric heating and cooling systems. Appl. Energy 251, 113387 (2019).
- Baniasadi, E., Toghyani, S. & Afshari, E. Exergetic and exergoeconomic evaluation of a trigeneration system based on natural gas-PEM fuel cell. Int. J. Hydrogen Energy 42, 5327–5339 (2017).
- Barbieri, E. S., Melino, F. & Morini, M. Influence of the thermal energy storage on the profitability of micro-CHP systems for residential building applications. Appl. Energy 97, 714–722 (2012).
- Berry, Chip. 2018. Space Heating and Water Heating Account for Nearly Two Thirds of U.S. Home Energy Use. https://www.eia.gov/todayinenergy/detail.php?id=37433.
- Bianchi, M., De Pascale, A. & Melino, F. Performance analysis of an integrated CHP system with thermal and Electric Energy Storage for residential application. Appl. Energy 112, 928–938 (2013).
- Bird, T. J. & Jain, N. Dynamic modeling and validation of a micro-combined heat and power system with integrated thermal energy storage. Appl. Energy 271, 114955 (2020).
- Dinçer, İbrahim, and Marc A. Rosen. 2010. Thermal Energy Storage. Chichester, UK: John Wiley & Sons, Ltd. http://doi.wiley.com/10.1002/9780470970751.
- Fopah-Lele, A. A Thermochemical Heat Storage System for Households: Thermal Transfers Coupled to Chemical Reaction Investigations. (Leuphana University of Lüneburg, 2015).
- Garrabrant, M., Stout, R., Keinath, C. & Glanville, P. Experimental Evaluation of Low-Cost Gas Heat Pump Prototypes for Building Space Heating. in International Refrigeration and Air Conditioning Conference at Purdue (2016).
- Kumar, Navin, and Debjyoti Banerjee. 2018. "Phase Change Materials." In Handbook of Thermal Science and Engineering, Cham: Springer International Publishing, 2213–75. http://link.springer.com/10.1007/978-3-319-26695-4_53 (July 10, 2019).
- Hirschey, J. R. et al. Review of Low-Cost Organic and Inorganic Phase Change Materials with Phase Change Temperature between 0°C and 65°C. in International High Performance Buildings Conference 10 (2021).
- IRENA. Innovation Outlook Thermal Energy Storage. (2020).

- Kishore, R.A., Bianchi, M., Booten, C., Vidal, J., Jackson, R. Optimizing PCM-integrated walls for potential energy savings in U.S. Buildings, Energy and Buildings, Vol. 226, 110355 (2020).
- LaFleur, J. & Glanville, P. Best Practices from the Field: Air-to-Water Heat Pump Combi Systems. in 2022 ACEEE Summer Study on Energy Efficiency in Buildings (2022).
- Mumme, Sven, James, Nelson, Salonvaara, Mikael, Shrestha, Som, and Hun, Diana E. Smart and Efficient Building Envelopes: Thermal Switches and Thermal Storage for Energy Savings and Load Flexibility. United States: N. p., 2020. Web.
- Nuytten, T. et al. Comparative analysis of latent thermal energy storage tanks for micro-CHP systems. Appl. Therm. Eng. 59, 542–549 (2013).
- Odukomaiya, A. et al. Addressing energy storage needs at lower cost via on-site thermal energy storage in buildings. Energy Environ. Sci. 14, 5315–5329 (2021).
- Paranjothi, G., Odukomaiya, A., Cui, S., Bulk, A., Evaluation of phase change plaster/paste composites for building envelopes. Energy and Buildings, Vol. 253, 111372 (2021).
- Rahimpour, Z., Faccani, A., Azuatalam, D., Chapman, A. & Verbič, G. Using Thermal Inertia of Buildings with Phase Change Material for Demand Response. Energy Procedia 121, 102–109 (2017).
- Rathore, P., Gupta, N., Yadav, D., Shukla, S., Kaul, S. Thermal performance of the building envelope integrated with phase change material for thermal energy storage: an updated review, Sustainable Cities and Society, Vol. 79, 103690 (2022).
- Shaneb, O. A. & Taylor, P. C. Evaluation of alternative operating strategies for residential micro combined heat and power. in 2010 IEEE International Energy Conference 143–148 (IEEE, 2010). doi:10.1109/ENERGYCON.2010.5771664.
- Wen, X., Ji, J. & Li, Z. Evaluation of the phase change material in regulating all-day electrical performance in the PV-MCHP-TE system in winter. Energy 263, 125919 (2023).
- Xu, T., Humire, E.N., Chiu, J. N., Sawalha, S., Latent heat storage integration into heat pump based heating systems for energy-efficient load shifting. Energy Conversion and Management, Vol. 236, 114042 (2021).

3. Micro-Combined Heat and Power

Summary of Technology Pathway

mCHP is a distributed energy resource (DER) that consumes fuels such as natural gas, propane, and hydrogen. As mCHP systems convert fuel to electricity, waste heat is recovered for water heating, space heating, or other process heating applications. Such mCHP systems can be defined as generating 50 kWe or less of power, which accords with the ASHRAE Method of Test for Rating Micro Combined Heat and Power Devices [ANSI/ASHRAE, 2020].

There are many mCHP technologies using various types of prime movers including internal combustion engines, microturbines, and mini-turbines, Stirling engines, fuel cells, steam and organic Rankine cycles, and other novel technologies. Depending on their electricity and thermal production attributes, mCHP systems can be electrically- or thermally-led, meaning the system tracks the electric or thermal loads of the application and its runtime or capacity cycles, or modulates to meet the loads. Electrically-led mCHP systems often have higher power-to-thermal output ratios than thermally-led mCHP systems. Typical applications for mCHP include residential and light commercial/industrial facilities where hot water and/or space heating loads are substantial. Those loads are often served by a hot water tank used to store thermal energy recovered from the mCHP system. Hydronic space heating can be achieved using radiators for radiant heating or hydronic air handlers for forced-air heating.

Some utilities require interconnection agreements between the electric utility and the mCHP operator to assure safe connection with the power system and define requirements and/or limitations for exporting power. Some utilities also have provisions for net-metering, which allow the mCHP operator to obtain credit for any power that is exported to the utility's electric grid. Credit for exported power can be as simple as having the electric meter running in reverse, resulting in lower electricity bills, or can involve a Power Purchase Agreement (PPA) with the utility that stipulates the terms of exported power. Generally, net-metering and PPAs provide for more favorable economics to the mCHP operator. However, interconnection agreements can sometimes be expensive and time-consuming to secure.

Energy resilience is a primary factor in market adoption of DERs, including mCHP. Driven by ambitious goals to decarbonize central power generation in the U.S., electrification— switching end-use equipment from non-electric to electric sources of energy—is an emerging trend. Such societal shifts toward decarbonization coupled with technological advancements and rapid R&D investments have contributed to an expanding electric Air-Source Heat Pump (ASHP) market, which will likely result in dramatic increases in building electric loads. These loads, combined with the effects of nascent electric vehicle markets, may strain power grids.

Figure 8, taken from the U.S. National Renewable Energy Laboratory's 2021 Electrification Futures Study (EFS) report [Murphy, 2021], shows an extraordinary need for new installed power capacity in the U.S., given medium and high electrification load growth scenarios. The report predicts that new power capacity will more than double by 2050, primarily through the addition of intermittent photovoltaic (PV) and wind energy resources with very little storage capacity. If such PV and wind capacity cannot be deployed in that timeframe, or the intermittent nature of it creates capacity challenges, deployment of fuel-fired DER such as combined heat and power

(CHP) will likely be needed. Such fuel-fired DERs can also add resilience to the energy sectors, and thus to built environments.

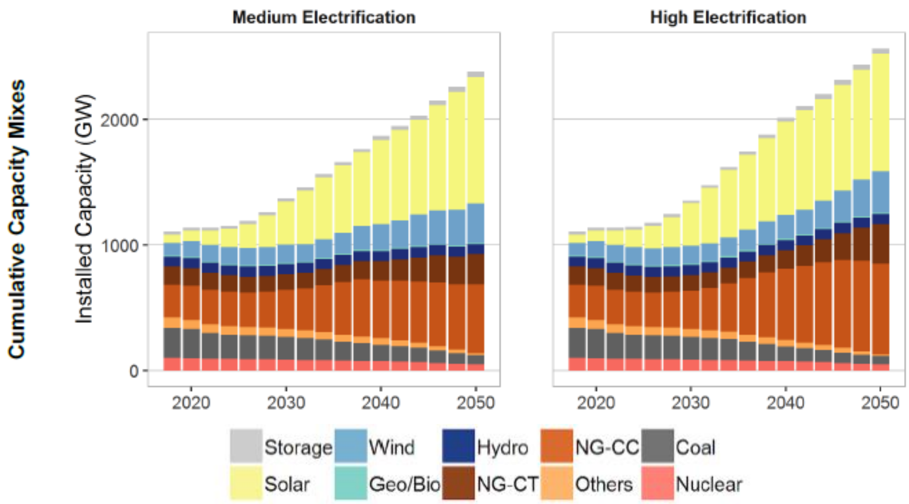


Figure 8: Power Capacity Predictions [Source: NREL]

As shown in Figure 9 [Smith, 2021], extreme weather-related events and other natural disasters in the U.S., compounded by an aging grid infrastructure, have caused a significant rise in major grid disturbances over the past 20 years. This has contributed to dramatic growth in the gaseous standby generator market, where the capacity of 5-20 kWe systems has more than quadrupled since 2000 [Nester, 2022]. Demand for energy resilience is growing in the residential and commercial sectors. Depending on black-start capabilities, some mCHP systems can provide a level of energy resilience while also reducing operating costs.

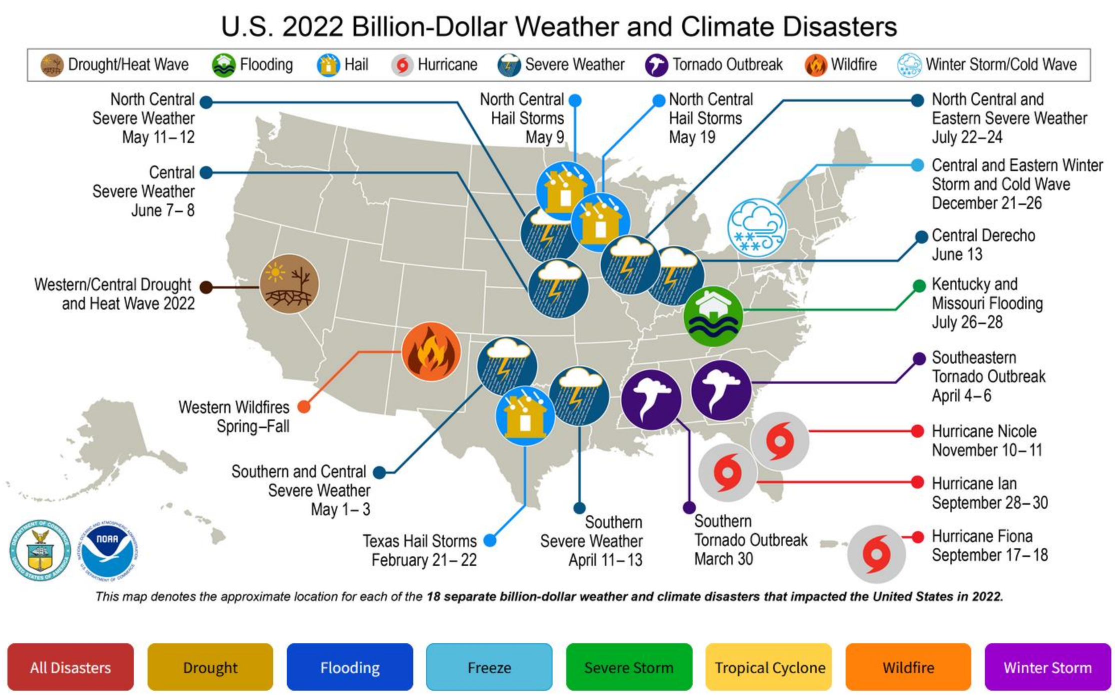


Figure 9: U.S. 2021 Billion-Dollar Weather and Climate Disasters

While energy resilience will help drive the market for mCHP, the potential for mCHP to reduce GHG emissions provides an additional societal benefit. Table 6 summarizes the performance attributes of three different mCHP system types for the residential and commercial sectors, including mini/microturbines (low power-to-thermal ratios), internal combustion engines (mid power-to-thermal ratios), and SOFC (high power-to-thermal ratios). Electrical and total (electric plus thermal) operating efficiencies and associated emission rates are based on manufacturers' published information. The mCHP column shows calculated GHG emission rates for mCHP based on manufacturers' NO_x, CO_2 and methane (CH_4) emission rates with respect to the amount of heat and power they produce. The Grid+Equip column shows emission rates from the utility electric grid, plus traditional water heating and space heating equipment operating at 85% efficiency. The GHG emission rate used for grid power was 969 lb/MWh, which is the average U.S. rate for all plants [EPA, 2021]. The GHG emission rate used for the heating equipment was 146 lb/MMBtu, which is the average U.S. rate for natural gas [EPA, 2021]. These calculations indicate mCHP GHG emission rates are almost 40% to over 50% lower than GHG emission rates from the current utility electric grid based on traditional water heating and space heating equipment.

The most favorable pathways for GHG emission reductions will come from highly electrically efficient mCHP systems like fuel cells and from mCHP systems that effectively use waste heat onsite and can operate on natural gas and potentially on blends of natural gas and hydrogen. Thus, mCHP systems *can* provide GHG emission reductions as an *Innovative Mechanical Solution*.

Table 6: Micro-CHP Performance Attributes and GHG Emissions Relative to Grid/Thermal Equipment

				Emission Rates (lbm/MMBtu)			GHG (lbm/MWh)	
Sector	**Micro-CHP System Type**	**Elec Eff.**	**Total Eff.**	**NOx**	**CO2**	**CH4**	**mCHP**	**Grid+Equip**
Residential	Mini-turbine	14%	85%	0.191	118	0.000	403	651
	Internal Combustion Engine	22%	81%	0.003	118	0.437	444	690
	Solid Oxide Fuel Cell	45%	88%	0.000	118	0.000	403	782
Light Commercial	Microturbine	25%	72%	0.135	118	0.000	403	718
	Internal Combustion Engine	30%	84%	0.004	118	0.486	449	746
	Solid Oxide Fuel Cell	53%	80%	0.000	118	0.000	403	840

Overview of Technology Status

There are now dozens of manufacturers positioning for the mCHP market, as shown in Figure 10. However, high-volume production of mCHP systems in North America has yet to be seen. Qualified technology supported by major manufacturers and implemented in innovative applications could help to spark the North American market and even expand the global market. Figure 10 provides a snapshot of the North American mCHP market landscape, although and it is not necessarily all-inclusive. Nonetheless, it identifies a wide array of mCHP technologies and plots each one at its electrical power capacity (kWe) and corresponding lower heating value efficiency. It is important to note, most mCHP systems can achieve 80% to 90%+ overall electrical plus thermal efficiencies.

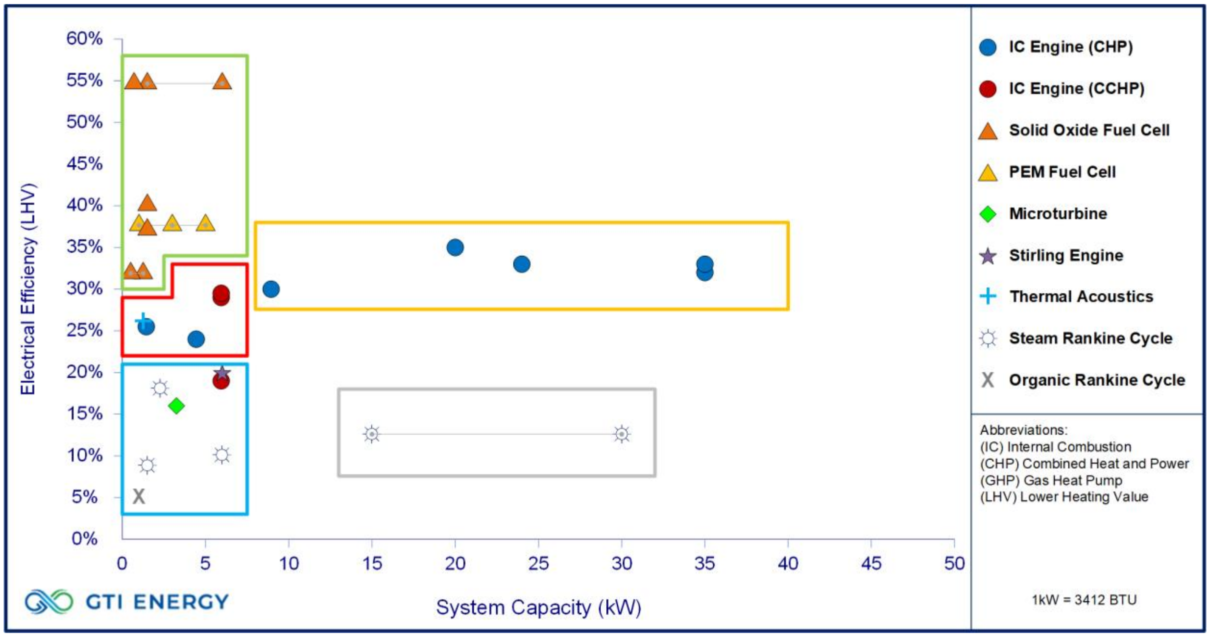


Figure 10: Micro-CHP Market Landscape in North America

The majority of existing and emerging mCHP technologies can be arranged into five technology categories as highlighted in Figure 10 by the colored boxes. The three residential-scale (≤7kWe) mCHP categories shown in the red box are grouped by electrical efficiencies. Technologies in the top green box represent mCHP systems with electrical efficiencies significantly greater than electric grid efficiencies. These are primarily SOFC systems. SOFCs consume hydrogen or syngas and chemically convert it to DC power. Therefore, to operate on natural gas, they require a fuel reformer. The key benefits of fuel cells are their high electrical efficiencies (32% to over 55% Lower Heating Value, LHV) and near-zero emission levels. Because many SOFCs can generate power more efficiently than grid power, they can help to support zero net energy applications. The key drawbacks of fuel cells are their low power densities, which make them expensive for the amounts of power they can produce. Moreover, certain fuel cells can take an hour or longer to reach maximum capacity from a cold start. Therefore, they are best applied where they can operate in a steady state mode with minimal on and off cycling. Applications for SOFC-based mCHP technologies are therefore practical when they are always on, or when power can be exported to the grid and the customer can obtain credit for the electricity, such as through utility net metering programs.

Technologies shown in the middle red box in Figure 10 represent residential-scale mCHP systems with electrical efficiencies near electric grid efficiencies. These systems are mostly reciprocating engine-based mCHP technologies. Engines are the most mature mCHP technology with the highest power densities and the lowest costs per power capacity (kWe). They are typically configured with a heat exchanger to recover waste engine heat to be stored in a tank. Sometimes engines can be used to drive compressors in addition to or instead of generators. The compressors can be used for vapor compression-based heating/cooling or refrigeration applications. Most commercially available mCHP systems with significant North American market adoption are engine-based.

Technologies shown in the bottom blue and grey boxes in Figure 10 represent residential and light commercial-scale mCHP systems, respectively, with electrical efficiencies significantly less than electric grid efficiencies, but with high thermal efficiencies. These systems are based on a myriad of mCHP technologies including Stirling engines, organic and modified Rankine cycles, and mini-turbines. Many are packaged systems with self-powered water heating or forced-air space heating functionalities and form-factors. Because they produce much more heat than electricity, they are often used in thermally-led configurations that can be operated without separate heat exchangers and tanks (although thermal storage with a tank can offer increased runtime advantages). Some of these mCHP systems also incorporate a means for thermal distribution, including blowers for forced-air systems and pumps for hydronic systems.

Technologies shown in the yellow box in Figure 10 represent light commercial-scale or multifamily mCHP systems. The majority of mCHP systems in this market space are also reciprocating engine-based. These systems may offer the best opportunity for near-term cost-effective widescale mCHP adoption. Some manufacturers have entered the market with products priced lower than PV (less than about $3/watt). Moreover, some can meet extremely low emission standards like the California Air Resources Board Distributed Generation Certification Regulation (CARB-DG).

While there are millions of potential residential and light commercial mCHP applications in North America, the market remains largely untapped. However, if decentralized mCHP systems can be integrated with hybrid electric and fuel-fired HVAC and water heating technologies at the building level to effectively support centralized power systems, such mCHP applications could become far more viable.

Overview of R&D and Industry Efforts

The subsequent figures provide snapshots of the North American mCHP market landscape by mCHP categories. They are not all-inclusive. Each market snapshot shows the manufacturers and associated mCHP technologies and where they are in terms of power capacities and electrical efficiencies. Those technologies with the GTI Energy logo next to them have been evaluated by GTI Energy. Those with the word CARB in green next to them indicate mCHP systems that GTI Energy has reason to believe can meet stringent CARB-DG certification for NOx, CO, and VOC regulation. Note, given the nature of fuel cells, GTI Energy believes all of the fuel cells shown on Figure 11 have the potential to meet CARB-DG regulations. Those with the word CARB and a check mark next to them indicate mCHP systems that GTI Energy has validated through laboratory research as able to meet CARB-DG regulations. However, CARB-DG also stipulates that an mCHP system can meet the NOx, CO, and VOC regulations for 15,000 hours of operation. That has not been validated for any of the mCHP systems by GTI Energy.

As identified per the legend at the bottom right of these figures, some of the mCHP systems are known by GTI Energy to be commercially ready and have the appropriate certifications for installation in the U.S. Since these figures represent a snapshot in time, the status of each mCHP system must be verified with each manufacturer. Likewise, some of the systems are far enough in their development where in-field trials are underway. Others are still in development. Here again, the status of each must be verified with the manufacturer.

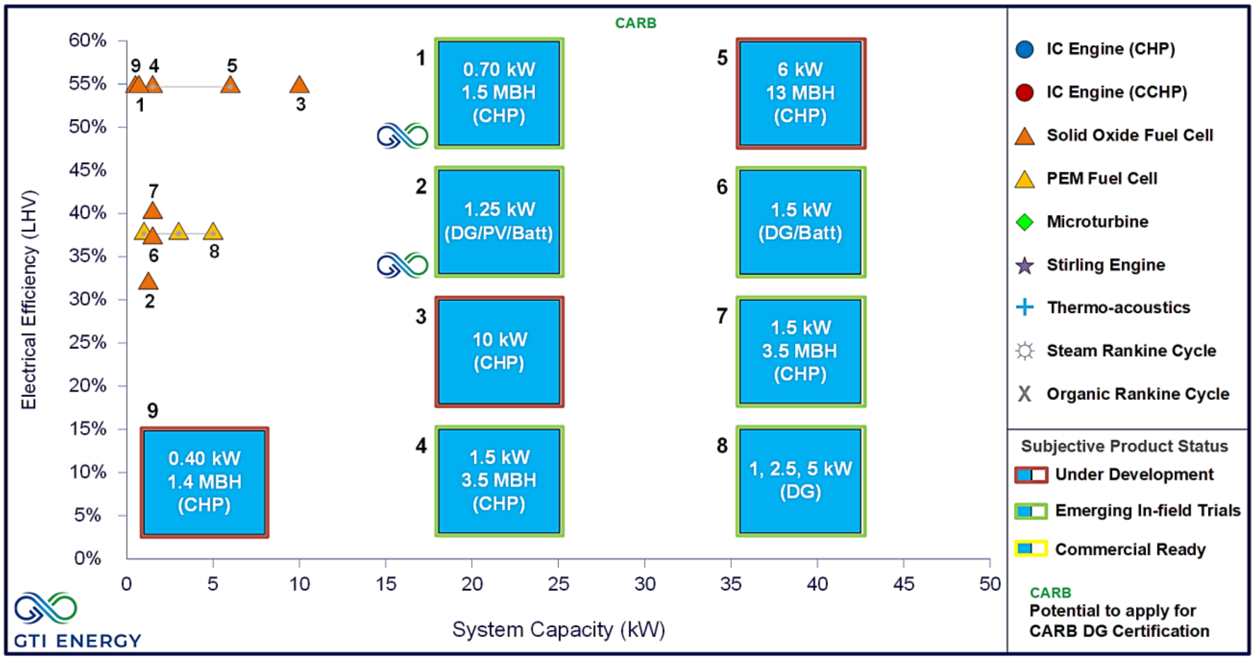


Figure 11: Residential mCHP Market Landscape (High Power-to-Thermal Ratio)

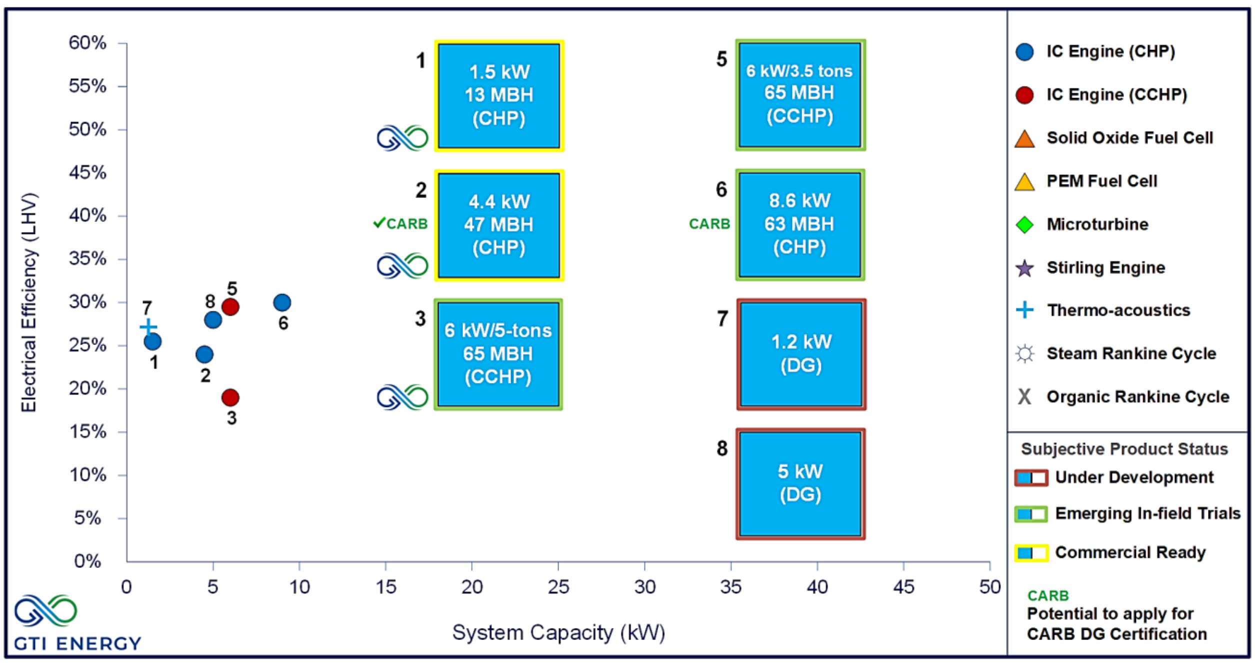


Figure 12: Residential mCHP Market Landscape (Mid Power-to-Thermal Ratio)

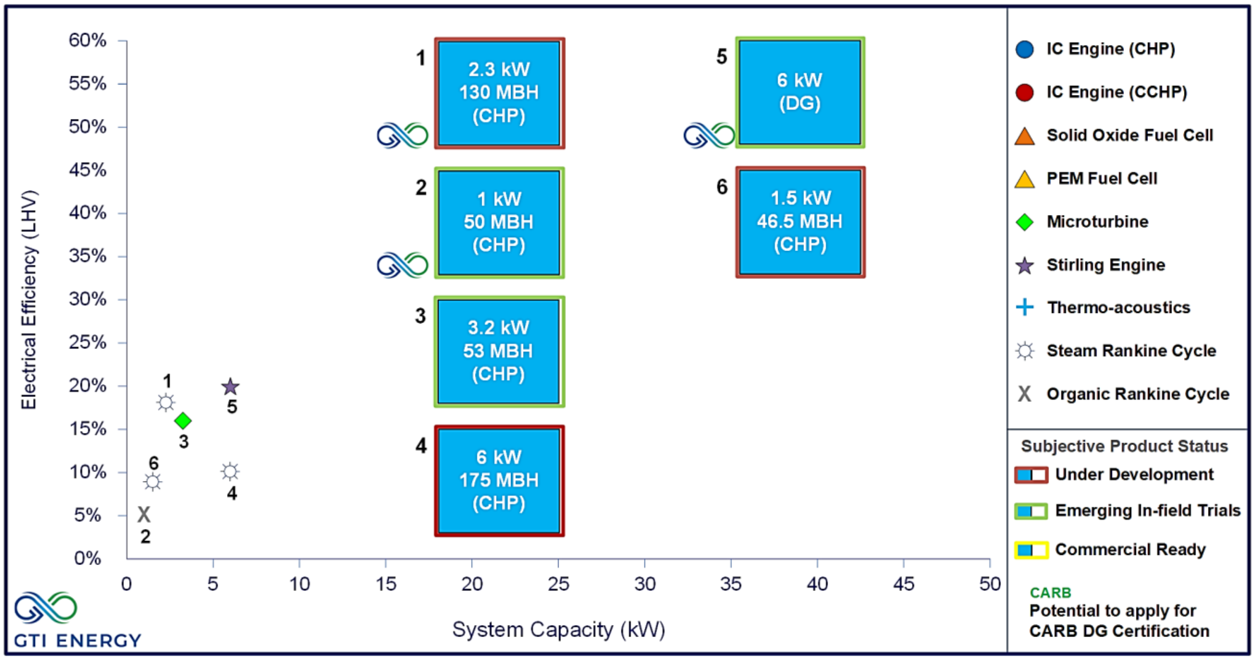


Figure 13: Residential mCHP Market Landscape (Low Power-to-Thermal Ratio)

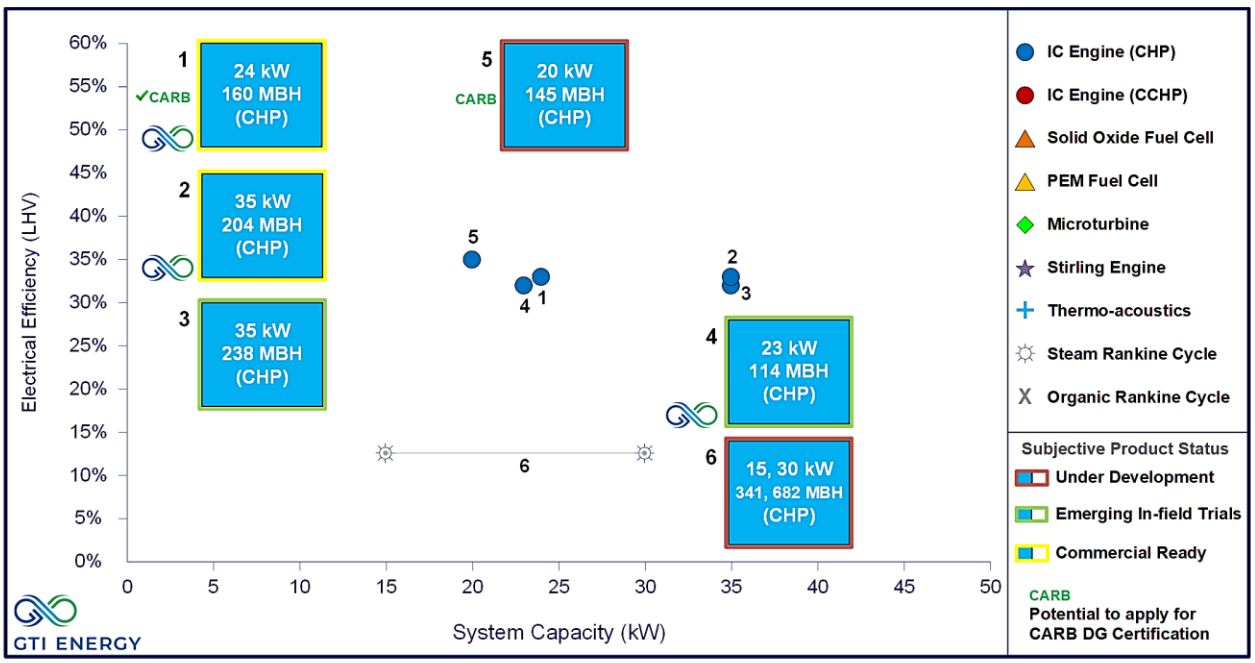


Figure 14: Light Commercial mCHP Market Landscape

Technology Pathway Outlook

The energy industry is on a fast track to decarbonize residential end-uses such as space and water heating. While electrification is one approach to reducing the carbon footprint associated with residential HVAC and water heating, it poses challenges as a sole solution. Similarly, the sole use of fuel-fired equipment faces challenges, primarily because the maximum achievable efficiencies are less than 100%. However, electric heat pump equipment, which can often achieve over 100% efficiencies, is challenged by an inherent lack of capacities, as well as inefficiencies in cold conditions. Another key challenge arises from inefficiencies of central generation and the associated electricity transmission and distribution system. This last issue can be addressed with DERs including electricity and heat generated and stored on site through renewables such as PV and fuel-fired sources such as mCHP.

Integrated energy systems (IES), which can be deployed today, provide a systematic approach that integrates hybrid space and water heating, leveraging the attributes of electrically-driven and fuel-fired equipment with DERs and energy storage to achieve efficient and reliable HVAC and water heating at reduced GHG levels, and with operating costs relative to electric-only or fuel-only alternatives. IES can be configured such that their energy sources (e.g., renewables, mCHP) and various loads (e.g., hybrid HVAC and water heating) are controllable, in which case they can be referred to as nanogrids or microgrids.

Microgrids and nanogrids are energy systems with multiple controllable energy sources and various controllable loads. A microgrid serves multiple buildings or dwelling units operated by a central energy system, while a nanogrid serves a single building operating as an energy system. They both provide opportunities to achieve energy resilience in self-powered HVAC and water heating, along with energy efficiency and, most importantly, GHG reductions by leveraging multiple energy streams including DERs. The challenge is to properly integrate and control the various systems and components to achieve those benefits in a practical and cost-effective manner.

Studies indicate that specific IES designs can achieve self-powered space heating/cooling and water heating at annual coefficients of performance greater than 1.0 on a source energy basis, with 30% to 50% lower operating costs and similar GHG emissions savings than with separate code compliant equipment in various climates [Kingston, 2022a and Kingston, 2022b].

In response to the growing demand for energy resilience, the expected need for alternative power sources, and the opportunity to develop a fuel-fired DER market, the energy industry can embrace mCHP technology as another path toward decarbonization. For mCHP to achieve widescale adoption, utilities must recognize mCHP as an opportunity and design programs around it, and where feasible mitigate challenges with permitting and utility interconnections. Utilities could consider programs where they own and operate the equipment, similar to renewable PV, potentially putting mCHP within reach of more homeowners and businesses. These programs can potentially be financed through customers' bills.

References for mCHP Section

- ANSI/ASHRAE 204: Method of Test for Rating Micro Combined Heat and Power Devices (2020).
- Murphy, C. et al. 2021. Electrification Futures Study: Scenarios of Power System Evolution and Infrastructure Development for the United States. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72330.
- Research Nester, 2022. North America Standby Generator Market (https://www.researchnester.com/reports/natural-gas-generator-market/77).
- Smith, Adam. 2021. U.S. Billion-dollar Weather and Climate Disasters: Data Sources, Trends, Accuracy and Biases. Asheville, NC: NOAA National Climate Data Center
- Kingston, T., Fridlyand, A., Guada, A. 2022a. Demonstration and Analysis of Hybrid and Grid-interactive Integrated Energy Systems Approaches. Proceedings of the 2022 ASHRAE Winter Conference, Las Vegas, NV.
- Kingston, T., Guada, A. 2022b. Integrated Energy Systems for Self-powered Single-family and Multifamily Residential HVAC and Water Heating. Proceedings of the World Gas Conference, Daegu, KR.
- United States Environmental Protection Agency (EPA). 2023. "Emissions & Generation Resource Integrated Database (eGRID), 2021" Washington, DC: Office of Atmospheric Protection, Clean Air Markets Division. Available from EPA's eGRID web site: https://www.epa.gov/egrid.

4. Fuel-Fired Heat Pumps

Summary of Technology Pathway

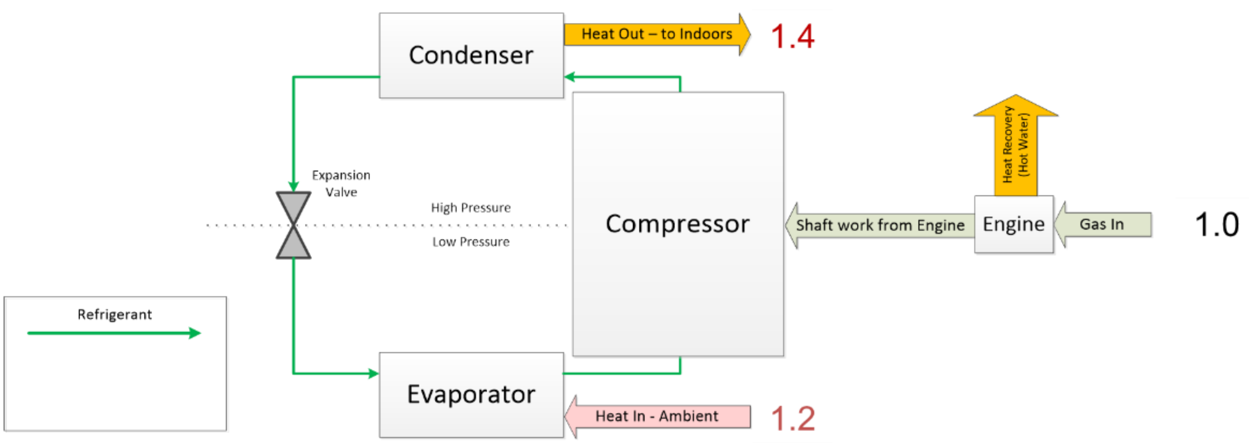
FFHPs are a class of technologies that are similar to conventional heat pumps in that they deliver thermal comfort by moving heat "uphill" from a low-temperature source to a high-temperature sink, and can operate reversibly to provide air-conditioning/chilling as well. Many FFHPs can, as designed, recover waste heat internally to provide hot water in addition to space heating and air-conditioning. Most FFHPs use refrigerants and thus, thermal energy from fuel combustion drives a refrigeration cycle. The underlying technology for a refrigeration process with thermal energy is not new. In many cases, it predates the widespread availability of utility electricity. This includes solar thermal-type sorption cycles used for ice production in 1878 [Butti, 1980] and engine-driven compressors to drive air-conditioning and refrigeration equipment that were used before the U.S. Civil War [Univ. of Fl, 2020].

Electrically-driven heat pumps are far more common than FFHPs, with millions sold per year compared to thousands of FFHPs sold per year.[9] This is due to their technical and market maturity, and the legacy of industry support and utility/government incentives. As a result, the term "heat pump" commonly refers to an electrically-driven heat pump, and the industry has standardized toward the *vapor compression* cycle and with that, common refrigerants (e.g., R-410A). By contrast, as an emerging technology, FFHPs currently have a broader diversity in technology-type and application. FFHPs primarily use thermal energy to drive the heat pump cycle and are frequently divided into two categories:

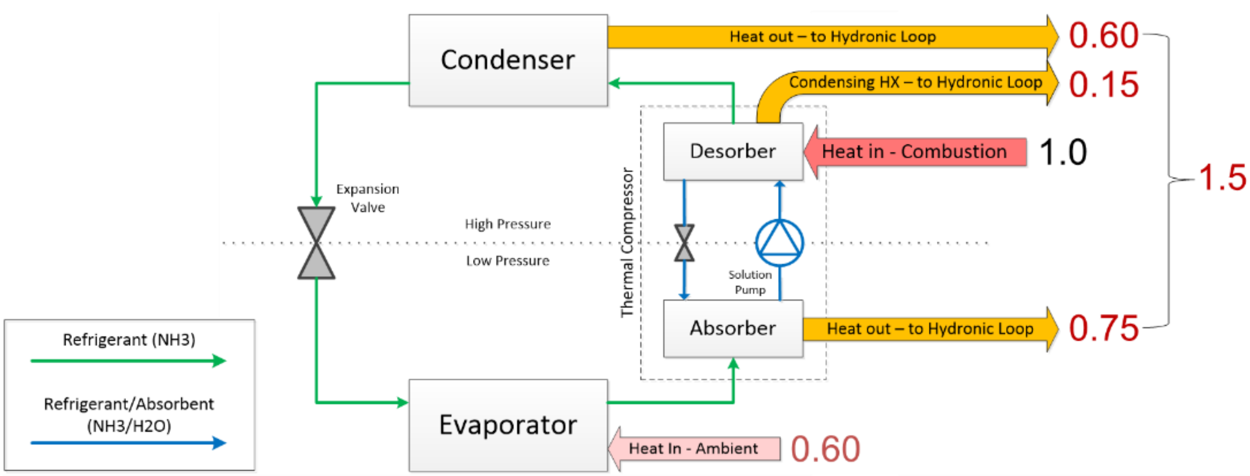
- Those that are *work activated*, or engine-driven and drive a refrigerant compressor with mechanical output of an engine.
- Those that are *heat activated,* which use heat generated by combustion or other source (e.g., solar thermal). The thermally-driven subclass of FFHPs can be based on a diverse set of cycles and employ a wide range of working fluids.

Figure 15 contains simplified diagrams of two of the most common FFHP types, the work activated *vapor compression*-type FFHP and the heat activated *sorption*-type FFHP (specifically, single-effect vapor absorption). The diagrams illustrate key differences between these cycles, including number and nature of heat exchangers, ability for internal heat recovery, and the nature of refrigerant and working fluid(s) selection. Where the familiar components for vapor compression-type cycles remain (evaporator, condenser, expansion device), it is the compressor that changes to accommodate these work or heat activated technologies, either through a direct-drive connection to a mechanical compressor or by employing additional vessels, heat exchangers, and sorbents to collectively act as a "thermal compressor". Note that in this section, where applicable and unless otherwise indicated, the Coefficient of Performance (COP) is defined as the ratio of useful heat delivered to the input fuel value on a higher heating value basis, at a nominal condition (e.g., 47°F ambient, 95°F return water).

9 In the U.S., AHRI estimates approximately 4.0 million residential electric heat pumps were shipped in 2021, while GTI Energy estimates that < 10,000 FFHPs were shipped in the same period.



(a)[10]



(b)

Figure 15: Simplified Diagrams of (a) Vapor Compression-type and (b) Vapor Absorption-type FFHPs with Approximations of COP_{Gas} for Nominal Operating Conditions

As a technology pathway for heating equipment, FFHPs drive decarbonization as an *Innovative Mechanical Solution* for fuel-fired energy efficiency in a number of product categories, similar to how heat pump technology broadly serves water heating and space heating solutions. In Table 7, the maximum rated efficiencies are shown for water heating and space heating product categories for both residential and commercial solutions, noting that FFHPs are not applicable to gas-fired infrared heating products. For applicable product categories, it is clear that the maximum baseline theoretical efficiency is 99%, albeit with practical limitations on capturing the total heating value of fuel combusted whenever useful. For each of the product categories listed, the demonstrated energy savings of FFHP technologies over common gas-fired baselines in addition to rated performance targets are shown. This highlights the advantages of operating

10 Note that the total engine waste heat, and that which is captured as useful heat, will vary widely from system to system, thus estimates are not shown in this illustrative diagram.

efficiencies >99%, with a portion of delivered heat captured from an environmental source.[11] With 40% to 50% energy savings over baseline demonstrated across product type and multiple demonstrations, approximately proportional to GHG reductions, it is feasible that a significant fraction of GHG reductions for gas-fired heating equipment end users can come from adopting FFHP technologies. Additionally for end users, FFHPs can provide other benefits relative to conventional heating equipment, such as:

- *Ultra-Low NO_x Combustion* is feasible with all applicable categories, either currently certified for U.S. or European markets or demonstrated as technically feasible.
- *Natural refrigerants* are commonly used by FFHPs (NH_3, CO_2, He, H_2O), with zero or very low global warming potentials.
- *No indoor combustion* because most air-source FFHPs are installed outdoors, eliminating impacts associated with indoor combustion such as air infiltration requirements on HVAC and potential impacts on indoor air quality.
- *Integrated heat recovery* allows many FFHPs to operate without the use of inefficient auxiliary/backup heating and with integrated defrost management solutions, improving thermal comfort while mitigating peak energy demand requirements.
- *Retrofit potential* for existing gas-fired equipment is often high from the perspective of existing utilities. FFHP gas, venting, and power distribution requirements are commonly at or below that of existing heating equipment, thus up-sizing of available utilities is not commonly required.

Table 7: Comparison of Maximum Heating Equipment Efficiencies to FFHP Performance

Category		Max. Efficiency Rating[12]	FFHP Field Demo Savings / Performance Target[13]
Residential	Water Heater	0.90 UEF (Storage) 0.96 UEF (Instantaneous)	>50% energy savings over 0.62 UEF baseline, >1.20 UEF target
	Warm-air Furnace	99.0 % AFUE	>45% energy savings over 92% AFUE furnace baseline, >140% $COP_{seasonal}$ target[14]
	Boiler	96.0% AFUE (Water) 83.4% AFUE (Steam)	
Commercial	Water Heater	97% TE (Storage) 99% TE (Instantaneous)	>50% energy savings over 82% TE baseline, >130% TE target

11 Typically, 25%-40% of delivered heating is from the heat pump cycle, with the balance as recovered heat of combustion.
12 Maximum efficiencies based on AHRI Certification Directory, inclusive of inactive equipment
13 Sources for savings and targets include: GTI and Brio, 2019; Glanville, 2020; Glanville, 2021, and Glanville 2022
14 Seasonal COP and AFUE metrics are based on the ANSI Z21.40.4 rating method

	Weatherized Furnace	>90% TE[15]	>40% energy savings over 80% TE baseline, >1.30 $COP_{heating}$ target
	Boiler	99.4% AFUE (Water) 84.2% TE (Steam)	>40% savings over 80% TE baseline, >130% TE target (N/A for steam)

Overview of Technologies and Status

Recently, GTI Energy developed an extensive catalogue of FFHP equipment design and performance data as part of a *Gas Heat Pump Technology and Market Development Roadmap* [GTI and Brio 2019]. The Roadmap focused on residential and light commercial-scale equipment that were commercially available or within five years of commercialization. With these criteria in mind, three major FFHP product categories emerged reflecting products available and under development: Vapor Compression (Engine-Driven), Sorption-type, and Thermal Compression-type equipment (see Figure 16). Building on a portfolio of RD&D efforts, the GTI Energy-led team compared FFHP categories and product types to identify strengths and weaknesses, technology maturity, technical and non-technical gaps and barriers, and a regional analysis of energy and GHG emission reduction potential. This work builds on an emerging portfolio of several excellent reviews of FFHP technologies issued over the past 10 years, including notable examples from the Netherlands, the UK, Canada, and from the U.S. Dept. of Energy, with a list provided in the end of this section.

Figure 16: Commercial/Prototype FFHPs in GTI Energy Demonstrations: Engine-driven VRF, Sorption-type Water Heater, Sorption-type Whole House Combi System, and Thermal Compression-type Heat Pump Boiler (Source: GTI Energy)

The three FFHP categories from the Roadmap are described below (summarized from GTI and Brio, 2019 and Winer, 2020). Due to fundamental and significant differences in designs, researchers and companies commonly select only one FFHP technology category to develop.

15 "Condensing RTUs" are commonly rated as industrial-type air heating equipment, thus value is based on recent studies of this category: http://betterbricks.org/uploads/resources/CRTU_pilotSummaryReport_3.23.20.pdf

Vapor Compression-Type FFHPs

The majority of conventional electrically-driven heat pumps use the *vapor compression* cycle, previously introduced, which can be electro-mechanically driven or, as in FFHPs, directly driven by an engine. At its core, the compression of a vapor refrigerant creates a pressure difference that drives the refrigeration effect, moving heat from the cold reservoir to the hot reservoir so that the saturation temperature during phase change favors heat flow from the evaporator to the condenser.[16] Electrically-driven HVAC commonly employs the *vapor compression* cycle, which is used in 99% of all air-conditioning (cooling) equipment and an increasing share of heating equipment. FFHPs using the vapor compression cycle are most commonly driven by internal combustion (IC) engines. The IC-FFHP often uses conventional refrigerants (e.g., R-410A) and can take advantage of similar components as more common electrically-driven heat pumps, but with the advantage of waste heat recovery as hot water and providing peak energy demand benefits.

This product category emerged in the 1980s in Japan, with a current market of more than 800,000 installed units and approximately 30,000 installed/year.[17] These products are successful where peak power demand is critical and three-phase power is costly in some retrofits (FFHPs commonly only require single-phase power). FFHPs are emerging throughout Asia, with South Korea and China as major secondary markets. Large legacy Japanese manufacturers have recently been joined by emerging Korean manufacturers to support the growing interest in FFHP-driven variable refrigerant flow (VRF) solutions. In North America, the market is small, ~150 units per year, supplied by established Japanese manufacturers, who introduced their products in the 2010s.

Figure 17: Side-by-side Comparison of FFHP and CCHP Solutions in 2020 [Rowley, 2020]

Prior RD&D efforts have driven unitary products into the market as well, most notably a residential-sized product that sold ~3,000 units in the 1990s but suffered from high equipment costs and reliability challenges. Also, a packaged rooftop unit (RTU) and a commercial water heating version of these FFHPs were introduced in 2011 and 2012, respectively. Performance tends to be good in both heating and cooling, comparable to electrically-driven heat pumps on the cycle itself, with COP_{Gas} ranging from 1.40-1.60 in both heating and cooling modes, with recent improvements in both cold-climate and part-load performance. Equipment costs tend to be higher, 2-3 times that of equivalently-sized electrically-driven equipment, ranging from $2,000/ton to $3,500/ton for residential and commercial-sized equipment. However, this is often balanced by operating cost benefits. A recent demonstration compared the performance and energy savings from a FFHP-based solution to a cold-climate (electrically-driven) heat pump (CCHP) solution. The FFHP solution yielded annual energy cost savings of 71% over baseline and 41% over the CCHP alternative

16 Technically the vapor compression cycle is a reverse Rankine cycle, for which the forward version is commonly applied to generating useful work from heat input over a temperature difference, the basis of steam engines and coal-fired/nuclear power generation cycles alike.

17 Data source: Osaka Gas, Tokyo Gas, JARN, GRI/GTI Energy, for 2018.

[Rowley, 2020]. Compliance with strict air pollution standards is typically not an issue, however, engine exhaust after treatment comes at an added cost.

Sorption-Type FFHPs

Sorption-type FFHPs include those using *vapor absorption* and *vapor adsorption* cycles, where the sorbent is in the liquid and solid phases, respectively. These cycles work on the principle that combining refrigerant/working fluid with a sorbent (liquid/solid), requires significantly less energy to raise refrigerant pressure, however, a thermal energy source is necessary to "desorb" the refrigerant/working fluid from the sorbent in order to yield a high-pressure vapor. Sorption heat pumps benefit by the ability to reach smaller scales, more suitable for residential-sized applications. Common absorption working fluid pairs are LiBr/H_2O (chilling) and NH_3/H_2O (heating), while common adsorption working fluids are H_2O or NH_3, and common adsorbents are activated carbon, zeolites, silicon dioxide, and various salts. Use of liquid versus solid sorbents each have their advantages. Generally, liquid-based sorption FFHPs have higher capacity/efficiency by virtue of their continuous nature while solid-based sorption FFHPs have fewer moving parts (e.g., no solution pumps with dynamic seals), and therefore have the potential for lower cost and greater reliability. In practice, liquid-based sorption FFHPs are more common in HVAC and water heating applications, with numerous products available domestically and internationally.

One notable advantage of Sorption-Type FFHPs is heating performance in *cold climates*, which exceeds that of vapor compression equipment. In the case of a single-effect vapor absorption cycle, the most common cycle deployed in sorption-type FFHPs, approximately 60% of the heat pump output is from internal heat recovery, while 40% of heat delivered to the building is from the ambient environment ("refrigeration effect"), based on GTI Energy testing and varying slightly over a range of operating conditions. For this reason, FFHPs in heating mode are much less sensitive to cold conditions and commonly do not require backup heating, whereas vapor compression-based solutions often operate at a lower temperature, which causes the unit to switch to electric-resistance heating. Additionally, ammonia is a common refrigerant for sorption-based FFHPs and has superior cold-climate performance when compared with conventional refrigerants (R-134a, R-410A, etc.). While ammonia has other advantages as a natural refrigerant with zero GWP and zero ozone depletion potential, it also requires care due to toxicity and mild-flammability concerns (B2L type). This places an upper limit on equipment size based on allowable ammonia charge in the vicinity of occupied residential and commercial buildings.

Given the advantages with sorption-based FFHPs in scaling down and performing well in heating-dominant climates, this class of FFHPs is favored in European-based developments both past and present, including efforts by several major boiler companies via internal development pathways, branding of solutions from FFHP manufacturers, and direct-to-market pathways for small FFHP manufacturers as well. In North America, residential and light commercial products are available from several manufacturers (international and domestic), both air-source and water-source types (see Figure 18). The companies collectively develop FFHPs over a wide range of sizes and types, including: (1) prototype integrated residential water heaters, with a projected uniform energy factor (UEF) of 1.20-1.30, a unit cost of approximately $1,800, and ultra-low NO_x

certification, transitioning from demonstration stage to commercialization [Glanville, 2020], (2) whole house heating as a boiler or furnace replacement, with a projected 140% annual fuel utilization efficiency (AFUE) (per ANSI Z21.40.4 method), unit cost of approximately $4,500, also ultra-low NO_x-certified and transitioning from demonstration stage to commercialization [Glanville, 2019], and (3) commercial-sized FFHPs,[18] installed as "hybrid" central plants in conjunction with boilers and commercial water heating systems, often taking advantage of the cooling function.

Figure 18: Commercial Installations of Sorption FFHP Equipment Including GTI Energy Demos in Multifamily Buildings (Left), Full-Service Restaurants (Center), and a Commercial Installation of Equipment (Source: GTI Energy/Robur)

Thermal Compression-Type FFHPs

Thermal compression FFHPs are commonly based on variants of the Stirling engine cycle, which can be driven by external combustion or non-combustion sources of heat *and* can use a wide range of working fluids. These FFHPs use power cycles that produce useful work (internal or external) with an *external* source of heat. Because these FFHPs decouple the source of heat from the working fluid's cycling performance, FFHP developers can increase operating temperature and pressure of the cycle while selecting working fluids well-suited for extreme conditions. FFHPs are "heat engines", converting a source of high temperature heat (e.g., combustion) into mechanical work, which in turn compresses a working fluid. The diagrams in Figure 19 show simplified versions of heat engines, vapor compression cycles, and thermal compression cycles.

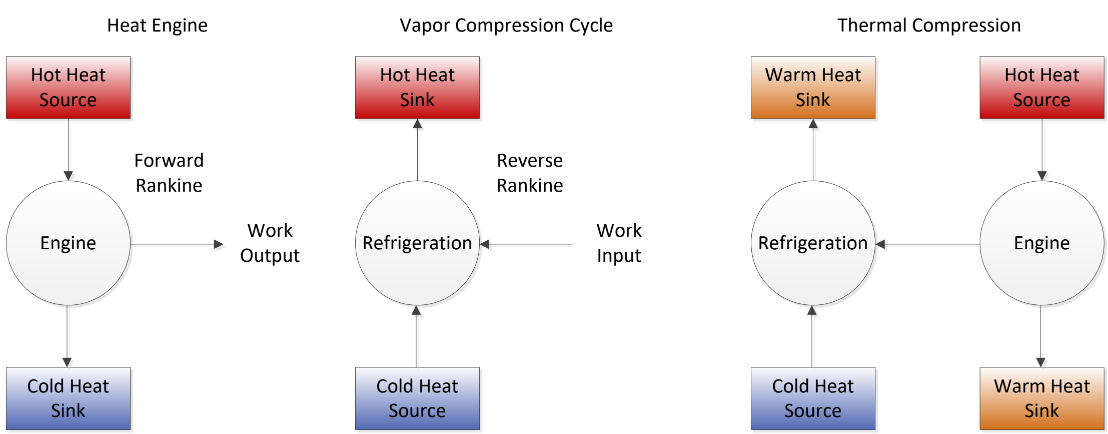


Figure 19: Diagrams of Heat Engines, Vapor Compression, and Thermal Compression Cycles

Generally speaking, the hotter the "hot end", the better the performance of these FFHPs. Thermal compression-type FFHPs are theoretically capable of (a) high temperature heating

18 Note that the well-established class of larger absorption chillers manufactured by major HVAC companies and smaller players were outside the scope of this assessment.

(>160°F), (b) low temperature chilling (even cryogenic cooling), and (c) non-incremental efficiency increases over other FFHP types. While multiple types of externally-fired engines exist, Stirling engine cycles are more favored for FFHPs, operating by expanding a specific volume of gas at one temperature and compressing it at another temperature. Typically, the Stirling cycle utilizes inert gases like air, helium, carbon dioxide, or hydrogen as the working gas. The Stirling cycle can be arranged as either a dual cylinder system, referred to as alpha-configured with separate cold and hot cylinders each with their own pistons, or as a one-cylinder system with an internal displacer, referred to as beta-configured. Within a single cylinder system, one end of the cylinder is hot and the other is cold. To realize a heat pump cycle, operating between three temperatures, simple Stirling cycles are commonly augmented to combine work output and fluid compression/expansions aspects of the FFHPs.

For thermal compression FFHPs, cycles selected are sorted by technology developer:

- A U.S.-based start-up uses a modified "Vuilleumier cycle," which combines a Stirling engine and Stirling heat pump. Unlike the duplex Stirling engine, the mechanical coupling is through a shared working medium rather than a shared piston.
- An EU-based start-up developed a transcritical CO_2-based heat pump wherein the compressor is replaced by a gamma-type Stirling engine with the power cylinder/piston replaced by inlet/exhaust ports with precise valve timing.
- A Canada-based start-up is using a modified thermo-acoustic cycle for both heating and power generation duties, with targeted applications for remote power and heat pumps, with other international entities developing similar technologies.

Compared to other FFHP categories that have mature products available for 10+ years in multiple segments, thermal compression FFHPs are less mature. The aforementioned start-up companies and their partners are in the laboratory testing and controlled pilot stages, with product re-designs underway in all cases. Additional technologies under development, but with a potentially longer horizon to technical maturity include ejector-based cycles, with prior efforts in Canada and in the U.S., with a focus on HVAC [Shahamiri, 2012 and Glanville, 2014] and water heating [Spitzenberger, 2022] applications, respectively.

With the high-risk and high-reward nature of this category, efforts have benefited from significant R&D investments from private and public entities. Due to technical challenges that remain, the path to broad commercialization within three years is feasible but challenging. These more complex FFHPs require specialized materials, the use of which enables the potential for higher operating efficiencies and a higher heating and/or lower chilling temperatures than other FFHP cycles. For example, the EU-based FFHP is certified with a heating rating of "A++", per EU metric, and with an LHV-based gas utilization efficiency of 1.81 at A7W35 (7°C ambient and 35°C water supply), and a seasonal estimated efficiency of 1.88 on an LHV basis for medium temperature heating. This performance that has been confirmed in recent GTI Energy laboratory testing.

Comparison Across Technologies

The table below summarizes key attributes of each of three FFHP technology types, (with liquid/solid sorption solutions split out). For the primary market segments served by FFHPs, the following qualitative assessment was performed as part of the aforementioned GTI Energy roadmap:

- **Residential water heating,** due to the integration with storage and common retrofit scenarios, is the smallest FFHP application, defined by ASHRAE as less than 20 kBtu/hr input. This application is best served by cycles that can scale down well, which sorption is best able to do cost-effectively.
- **Residential HVAC** market segments presents mixed results:
    - For heating-focused applications, particularly in cold-climates, sorption-based FFHP combi-systems may be the most cost-effective FFHP option, while thermal compression offers incrementally higher performance.
    - Where cooling is more important than heating modes, vapor compression has advantages in technical maturity and again, thermal compression can have incrementally higher performance.
- **Commercial water heating**, with larger-scale vapor compression, is an option with products available, however, sorption may again represent the most cost-effective option. Thermal compression, with high performance, may have challenges with cost-effectiveness in this segment.
- **Commercial HVAC** has mixed results as well:
    - For unitary air-delivery heating systems, vapor compression is a technically mature option as with residential packaged HVAC, however, "split" style sorption based equipment may prove more cost-effective in the near term though installations may be more complex.
    - In hydronic heating and chilling applications, installed as systems with conventional heating and cooling equipment installed with FFHPs in a baseload versus peaking arrangement, FFHPs have advantages for X-to-water/brine equipment like sorption (near term) and thermal compression (long term).
    - For VRF installations, current codes and standards only permit certain refrigerants for use in this application, thus leaving vapor compression as the only option.

Table 8: General Comparison Amongst FFHP Technology Categories

	Vapor Compression	Sorption		Thermal Compression
		Vapor Absorption	Vapor Adsorption	
Installation Type	Air-to-Air with hydronic heat recovery & direct-expansion/VRF	Air-to-water/brine or Water-to-water/brine		Water-to-water/brine, air-source requires additional coil
Common Working Fluids	R-134a, R-410A	NH_3/H_2O or $LiBr/H_2O$	H_2O/Zeolite, NH_3/Carbon, NH_3/Salt	Helium, CO_2
Cold Climate Performance (Heating)	Acceptable	Good	Acceptable	Excellent
Hot Climate Performance (Cooling)	Good	Acceptable	Acceptable	Excellent
Environmental Impact	High-GWP refrigerants are common, after-treatment for NO_x	Ultra-Low NO_x certified, low/zero GWP refrigerants	Ultra-Low NO_x capable, low/zero GWP refrigerants	Ultra-Low NO_x capable, low/zero GWP refrigerants
Mfrs.	Asia, N.A.	Asia, N.A., EU/UK	N.A., EU/UK	N.A., EU/UK

Overview of Industry Efforts and Path-to-Market

Residential Technologies – Water Heating

FFHPs applied as gas-fired heat pump water heaters (GHPWHs) are a replacement for residential gas-fired storage-type water heaters, which are primarily low efficiency. Of the ~4 million products sold each year in the U.S. 95% of all products have a rated UEF of less than 0.67. GHPWHs are an emerging solution to address this market that is challenged by cost-effective energy efficiency, in addition to 0.88 UEF storage-type solutions and 0.97 UEF tankless-type solutions available today [Glanville, 2020]. To address this need, an effort between technology start-ups, GTI Energy, and multiple water heater manufacturers were successful in developing and demonstrating a retrofit-ready GHPWH unit with a target total installed cost of $1,800 and with ultra-low NO_x certification (<10 ng NO_x/J output).

The most prominent of these efforts is the development of a sorption-type GHPWH using a single-effect NH_3/H_2O cycle for retrofit and new construction applications (see Figure 20). In a five-site demonstration in the Los Angeles area between 2019-2020, the per-site energy and

GHG emissions reductions were 50% or greater over 12-month monitoring period, as compared to a measured baseline. Operating COP_{Gas} was consistently 1.25-1.60, electric power demand was 0.2% - 2.0% of total output, and end users surveyed indicated satisfaction with the hot water capacity delivered at average temperatures of 125°F. Laboratory testing of the current pre-production generation of GHPWHs demonstrated a path to achieving 1.20 UEF certification, while subsequent analysis and modeling of potential interactive effects between the GHPWH and HVAC equipment revealed a minimal impact on "false loading", substantially less than the impact of eliminating the natural draft baseline water heater product or an electric-type HPWH. This analysis suggests that a ducted evaporator is neither necessary nor cost-effective [Glanville, 2020]. A parallel effort at the technology development and validation stage involves a vapor adsorption cycle applied to a storage-type water heater, using the NH_3/salt working pair, with similar performance targets and markets addressed [Ekblad, 2022].

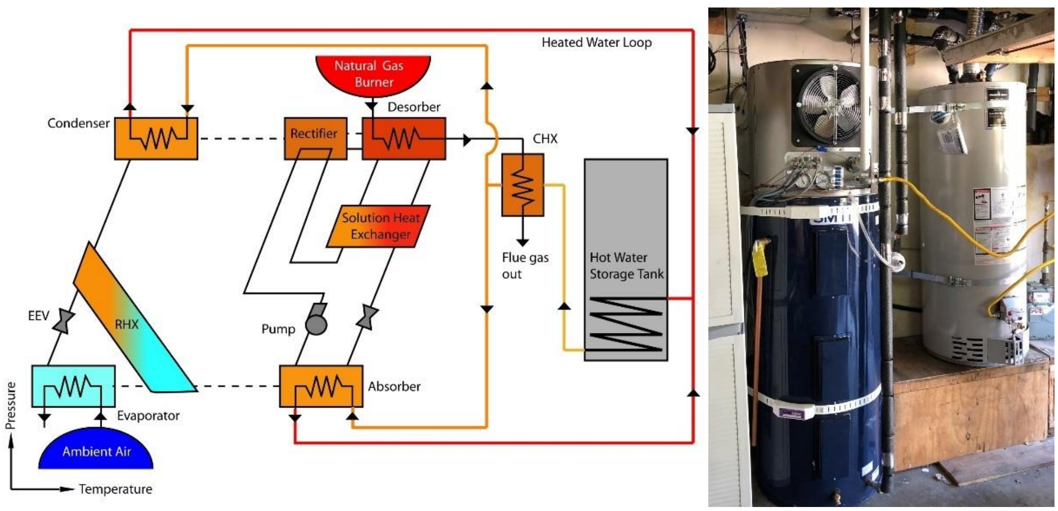


Figure 20: Diagram of Simplified GHPWH Cycle (Left, Source: SMTI) and Photo of GHPWH Pilot Installation (Right, Source: GTI Energy)

Residential Technologies – Space Heating

For residential space heating, furnaces are the primary product in the U.S., where 73% of homes have forced-air distribution for heating and cooling. Of those that use natural gas as a primary heating fuel, 88% have central warm-air furnaces [U.S. Census, 2019]. For these homes, and those with hydronic heating, residential FFHPs have been demonstrated in multiple applications. Predominantly sorption-type FFHPs have been demonstrated in Europe, where multiple residential-sized sorption-type FFHPs have been developed and commercialized [GTI and Brio, 2019]. Air-to-air FFHPs using vapor compression cycles have also been developed for air-conditioning applications primarily, targeting the U.S. market [Mahderekal, 2017]. Similarly, for North America, the primary FFHP technology class is sorption-type cycles and, generally, the NH_3/H_2O working pair is used (see Figure 21). When applied in boiler-type or hydronic heating installations, these FFHPs (commonly air-to-water) can be installed as either a direct replacement or supplement to existing equipment, delivering heat to radiators/emitters for space heating and to indirect storage tanks for water heating (if as a combi system, per Figure

22). However, given that the majority of homes have forced-air heating distribution, many FFHPs may be preferably installed as a combi system with forced-air heating delivered via an air handling unit (AHU) for forced-air distribution, per the diagram the figure below.

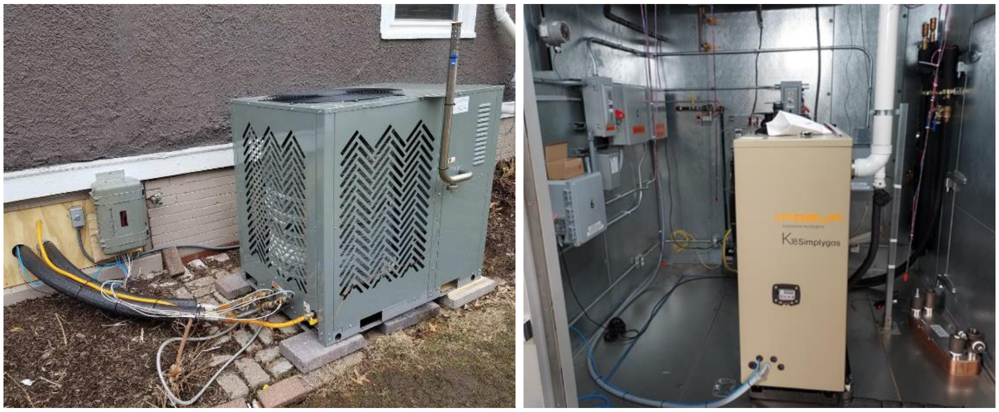


Figure 21: FFHP Installation Site for Hydronic Heat Distribution/Hot Water (Left) and Commercially-Available Residential FFHP at GTI Energy Laboratory (Right)

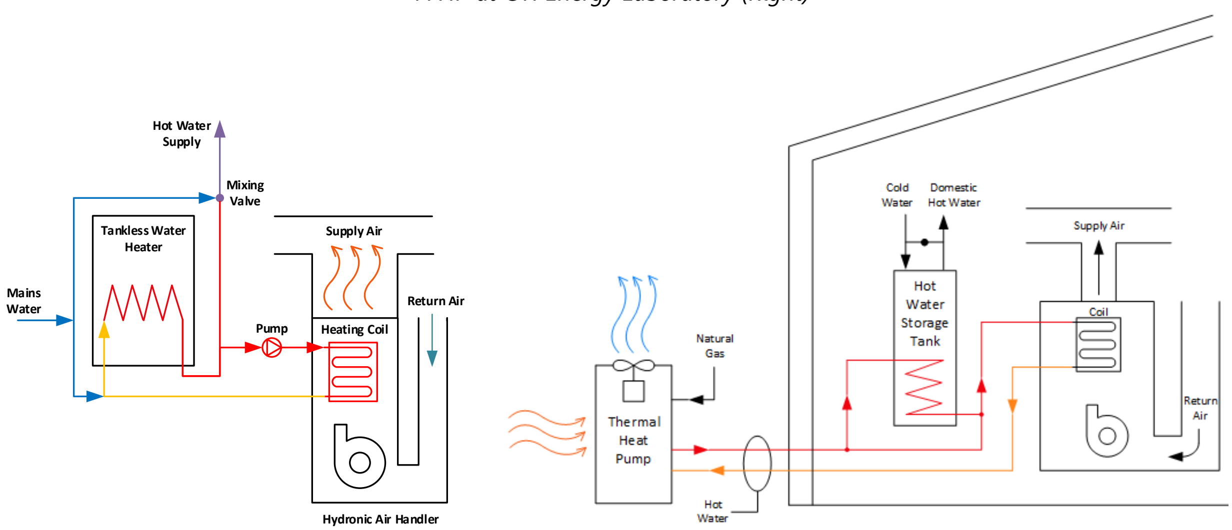


Figure 22: Tankless Water Heater (Left) and FFHP (Right) Based Combi Systems for Forced-Air Distribution

Several FFHP-based combi systems have been proven in the field, in cold climate locations ranging from Illinois, Indiana, Ontario, Tennessee, and Wisconsin. FFHP-based combi systems with a core NH_3/H_2O-based absorption cycle with a target production price of \$4,500 have demonstrated up to 46% therm savings over measured high-efficiency furnace baseline and standard water heaters, with estimated operating COP_{Gas} ranging 1.40-1.90, an extreme operation of 1.20 at -13°F with 95°F return water and operation above 1.0 at below -30°F, and peak power demand at or below 600 W [Garrabrant, 2020]. Similar to the GHPWH noted, this unit was also certified as ultra-low NO_x (<14 ng NO_x/J output) and in laboratory testing a recent prototype demonstrated a Seasonal COP_H of 1.41 using the pertinent testing standard for U.S. Climate Region IV and 1.38 for the colder Climate Region V [Fridlyand, 2022]. At present, there are multiple larger-scale demonstrations of four competing residential FFHP technologies consisting of three vapor absorption (NH_3/H_2O) type FFHP technologies from the U.S., China, and Europe and one thermal compression solution from the U.S. In total ~100 products or pre-commercial prototypes will be installed and operated through the end of 2023 across U.S. and Canadian demonstrations.

Comparative seasonal energy modeling of this FFHP-based combi system versus high-efficiency gas-fired and electrically-driven alternatives, including cold climate air-source heat pumps, showed the FFHP system as the lowest-cost, lowest GHG emitting solution in all modelled scenarios [Fridlyand, 2021]. In addition to efficiency advantages, of the 12+ residential FFHP-combi demonstrations to date in North America led by GTI Energy, end users have been satisfied with the level of heating and hot water, noting other advantages in terms of use of natural refrigerant/working pair and that combustion occurs outdoors, eliminating indoor air quality or air infiltration/venting concerns. In terms of additional components during the installation, manufacturers have adopted third-party indirect storage tanks and AHUs, and others have developed custom and integrated solutions. Multiple additional field demonstrations are underway at the time of writing in North America, including thermal compression-based FFHPs, with results expected in 2023.

Additionally, efforts are underway to characterize and address the installation complexity of these FFHP combi systems [LaFleur, 2022]. While limited data exist on actual installations of sorption or thermal compression-based residential FFHP systems, initial data collected by GTI Energy indicate that installation costs are approximately 50% of the equipment costs. Adding to these costs are other components. For example, in order to integrate with a forced-air HVAC distribution system (see Figure 23), an AHU is necessary, adding approximately $1,000 to $1,400 in equipment costs. Also, for a combi system providing hot water, an indirect storage tank is necessary as well, adding up to $1,600 in equipment costs [GTI and Brio, 2019].

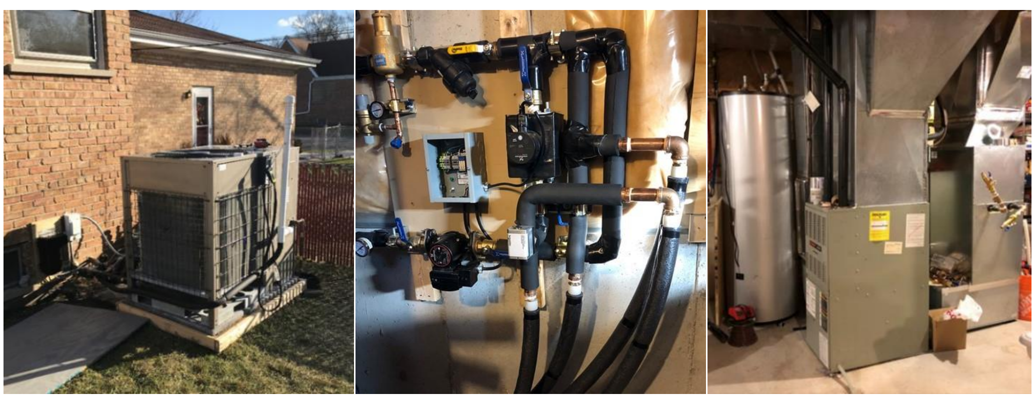


Figure 23: Photos of Forced-Air Type FFHP Combi Demonstrations

Commercial Technologies

As noted in the introductory sections, there is a mature market for vapor compression-type FFHPs abroad and a maturing market in Europe and North America for heating-focused, often sorption-type, FFHPs as well. For the former, engine-driven FFHPs are most commonly deployed for cooling-lead applications, where (a) electricity rates are high relative to natural gas, (b) where the cost of adding or upgrading three-phase electrical infrastructure is high, (c) resiliency of operations is important,[19] or (d) some combination thereof. As a result, equipment costs are commonly cited as being $2,000/ton to $3,500/ton. By comparison to the international market with 100,000s of units installed and 10,000s of units sold per year, the North American market is small, placing upward pressure on equipment costs. However, with additional market leaders expanding globally, including many major Asian technology conglomerates, equipment costs are coming down particularly for larger-sized FFHPs, ranging from $1,800/ton to as low as $1,200/ton [GTI and Brio, 2019]. For sorption-type FFHPs, the primary North American manufacturer has both direct sales and branded product sales. Projects commonly consist of up to 30 units, with estimated equipment costs of up to $15k per unit installed,[20] or between $226 to $313 per MMBtu/h of demand.[21]

For engine-driven vapor compression type FFHPs, the maturity of the product portfolio is unique, consisting primarily of internationally-sourced FFHPs. As a result, RD&D efforts are focused less on proving the technology and more on defining the value proposition to the end user and affected stakeholders (e.g., utilities). These targeted commercial-type demonstrations led by GTI Energy and others have included demonstrations of RTU-type equipment (see Figure 24), noted previously, and multiple VRF-type applications (2/3-pipe), of which the aforementioned side-by-side cold climate comparison was most recently completed [more detail can be found in GTI and Brio, 2019].

Figure 24: Installations of Multiple Vapor Compression-Type FFHPS (Source: Multiple Manufacturers)

For sorption-type commercial-sized products or prototypes, direct-fired vapor absorption cycles (single-effect and GAX-type) units with maximum outputs from 80 to 140 kBtu/h were operated in conjunction with existing site boilers and/or commercial water heaters as a retrofit for periods of 12 months or more in California, British Columbia, Illinois, Ontario, and Oregon. Results showed a reduction in site fossil gas consumption by 18% to 53% [TAF, 2018; Pratt, 2020; Glanville, 2021; Glanville, 2022]. One study used a hybrid air/water-source approach to provide supplemental A/C in addition to hot water for two full-service restaurant sites, yielding an additional 14% reduction in electricity demand for A/C in addition to hot water fuel savings, for a net 48% reduction in overall GHG emissions [Glanville, 2021]. For these studies, it is just as important to optimize FFHP performance along with the full system, including storage, distribution, and boilers/water heaters in series or parallel. With the strong potential for energy savings and GHG emission reductions, numerous North American utilities are developing or

19 Multiple FFHP products that are engine-driven are developed to have "black-start" capabilities, to operate during interruptions of grid power.
20 https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf
21 https://www.eia.gov/outlooks/aeo/assumptions/pdf/commercial.pdf

implementing incentives specifically to stimulate the market for these sorption-type heat pumps, with incentives of up to $37,500 per project [FortisBC, 2022].

Other Considerations – Maintenance

Generally, maintenance requirements of FFHPs mirror that of other similar equipment, including replacing or servicing simple components (e.g. flame rod, pump belt) and cleaning or replacing filters and coils. For machines with sealed ammonia circuits, maintenance of the sealed system is limited (factory sealed) and if specified by the manufacturer, technicians may require the same level of certification typical for HVAC maintenance (refrigerant recovery, etc.) and, depending on exemptions from IIAR-2 (where NH_3 is concerned), may require other certifications as they do in industrial refrigeration. For FFHPs using engine-driven designs, engine-specific maintenance is comparable to automotive or stationary generators, but can vary widely in estimated costs depending on manufacturer specifications. In one study, FFHP maintenance costs were estimated to be 30% lower than an electrically-driven heat pump heat pump alternative for the same facility [Rowley, 2020] while another study estimated that engine maintenance costs displaced nearly 1/3 of the energy savings [Energy350, 2018].

Other Considerations – Standards and Programs

In 2022, the test method developed by ASHRAE (Standard 118.2) went through a revision and introduced a new category of the "Gas-fired Heat Pump Water Heater," defined as products that use gas as the main energy source with a nameplate rating of 20 kBtu/h input or less, have a rated storage of not more than 120 gallons, heat water to not more than 180°F, and do not require greater than 24 A/250 VAC. Similarly, for commercial water heating and pool heating, ANSI/ASHRAE 118.1-2022 and 146-2020, respectively, introduced gas-fired heat pump categories that provide a pathway for rating these emerging equipment types in these applications, yielding a UEF or COP, for comparison across products. While these test methods have not yet been adopted by a standards body or government (e.g., U.S. DOE), numerous utility programs and other structures are emerging to support this new product category, prominently the Northwest Energy Efficiency Alliance's (NEEA) advanced product specification which identifies advanced performance tiers of UEFs, >1.0, >1.15, and >1.30 [NEEA, 2019], has laid the groundwork for utility incentive programs, work that others are building off of (Consortium for Energy Efficiency, EnergyStar).

The relevant safety and performance standards for North America for HVAC applications of FFHPs are ANSI/CSA Z21.40.1, Z21.40.2, and Z21.40.4, including the test method to define both steady state and seasonal efficiency. The scope of the standard is inclusive of FFHPs applied to both residential, commercial, and industrial building applications, in addition to air-source/water-source and air-delivery/water-delivery type equipment, with or without paired indoor equipment. Concerning the efficiency standard, Z21.40.4, the major revision is complete and undergoing industry review, summarized in a recent paper [Fridlyand, 2022]. While efficiency standards for furnaces, boilers, and combi systems do not yet include provisions for COP >1.0 equipment, there are numerous examples where advanced tier [CEE, 2021] or national stretch goals [NRCan, 2018] are in place for the U.S. and Canada, with more under development, laying out requirements or model incentive tiers for FFHP-based solutions with Seasonal COPs of greater than 1.0 or 1.20.

Technology Pathway Outlook

The decarbonization potential from FFHPs as a category is summarized in this section. The equipment categories described often have measured GHG reductions from efficiency gains of 40% or greater over baseline water heaters, furnaces, and/or boilers. With a selection of technologies applicable to FFHPs, ranging from the technologically mature vapor compression-type FFHPs (100,000s installed) to the emerging heating-focused sorption-type (10,000s installed) to the high risk/high reward earlier stage thermal compression-type (pre-commercial), a wide diversity of applications have been reviewed that cover the major product categories (e.g., residential water heaters, weatherized RTUs).

As a thought exercise, a 40% reduction in GHG emissions from all natural gas used in U.S. buildings for space and water heating by adopting FFHPs would reduce GHG emissions by 150 MMTCO_2e/year[22]. For this reason, FFHPs are a critical technology pathway for decarbonization, particularly for existing buildings currently using fossil gas, as a means of reducing emissions with existing technologies and existing infrastructure (both utility and building). The ease of retrofit of FFHPs for existing gas-fired equipment has been demonstrated over a range of projects. Thus, it is possible that the installed base of gas-fired equipment could transition to FFHP technologies, as non-condensing efficiency equipment have transitioned in many applications to condensing efficiency. For residential water heaters, furnaces, and boilers, it is likely the FFHP will entail a full replacement. For commercial applications of the same equipment, it is feasible to install "hybrid" solutions that phase in one or more FFHPs to operate in conjunction with conventional heating equipment. In addition to the primary need for cost reductions in FFHPs, their installation requires significant innovation to make for greater ease of retrofit over the range of installation scenarios.

While product development and technology innovation will continue to improve efficiency, performance, economics, and reliability, the primary needs for broader adoption of FFHPs are increased availability of products, increased market pull from early adopters and utility programs, and greater awareness by end users and stakeholders alike. The solutions for commercial buildings are currently available, with increasing market share of domestic and imported FFHP products, however, it is in residential-sized FFHPs where new categories are being filled. Based on current announcements, it is feasible that by 2024 in North America, there may be up to five manufacturers of residential-sized FFHPs for space and/or water heating, primarily using sorption-type equipment. As product developments and demonstrations are accelerating, the relevant codes and standards are evolving in parallel. GTI Energy has summarized these, with a focus on ammonia safety [GTI and Brio, 2019]. Concerning market pull, market players are evolving with the emerging product categories as noted. In addition to utility-facing players such as NEEA and CEE, a standalone collaborative, the North American Gas Heat Pump Collaborative,[23] formed to solve the market transformation challenges on behalf of utilities. Collectively and individually, utilities are motivated to develop and provide incentives for their ratepayers to adopt FFHPs,[24] identify and support trained installers as trade allies, and

22 Estimated using the Dept. of Energy's *SCOUT* tool: https://scout.energy.gov/baseline-energy-calculator.html
23 https://gasheatpumpcollab.org
24 Several utilities currently have or have recently sought approval for incentives for FFHPs, including the aforementioned Fortis BC, Nicor Gas, New Jersey Resources, and several others.

undertake other activities to drive efficient technologies to the market. It is also important to note that within the 2022 U.S. *Inflation Reduction Act* “natural gas heat pumps” for heating and water heating alike are eligible for tax credits.[25]

25 https://www.congress.gov/117/bills/hr5376/BILLS-117hr5376enr.pdf

References for FFHP Section

- Butti, Ken; Perlin, John (1980). A Golden Thread: 2500 Years of Solar Architecture and Technology. Cheshire Books.
- Consortium for Energy Efficiency (CEE), 2021. CEE Residential Heating and Cooling Systems Initiative, Link: https://library.cee1.org/system/files/library/12048/CEE_ResHVAC_GasSpecs_15Jan2021.pdf.
- Ekblad, M. Towards a Cost-Effective Residential Retrofit Gas Heat Pump Water Heater, Proceedings of the 2022 ACEEE Hot Water Forum, link: https://drive.google.com/file/d/18wigg9iwN0FJiPxZJS33u6UVmYSjDqpn/view
- Energy350, 2018, Natural Gas Internal Combustion Engine Heat Pump Field Trial Final Report, Report prepared for NEEA, link: https://energy350.com/wp-content/uploads/2018/12/ICE-Heat-Pump-Final-Report-2-6-18.pdf
- FortisBC, 2022, From Pilot to Program: Advancing Gas Heat Pump Technologies, Presentation during the 2022 ACEEE Hot Water Forum.
- Fridlyand, A., Glanville, P., Garrabrant, M., 2021, Pathways to Decarbonization of Residential Heating: Potential for Thermally-Driven Heat Pumps, 18th International Refrigeration and Air Conditioning Conference at Purdue, No. 3436.
- Fridlyand, A., Glanville, P., Kumar, N., 2022. A Review and an Evaluation of the Updated Method of Test for Rating Fuel-fired Heat Pumps in HVAC, Proceedings of the ASHRAE Winter Conference, Las Vegas, NV.
- Garrabrant, M., and Keinath, C., 2020. Pre-Commercial Scale-Up of a Gas-Fired Absorption Heat Pump, Report DOE-SMTI-8219-1 prepared for DOE under contract DE- EE0008219.
- Glanville, P., Zhong, Y., Ruben, P., and May, W., Development of Thermally-Driven Ground Source Heat Pump Concept, Proceedings of the 11th Int'l Energy Agency Heat Pump Conference, Montreal, QC, 2014.
- Glanville, P.; Fridlyand, A.; Keinath, C.; Garrabrant, M. Demonstration and Simulation of Gas Heat Pump-Driven Residential Combination Space and Water Heating System Performance. ASHRAE Transactions, 2019, Volume 125, pp. 264-272.
- Glanville, P. et al. (2020) "Integrated Gas-fired Heat Pump Water Heaters for Homes: Results of Field Demonstrations and System Modeling", Proceedings of the 2020 ASHRAE Winter Conference, Orlando, FL.
- Glanville, P., Mahderekal, I., Mensinger, M., Bingham, L., Keinath, C., 2021. Demonstrating an Integrated Thermal Heat Pump System for Hot Water and Air-Conditioning at Full-Service Restaurants, ASHRAE Transactions; Vol. 127 363-370.
- Glanville, P., Mensinger, M., Blaylock, M., Li, T. and Hardesty, R. "Hybrid Heating and Hot Water in Multifamily Buildings: Demonstration and Analysis of Integrated Boilers and Thermally-Driven Heat Pumps", Proceedings of the ASHRAE Winter Conference, Las Vegas, NV (2022).
- GTI and Brio. 2019. The Gas Heat Pump Technology and Market Roadmap.
- LaFleur, J. and Glanville, P., 2022. Best Practices from the Field: Air-to-Water Heat Pump Combi Systems, Proceedings to the 2022 ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar, CA.

- Mahderekal, I., Vineyard, E., Design and development of a residential gas-fired heat pump, 12th IEA Heat Pump Conference, March 2017, Rotterdam, The Netherlands.
- Northwest Energy Efficiency Alliance (NEEA), 2019, Advanced Water Heating Specification for Gas-Fueled Residential Storage Water Heaters Version 1.0, link: https://neea.org/img/documents/Natural-Gas-Advanced-Water-Heating-Specification.pdf
- NRCan, National Energy Use Database, Residential Sector for year 2018, link: https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/home.cfm?attr=0
- Pratt, J. et al., 2020. Robur Heat Pump Field Trial, Report #E20-309 prepared for the Northwest Energy Efficiency Alliance.
- Rowley, P. et al. Gas Engine-driven Heat Pump (GHP) Cold Climate Field Demonstration – Final Report. Report prepared under ESTCP Project EW-201515, Link: https://www.serdp-estcp.org/projects/details/0786546a-b196-4f7a-8524-d62bcf0dba16/ew-201515-project-overview
- Shahamiri S, Salek M, May W, Martinuzzi RJ. Application of Binary Fluid Ejector in Thermal Vapor Compression Distillation Systems. ASME. ASME International Mechanical Engineering Congress and Exposition, Volume 7: Fluids and Heat Transfer:1783-1788, 2012.
- Spitzenberger, J. et al. Theoretical Analysis of a Single-Stage Gas-Fired Ejector Heat Pump Water Heater, J. Thermal Sci. Eng. Appl. Apr 2022, 14(4): 041009.
- Toronto Atmospheric Fund (TAF). 2018. "Gas Absorption Heat Pumps: Technology Assessment and Field Test Findings", Prepared for Enbridge Gas and Union Gas.
- Winer, A. and Glanville, P., 2020. Thermal Heat Pumps – The Time is Now! Proceedings of the 2020 Virtual ACEEE Summer Study on Energy Efficiency in Buildings.
- U.S. Census, American Housing Survey, link: https://www.census.gov/programs-surveys/ahs.html
- Univ. of Florida, "Gorrie's Fridge", http://www.phys.ufl.edu/~ihas/gorrie/fridge.htm.

List of Technical Reviews of Fuel-fired, Thermally-driven, and/or Non-Vapor Compression Heat Pump Technologies:

The following list features several excellent technology reviews of FFHP technologies issued within the past 15 years, collected as part of the GTI Energy *Gas Heat Pump Technology and Market Development Roadmap* [GTI and Brio 2019]:

- **GasTerra** of the Netherlands published an excellent survey of FFHP technologies in Europe in 2010 which, while some material is dated, continues to serve as a comprehensive overview of technologies.

GasTerra, "Gas Heat Pumps: Efficient Heating and Cooling with Natural Gas," Report issued 2010. Link: https://www.gasterra.nl/uploads/fckconnector/1a2e9c26-1481-4cc5-b5bd-18cc39ba65b2

- **University of Warwick** in the UK has long tracked the FFHP technology developments in Europe with several publications issued in the past decade including market overviews, technology surveys, and an overall summary of Thermally Driven Heat Pumps issued to the International Energy Agency (IEA) Annex group.

Critoph, R., "Gas Driven Heat Pumps: Market Potential, Support Measures, and Barriers to Development of the UK Market," Report issued in 2013.

Critoph, R., "State of the Art in Gas Driven Heat Pumps," Report issued in 2013, Link: http://wrap.warwick.ac.uk/97394/7/WRAP-state-art-gas-driven-heat-pumps-Critoph-2017.pdf

Critoph, R., "UK Summary Report on IEA Heat Pump Annex 43 'Thermally Driven Heat Pumps," Report prepared in 2018.

- **TU Berlin**, on behalf of the same IEA Annex group issued an expansive review of thermally-driven heat pump technologies, with a large volume of results from European RD&D efforts.

Kuhn, A. (Ed.), "Thermally Driven Heat Pumps for Heating and Cooling," Prepared on behalf of IEA Annex 43, 2013. Link: https://nachhaltigwirtschaften.at/resources/iea_pdf/iea_hpp_annex34_handbuch_thermally_driven_heatpumps.pdf

- **Graz University of Technology**, an Austrian contributor to the same IEA Annex group issued its own summary of technologies and product updates, with a focus on sorption.

Wechsler, R. and Rieberer, R., "Fuel-driven sorption heat pumps: State-of-the-art and research activities," Report issued in 2014, Link: https://nachhaltigwirtschaften.at/resources/iea_pdf/hpt-annex-43-state_of_the_art_report-2014.pdf

- **UK Government**, via its Department of Energy & Climate Change later named the Department for Business, Energy, and Industrial Strategy, issued several reports examining FFHP technologies as an option for meeting GHG reduction goals.

Delta Energy & Env., "RHI Evidence Report: Gas Driven Heat Pumps," Report issued 2014, Link: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/371695/RHI_Evidence_Report_-_Gas_Driven_Heat_Pumps.pdf

The Carbon Trust, "Evidence Gathering – Low Carbon Heating Technologies: Gas Driven Heat Pumps," Report issued 2016, Link: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/787321/Gas_Drive_heat_pumps.pdf

The Carbon Trust, "Evidence Gathering – Low Carbon Heating Technologies: Domestic Heat Temperature, Hybrid, and Gas Driven Heat Pumps," Report issued 2016, Link: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/565248/Heat_Pumps_Combined_Summary_report_-_FINAL.pdf

- **Toronto Atmospheric Fund** issued a performance review of heat pumps, gas-fired and electric, including surveys of field assessment results.

TAF, "Global Heat Pump Performance Review," Report issued 2015, link: https://taf.ca/wp-content/uploads/2015/06/TAF-Heat-Pumps-Final-Report-2015.pdf

- **CEATI International** commissioned a pre-feasibility study of gas-fired heat pumps for Fortis BC which, while not a publicly available document, has a concise review of GHP technologies with a Canadian market focus.

CEATI, "Prefeasibility Study on Natural Gas Heat Pumps," Report issued 2017.

- **US Department of Energy** issued a report concerning non-vapor compression HVAC, inclusive of GHP technologies, as an R&D scoping document.

US DOE, "Energy Savings Potential and RD&D Opportunities for Non-Vapor-Compression HVAC Technologies," Report prepared by Navigant Consulting and issued 2014, Link: https://www.energy.gov/sites/prod/files/2014/03/f12/Non-Vapor%20Compression%20HVAC%20Report.pdf

5. Hybrid Heat Pumps

Summary of Technology Pathway

Hybrid or "dual fuel" heating systems use fuel-fired and electrically-driven heating components to serve a common thermal load. Typically, this approach is used with furnaces and boilers, wherein the combustion-based heating is employed under peak, colder conditions and the electrically-driven heat pump is employed under milder conditions where efficiency can drive energy and emission savings. Hybrid heating systems are commercially available in multiple product categories today, including residential HVAC, commercial HVAC, and a range of boiler sizes.

Hybrid heat pumps provide the benefits of *partial electrification*. They are particularly beneficial in retrofit scenarios wherein a building served by fuel-fired furnaces or boilers would prove prohibitively costly for full electrification, which often requires additional efficiency and conservation measures (e.g., deep energy retrofits) and potentially capacity increases to size the electrically-driven heat pump for the peak heating demand. Additionally, recent studies have concluded that full conversion of fuel-fired heating in many markets via electrification will result in near-term increases in societal costs and GHG emissions [Vaishnav, 2020]. (Although technically feasible, packaged hybrid heat pump water heating is not as common, primarily because of the inherent energy storage in most water heaters. Suitable retrofits can balance the reduced capacity heat pumps with increased energy storage for a given thermal load.)

As a technology pathway consideration, studies of hybrid heat pumps have shown significant peak demand reductions of 20% or more (see Figure 25). Immediate GHG savings relative to baseline have been demonstrated without loss of thermal comfort, up to 16% overall when considering hourly grid GHG intensity in Michigan[26] [Margolies, 2019 and Margolies, 2020]. Later studies have shown a potential for 15% to 30% GHG savings.

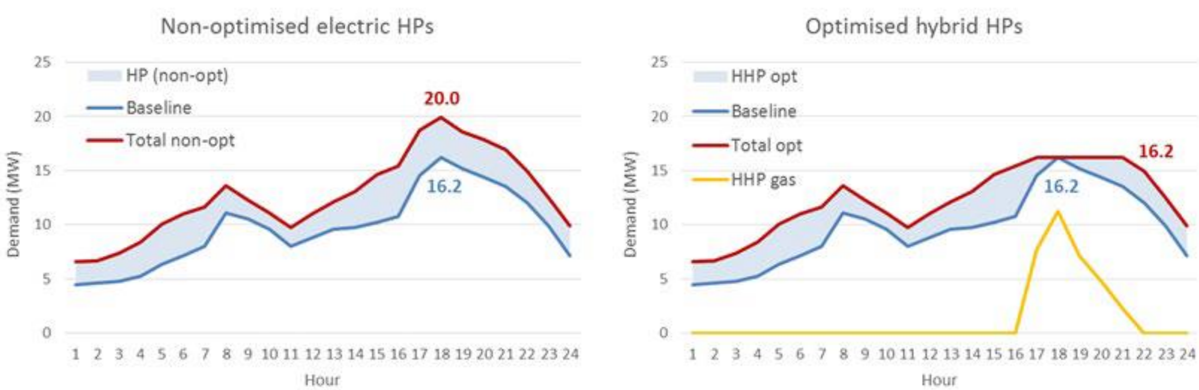


Figure 25: Illustrative Example of Daily Energy Use Pattern Where Non-optimized (Left) and Optimized (Right) with Hybrid Heat Pump (HHP) Option to Mitigate Peak Demand [Friedel, 2019]

26 Note this study concerned propane/electric hybrid heat pumps.

Residential Hybrid Heat Pumps

For furnace-type applications, either weatherized or non-weatherized, can be forced-air ducted or ductless systems (see Figure 26) or can incorporate hydronic radiant heating as well. This dual-fuel option provides potential benefits including increased energy efficiency, reduced GHG emissions, reduced operating costs, reduced peak energy demands, and increased resilience. The extent of those benefits depends on the type of system and how it is operated, along with other factors such as regional GHG emission factors and energy rates. This summary focuses on forced-air ducted systems, which are the dominant space heating systems in the U.S.

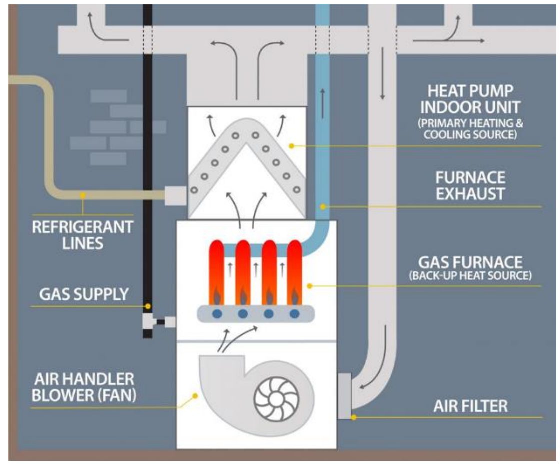


Figure 26: Diagram of Residential Hybrid Heat Pump [Source: Michigan Energy]

The most common forced-air hybrid system for residential applications is a traditional ducted gas furnace with an electric ASHP. In this system, hot air is distributed throughout the home by the blower in the furnace, and heat is generated by the furnace through direct gas combustion or by the ASHP via a traditional vapor compression cycle. Some hybrid systems may use a hydronic AHU instead of a furnace, whereby direct gas combustion is used to heat water, which is distributed to a hot water coil in the hydronic AHU. Also in this category are "hybrid boilers," wherein a fuel-fired boiler is internally coupled with either air-to-water or water-to-water heat pumps. Hybrid boilers are also suitable for hydronic heating systems. For all these applications, hybrid heat pumps are commercially available in many markets [Friedel, 2019]. It is most common for hybrid heat pump equipment to have the heat pump coil downstream of the furnace portion, primarily to accommodate the conventional placement of system integration of furnaces and air-conditioners. However, it may be preferable to place the heat pump coil upstream of the furnace, to limit the impact of preheating on the heat pump (larger efficiency penalty) and generally to create a more exergy-favorable arrangement. Taking this concept further from pairing of conventional components (e.g., furnaces and A-coils), there are efforts underway to design optimized hybrid heat pumps, which may operate the heat pump and combustion component simultaneously, allowing for more favorable sizing and control of each component [Li, 2022].

Commercial Hybrid Heat Pumps

For hybrid heat pumps in commercial buildings, weatherized RTUs are common, with ten product lines available in North America from six major manufacturers. Sizing of these products skews light commercial, with only two of the product lines noted with capacities of 7.5 to 10 tons or greater for heating. Most manufacturers offer both single and three phase type units. All furnaces with these systems are non-condensing, 80% to 81% AFUE, though condensing RTUs are available as standalone systems. Similarly, the heat pump portions are relatively low efficiency for existing products, up to 8.9 HSPF for all considered. Controls for these systems allow for some flexibility amongst products, with changeover settings between 5°F and 55°F available to the operator. A logic control scheme (see Table 9) must be taken into account with the system capacity (see Figure 27). GTI Energy and other researchers are investigating optimal best practices for hybrid RTU sizing, installation, and operation to balance operating costs, comfort, and GHG emissions, with anticipated findings published in 2023 from pilots in Illinois. Like the residential market, hybrid HVAC is more commonly applicable in North America, but hybrid heat pumps for hydronic heating and hybrid steam boilers (with standard electric heat) are commercially available, with studies underway to quantify their savings versus baseline and as a function of operating controls.

Table 9: Control Logic of Hybrid RTUs Considered [Source: GTI Energy]

	Outdoor Temperature		Thermostat Setpoint		Indoor Temperature		Heating System
IF	Above changeover *	**AND**	Less than 2°F above indoor temperature	**AND**	Increasing sufficiently after 15 minutes of heating	**THEN**	Run primary heat source, **heat pump**
IF	Below changeover *	**OR**	More than 2°F above indoor temperature	**OR**	Not increasing sufficiently after 15 minutes of heating	**THEN**	Run supplemental heat source, **gas furnace**
* Changeover (aka crossover or balance point) can be set to values between 5°F and 55°F							

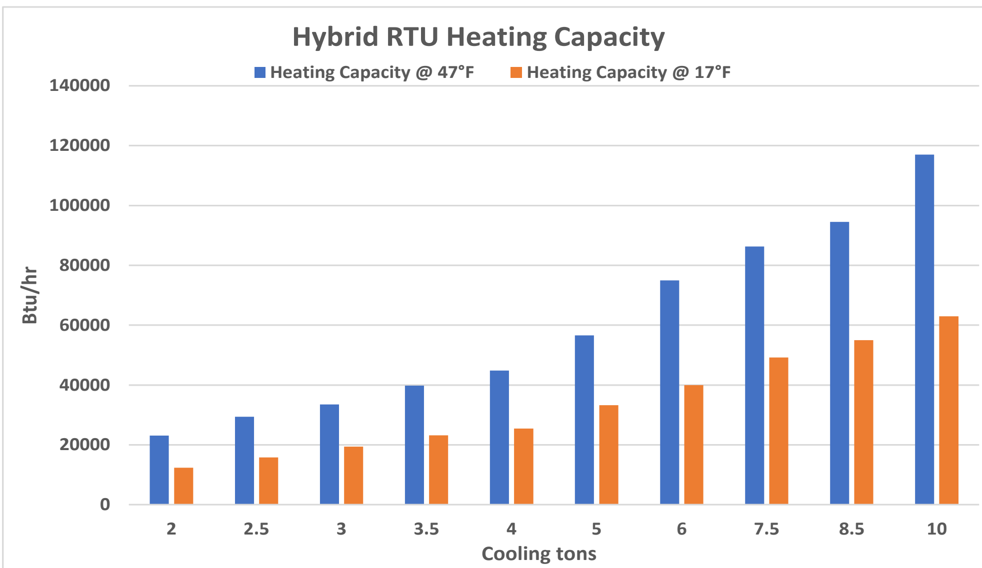


Figure 27: System Capacities as Function of Cooling Capacity [Source: GTI Energy, multiple OEMs]

Overview of Technology, R&D, and Industry Status

As previously noted, there are hybrid products available in the majority of categories, in rough order of magnitude: residential HVAC, commercial HVAC, and boilers. Hybrid heat pump water heaters (electric air-source heat pump with integrated combustion-based heating) are technically feasible but not actively under development for the North American market. This application, like fuel-fired heat pumps for water heating, is more suitable for balancing the limited capacity (or increased cost-per-output) of heat pump technology with increased hot water storage instead of employing high-capacity fuel-fired auxiliary or backup heating. However, this situation may evolve as hybrid heat pump technologies find footholds in other market applications. Also, like fuel-fired heat pumps, these technologies are not applicable to infrared heating.

In general, hybrid system switching controls typically built into the thermostat/aquastat determine when heating is provided by the fuel-fired equipment versus when it is provided by the electrically-driven equipment. In its simplest form, a hybrid system can be controlled with a 2-stage thermostat/aquastat that switches from the electrically-driven heat pump to the fuel-fired system after a preselected time. In an HVAC context, for example, the ASHP provides stage-1 heating. If, after 30 minutes, the thermostat setting cannot be met, it switches to the furnace for stage-2 heating. For space heating and systems with air-source heat pumps, outdoor air temperature (OAT) reset is another simple hybrid control, where the switchover point is based on a preselected OAT. For example, the ASHP provides heating when the OAT is 45°F or warmer but switches to the furnace for heating when the temperature drops below 45°F. These two simple control strategies have been available for decades and can be performed by countless combinations of electric ASHPs and fuel-fired systems using traditional 24V thermostats or smart thermostats. As Figure 28 illustrates, 2-stage and OAT reset strategies allow the user to make setting adjustments to satisfy comfort level, irrespective of the impacts on operating cost, energy efficiency, and GHG emissions.

Smart dual-fuel switching is a more advanced hybrid technology pathway that uses the thermostat/aquastat, along with other cloud-based controls, to switch between electrically-driven heating and fuel-fired heating based on factors such as equipment efficiencies, utility energy rates, utility demand response signals, and GHG emission levels for electricity and fuel. However, these factors can sometimes conflict, as illustrated in Figure 28. From an environmental perspective, switching controls may be optimized to maximize energy efficiency and minimize GHG emission levels. Conversely, from the user perspective, comfort and/or cost may be the deciding factors. The challenge with smart dual-fuel switching is achieving cost-effective decarbonization without compromising comfort.

Utilities are already considering, planning, or executing residential dual-fuel space heating, or “hybrid” demonstrations. Decarbonization studies often call out hybrids as a high priority residential technical pathway [Liss, 2021]. However**, without a standard test method and given the dynamic operation between energy sources, evaluating the environmental impacts and cost-effectiveness of hybrid systems is difficult.** Efforts are underway by GTI Energy and others to develop load-based methods to evaluate hybrid HVAC [Fridlyand, 2022], which the lack of a rating method remains a pain point for this product category. Research in this area is still underway seeking to answer the following key questions that will provide guidelines for effective hybrid system implementation in various climates:

- What are the electricity and natural gas end-user and societal benefits of hybrid systems?
- What regional barriers exist and what incentives are needed for customers to switch from alternatives such as traditional fuel-fired or all-electric equipment to hybrid solutions?
- What unique features and advantages differentiate some hybrid technologies from others, and what technology RD&D needs should be addressed?
- What adaptive controls can be implemented in hybrid systems to satisfy potentially conflicting environmental and customer goals?

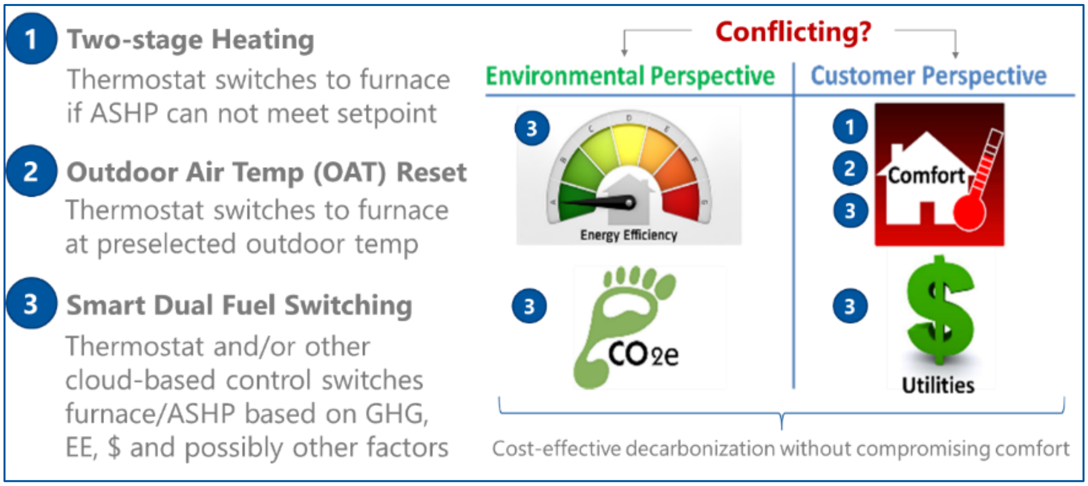


Figure 28: Smart Dual-Fuel Switching

GTI Energy's previous research characterizing the full performance spectrum of fuel-fired residential space heating systems [Guada, 2022a, Fridlyand, 2022], as well as cold-climate and non-cold-climate ASHPs [Guada, 2022b], indicates that these systems, if properly integrated and controlled, can generate energy, cost, and GHG savings by 15% to 30% (see Figure 29). More importantly, these savings can be realized now, with off-the-shelf equipment that gives customers choices in the fuels they use to heat their homes cost-effectively while realizing environmental and resiliency benefits. However, system design and operation (both by end-user and utility) will have a significant impact on outcomes. Given grid mix, energy rates, and a variety of other factors the "right" system will vary depending on program objectives, building type, and climate.

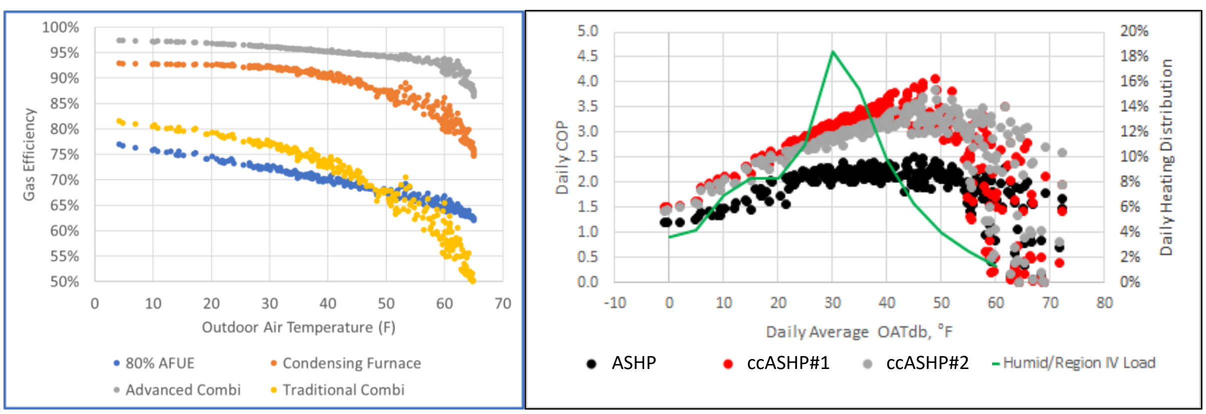


Figure 29: Fuel-fired Space Heating Performance (Left) and ASHP Space Heating Performance (Right) [Source: GTI Energy]

Research is underway to provide better insight into hybrid performance across a wide variety of factors to support more informed decision-making by utilities, consumers, and installers. These residential results are collected in tandem with large-scale trials of residential hybrid heat pumps, often with incentives[27] and with demonstrations of larger-scale hybrid heat pumps in

27 https://www.enbridgegas.com/sustainability/clean-heating/hybrid-heating

multifamily and commercial building applications [Hackel, 2022]. GHG emission reductions of 22% were seen in the residential trials [Neubert, 2022].

Technology Pathway Outlook

Hybrid systems can also operate based on utility demand response signals. Driven by ambitious goals to decarbonize the nation's power generation system, electrification is an emerging trend to switch end-use equipment from non-electric to electric sources of energy. Such societal shifts toward decarbonization coupled with technological advancements and rapid R&D investments have contributed to an expanding North American electric ASHP market. Those loads, combined with the effects of a nascent electric vehicle market, will likely strain the nation's power grid.

Figure 30 from NREL's 2021 Electrification Futures Study Report [Murphy, 2021] shows an extraordinary need for new installed power capacity given medium and high electrification load growth scenarios. In that report, new power capacity is predicted to be more than doubled by 2050, primarily met with intermittent PV and wind energy resources with very little storage capacity.

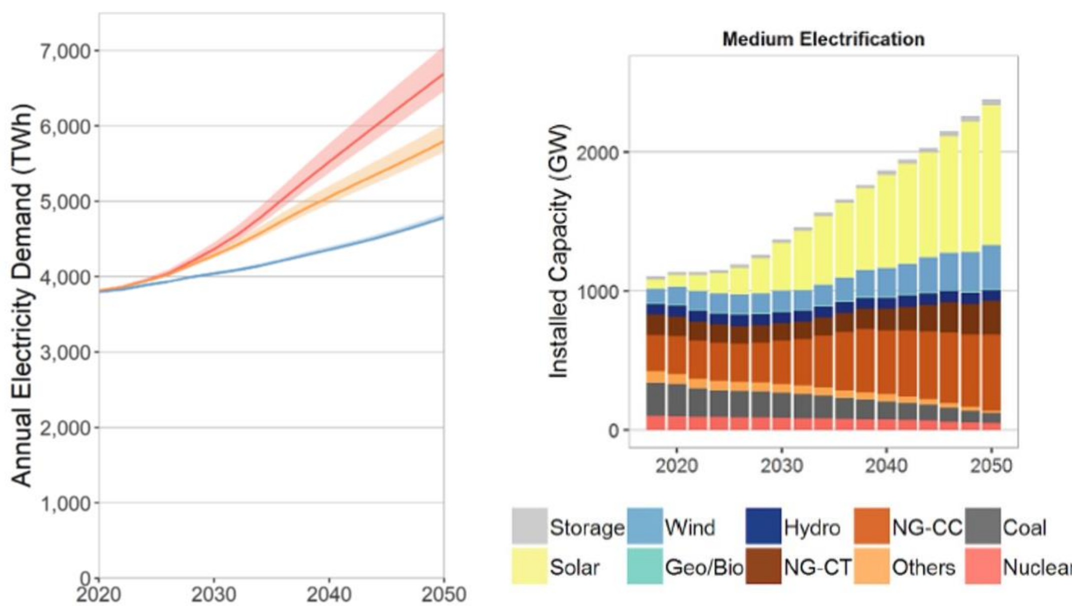


Figure 30: U.S. Power Capacity Predictions [Murphy, 2021]

Figure 31 shows the estimated average hourly electric demand (kWe) for three cold-climate pre-2010 construction residential scenarios, including: (1) gas furnace/tankless water heater (dark blue), (2) electric ASHP/HPWH (yellow), and (3) hybrid gas furnace/ASHP/tankless water heater (light blue). While the estimated winter electric demands for the hybrid system are higher than the gas scenario, they are significantly lower than the electric scenario.

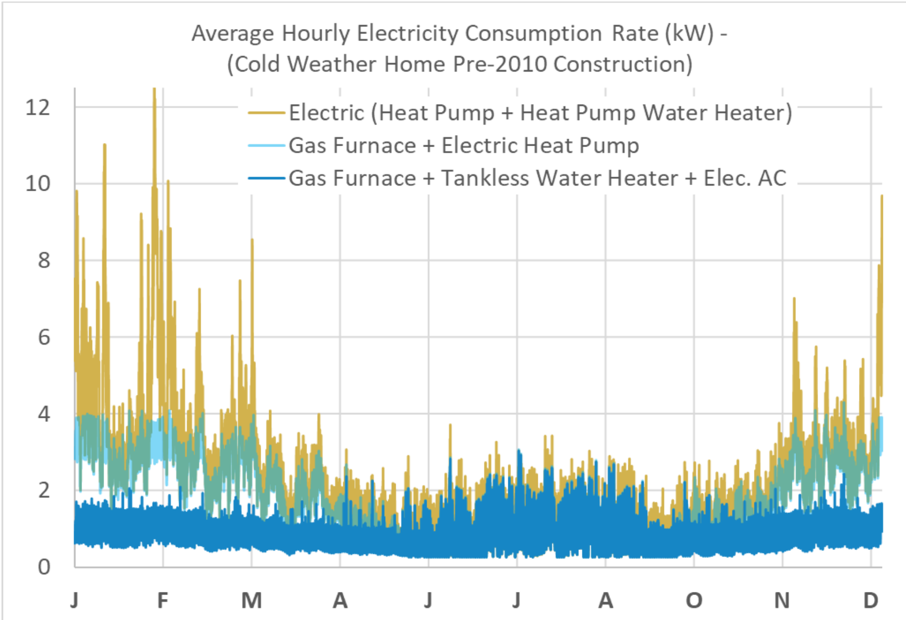


Figure 31: Fuel-fired, All-electric and Hybrid Electric Demand

As noted previously, with the nature of hybrid heat pumps is to integrate existing technologies with different energy inputs to serve a common load, often in packaged forms (with exceptions of optimized hybrid heat pumps, such as in Li, 2022), the innovation and market needs often stem in the form of (a) optimal product cost and heating component sizing and (b) the controls of the hybrid components to meet a range of different optimization scenarios. Preliminary research indicates most hybrid systems control the operation of the furnace and ASHP with a single cutoff setpoint based on OAT. The OAT setpoint is generally a manual selection set by the homeowner or the HVAC contractor who installed the hybrid system. Figure 32 shows a number of hybrid cutoff points when the system would switch from ASHP to furnace. An HVAC contractor might base the setting on the Balance Point – the point at which the ASHP can theoretically no longer meet the building load because it is too cold outside. A homeowner may base the setting on comfort. Furthermore, from a purely energy efficiency perspective, it may be more efficient to switch to the furnace at a lower OAT than the Balance Point because the ASHP can still operate more efficiently than the furnace. In contrast, it may be more cost-effective to switch to the furnace at a higher OAT than the Balance Point because it is more expensive to operate the ASHP than the furnace. These various parameters can be addressed by adaptive controls that satisfy potentially conflicting environmental and customer goals.

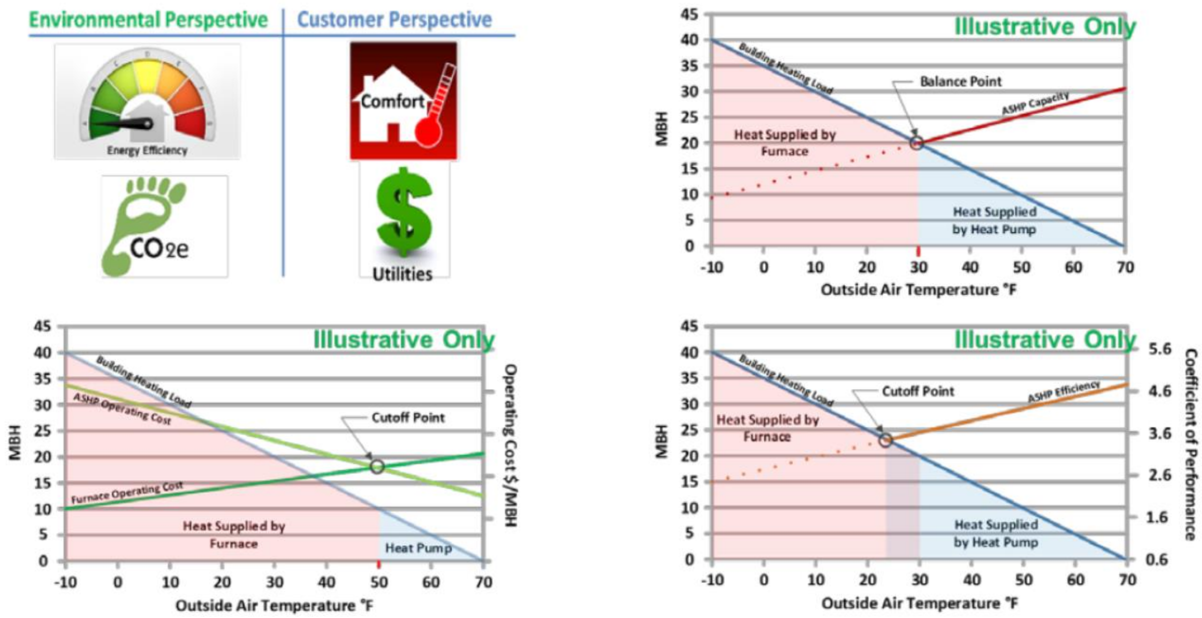


Figure 32: Examples of Hybrid Cutoff Points

Figure 33 shows how additional adaptive controls can be implemented in a typical hybrid system. In the example, the furnace and ASHP are controlled by the smart thermostat (proprietary or third-party) and the thermostat has some cloud services such as OAT data. A separate cloud control platform can be implemented so that it communicates with the thermostat cloud and adds additional adaptive controls such as real-time utility costs, GHG factors, utility demand signals, etc. Moreover, the adaptive controls can be configured so homeowners can control how they operate their system (e.g., lower operating cost, lower GHG, or some balance between the control parameters).

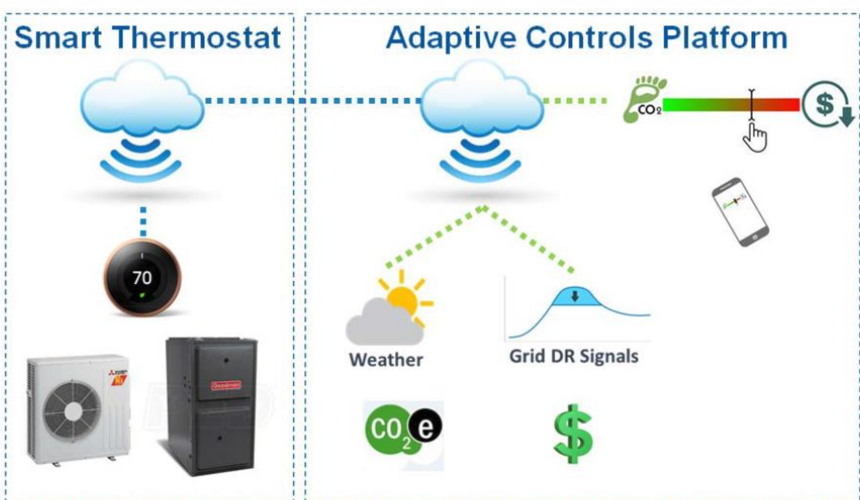


Figure 33: Example of Adaptive Control Platform

Because hybrid systems use both electricity and delivered fuels, it is difficult to estimate annual operating cost, carbon intensity, or other performance metrics. Further, **there is no standard test method to reference for evaluating the performance of hybrids**. Hybrid systems are expected to grow in market share and may offer a critical decarbonization pathway, serving as the lowest cost alternative. However, today it is challenging to evaluate the cost, carbon, or efficiency of this system relative to a gas or electric-only baseline. Comparative analysis across different variables is necessary to evaluate the role hybrid systems can play in cost-effective decarbonization. These are some of the primary gaps to address to realize the potential of hybrid heat pump technologies.

References for Hybrid Heat Pump Section

- Friedel, P. et al. 2019. Hybrid Heat Pumps: HPT Annex 45 Final Report, Report prepared for the International Energy Agency. Link: https://heatpumpingtechnologies.org/annex45/
- Li, Z. et al. 2022. Seamlessly Fuel Flexible Heat Pump with Optimal Model-based Control Strategies to Reduce Peak Demand, Utility Cost, and CO_2 Emission. Proceedings of the 2022 ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar, CA. Link: https://www.osti.gov/servlets/purl/1885311
- Fridlyand, A.; Guada, A.; Kumar, N.; Ahsan, A.; Kingston, T.; and Glanville, P., "Load-based Testing of Heating and Cooling Equipment Informed by Detailed Energy Models" (2022). International Refrigeration and Air Conditioning Conference. Paper 2390. https://docs.lib.purdue.edu/iracc/2390
- Guada, A., Kingston, T. 2022a. A Novel Approach to Determining As-installed Space and Water Heating Equipment Performance and Quantifying Potential Energy and Cost Savings in Buildings: GTI Energy. ASHRAE LV-22-C021.
- Guada, A., Kingston, T. 2022b. Combined Cold-climate Air-source Heat Pump and Heat Pump Water Heater System Performance in Multiple Climate Zones: GTI Energy. ASHRAE LV-22-C019.
- Hackel, S. et al. 2022. The Present and Future of Decarbonizing through Electrification in Commercial Buildings in the Midwest. Proceedings of the 2022 ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar, CA. Link: https://slipstreaminc.org/sites/default/files/documents/publications/present-and-future-decarbonizing-through-commercial-electrification-midwest.pdf
- Liss, W., Rowley, P. 2021. Assessment of Residential Natural Gas & Electric Decarbonization in Washington State: GTI Energy.
- Margolies, J. and Grimes, K. 2019. 2019 Dual Fuel Air-Source Heat Pump Monitoring Report, report prepared by Slipstream, Inc. Link: https://slipstreaminc.org/sites/default/files/2022-05/dual-fuel-air-source-heat-pump-pilot.pdf
- Margolies, J., Thayer, A. 2020. Advancing Beneficial Electrification: The Role of Dual Fuel Home Heating Systems in Cold Climates, Report prepared in partnership with NRECA and Beneficial Electrification League. Link: https://www.cooperative.com/programs-services/bts/documents/techsurveillance/surveillance-beneficial-electrification-dual-fuel-heating-march-2020.pdf
- Murphy, Caitlin, Trieu Mai, Yinong Sun, Paige Jadun, Matteo Muratori, Brent Nelson, and Ryan Jones. 2021. Electrification Futures Study: Scenarios of Power System Evolution and Infrastructure Development for the United States. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72330.
- Neubert, D.; Glück, C.; Schnitzius, J.; Marko, A.; Wapler, J.; Bongs, C.; Felsmann, C. Analysis of the Operation Characteristics of a Hybrid Heat Pump in an Existing Multifamily House Based

on Field Test Data and Simulation. *Energies* 2022, *15*, 5611. https://doi.org/10.3390/en15155611

- Vaishnav, P. and Fatimah, A. M. Environmental Science & Technology 2020 54 (16), 9814-9823, DOI: 10.1021/acs.est.0c02705.
- Liss, W., Rowley, P. 2021. Assessment of Residential Natural Gas & Electric Decarbonization in Washington State: GTI Energy.

6. Low-Carbon and Zero-Carbon Fuels

Summary of Technology Pathway

All heating equipment described in this analysis—water heaters, boilers, furnaces, and infrared heaters—emit net CO_2 emissions when operating with fossil fuels, specifically:[28]

- Natural gas combustion will yield 145.7 lb CO_2e/MMBtu consumed
- Propane combustion will yield 168.5 lb CO_2e/MMBtu consumed
- Heating Oil combustion will yield 195.6 lb CO_2e/MMBtu consumed

To put these values into perspective, a natural gas-fired residential water heater and furnace operating in a typical cold climate home would emit approximately 2 and 7 metric tons of CO_2e/year, while a typical commercial water heater or boiler serving larger thermal loads would emit approximately 80 and 440 metric tons of CO_2e/year.[29] To fully mitigate these GHG emissions requires a portfolio of solutions, which often includes energy conservation, efficiency measures (e.g., fuel-fired or hybrid heat pumps), mitigation of methane emissions along the fuels value chain, carbon capture, utilization, and storage, and displacing the use of fossil fuels with low-carbon and zero-carbon fuels, wholly or in part. This section concerns the last item. Increasingly, non-fossil fuels are available either by pipeline distribution or by transport, to reduce GHG emissions with a decarbonized energy supply in a similar manner to direct use of renewable electricity. The importance of this supply-side decarbonization can be seen in a scenario modeled as part of a prominent study for the American Gas Association, which showed that the potential for full replacement of fossil gas is responsible for nearly 60% of GHG emission reductions, largely through blended low-carbon hydrogen with renewable or synthetic methane [AGA, 2022], (see Figure 34). This approach is mirrored by several utility decarbonization plans [National Grid, 2022 and Northwest Natural, 2021].

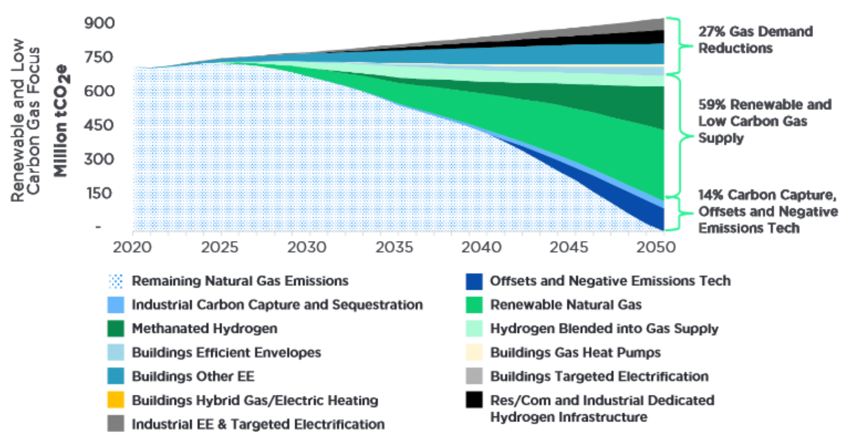


Figure 34: Example of Decarbonization Strategy – AGA Net Zero to 2050 Scenario [AGA, 2022]

[28] Emission factors from https://cmicseeatcalc.gti.energy/
[29] For water heating, 84 and 5,000 gal/day are assumed for residential and commercial loads respectively. For space heating, 0.1 MMBtu/h maximum input furnace and 4.0 MMBtu/h maximum input boiler are assumed, to operate with 1,022 and 1,670 equivalent full load hours respectively per State of Illinois Technical Reference Manual.

The primary low-carbon and zero-carbon fuels discussed in this section are (1) *hydrocarbons*, frequently direct substitutes for existing fossil fuels but generated by mitigating the GHG impact of waste streams (e.g., wastewater treatment) and/or renewable feedstocks (e.g., biomass), and (2) *hydrogen-based fuels*, an emerging low- or zero-carbon energy vector generated from renewable power or decarbonized hydrocarbons. In terms of GHG emissions displaced by these non-fossil fuels, complex accounting is often required, similar to tracking the carbon intensity of delivered electricity. This remains an important area of research and policy development. As such, the GHG emissions benefit of these emerging fuels may evolve regionally over time, however, they represent an important supply-side decarbonization strategy for combustion-based building equipment.

Fuels delivered by transport:

- Propane substitutes include biogenically-produced direct substitutes (e.g., *biopropane*) or alternatives such as biogenically-produced rDME, which can collectively displace fossil propane GHG emissions through net mitigation of lifecycle emissions overall, with estimates of 70% reductions or greater.[30]
- Similar to propane, low-carbon liquid fuels are emerging as substitutes for heating oil. These include biogenic heating oil or renewable diesel fuels, which can offer net GHG emission reductions of between 50% and over 90%, over fossil fuels.[31,32]

Fuels delivered by pipeline distribution :

- Natural gas substitutes are biogenic or synthetic methane-rich mixtures that include *renewable natural gas*, or alternatively *biomethane*, and pre-processed *biogas*. Net GHG emission benefits from the fuel depend on its generation, but range from 66%-100% reduction vs. fossil natural gas.[33]
- Hydrogen-based fuels may be delivered by repurposed natural gas infrastructure and equipment (as a blend) or purpose-built versions of the same. These fuels have significant reductions in GHG emissions primarily through elimination of CO_2 emissions at the point of use. While net GHG emissions reductions will vary with the method of hydrogen generation employed, they can reach 90% or greater.[34] However, significant consideration is required for the substitution of natural gas-fired equipment to accommodate hydrogen-based fuels because of the impact of fuel energy density and overall compatibility, which are discussed below.

As a technology pathway, low-carbon and zero-carbon fuels drive decarbonization as an *Upstream and Downstream Decarbonization* solution: they are the primary supply-side solution for heating equipment. *Most* of the low-carbon fuels listed above are practically indistinguishable from the fossil fuels they replace (e.g., natural gas vs. RNG). Thus, their ability to scale up to drive significant GHG reductions with existing and new heating equipment is a

[30] Emission factors from https://cmicseeatcalc.gti.energy/
[31] Source: https://f542d7.p3cdn1.secureserver.net/wp-content/uploads/2019/01/Environmental-Benefits-of-Biodiesel.pdf
[32] Source: Based on emissions factors from https://cmicseeatcalc.gti.energy/ and *NYSERDA. 2022. "Fossil and Biogenic Fuel Greenhouse Gas Emission Factors," NYSERDA Report Number 22-23. Prepared by E3, Inc. San Francisco, CA.*
[33] Ibid.
[34] Estimate based on low-carbon hydrogen thresholds established within the U.S. *Inflation Reduction Act.* (https://www.congress.gov/117/bills/hr5376/BILLS-117hr5376enr.pdf).

function of their availability and cost. Availability is increasing rapidly as many North American utilities and other energy suppliers provide these fuels today, although be noted that concerns remain on the overall scalability of these fuel supplies[35] when coupled with a full portfolio of decarbonization solutions. Nonetheless, gas networks in Europe are demonstrating that full conversion from fossil to low-carbon gases is feasible, with the Danish distribution network achieving a 30% biomethane/natural gas blend today, and projecting 100% biomethane network-wide before 2030.[36] Costs of these low-carbon fuels typically range from 2 to 4 times higher the fossil fuel replaced,[37] however, this premium can be reduced when credits/incentives are available.

Research and technology gaps for "drop-in" low-carbon fuels are minimal, primarily concerning the impact of fuel quality variations on equipment. Hydrogen-based fuels are a unique case, however. These fuels have the benefit of eliminating stack GHG emissions, thus comparably obviating most concerns with site versus net full-cycle GHG emissions central to biogenic low-carbon fuels. However, hydrogen-based fuels are not a "drop-in" fuel. They require care when used in conventional equipment (e.g., as a blend in modified equipment designed for natural gas), as well as in purpose-built equipment for hydrogen firing. Compared to hydrocarbons, hydrogen's distinct physical and chemical attributes necessitate unique approaches to retain the expected safety and performance of water heaters, boilers, furnaces, and infrared heaters. While research and technology gaps remain to accommodate the use of hydrogen-based fuels in these types of equipment, these gaps are currently being addressed, and significant investments are seen on the supply-side. Numerous North American utilities are performing demonstrations and controlled trials of blending hydrogen into their gas grids today, building on both blended and 100% hydrogen distribution trials in the UK and Europe, with future intent to incorporate hydrogen-based fuels in their supply mix. These efforts are not only spurred by utility efforts to decarbonize their Scope 3 GHG emissions (those from utility customers), but by significant government support and incentives as outlined in the *Hydrogen Strategy for Canada* and in the U.S. *Inflation Reduction Act*,[38] which outlines significant tax credits as shown in Figure 35.

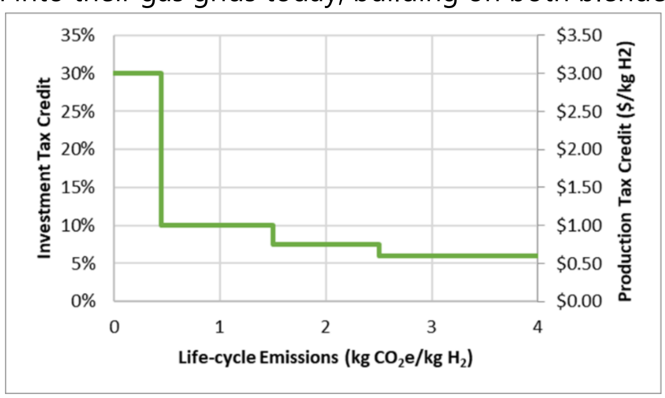


Figure 35: Tax Credits for Hydrogen in the U.S. IRA

In summary, it is technically feasible to fully decarbonize combustion equipment in buildings with the use of these emerging non-fossil fuels on either a site or full-cycle basis, using fuels that are currently distributed to end users in North America or abroad. Like the potential for

35 These concerns include impacts on land use, challenges with availability, collection, and scale of waste streams, and specific challenges with the expansion of so-called "energy crops."
36 Source: https://en.energinet.dk/Gas/Biomethane#Info
37 Ibid.
38 Source: https://www.nrcan.gc.ca/sites/nrcan/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf and https://www.congress.gov/117/bills/hr5376/BILLS-117hr5376enr.pdf

electrically-driven heating equipment, where 100% emission-free delivered electricity is also feasible, the availability and cost of the low/zero-carbon fuels as an enabling resource remains to be determined. As outlined in this section, the transition of low-carbon and zero-carbon fuels to displace fossil fuels is underway, wherein the GHG-intensity of delivered fuels will decline with time. This mirrors the process already underway in the electricity grid, which by significant investments and efforts has increased the share of wind and solar generation from 3% to 12% of total U.S. generation from 2010 to 2021.[39] Therefore, it is important for heating equipment to be compatible with these emerging fuels, where technically feasible, and when the fuels are regionally available, and cost-effective, as discussed below.

Overview of Technology Status

For water heaters, boilers, furnaces, and infrared heating equipment, technology gaps to transition to the aforementioned low-carbon and zero-carbon fuels fall into one of three categories:

1) Components and system designs that *permit consumption* of these emerging fuels given the change in fuel properties relative to existing components and system designs employed for conventional fossil fuels. As most hydrocarbon-based low-carbon fuels are functional "drop in" fuels to the fuels they displace, this is primarily a concern for hydrogen-based fuels. An example of a technology gap is flame supervision controls suitable for natural gas or hydrogen-based fuels.
2) Technology solutions that enable flexibility of fixed assets with the *evolution of and variability in delivered fuels*, under the premise that the transition of fuels delivered by transport or pipeline distribution will vary regionally and over time. Similarly where blending of low-carbon and zero-carbon fuels is performed, amongst these fuels and with conventional fossil fuels, the nature and composition of fuel mixtures may vary dynamically within the span of months, weeks, and days. An example of a technology gap is low-cost distributed gas quality sensing equipment and their method of use with stationary combustion equipment.
3) Components and system designs that *mitigate long-term impacts* of exposure to the use of these emerging fuels, relative to conventional fossil fuels. Similar to #1, this primarily concerns hydrogen-based fuels but also trace contaminants and other species that may be present in hydrocarbon-based fuels. An example of a technology gap is the materials of construction or coatings necessary to mitigate hydrogen permeation through component walls and seals.

These technology gaps and their RD&D status will vary with application and low-carbon/zero-carbon fuel concerned, and there is a growing body of research defining the range of potential operational challenges with typical combustion equipment in buildings. As such, it is useful to start with a review of these fuels and the research concerning their impacts on equipment.

39 Source: https://flowcharts.llnl.gov/commodities/energy

Review of Low-Carbon and Zero-Carbon Fuels – Biomethane, Biogas, and other Hydrocarbons

The first of two groups of low-carbon/zero-carbon fuels are hydrocarbons, biogenic or synthetic, inclusive of methane-rich mixtures as a substitute for natural gas, substitutes or replacements for fossil propane, and low-carbon liquid fuels.

Low-carbon liquid fuels as a replacement for heating oil are increasingly available in the U.S. Northeast, the primary regional market for heating oil. Under the "Bioheat®" label, blends of biodiesel with ultra-low sulfur fossil heating oil include low (2%-5%), mid (5%-20%), high (20%+), and pure biodiesel (B100). Biodiesel is sourced from multiple feedstocks for heating. These include used cooking oil and canola oil, which result in GHG emissions avoided of 79% to 52%, respectively.[40] With active research performed or supported by the *National Oilheat Research Alliance* (NORA) and their partners, multiple technical gaps to adopting higher blends of biodiesel in equipment components and operation are being addressed. Increasing the amount of biodiesel shifts key properties of the fuel, including composition (e.g., O_2 content increases from 0% to 11%), physical properties (e.g., viscosity changes), material compatibility, and overall shelf life. Thus, water heaters, boilers, furnaces, infrared heaters, and other equipment adopting these fuels need to account for these impacts.[41] Key research areas include impacts on oil pumps concerning seal wear and leakage, long-term compatibility with "yellow metals" like copper, tuning of combustion equipment, and impacts of long-duration storage of biodiesel in tanks [Butcher, 2019 and Kerr, 2022]. With recent demonstrations of these impacts in field demonstrations, comparing standard heating oil or low blends (e.g., B5) with higher blends in components (see Figure 36), no substantial technical barriers have been identified to widespread adoption to this low-carbon fuel.

Figure 36: Burner Operating with B5 through B100 Low-Carbon Liquid Fuels (Source: NORA)

Low-carbon substitutes for propane include renewable propane (alternatively "bio-LPG") and other biogenically produced molecules such as rDME. Like biodiesel, there are parallel markets for these low-carbon fuels in the transportation sector, and similarly there are low-carbon "drop-in" fuels available today in North American[42] and UK/European markets.[43] For propane/LPG-type fuels, case studies verify these claims from LPG suppliers of "drop-in" characteristics,[44] however, limited research has been performed to characterize impacts of trace contaminants or longer-term impacts, which have been performed for liquid fuels. DME, for blending with or substitution of with LPG-type fuels, has been less studied across the heating equipment categories cited. Where suppliers claim that a 20% rDME blend requires no modification to existing equipment, this may largely be based on limited distribution to customers [WPGA,

40 https://mybioheat.com/wp-content/uploads/2021/05/Bioheat-One-Choice-Flyer-NBB-Greenhouse-Gas-Emissions.pdf
41 Source: https://noraweb.org/equipment/
42 https://www.suburbanpropane.com/suburban-propane-experience/suburban-renewables/rdme/
43 https://www.shvenergy.com/what-we-do/sustainable-fuels/biolpg
44 Ibid.

2021]. For DME specifically, limited research provides further insight into the impacts on cooking equipment [Anggarani, 2014] and stationary engines [Dames, 2016 and Fabis, 2021]. Thus, more research is needed to quantify the impacts and technology gaps of adapting low-carbon substitutes for propane that are not "drop-in" mixtures.

Methane-based low carbon fuels are further grouped into biogenic fuels and synthetic fuels.[45] Biogenic fuels include raw *biogas*, which is often the output of anaerobic digestion of animal/plant wastes (commonly agricultural, landfill, and wastewater treatment-based sources). *Biogas* can also be upgraded to *biomethane* (alternatively "renewable natural gas"), to remove impurities, reduce quantity of inert gases (primarily CO_2), and otherwise generate a mixture identical to natural gas. *Biomethane* can also be generated through the thermal conversion of biomass feedstocks. Synthetic gaseous fuels are generated through the conversion of hydrogen and CO_2, "*e-methane*" (alternatively "synthetic natural gas"), which is a direct substitute for fossil natural gas, akin to biomethane. Pilot demonstrations have utilized renewable energy and captured CO_2 to generate the e-methane.

For *biogas* upgraded to *biomethane*, the IEA sustainable development scenario points to a >3 times increase in overall *biomethane* use from 2025-2040, with consumption in buildings as the largest sector [IEA, 2020]. Provided that the feedstock is a renewable resource, the fuel can be credited as renewable energy, inclusive of methane emission mitigation benefits from waste streams. However, energy crops may be limited as a resource. In Europe, for example, only up to 12% of biomethane produced in Denmark can be from energy crops [Sejbjerg, 2022]. Broadly for distribution utilities, many are delivering RNG blends with natural gas today, with ambitious near-term goals. This includes market leaders in Europe, like Evida in Denmark with projections of 100% RNG in network before 2030, and in North America many utilities have committed to ramping up supply. This includes 20% of SoCalGas' supply by 2030 (Southern California) and 5% of Enbridge's supply by 2030 (Greater Toronto Area), representing the largest utilities in the U.S. and Canada respectively. These goals have stimulated a significant increase in the production of RNG. U.S. biomethane projects increased from 13 to 174 between 2005 and 2021 [EPA, 2022]. Where North America differs from Europe and the UK is the absence of a national gas quality standard, like the DVGW G 260 standard in Germany. Thus, utilities and distribution operators must define their own injection requirements. Table 10 provides an example of SoCalGas' Rule 30 limits, where these same requirements apply to synthetic fuels, generated via methanation of H_2 and CO_2.

45 Note that there exist synthetic pathways to generate low-carbon substitutes for propane and heating oil, though while technically feasible these are less common generation pathways as compared to synthetic methane.

Table 10: Example of Injection Requirements for RNG Into Utility Gas Grid – SoCalGas Rule 30 (Source: SoCalGas)

	Min.	Max.		Less than	
Heating Value	970	1150	Water	7	lb/MMscf
Wobbe Index	1279	1385	H_2S	4	ppm
Lifting Index		1.06	Mercaptan Sulfur	5	ppm
Flashback Index		1.2	Total Sulfur	12.6	ppm
Yellow-Tip Index	0.8		CO_2	3%	by vol.
			O_2	0.20%	by vol.
			Inerts	4%	by vol.

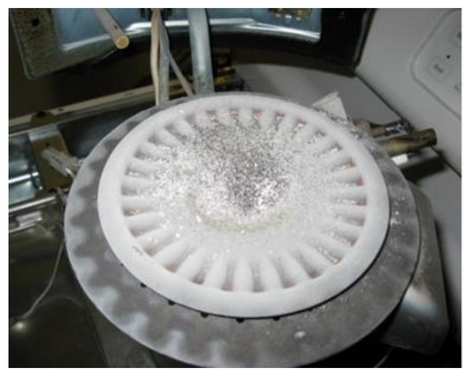


Figure 37: Impact of Siloxanes on Water Heater Burner Above Typical Tariff Thresholds

Provided that biomethane ("RNG") or synthetic methane ("e-methane") is chemically indistinct from natural gas and criteria are met for pipeline injection by utility tariffs/rules, there are no special requirements for infrastructure or equipment for this "drop-in" fuel, as consumed or blended with natural gas. There is emerging research concerning trace contaminants above or below detection or regulatory thresholds, however, those that present potential challenges to the reliability and operability of combustion equipment include: silica-based compounds (siloxanes) and sulfur-bearing compounds. The former are generally present in biomethane produced from landfill gas and wastewater treatment facilities, originating from a wide range of consumer activities (e.g., use of cleaning products). When present in trace quantities, layers of silica (SiO_2) form on surfaces close to the flame. Extreme laboratory tests, including those performed by GTI Energy (see Figure 37), have resulted in increased operating temperatures, reduced combustion airflow leading to increased carbon monoxide emissions, and reduced efficacy of flame sensing components [Von Wald, 2019]. For sulfur-bearing compounds, primarily H_2S, these are naturally present in biogas but generally removed through desulfurization in biomethane upgrading. Sulfur-based compounds are also used in odorizing natural gas, tertiary-butyl mercaptan for example. With an odor threshold of less than 1 ppb, the prior desulfurization in natural gas production produces a fuel that readily complies with standard requirements (e.g., 17 ppm of total sulfur permitted and 4 ppm of H_2S permitted in California). If biomethane contains sulfur-based compounds that are closer to these allowable thresholds, long-duration weakening of equipment surfaces is possible. This remains an active area of research.

Review of Low-Carbon and Zero-Carbon Fuels – Hydrogen-Based Fuels

The concept of hydrogen as a low carbon energy vector within the gas grid isn't new, with references to the "green hydrogen" concept going back to the 1970s [IGT, 2017]. Hydrogen-based fuels are considered as a decarbonization vector to be blended with fossil and/or low-carbon fuels, or used directly. Like electricity, hydrogen can be generated in multiple ways, as a means of storing renewable energy ("green" H2) or decarbonizing fossil natural gas with integrated carbon capture ("blue", "turquoise" H2). While popular as short-hand for methods of production, the use of hydrogen "colors" does not adequately capture the embedded GHG emissions of these fuels, and there are efforts to increase market transparency, such as the U.S. Open Hydrogen Initiative.[46] Numerous utilities have announced hydrogen injection programs, spurred by national government initiatives. These include the Canadian National Hydrogen Strategy [NRCan, 2020] and the U.S. Dept. of Energy's EarthShot [DOE, 2021] to reach a goal of $1/kg H2, and aforementioned incentives within the 2022 *Inflation Reduction Act*. However, hydrogen presents challenges when re-purposing infrastructure and equipment designed for natural gas because hydrogen's unique properties as a fuel relative to natural gas are manifold [Glanville, 2022]. With technical and cost limitations considered, to re-use and retrofit existing infrastructure in the near term, the vast majority of projects underway now concern gradual blending of hydrogen with delivered natural gas in North America, as opposed to distribution of pure hydrogen, though this is evolving and will be discussed further below.

- **Initial blending** of hydrogen into the gas grid, displacing fossil gas and potentially blended with renewable or synthetic methane as well, is a near-term approach to achieving broad decarbonization across multiple end use sectors. Blending into gas grids is seen as one of the largest sources of *sustained demand* of hydrogen, as a clean energy commodity, while the costs of generation, storage, and transmission decline. With proposed blending ratios often <25% by volume and, due to the reduced volumetric energy density of hydrogen, the fact that there is a non-linear relationship between hydrogen blended and GHG emission reductions, one can be excused by initially viewing this as a minor decarbonization opportunity. This viewpoint is centered on the effort to deliver a fuel mix with 20% renewable hydrogen to achieve a 6%-8% reduction in GHG emissions for a given piece of combustion equipment.[47] However this is a narrow viewpoint, as the opportunity is in the near term and in the aggregate. As an example, California has an estimated annual 34 $MMTCO_2e$/year of GHG emissions associated with fossil natural gas consumed in homes and businesses [EFI, 2019]. An effort underway by the state's major investor-owned utilities to blend up to 20% renewable hydrogen into the gas grid in the near term [Sempra, 2020] would reduce GHG emissions from California homes and businesses by up 3 $MMTCO_2e$/year, an amount approximately equal to eliminating *all* vehicle miles travelled in Los Angeles County[48] for more than a month [EPA, 2022 and LA County, 2017].

46 https://www.gti.energy/ohi/

47 Actual GHG emission reductions will depend on specific equipment, impact on thermal efficiency, and whether or not in-situ adjustments are made to accommodate hydrogen-based fuels.

48 Note that Los Angeles County is not only the most populous county in the U.S., nearly twice the population of the second-most populous county, but its population is renowned for its car-dependence in mobility.

- Over a longer term, once hydrogen blending is well established by a given utility, meeting or approaching goals of delivered hydrogen costs and low carbon energy content, the feasibility for **hydrogen distribution networks** improves and, by extension, 100% hydrogen compatible equipment proliferates. Efforts toward this transition in the U.S. trail those in Europe and the UK, where small pilots of hydrogen-ready homes and buildings lead to 100s and 1,000s of utility customers over the 2023-2026 timeframe. However, North American efforts are now underway to (a) utilize a gas grid carrying a hydrogen gas blend to serve hydrogen-fueled equipment, by extracting pure hydrogen from the blend, and (b) demonstrate 100% hydrogen compatible buildings, with example shown in Figure 39 [SoCalGas, 2022]. Additionally, in support of the transition from equipment suitable for blended hydrogen/natural gas toward equipment that is compatible with 100% hydrogen, "hydrogen ready" labelling schemes are under development. These recognize equipment capable of (a) operating with hydrogen blends, (b) designed for 100% hydrogen, or (c) convertible in-situ from one to another.[49] Multiple demonstrations of 100% hydrogen-ready equipment have been announced, ranging from cooking appliances, space heating equipment (boilers,[50] infrared heaters, furnaces[51]), tankless water heaters,[52] hearth products, supporting components (e.g. premix blowers), and other equipment [Hy4Heat, 2022].

Figure 38: Hydrogen Labeling Scheme in UK [Source: HHIC]

Figure 39: "Hydrogen Home" Concept by Southern California Gas [SoCalGas, 2022]

As a combustion fuel, hydrogen's unique properties are well documented. For instance, using a 20% blend by volume based on standard gas quality calculations, specific gravity is reduced by 17%, heating value by 14%, combustion air requirement by 15%, Wobbe Index by 5%, CO_2 emission factor by 7% (energy-adjusted), and an increase in stoichiometric laminar flame speed of 15%. Each of these shifts in properties can impact end use equipment, from operating

49 https://www.hhic.org.uk/news/heating-industry-agree-hydrogen-appliance-labels
50 https://hydrogentechnologiesinc.com/wp-content/uploads/sites/2/2022/08/HT-Spec-Brochure-2022.08.pdf
51 https://www.ngif.ca/ngif-industry-grants-announces-its-round-7-innovation-challenge-cleantech-startup-finalists-with-2-48-million-in-funding/
52 https://www.rinnai-uk.co.uk/about-us/hydrogen-sustainability

efficiency, flame stability, NO_x emissions, to surface temperatures, among other impacts. The nature and severity of impacts depend not only on the quantity of hydrogen blended, but also heavily on the burner type (premix vs. partially-premix vs. diffusion type), equipment category and design, nature of product installation, level of maintenance, and other operating factors (e.g., elevation). In addition to equipment operation, hydrogen blending may impact fuel leakage rate within components and connections downstream of the utility meter. These factors are summarized in Table 11, and in a brief appendix, with a greater detailed by Glanville [Glanville, 2022].

Table 11: Summary of Key Hydrogen Properties Compared to Methane

Feature	Compared to Methane	Possible Equipment Issues
Volumetric Energy Density	At equal operating pressures, H_2 has ~1/3 the energy density on a volumetric basis even though it has ~2.5X the energy density on a mass basis	With increasing H_2 blends, the effective heating rate of the appliance decreases, ranging from 7% derating (10% H_2 blend) to 34% derating (50% H_2 blend)
Flame Temperature	Adiabatic flame temperature is ~500°F (278°C) hotter than methane	Flame burns hotter, can lead to uneven heat transfer and material degradation
Flame Speed	Methane/air has a laminar flame speed of ~38 cm/s, however increasing H_2 volumes can increase over 2X	Can lead to flame stability issues, ignition problems and flashback
Flammability Range	Hydrogen has extremely wide flammability range (4% LEL to 75% UEL) compared to methane (5% LEL to 15% UEL)	H_2 portion can ignite prematurely in rich pockets of fuel/air mixture, via pre-ignition
By Products	Produces only water vapor when oxidized (no CO_2)	Flue gas dew point will be higher for constant λ, leading to unwanted condensation/corrosion. Also, many products are calibrated or controlled to stack CO_2 which will be off with the addition of H_2.
Visibility / Ionization	Hydrogen burns with reduced luminosity, ionization issues	Safety equipment to detect flame (flame rod, etc.) and technicians/operators will need updating/training

Perspectives from the Manufactured Gas Era[53]

The use of manufactured gases grew as the heating industry matured, from the late 19th to early 20th century. During this time, standards also formulated. The majority of standards today that concern gaseous fuels still allow for testing with manufactured gases, typically defined as having a higher heating value (HHV) of 535 btu/ft^3, specific gravity of 0.38 (natural gas is 0.65), and a reduced test pressure to that of natural gas (appx. ½) [ASHRAE Standard 103, 2017]. In other industry standards, notably those under the ANSI/CSA Z21/83 umbrella concerning the performance and safety of the majority of stationary combustion equipment, manufactured gases are defined identically as one test gas (Test Gas C), with an additional "mixed gas" option

53 Portions of this summary were developed in conjunction with a conference paper accepted for the 2023 ASHRAE Winter Conference.

with a HHV of 800 btu/ft^3 (29.8 MJ/m^3) and specific gravity of 0.50 [ANSI Z21.10.3, 2017]. This "mixed gas" is intended to reflect both the transitional period from manufactured to natural gases and the common practice of addressing peak demand with blended gases [Hamper, 2007 and Tarr, 1999]. Today manufactured gases have largely been replaced by modern gaseous fuels, due to the cost, complexity, and environmental hazards associated with historic approaches to gasification of solid/liquid fuels, although exceptions are made for populous islands. Singapore maintains one of the largest active manufactured gas networks today, serving 880,000 customers with a 1.6 million m^3/day production facility with a high-hydrogen containing fuel mixture, typically 50% hydrogen by volume [City Energy, 2021]. In the U.S., Hawaii Gas has long operated a distribution network on Oahu delivering a manufactured gas containing 10%-15% hydrogen by volume[54] serving 30,000 customers [Hawaii Gas, 2022].

Overview of R&D and Industry Efforts

Today efforts are underway to "reverse" this early 20th century conversion, replacing fossil natural gas with a combination of biomethane/e-methane and hydrogen, a low carbon mixture that may be locally produced. As noted previously, low-carbon fuels based on hydrocarbons are available today. Their production rate, the availability of incentives/credits, and costs to end users are projected to improve in the coming years. However, based on the current emerging status of hydrogen-based fuels, significant activities are underway to understand the impacts of their distribution and use, and demonstrate the feasibility of scale-up. As a result, the balance of this section will concern gaps and RD&D efforts focused on hydrogen-based fuels. Initially in the U.S./Canada, and already underway in Europe and Asia, utilities are blending hydrogen into existing gas grids as a near-term means of abating emissions from existing combustion equipment, while driving demand of a low-carbon fuel to improve the economics of generation, storage, and delivery. There are many active blending pilots at the time of writing. An excellent summary by Mahajan [Mahajan, 2022] and other updates collected include the following highlights from North America:

- California: A joint effort between San Diego Gas & Electric and SoCalGas for multiple demonstrations of blending initially from 1%-5% hydrogen by volume up to 20%, in multiple portions of their networks, running from 2021-2026, in addition to the demonstration *Hydrogen Home* as a flagship pilot in Los Angeles.
- Minnesota: One of the largest green hydrogen generation and injection demonstrations was operational mid-2022, involving generation of nearly 500 kg/day of hydrogen.
- New Jersey: Currently piloting one of North America's first green hydrogen injection pilots, New Jersey Natural Gas has been blending hydrogen into a section of its gas grid up to 15% by volume since late 2021 with plans to expand.
- New Mexico: Currently pursuing controlled pilots of hydrogen blending up to 15% by volume, with efforts looking at higher blends. New Mexico Gas Company plans to inject into a mixed residential/commercial section of their network as soon as 2023.

54 Note that the gas contains hydrogen due to the manufactured gas feedstock, like other manufactured gases, and it is not explicitly a "hydrogen blending" initiative.

- New York: National Grid has initiated a green hydrogen project on Long Island, serving a mixture of customers for transportation and approximately 800 homes, although the level of blending and timelines are uncertain.
- Nevada and Arizona: Working with universities and other partners, Southwest Gas has initiated an investigation in both Phoenix-area and Las Vegas-area facilities to confirm suitability with up to 20% hydrogen natural gas blends with intent to blend into customer networks as soon as 2023.
- Oregon: With testing at 5% hydrogen blended at a Northwest Natural-owned facility complete, the utility serving the Portland-area is expanding efforts to investigate higher blends and pilots in customer networks as soon as late 2022.
- Utah: Beginning with 5%-10% injection at a training facility in the Salt Lake City region, Dominion Energy will expand to customer networks starting in 2022, in Delta, UT.
- Alberta: ATCO Gas is planning to inject 5% of hydrogen by volume starting in late 2022, into a section of its customer network serving approximately 2,000 customers.
- British Columbia: FortisBC plans to deliver up to 20% blended hydrogen fuels to end users before 2025, serving the Vancouver-area, following a partnership with a local university and other partners.
- Ontario: Enbridge Gas is initiating an injection of ~2% hydrogen by volume into a network serving approximately 3,600 customers in the Toronto metropolitan area.
- Quebec: With multiple utility-scale trials underway, the largest green hydrogen injection demonstration is in the pre-installation and commissioning stages in a trial impacting 1,000s of customers.

Summary of Research on Hydrogen-Based Fuel Impacts

There are numerous reviews available outlining the manifold technical and economic challenges to distribute hydrogen in North America. The following list is not exhaustive; however, these selected references provide excellent reviews on several aspects of the broader infrastructure compatibility and decarbonization challenge:

- Researchers at UC Irvine have spelled out the comprehensive benefits of hydrogen as a decarbonization vector, broadly defined for the U.S. [Saeedmanesh, 2018] and in a roadmap for California [Reed, 2020]. The roadmap highlights hydrogen's importance as a means of long-duration renewable energy storage and the ability to scale-up effectively to meet up to 10% of California's natural gas demand for process/comfort heating by 2025.
- Concerning the risks and technical potential of blending hydrogen into the existing natural gas networks in the U.S., there are several excellent overviews with a focus on infrastructure concerns. These include an NREL/GTI technical review focused on pipeline/distribution concerns [Melaina, 2013] followed by multiple industry reviews. Most recently, the heating equipment industry commissioned its own summary, with a focus on equipment [Needley, 2021]. Concerning end use equipment, these reports provide a range of recommendations:

- The 2013 NREL/GTI study largely pertained to the European NaturalHy Project [De Vries, 2007], which ran from 2004-2009, and concluded that minor adjustments to end use equipment in Europe could accommodate fuel blends with up to 20% hydrogen. However, given the uncertainty of with variations in equipment in the U.S. vs. Europe, the 2013 study pointed to **5%-15%** as a suitable range that would "*appear to be feasible with very few modifications to existing pipeline systems and end-use appliances*."

- Building on the information gathered by the aforementioned report and many other references, several industry studies described the acceptable ranges of hydrogen in end use equipment more in terms of levels of uncertainty. While an **up to 20%** limit was generally accepted as suitable, a Pipeline Research Council International (PRCI) study indicates a steep decline in data/information for higher blends (see Figure 40). The PRCI study highlighted more recent European studies wherein these ranges of blended hydrogen were demonstrated in limited field demonstrations, with one prominent example of the Dutch pilot on the island of Ameland, wherein boilers and cooking equipment were operated on 5%-20% hydrogen blends after being pre-tested on 30% blends [Kippers, 2011].

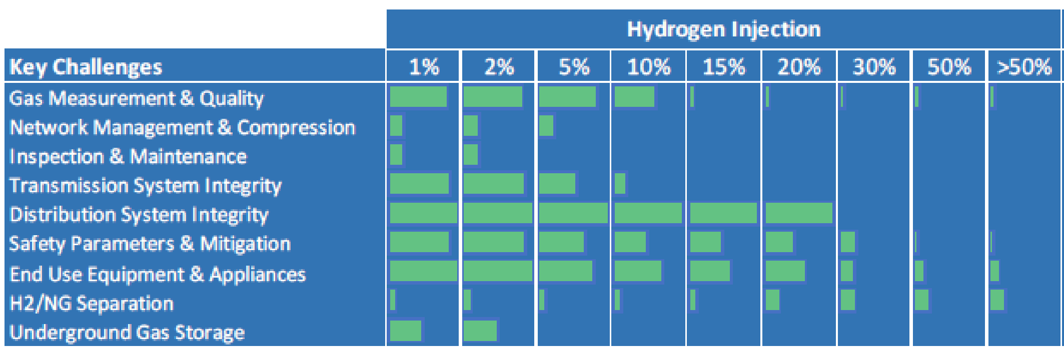


Figure 40: PRCI Table Quantifying Level of Knowledge as Function of Hydrogen Injection Percentage [Source: PG&E[55]]

- Recently, the AHRI-commissioned report by Enertek International had a detailed approach from the manufacturers' perspective, including FMEA-type reviews of the major appliance categories,[56] concluding that currently produced equipment should be safe to operate with **up to 20%** hydrogen blended, provided no adjustments are made regarding the reduction in heating capacity. Citing the efficiency benefit of newer products, the study also recommended that existing equipment be replaced and did not specify a hydrogen blend tolerance for equipment currently in operation [Needley, 2021].

- In parallel to more recent reviews, there has been continued laboratory and field-based research to quantify impacts of hydrogen blends on specific building-type equipment, including studies in Europe [Schaffert, 2020] and in North America by UC Irvine [McDonell, 2020], Appliance Engineering on behalf of CSA [Suchovsky, 2021], AHRI [Needley, 2021], and GTI Energy [Glanville, 2022]. These studies broadly point to suitable operation of unadjusted equipment with up to 20% or 30% hydrogen blended. Across these studies, the product

[55] https://efiling.energy.ca.gov/GetDocument.aspx?tn=237347

[56] Furnaces, boilers, control valves, venting, water heaters, and pool heaters.

categories of interest—water heaters, boilers, furnaces, and infrared heaters—*have* been included in equipment tested (as components or in-situ), however, published data regarding these equipment types remains limited and with a focus on smaller-scale equipment. Key trends from these studies, generally up to 15% or 30% hydrogen blended (see Figure 41), include: (1) few instances of flame stability, or other issues upon start-up, (2) measurable but limited impacts on efficiency, (3) tendency for surface temperatures, NO_x, and CO emissions to decline with increasing hydrogen blends due to λ shift, and (4) heating capacity declines in line or slightly in excess of prediction from fuel Wobbe Index. Concerning enhanced leakage, both the CSA study and a separate study by UC Irvine [Meija, 2020] concluded that hydrogen-based fuels do not leak at an increased rate when compared to natural gas under similar conditions.

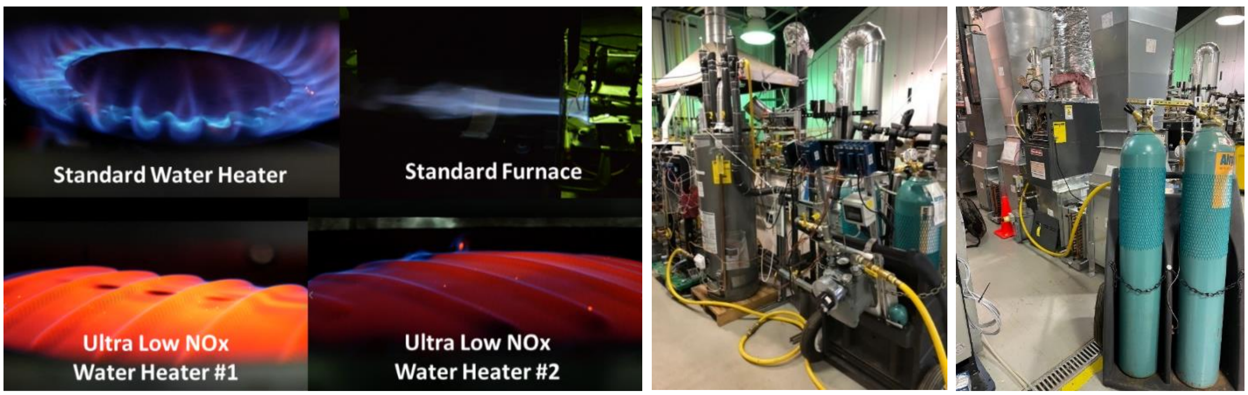


Figure 41: Photos of Burners and In-situ Appliances Operating with 30% Hydrogen Blends [Glanville, 2022]

Looking ahead to 100% hydrogen compatible heating, once hydrogen blending is well established by a given utility—which includes (1) meeting or approaching goals of delivered hydrogen costs and low GHG content and (2) demonstrating the feasibility for hydrogen distribution networks—the authors anticipate that 100% hydrogen compatible equipment will proliferate. As noted previously, there is an accelerated effort to develop and demonstrate 100% compatible versions of the equipment discussed (water heaters, boilers, furnaces, and infrared heaters) and facilitate their in-situ conversion using the so-called "Hydrogen Ready" equipment [Mahajan, 2022 and Hy4Heat, 2022]. With the focus of RD&D on a two-pronged approach, to quantify the impacts of hydrogen-blends on existing equipment and to develop and demonstrate equipment suitable for higher blends of hydrogen (up to 100%), these efforts focus on the first of three categories of solutions—to *permit consumption* of these low-carbon/zero-carbon fuels. For the other two categories of identified technology gaps, (a) technology solutions that enable flexibility of fixed assets with the *evolution of and variability in delivered fuels* and (b) components and system designs that *mitigate long-term impacts* of exposure to the use of these emerging fuels, the RD&D in these areas concerning building heating equipment are less active and require greater attention.

Technology Pathway Outlook

The potential for low-carbon and zero-carbon fuels to fully decarbonize existing heating equipment is applicable to all combustion equipment in buildings. Thus, it is technically feasible to eliminate net GHG emissions for water heaters, furnaces, boilers, and infrared heaters, provided the fuels are available, cost-competitive, and the equipment are suitable for operating on these fuels, with the last item primarily a concern for hydrogen-based fuels. Overall, commodity costs of these low-carbon/zero-carbon fuels is highly uncertain, however, estimates of 2 to 4 times higher than the fossil fuel replaced are generally acceptable, excluding any incentives or credits.

- For **hydrocarbon fuels**, of which biomethane/RNG, bioLPG/renewable propane, and biodiesel are "drop-in" fuels that are functionally equivalent to the fossil fuels they replace, the barriers to wider adoption and thus decarbonization of heating equipment are limits on the availability of the fuels and their cost-competitiveness. Equipment compatibility and long-term impacts of using these low-carbon fuels remains a topic of research, ranging from quantifying the impacts of trace contaminants in RNG to understanding the upper tolerance of blending rDME or biodiesel into conventional fuels. However, it is important to note that these fuels (as blends or 100%) are available today in North American regional markets. Natural gas utilities and distributors of LPG and heating oil are working to aggressively expand production and access to these fuels. Thus, it is important for heating equipment manufacturers to (a) resolve any outstanding research gaps concerning the use of these fuels and (b) assure that codes/standards accommodate the potential variations in equipment safety and performance that may result.
- For **hydrogen-based fuels**, which are not "drop-in" fuels, a key near-term research gap concerns their impact on the large variety of equipment currently operating in buildings which are designed for operation with conventional fuels. Care must be taken when understanding, mitigating, and planning for the impacts of operating with fuel mixtures beyond the intended design and certification. Up until recently, the majority of investigations of blended hydrogen impacts on building equipment, including the highly cited "NaturalHy" project [De Vries, 2007], were performed in the UK and Europe. The equipment evaluated in these studies differed from what is in use in the U.S. and Canada, which by contrast overwhelmingly use partially-premixed combustion designs, as opposed to the more common premixed combustion designs prevalent in Europe. Within the last few years, there is a growing body of research investigating these impacts, often through laboratory-based testing of heating equipment with up to 20% or 30% hydrogen blended. As summarized in a recent study [Glanville, 2022], recommended actions to address these research and technology gaps include:
    - Expand the Dataset: Further quantify the emissions, efficiency, and safety impacts on a wider range of equipment types, including a greater diversity of water heaters, boilers, furnaces, and infrared heaters. Investigations should include identifying upper limits and failure modes as a function of hydrogen blending, cover a wider range of gas qualities (e.g., natural gas mixtures), weatherized and non-weatherized equipment, new versus aged equipment, and emerging technologies.
    - Quantify Long-term Impacts: Long-term impacts are more poorly understood, ranging from impacts on equipment operating life, maintenance needs, material and component degradation, and on the infrastructure (e.g., piping, venting).

Additionally, efforts to better quantify enhanced leakage and aggregate air emission impacts are critical.

- Gain Experience in the Field: True in-situ testing will be valuable in the field, to verify laboratory-based findings in addition to (a) quantifying impacts on installation, operation, and maintenance of equipment, (b) establishing best practices concerning re-commissioning and troubleshooting equipment issues, (c) implementing simple retrofit packages to enable hydrogen-blended fuel tolerance, and (d) establishing the use case(s) for enhanced sensors for equipment and building systems.
- Modernize Codes and Standards: To operate the equipment in aforementioned research studies with a 30% hydrogen/natural gas blend will invalidate its certification,[57] alter its performance with efficiency and emissions ratings, and raise concerns of manufacturer liability.[58] Modernization of the associated codes and standards is essential in parallel to expanding these RD&D efforts.

Concerning equipment suitable for higher hydrogen blends, up to 100%,[59] a different set of RD&D needs are required over those concerning blending hydrogen into natural gas grids. These include the development of suitable hydrogen-fired equipment in all categories concerned, equipment-focused RD&D to demonstrate acceptable levels of safety and performance in addition to the development of guidance, such as that produced in the UK Standard *PAS 4444:2020/2021 – Hydrogen-fired Gas Appliance Guide*.[60] Additionally, and more broadly, approaches to risk assessment will be necessary for the installation and operation of these hydrogen-fired equipment, inclusive of end user-owned distribution, storage, or other aspects (e.g., leak detection and abatement), informing the development of and best practices with hazard detection and mitigation. With increasing concentrations of hydrogen in the fuel, it will be necessary to investigate the efficacy and equipment-specific impacts of emerging odorants and colorants. Finally, similar to the case of blended hydrogen/natural gas, modernization or creation of new safety and performance standards will be necessary for the design and installation of hydrogen-fired equipment. In sum, with accelerating technology transfer on safe and effective use of hydrogen, this fuel can provide compelling GHG reduction pathways for combustion equipment.

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57 https://www.csagroup.org/article/use-of-hydrogen-and-natural-gas-mixtures-in-products-certified-for-natural-gas-in-canada-and-the-us/
58 https://www.esmagazine.com/articles/102666-hydrogen-blending-protecting-against-manufacturer-liability
59 Note that retaining a small fraction of hydrocarbons (e.g. methane) in hydrogen fuels is one proposed method of flame colorization.
60 https://knowledge.bsigroup.com/products/hydrogen-fired-gas-appliances-guide/standard

References for Low-Carbon and Zero-Carbon Fuels Section

- American Gas Association (AGA), (2022). Net-Zero Emissions Opportunities for Gas Utilities, Report prepared for the AGA by ICF, link: https://www.aga.org/globalassets/research--insights/reports/aga-net-zero-emissions-opportunities-for-gas-utilities.pdf
- Anggarani, R., Wibowo, C., and Rulianto, D. (2014). Application of Dimethyl Ether as LPG Substitution for Household Stove., *Energy Procedia*, Vol. 47, pp 227-234.
- ANSI Z21.10.3-2017 (2017). Gas-fired water heaters, volume III, storage water heaters with input ratings above 75,000 Btu per hour, circulating and instantaneous.
- ASHRAE Standard 103-2017 (2017). Method of testing for annual fuel utilization efficiency of residential central furnaces and boilers.
- Butcher, T, (2019). B20 to B100 Blends as Heating Fuels. Brookhaven National Laboratory, report BNL-211771-2019-INRE, Link: https://www.osti.gov/servlets/purl/1526692
- City Energy, (2021). Handbook on Gas Supply, link: https://www.cityenergy.com.sg/wp-content/uploads/2021/11/City-Energy-Handbook-on-Gas-Supply-Dec-2021.pdf
- Dames, Enoch E. et al. (2016) "A Detailed Combined Experimental and Theoretical Study on Dimethyl Ether/propane Blended Oxidation." Combustion and Flame 168: 310–330, The Combustion Institute. Link: https://dspace.mit.edu/handle/1721.1/115092
- De Vries, H.; Florisson, O.; Thiekstra, G.C. (2007). "Safe Operation of Natural Gas Appliances Fueled with Hydrogen/Natural Gas Mixtures (Progress Obtained in the NaturalHy-Project)." Presented at the International Conference on Hydrogen Safety, September 11-13, San Sebastian, Spain.
- Energy Futures Initiative, 2019. Pathways for Deep Decarbonization in California. link: https://energyfuturesinitiative.org/wp-content/uploads/sites/2/2022/03/OptionalityFlexibilityInnovation_Report_compressed.pdf
- Environmental Protection Agency (EPA), Data Accessed 2022. Greenhouse Gas Equivalencies Calculator. link: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results
- Environmental Protection Agency (EPA), (2022). Renewable Natural Gas, link: https://www.epa.gov/lmop/renewable-natural-gas#rngmap
- Fabiś, P.; Flekiewicz, B. Influence of LPG and DME Composition on Spark Ignition Engine Performance. *Energies* 2021, *14*, 5583. https://doi.org/10.3390/en14175583
- Glanville, P.; Fridlyand, A.; Sutherland, B.; Liszka, M.; Zhao, Y.; Bingham, L.; Jorgensen, K. (2022). Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance. Energies 2022, 15, 1706. https://doi.org/10.3390/en15051706.
- Institute of Gas Technology (IGT) (1972), "A Hydrogen–Energy System". Report prepared for the American Gas Association, Catalog No. L21173.

- Hamper, M. (2007). Manufactured Gas History and Processes. Journal of Environmental Forensics, Vol 7, Issue 1, pp 55-64.
- Hawaii Gas, (2022). Main website and personal communications, link: https://www.hawaiigas.com/clean-energy/decarbonization
- Hy4Heat (2022). Link: https://www.hy4heat.info/
- Kerr, R., Butcher, T., Islam, N., and Haverly, M. (2022). Monitoring Biodiesel Blends in Heating Applications – Effects of Exposure Conditions, Proceedings of IASH 2022, the 17th International Conference on Stability, Handling and Use of Liquid Fuels, Dresden, Germany.
- Kippers, M., De Laat, J., Hermkens, R. 2011. Pilot Project on Hydrogen Injection in Natural Gas on Island of Ameland in the Netherlands, Proceedings of the 2011 International Gas Research Conference.
- Los Angeles County, Data for year 2017. Total and Average Daily Vehicle Traveled in LA County (2005-2017). link: https://data.lacounty.gov/Sustainability/Total-and-Average-Daily-Vehicle-Traveled-in-LA-Cou/ygmt-sd4z/data?no_mobile=true
- Mahajan, D., et al. (2022). Hydrogen Blending in Gas Pipeline Networks—A Review. *Energies* 15, no. 10: 3582. https://doi.org/10.3390/en15103582
- McDonell, V., Zhao, Y., Choudhury, S. 2020. Implications of Increased Renewable Natural Gas on Appliance Emissions and Stability, Report CEC-500-2020-070 prepared for the California Energy Commission under Contract PIR-16-017.
- Meija, A., Brouwer, J., MacKinnon, M., (2020). Hydrogen leaks at the same rate as natural gas in typical low-pressure gas infrastructure. International Journal of Hydrogen Energy, Vol. 45, Issue 15, pp 8810-8826.
- Melaina, M., Antonia, O., Penev, M. 2013. Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues, Technical Report NREL/TP-5600-51995 prepared under Contract No. DE-AC36-08GO28308 for the U.S. Dept. of Energy.
- National Grid, 2022. Our Clean Energy Vision – A Fossil-Free Future for Cleanly Heating Homes and Businesses, link: https://www.nationalgrid.com/document/146251/download.
- Natural Resources Canada (NRCan). Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen, 2020. Link: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf
- Needley, P. and Peronski, L. 2021. Assessment of Hydrogen Enriched Natural Gas, Report AHRI-8024 prepared for the Air-Conditioning Heating and Refrigeration Institute.
- Northwest Natural, 2021. Vision 2050: Destination Zero, link: https://www.nwnatural.com/about-us/the-company/destination-zero
- Reed, J. et al. 2020. Roadmap for the Deployment and Buildout of Renewable Hydrogen Production Plants in California. Report CEC-600-2020-002 prepared under Contract 600-17-008 for the California Energy Commission.

- Saeedmanesh, A., MacKinnon, M., Brouwer, J. 2018. Hydrogen is Essential for Sustainability, Current Opinion in Electrochemistry, 12: 166-191. https://doi.org/10.1016/j.coelec.2018.11.009
- Schaffert, J. et al., 2020. Impact of Hydrogen Admixture on Combustion Processes – Part II: Practice, Deliverable D2.3 as submitted from the THyGA Project. Link: https://thyga-project.eu/wp-content/uploads/20201211-D2.3-Impact-of-Hydrogen-in-Practice_final.pdf
- Sejbjerg, A. (2022). The path towards a fully decarbonised gas distribution system by 2035 - decentral biomethane production in Denmark. Proceedings of the 2022 World Gas Conference, Daegu, Korea, 2022.
- Sempra, 2020. Joint Application to the California Public Utilities Commission. link: https://www.socalgas.com/sites/default/files/2020-11/Utilities_Joint_Application_Prelim_H2_Injection_Standard_11-20-20.pdf
- SoCalGas, 2022. 2021 Annual RD&D Report. link: https://www.socalgas.com/sites/default/files/2021%20SoCalGas%20RD%26D%20Annual%20Report.pdf
- Suchovsky, C.J., Ericksen, L., Williams, T.A., Nikolic, D.J. 2021. Appliance and Equipment Performance with Hydrogen-Enriched Natural Gases. Canadian Standards Association, Toronto, ON.
- Tarr, J. (1999) "Transforming An Energy System: The Evolution of the Manufactured Gas Industry and the Transition to Natural Gas in the United States (1807-1954)," in Olivier Coutard (ed.), The Governance of Large Technical Systems (London: Routledge, 1999), 19-37.
- U.S. Department of Energy (DOE), 2021. Link: https://www.energy.gov/articles/secretary-granholm-launches-hydrogen-energy-earthshot-accelerate-breakthroughs-toward-net
- Von Wald, G. and Brandt, A. (2019). "The Updated State of Science Regarding Maximum Permissible Siloxane Concentration," prepared for the California Council on Science and Technology (CCST), a CCST facilitated expert opinion.
- WPGA, (2021). Renewable Propane Synopsis. Link: https://westernpga.org/wp-content/uploads/sites/33/2021/04/WPGA-Renewable-Propane-Synopsis_4_1_21.pdf
- Zhao, Y. et al. (2022). Residential Fuel Transition and Fuel Interchangeability in Current Self-Aspirating Combustion Applications: Historical Development and Future Expectations. Energies 15, no. 10: 3547. https://doi.org/10.3390/en15103547.

Appendix: Brief Review of Impacts of Hydrogen Blending by Combustion System Type

Initially, it is useful to define the three major classes of combustion systems, which are defined by the quantity of fuel mixed with air prior to ignition at the flame. As a brief review of basics, the combustion stoichiometric air-to-fuel ratio describes the ratio of the volume of air per volume of fuel necessary for complete combustion, where for methane in atmospheric air, the ratio is 9.52. It is common practice to have excess air with combustion, to assure complete and stable combustion, it is useful to define the ratio of actual combustion air to the stoichiometric air as: $\lambda = \frac{(Air\ to\ Fuel\ Ratio)_{actual}}{(Air\ to\ Fuel\ Ratio)_{stoichiometric}}$, and alternatively as the inverse equivalence ratio of $\varphi = \frac{1}{\lambda}$.

As hydrogen is blended with natural gas, all equipment will see reductions in heating rate/capacity with increased hydrogen added. For steady-state (e.g., on/off) equipment, manual adjustments are possible but may not be necessary. For equipment meeting a thermal demand, equipment may be manually or automatically adjusted to compensate, and unadjusted equipment will compensate with longer runtimes. Other, equipment-specific impacts break down by the three classes of combustion systems, which are:

- ***Non-premixed Combustion***, or alternatively *diffusion flames*, is combustion characterized by the fuel and air meeting at the reaction zone (flame), where no air is mixed with the fuel prior to ignition. While there are many examples of non-premixed combustion in daily life, from candle flames to wood fires, these are not common with gaseous fuels due to the poor combustion control. Examples in buildings of non-premixed combustion are limited to decorative flames (e.g., gas lights), log lighters, and individual pilot lights. For these systems, upstream of ignition $\lambda = 0$.

  With increasing hydrogen blended, these types of equipment are likely to see a greater tendency toward flame stability issues, though these have been observed to be minor in practice at moderate ranges of blending (up to 30%).

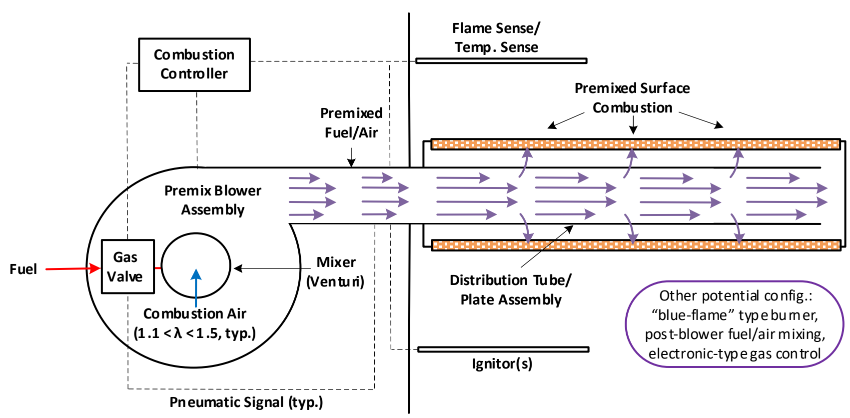

Figure 42: Representative Diagram of a Premixed Combustion System

- ***Premixed Combustion*** is characterized by mixing stoichiometric or greater quantities of air with the fuel prior to ignition, such that $\lambda \geq 1.0$ upstream of ignition. Commonly this air/fuel mixing is performed with the aid of a blower and/or inducer fan and the system is "tuned" to operate within a given range of gas qualities. With variable speed and precise air-to-fuel ratio control, modulation is feasible where a given burner can cover a range of 20%-100% capacity (5:1) or greater. Two styles of modulation control predominate in combustion equipment: *pneumatic controls* use a pressure signal to adjust the fuel injection as a function of blower outlet pressure while *electronic* or *constant lambda controls* independently vary the fuel and air flow rates with greater precision using a measurement in the combustion chamber (flame temperature, flame ionization signal) to infer heating output. Premixed combustion systems are commonly used in high-efficiency equipment where the precise control and modulation can be valued, and pressurization of the combustion chamber(s) is needed to overcome heat exchanger pressure losses.

With increasing hydrogen blended, not surprisingly the impact will vary by the control of fuel/air mixing. For common pneumatically controlled fuel/air mixing, the air flow remains approximately constant as hydrogen is added, thus combustion shifts leaner (λ increases), which can counteract the impact hydrogen has on flame temperature, speed, and stability. For electronically (or "digitally") controlled fuel/air mixing, often a constant λ approach is employed and the equipment automatically compensates for the change in fuel properties with added hydrogen, which may require additional compensation to avoid flame stability issues.

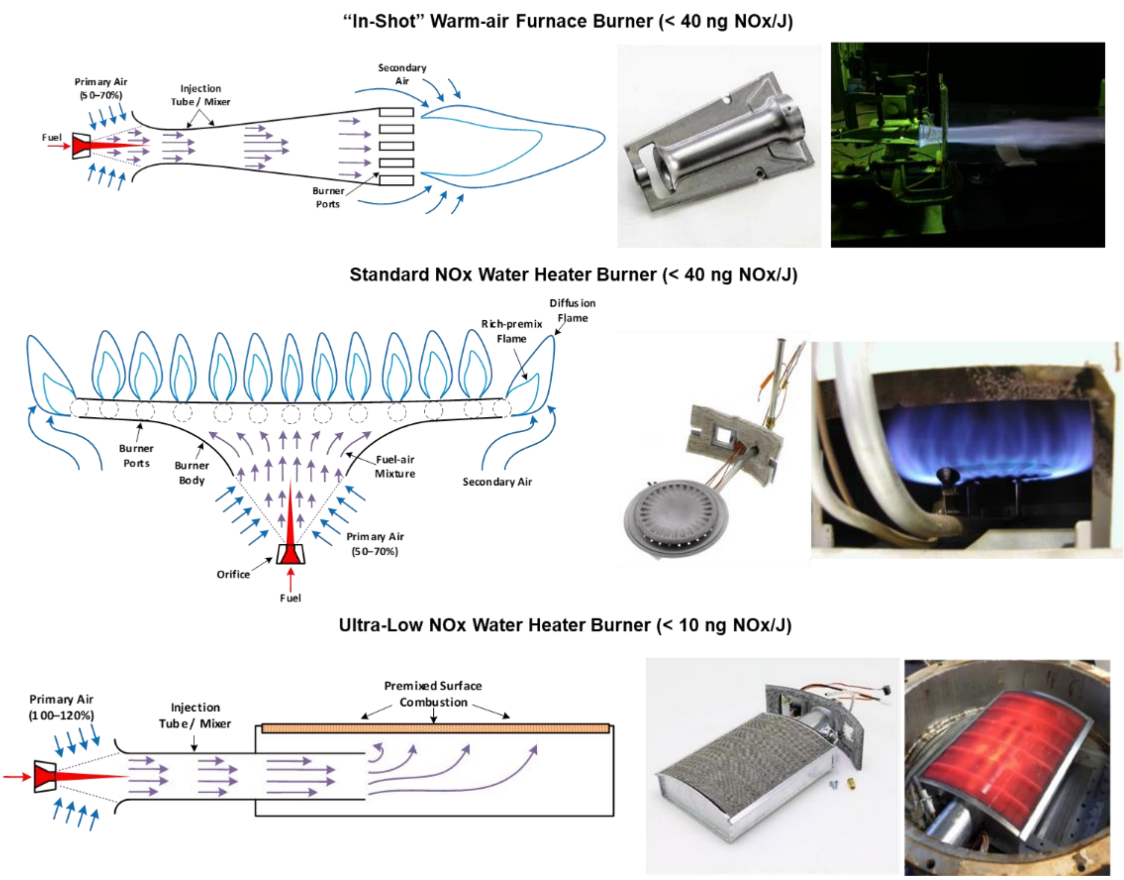

Figure 43: Representative Diagrams of Common Partially-Premixed Burners

- ***Partially-premixed Combustion*** is between non-premixed and premixed combustion, where some air is mixed with fuel prior to ignition but not enough for complete combustion, such that $0 < \lambda < 1.0$ upstream of ignition. Partially-premixed burners commonly operate with natural draft or induced draft venting, where the combustion chamber is negatively pressurized to draw in combustion air. As the fuel ejects from the orifice, it expands and entrains *primary air* ($\lambda_{primary} < 1.0$) prior to ignition, and at the point of ignition available *secondary air* in the chamber provides for complete combustion such that ($\lambda_{primary} + \lambda_{secondary}$) > 1.0. **Most fuel-fired equipment in North American buildings use *partially-premixed* combustion approaches** due to its low cost and reliability, hence the focus in this paper, including most furnaces, water heaters, boilers, cooking equipment, hearth products, and other outdoor equipment.

  With increasing hydrogen blended, these systems will likely see an increase in primary aeration ($\lambda_{primary}$ moves toward 1.0), resulting in the potential for concerns with flame stability (flashback) and temperature (NO_x emissions). However, test data shows that for moderate ranges of blending (up to 30%), flame stability is generally not an issue and NO_x emissions are stable or decline.

7. Distributed Carbon Capture

Summary of Technology Pathway

Carbon Capture, Utilization, and Storage consists of capturing of CO_2 from a process stream or directly from the air and either using the CO_2 as a feedstock for industrial or manufacturing processes, or to storing it underground. Most carbon capture technologies are designed and sized to capture CO_2 from large stationary sources such as power generation and industrial facilities. The Intergovernmental Panel on Climate Change (IPCC) categorizes large stationary sources as those generating >0.1 $MtCO_2$/yr [Gale, et al., 2018]. The most commonly used type of carbon capture for large stationary sources is post-combustion carbon capture, which removes CO_2 from flue gas downstream of the combustion process. Post-combustion carbon capture technology has been shown to capture CO_2 at a rate of up to 800 tonnes/day [DXP, 2022].

The need for small-scale, post-combustion carbon capture has been recently realized due to the high carbon intensity of the buildings sector. According to the US EPA, the building sector was responsible for 13% of total US GHG emissions in 2020 [US EPA, 2022], which includes both direct and indirect emissions. According to the U.S. Energy Information Administration (EIA), CO_2 emissions in 2021 from primary energy consumption were 559 $MtCO_2$ [U.S. EIA, 2022]. Within the residential sector, space heating and water heating accounted for 43% and 19% of end-use energy consumption, respectively [US EIA, 2018].

To reduce emissions from combustion-based building equipment, distributed carbon capture will need to be considered as an alternative decarbonization pathway. Two technology developers that are working on distributed carbon capture technologies are Manufacturer A and Manufacturer B, based in Canada and the U.S., respectively. Both manufacturers are developing post-combustion carbon capture technologies that are tied to the venting of a fuel-fired appliance and capture a portion of the CO_2 emissions in the flue gas. Manufacturer A utilizes a wet scrubbing, chemisorption approach to reduce the CO_2 emissions by up to 20% while converting the captured CO_2 into a useful byproduct. Manufacturer B utilizes a pressure swing adsorption technique in which the CO_2 is separated from the flue gas and liquefied, to be reused or sequestered. There are additional technologies under development for the building sector, but they are not at the same technical maturity and are targeting building-type combustion equipment.

Overview of Technology Status

Manufacturer A has developed its carbon capture technology primarily for boilers and water heating equipment with energy inputs ranging between 250 – 1,500 kBtu/hr. The device is designed to be installed in close proximity to the water heater and tied to both the water supply line feeding the appliance and the flue gas venting exiting the appliance. The device reduces the carbon emissions of the water heating appliance in two primary ways:

- Capturing CO_2 from the appliance's combustion products by diverting a portion of the flue gas stream into a reaction chamber containing potassium hydroxide and converting it to potassium carbonate, and

- Reducing the energy consumed by the appliance by recovering waste heat from the flue gas and exothermic energy from the reaction to preheat water entering the appliance.

According to Manufacturer A, each unit reduces CO_2 emissions by a total of 7.5 tonnes per year, which includes the CO_2 captured directly by the chemical and the CO_2 generation that is offset by the waste heat recovery. With a stated lifespan of 20 years, each unit is expected to offset 150 tonnes of CO_2 over its lifetime. A process schematic of Manufacturer A's device is shown in Figure 44.

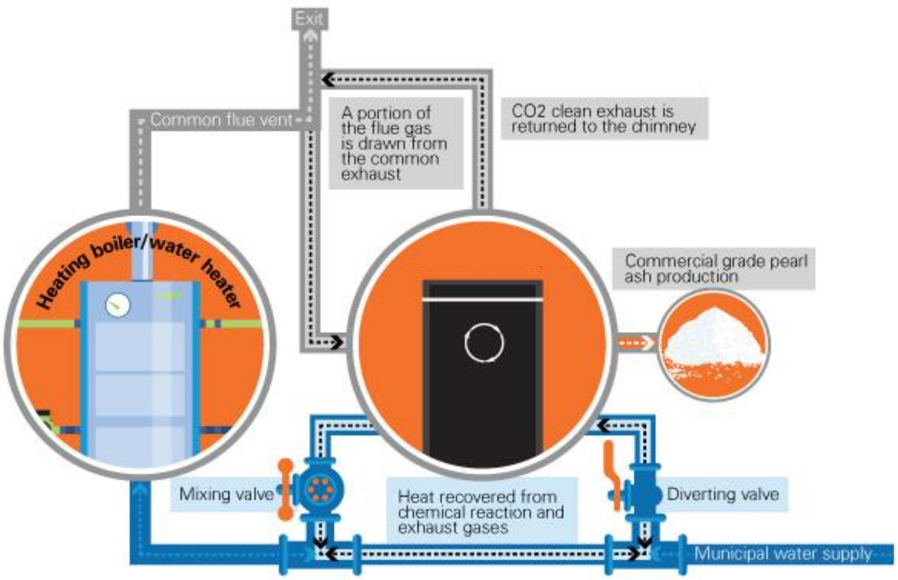

Figure 44: Process Flow Schematic of Manufacturer A's Carbon Capture Device [Centerpoint Energy, 2019]

Manufacturer A currently sells a prototype of their carbon capture device, which is only compatible with non-condensing water heating appliances. Depending on the Authority Having Jurisdiction (AHJ), the unit may be installed on only Category I or both Category I and Category III venting appliances. For Category III venting appliances, it is recommended to have approval from the boiler manufacturer prior to making modifications to the venting for purposes of installing the carbon capture device.

Manufacturer A has made significant progress in preparing their technology for market deployment by acquiring multiple certifications, including the following:

- NSF/ANSI 5 - Water Heaters, Hot Water Supply Boilers, And Heat Recovery Equipment
- UL Standard 73 - Motor-Operated Appliances
- UL Standard 462 - Standard for Heat Reclaimers for Gas-, Oil-, or Solid Fuel-Fired Appliances
- CSA C22.2 - Canadian Electrical Code

Currently, the manufacturer is working on developing a unit that will be compatible with condensing appliances as well. Manufacturer A is aiming to have this prototype ready in 2023.

Manufacturer B has developed an alternate post-combustion carbon capture technology that utilizes a pressure swing adsorption cycle. The technology is installed on a skid either indoors or outdoors, and occupies space equivalent to three parking spots. The manufacturer offers a range of customized product configurations to fit a wide variety of building types and sizes, such as for residential and commercial buildings, industrial buildings, universities, schools, and hospitals. This technology is designed to capture CO_2 from large fuel-fired appliances such as boilers, adsorption chillers, and CHP units, with a CO_2 concentration of at least 4% in the flue gas. The manufacturer recommends that the technology only be installed in buildings consuming >125,000 therms/year of natural gas.

Similar to Manufacturer A's device, this technology is tied to the common vent leaving the building. The flue gas stream is first separated and cooled in a condensing loop to remove moisture. The flue gas is further dried before being piped to the pressure swing adsorption unit to separate the oxygen and nitrogen from the CO_2. The purified CO_2 stream is then liquefied and stored in tanks to be picked up and transported to the end-use site. A process schematic of Manufacturer B's technology is shown below in Figure 45.

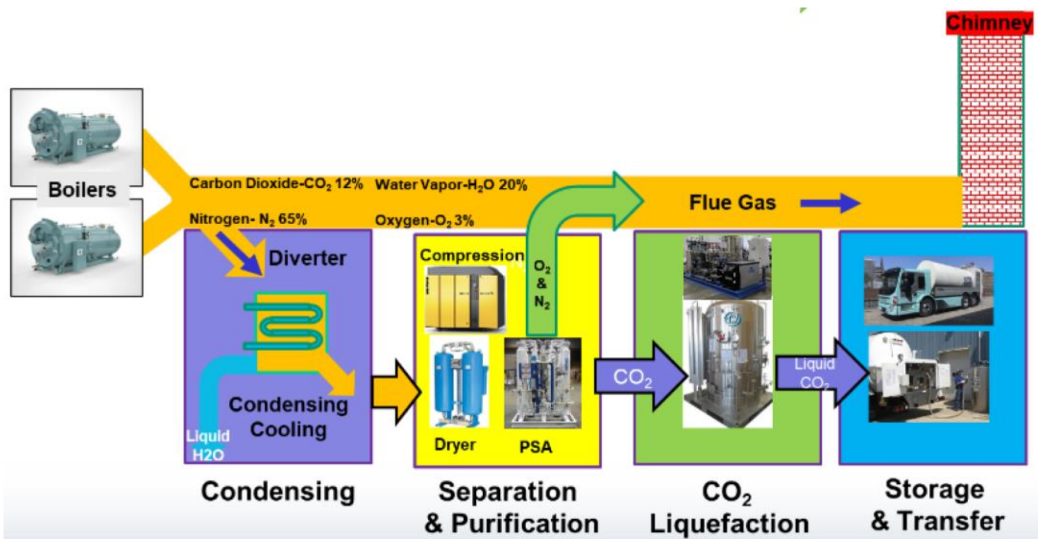

Figure 45: Process Schematic for Manufacturer B's Carbon Capture Technology [Source: Mfr B]

Manufacturer B currently offers a 400 SCFM-rated unit that can capture up to 1,000 tonnes CO_2/year. This unit currently demonstrates a carbon capture rate of 25% but can be designed to capture up to 100% of the CO_2 in the flue gas stream.

Overview of R&D and Industry Efforts

Manufacturer A has engaged with multiple utilities in Canada and the U.S. to perform pilot demonstrations of their technology. One of Manufacturer A's earlier prototypes was installed in an office building owned by a Canadian utility, shown in Figure 46. A lifecycle assessment was conducted in collaboration with a Canadian university to determine the overall GHG emissions reduction of the technology, which was determined to be 21-27% [CleanO2, 2022].

Manufacturer A has also engaged with a few other utilities to perform field demonstrations of their technology. These demonstrations involve the installation of 3-10 units in buildings such as hotels, offices, schools, retirement homes, and shopping malls. Some of these demonstrations faced regulatory and permitting challenges with regard to tying the units to domestic water lines and positive vent ducting. The manufacturer has since received NSF and UL certification, which has allowed the utilities to overcome some of these challenges.

Figure 46: Installation of Manufacturer A's Carbon Capture Unit at Facility Owned by Canadian Utility [CBC, 2019]

A prototype of Manufacturer A's carbon capture unit is also installed at GTI Energy. The unit is being tested using a simulated water heater with a range of flue gas conditions. The goal of the study will be to evaluate the carbon capture and waste heat recovery efficiencies. GTI Energy is also leading a demonstration of this technology at the Naval Station Great Lakes in Illinois. The site selection process for this project is currently underway with the goal of the project being to validate the manufacturer's claims in a controlled field setting.

Figure 47: High-rise Building in New York City [Source: Mfr B]

Manufacturer B is currently performing a demonstration of their carbon capture technology in a multi-family residential high-rise in New York City, shown in Figure 47. The 380,000 ft^2 building consumes approximately 250,000 therms annually, with the equivalent of 2,913 tons of CO_2 released annually. One of the motivations behind implementing carbon capture in New York City is Local Law 97, which will begin imposing penalties on buildings greater than 25,000 ft^2 in 2024, and will affect approximately 50,000 buildings. The penalty will begin at $268 per tonne of CO_2 that is emitted above the specified limit based on the building's occupancy group. With the implementation of their technology, Manufacturer B expects to eliminate the penalty, which for the period of 2024 – 2029 would cost the owner approximately $97,630/year.

Manufacturer B is also a proponent of a green, circular economy, and is focused on captured carbon utilization. For their New York City-based demonstration, the manufacturer sells the capture CO_2 to a concrete paver manufacturer in New York City, where it is mineralized in concrete and sold back to city buildings.

Technology Pathway Outlook

Manufacturer A plans to make incremental improvements to their carbon capture technology and hopes to reach an eventual carbon capture rate of 100%, as shown in their technology outlook chart in Figure 48. To achieve this target, the manufacturer will need significant technology upgrades, specifically to the reactor chamber design, sorbent selection, and flue gas pathway and residence time. In parallel to improving the carbon capture efficiency of their current prototype, the manufacturer is developing another product line to tie in with boilers having firing inputs >1,500 kBtu/hr. The manufacturer will continue to focus primarily on water heating appliances for all future technology developments.

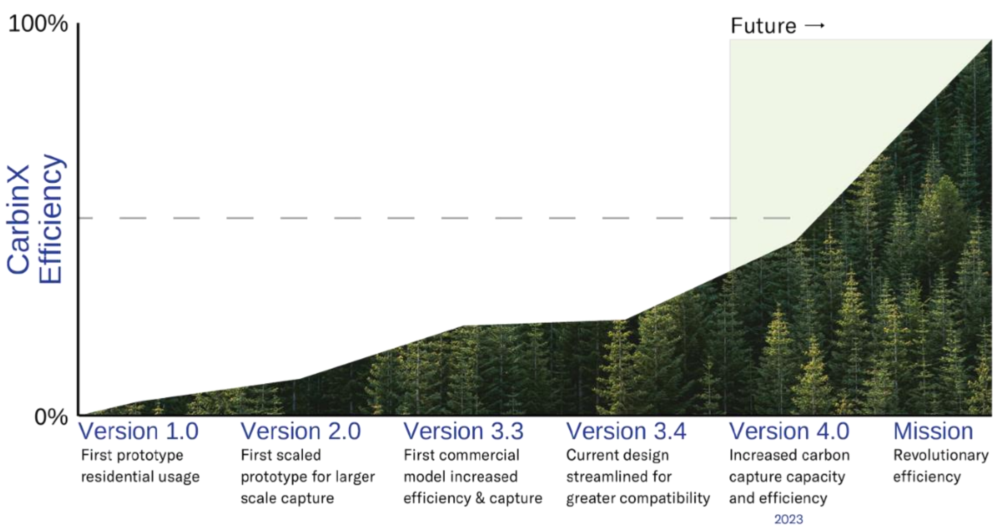

Figure 48: Manufacturer A Carbon Capture Technology Outlook [Source: Mfr A]

Similar to Manufacturer A, Manufacturer B is also targeting a carbon capture rate of 100% for their technology. The manufacturer claims that they are capable of designing their smaller systems to reach this capture rate, although they have not yet built such a unit. The manufacturer will be deploying five more units in New York City as part of a regional demonstration and will be demonstrating 70% carbon capture with these units. The total carbon captured from all five sites combined will be approximately 3,500 tonnes CO_2/year.

The manufacturer is receiving interest from larger institutions such as universities and hospitals. They are also interested in pursuing carbon capture for small district heating facilities and are designing larger units to accommodate these sites. A breakdown of the manufacturer's planned product offerings by size is shown in Table 12. The manufacturer has not yet built the two larger product configurations and will need to make changes to the technology design pertaining to the separation, purification, and liquefaction stages (i.e., new sorbent, compressor, piping design).

Table 12: Manufacturer B Carbon Capture Product Category

Product Size (SCFM)	Annual CO_2 Capture (tonnes)*	Site Location
400	1,000	Indoor/Outdoor
800	2,000	Indoor/Outdoor
1,600	4,000	Outdoor
3,200	8,000	Outdoor

*Design capacity at 9% CO_2 and 95% utilization

To accelerate wider technology adoption, the manufacturer is placing a significant focus on finding a diverse base of CO_2 off-takers. Currently, their main off-take stream is concrete block manufacturing. They are looking to expand their off-take base to eventually include CO_2 utilization in fuels, construction aggregates, chemicals, etc. They also plan to take advantage of the 45Q tax credit to further incentivize their technology to building owners.

Concerning the role of utilities, as discussed with regards to Manufacturer A, utilities are already playing a significant role in supporting distributed carbon capture. By performing field demonstrations and validating the equipment performance, they provide beneficial feedback to technology developers while demonstrating the need for distributed carbon capture as a decarbonization pathway. The involvement of utilities also gives creditability to this nascent technology category and encourages building owners to consider implementing this technology to decarbonize while also earning a revenue stream.

To further support carbon capture for combustion-based building equipment, utilities will be expected to work more closely with AHJs to navigate the potential regulatory hurdles that are in place for the implementation of carbon capture technologies. The cooperation of utilities, policy makers, and technology developers will be required for distributed carbon capture to be more widely adopted.

References for Distributed Carbon Capture

- CarbonQuest. (2022). CarbonQuest projects & case studies. Retrieved from CarbonQuest: https://carbonquest.com/projects
- CBC. (2019, September 3). Meet the startup turning CO_2 emissions into handcrafted soap. Retrieved from CBC News: https://www.cbc.ca/news/business/cleano2-cnrl-soap-carbinx-1.5265780
- CenterPoint Energy. (2019). Piloting an Innovative New Carbon Capture Technology - See more at: https://www.centerpointenergy.com/en-us/business/services/clean-energy-innovation/carbon-capture-recycling?sa=mn#sthash.84grignY.dpuf. Retrieved from CenterPoint Energy: https://www.centerpointenergy.com/en-us/business/services/clean-energy-innovation/carbon-capture-recycling?sa=mn
- CleanO2. (2022). Retrieved from https://www.carbinx.com/resources
- DXP. (2022, May 27). Pre-Combustion vs. Post-Combustion Carbon Capture Technologies. Retrieved from https://www.dxpe.com/pre-combustion-vs-post-combustion-carbon-capture/
- Gale, J., Bradshaw, J., Chen, Z., Garg, A., Gomez, D., Rogner, H.-H., . . . Williams, R. (2018). IPCC Special Report on Carbon dioxide Capture and Storage. Retrieved from https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter2-1.pdf
- U.S. EIA. (2022, June 24). Energy and the environment explained Where greenhouse gases come from. Retrieved from U.S. Energy Information Administration: https://www.eia.gov/energyexplained/energy-and-the-environment/where-greenhouse-gases-come-from.php
- US EIA. (2018, November 7). Space heating and water heating account for nearly two thirds of U.S. home energy use. Retrieved from U.S. Energy Information Administration: https://www.eia.gov/todayinenergy/detail.php?id=37433
- US EPA. (2022, August 5). Sources of Greenhouse Gas Emissions. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#:~:text=Commercial%20and%20Residential%20Sector%20Emissions,of%20these%20greenhouse%20gas%20emissions.

8. Mitigating Utility Customer Methane Emissions

Summary of Technology Pathway

Although GHG emission reductions in buildings often focus on CO_2, the impact of CH_4 emissions in buildings are increasingly recognized as a significant source of GHG emissions. Methane is the primary constituent of natural gas delivered to homes and businesses. It is a potent GHG, as when CH_4 is released to the atmosphere instead of combusting to CO_2, it has a GWP 28x that of CO_2 on a 100 year time horizon.[61] These emissions come in the form of fugitive methane emissions from very small leaks in building piping or from combustion equipment. Emissions via "methane slip" from stationary combustion equipment may present during transient behavior of the appliance (e.g., on/off cycling), steady-state operation due to incomplete combustion of the fuel, poorly controlled combustion of standing pilot lights, or low levels of seal leakage around control valves or from other fittings within equipment piping. Efforts for both the quantification and the mitigation of such fugitive methane emissions from combustion equipment are in the early stages of research and development. These are applicable to all sizes and equipment types in this study, across water heaters, furnaces, boilers, and infrared heaters.

The historic focus of methane emissions both in research and inventories has been in the natural gas production and distribution systems. Recent field and laboratory studies, however, point to end use equipment as an underestimated source of methane emissions, resulting in increased scrutiny of methane releases from residential appliances, and commercial/industrial equipment. Per the U.S. EPA *Compilation of Air Pollutant Emission Factors AP-42* [EPA, 2022], the methane emission factor for natural gas external combustion (the majority of residential appliances) is 2.3 lb/MMSCF, or approximately 0.0002 lb CH_4 emitted per therm consumed, or 0.005% on a volumetric basis. This emission factor would suggest, for example, that a residential water heater consuming 250 therms (a typical consumption rate [Kosar, 2013]) per year would emit 0.056 lbs of CH_4 annually. Recent field and laboratory sampling efforts discussed later in this review suggest that the EPA's single emission factor for methane from natural gas combustion is insufficient to cover the diversity of emissions from residential and commercial equipment, where emissions may be an order of magnitude or more than previously estimated [Merrin, 2019 and Lebel, 2020].

Research of methane emissions from residential and commercial combustion equipment is still limited to a small number of field and laboratory studies, however, data are starting to enter GHG inventories due to the recognition that inventories were underestimating methane emissions from building piping and combustion equipment. California's GHG inventory has included "behind-the-meter" emissions since 2019.[62] These account for natural gas leaks after the gas passes through building-level gas meter, including leaks from valves and joints of gas pipes and gas appliances [CARB, 2019]. The U.S. EPA Greenhouse Gas Inventory (GHGI) also added a "Post-Meter" category in the most recent 2022 release in addition to the already

61 100-year time horizon Global Warming Potential (GWP) of methane from IPCC Fifth Assessment Report, 2014 (AR5), excluding climate-carbon feedbacks.

62 California Air Resources Board. Inventory Updates Since the 2018 Edition of the Inventory: Supplement to the Technical Support Document. August 2019. https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2017/ghg_inventory_00-17_method_update_document.pdf

present CH_4 emissions from stationary combustion category [EPA, 2020]. While inventories will continue to see updates as methane research advances and more studies are released that develop emission factors for specific end use categories, the current GHGI helps put methane emissions from combustion appliances into perspective, helping to demonstrate the relative impact of CH_4 emission reductions and CO_2 emissions.

As shown in the adjacent Figure 49, of the total U.S. GHG emissions of 6 billion tonnes CO_2e, 11% (0.67 billion tonnes CO_2e) is from methane [EPA, 2020]. Shown in Figure 50 and Figure 51, of that 11%, about a quarter of it is from natural gas systems (0.16 billion tonnes). The recently added post-meter category for natural gas systems includes emissions from residential and commercial appliances, industrial facilities and power plants, and natural gas fueled vehicles. Leak emissions from residential appliances and industrial facilities and power plants account for the majority of post-meter CH_4 emissions. The main data source for this addition is Fischer et al. 2019 (used for residential), which is discussed later in the report, and IPCC (2019) (used for commercial, industrial, vehicle).

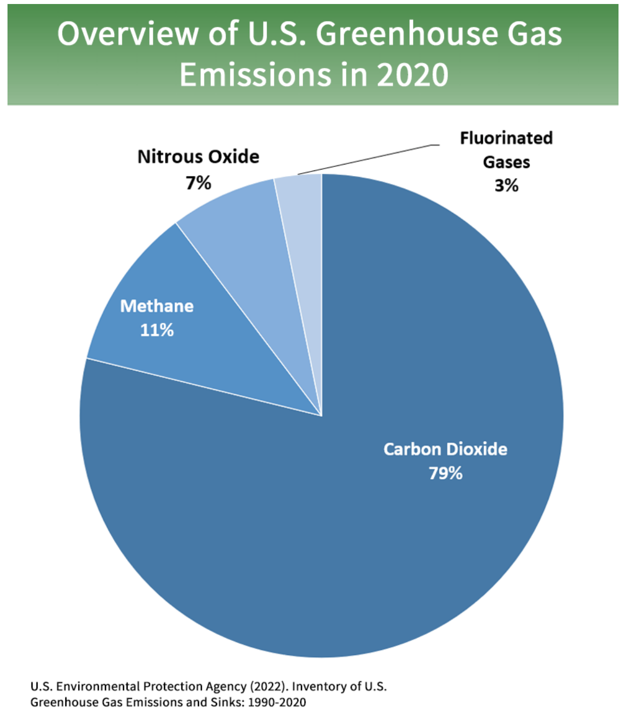

Figure 49: Overview of U.S. Greenhouse Gas Emissions in 2020 [Source: EPA]

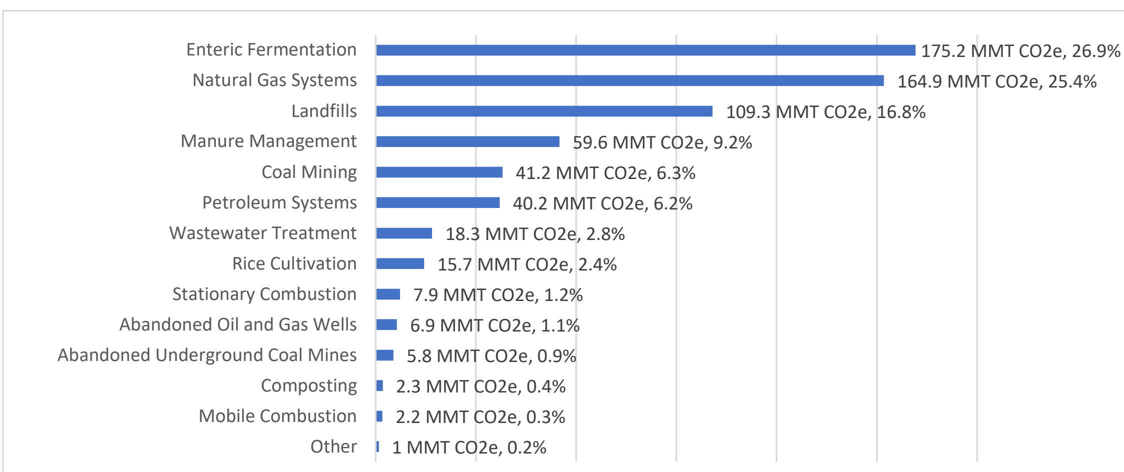

Figure 50: 2020 U.S. CH_4 Emissions (MMT CO_2 Eq.) [Source: EPA U.S. GHGI, 1990-2020]

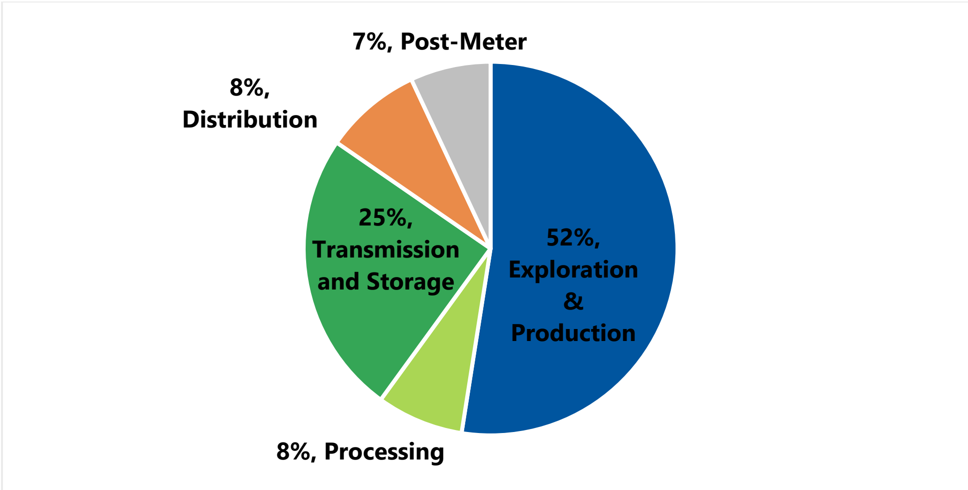

Table 3-68: CH_4 Emissions from Natural Gas Systems (MMT CO_2 Eq.)

Stage	1990	2005	2016	2017	2018	2019	2020
Exploration	**3.0**	**9.0**	**0.7**	**1.2**	**2.3**	**1.9**	**0.2**
Production	**61.3**	**83.4**	**90.1**	**92.6**	**93.8**	**92.8**	**86.4**
Onshore Production	37.5	56.8	52.6	53.4	54.3	51.6	47.6
Gathering and Boosting	18.5	24.0	36.4	38.3	38.7	39.9	37.5
Offshore Production	4.3	1.8	0.8	0.7	0.8	0.8	1.0
Processing	**21.3**	**11.6**	**11.2**	**11.5**	**12.1**	**12.6**	**12.4**
Transmission and Storage	**57.2**	**39.5**	**38.3**	**36.5**	**38.4**	**39.6**	**40.6**
Distribution	**45.5**	**25.5**	**14.2**	**14.1**	**14.0**	**13.9**	**13.9**
Post-Meter	**7.2**	**8.6**	**10.7**	**10.6**	**11.1**	**11.4**	**11.5**
Total	**195.5**	**177.5**	**165.2**	**166.6**	**171.8**	**172.1**	**164.9**

Note: Totals may not sum due to independent rounding.

Figure 51: CH_4 Emissions from Natural Gas Systems Including Post-Meter Emission [Source: EPA]

The category for Stationary Combustion emissions in the inventory includes CH_4 emissions directly from combustion equipment operation. Stationary combustion emissions of CH_4 in the inventory are a function of the CH_4 content of the fuel and combustion efficiency, estimated in a top-down approach by multiplying fossil fuel consumption data by emissions factors associated with sector and fuel type. For residential and commercial natural gas, this factor is 5 g/GJ or roughly 0.001 lb/therm [EPA, 2020]. To prevent double counting, EPA subtracted the CH_4 emissions for residential natural gas combustion from the estimated residential post-meter emissions [EPA, 2020]. The GHGI authors recognize inherent uncertainties in these estimates due to emission factors representing only a limited subset of combustion conditions, as well as uncertainties around combustion technology type, age of equipment, emission factors used, and activity data projections.

Recent field and laboratory studies have attempted to resolve this gap in information and quantify the contribution of building equipment to overall CH_4 emissions. A number of recent studies indicate that inventories are underestimated, particularly due to higher methane leakage from transient behavior of equipment as well as from leaks in equipment fittings and valves that were previously unaccounted for.

In general, research methods for quantifying methane emissions tend to fall into two general categories: top-down measurements that are derived from atmospheric methane measurements or bottom-up methods that account for individual systems components and their emissions rates to calculate cumulative emissions. Methods to quantify residential and commercial equipment generally fall in the bottom-up category, measuring emissions from single pieces of equipment, because of the difficulty of disaggregating equipment-level emissions from distribution leaks and other regional CH_4 sources in atmospheric measurements. There is no standard method for measuring CH_4 emissions from appliances, but all methods need to be able to address a number of specific challenges to accurately quantify and attribute combustion equipment methane emissions. First, methane concentrations in the exhaust of combustion equipment over a full duty cycle have a large range, which is typically larger than a single instrument can accurately measure if taking direct measurements of the exhaust. Pre-ignition and extinction "puffs" can be several thousand ppm, while steady-state emissions may be in the tens of ppms down to below one ppm. Second, peak emissions are highly transient, with ignition and extinction peaks lasting only a few seconds. Third, the assumed duty cycle has a significant impact, since a large portion of emissions are associated with ignition and shut down of the equipment. All the studies reviewed in the following sections used unique methods to quantify the emissions from equipment, which can roughly be categorized into three types of measurements:

- Collection of exhaust gas in larger airstream of known flowrate with CH_4 measurement. This method allows for direct calculation of CH_4 emission rates from a known flow rate and CH_4 concentration in the exhaust. Since the CH_4 will be highly diluted, it requires a gas analyzer with high resolution and accuracy to detect changes in CH_4 concentration.
- Exhaust gas sampling (CO_2, CH_4) paired with measured or assumed gas input. This method uses combustion stoichiometry to calculate the exhaust flow rate in order to determine the total emissions of CH_4 as measured in the exhaust. Limitations are present during ignition and extinction phases of sampling, and often require significant assumptions about exhaust flow during these periods or use of one of the other methods to quantify transients.
- Exhaust gas sampling (CH_4) and exhaust gas volumetric measurements. This method allows for direct calculation of the emissions from the measured CH_4 concentration and the exhaust flow rate. This method is best suited to laboratory measurements where sensitive flow equipment can be calibrated and secured permanently.

There are a number of sources of emissions in residential and commercial combustion equipment.

- **Ignition:** All field and laboratory testing discussed later in this review demonstrate the presence of methane emissions at the start-up of equipment when combustion is being established. This is typically a transient puff of methane that quickly dissipates as the equipment reaches steady-state combustion. These emissions may be present at initial start-up of the equipment or at the ignition of stages within multi-staged equipment.
- **Steady-state:** Incomplete combustion will result in methane emissions from the burner during steady-state operation, called fuel slip, which is generally very low [Saint-Vincent, 2020]. This may be the result of burner design and operation, or in cases of high emissions, a poorly tuned, damaged, or dirty burner.
- **Shut-off:** There will be some level of residual gas left in the gas manifold after shutdown of equipment. This gas may remain and slowly dissipate, or it may be flushed out of the

equipment during a post-purge. In the case of equipment with multiple stages, the shutoff of a stage generally results in emissions during operation.

- **Gas Valve Trace Leakage:** All gas valves have some level of leakage, even when operating properly, due to trace leakage through rubber compounds and fillers for the valve diaphragms.[63] Valve manuals include levels of acceptable leakage, as per the example below:

Table 13: Example of Maximum Acceptable Valve Seat Leakage Per Pipe Size for a Combustion Equipment Control Valve[64]

Pipe Size (in. NPT)	Maximum Seat Leakage (UL)	Maximum Number of Bubbles in 10 sec.
½ - ¾	235 cch	6
1	275 cch	7
1 ¼	340 cch	8

- **Pilot Light:** Several studies have indicated that poorly controlled combustion of standing pilot lights can be a significant source of methane emissions for residential equipment. [Lebel, 2020; Fischer, 2018].
- **Leaking components within equipment piping:** Although there is a certain expected level of low-level leakage from gas valves, unexpectedly high leakage through gas valves or from other piping connections within the equipment itself may lead to high methane emissions. Depending on the method being used to measure CH_4 emissions, this leakage may be picked up as emissions during combustion or as emissions during the off-stage of equipment operation. They may be difficult to distinguish from other sources of emissions if a detailed component survey with a gas sniffer is not performed.

Overview of Technology Status

Regulatory entities like the U.S. EPA or California Air Resources Board and industry bodies like ANSI/CSA have established practices for equipment-specific field sampling or laboratory measurement protocols of CO or NO_x,[65] however, this is not the case for methane emissions from gas-fired appliances. Direct emissions of methane are not regulated for natural gas-fired appliances. The industry is at an early stage with respect to methane emissions from gas-fired appliances. While there is not yet a general consensus on the characterization and magnitude of methane emissions from gas-fired appliances, a potentially more critical issue is that there is no established methodology for sampling and quantifying these emissions from these appliances, either through in-situ field measurements or through laboratory-based standardized testing. Given that the bulk of methane emissions from these appliances appear to be caused by highly transient short "puffs" on the order of a few seconds, this places unique challenges on testing/sampling protocols to accurately quantify these emissions, as discussed previously.

63 "The Truth About Gas Leakage Complaints and Gas Valves." Honeywell. Form Number 70-2320.
64 Honeywell V4730C Manual
65 Gas-fired furnaces are commonly certified to *ANSI Z21*.47 / CSA 2.3 to have CO emission rates of no more than 400 ppm (air free) and, in some jurisdictions, emissions of NO_x are limited to as low as 14 ng/J per the South Coast Air Quality Management District's *Rule 1111.*

Some validity to this quantification challenge is suggested by recent field and laboratory studies that have reported emission factors for individual appliance types with differences of 3X to 15X depending on appliance type and operating mode [Merrin, 2019]. Likewise, estimates depend heavily on assumptions of frequency and nature of appliance cycling, pointing to a need for a more robust dataset, as indicated by recent studies on tankless water heater emissions. GTI Energy's recent laboratory-based study on methane emissions from tankless water heaters deployed the simulated use test from which determinations of energy efficiency are based,[66] suggesting between 0.27% and 0.36% of fuel consumed by the appliance will be emitted as methane [Bonetti, 2020]. In contrast, a field-based study by Stanford University researchers estimated 0.93% of tankless water heater TWH natural gas consumed was emitted, with an average of 31.9 activations of the TWH per day [Lebel, 2020].

With respect to mitigation efforts, with no performance standard for methane emissions, equipment is only secondarily designed to minimize methane emissions. Design features to improve combustion efficiency to meet CO limits would likely also reduce incomplete combustion leading to methane emissions during steady state operation. Since a significant source of methane emissions from equipment operation occurs during transient states and from component leakage, the impact will be limited.

With field studies suggesting that a significant portion of emissions occur during the off-state of equipment, either from poor combustion of pilot lights or from leaks from piping and equipment components, and that a small percentage of appliances contribute the majority of emissions due to the long-tailed distribution of measurement results, attention would be well spent not only on burner and operation design, but also on quality control of component assembly and installation practices.

Overview of R&D and Industry Efforts

With increased focus on methane emissions across the value chain, studies have been released in the last five years seeking to better quantify methane emissions from end use equipment and identify opportunities for mitigation. In this early stage of research, many studies are focused on improving quantification but none have yet trialed mitigation measures. A unique methodology was used for each study described below. The results are consistent in indicating that the current emission factors for natural gas equipment underestimate CH_4 emissions, but the magnitude of estimated emissions for appliances can vary ten-fold or more.

Top-down studies focusing on residential and commercial sectors have been published [He, 2019], however, these cannot be used for individual source attribution, meaning they provide useful information regarding the discrepancy between current inventories and top-down surveys [Saint-Vincent, 2020], but cannot positively identify the contribution of individual appliance types to identify mitigation options. The following overview covers only bottom-up studies.

CEC-500-2018-021 Natural Gas Methane Emissions from California Homes, 2018 [Fischer, 2018]

In 2018, Lawrence Berkeley National Laboratory released a study of 75 California homes to estimate statewide mean methane emissions from residential natural gas consumption.

66 10 CFR Appendix E to Subpart B of Part 430 – "Uniform Test Method for Measuring the Energy Consumption of Water Heaters".

Measurements included inactive house leakage (pipe-fitting leaks and pilot light flames), as well as a subset of emissions from operating combustion equipment. Inactive emissions were determined using a mass balance method—depressurizing the home using a blower door and measuring the stable methane concentration of the air pulled from the house versus ambient outdoor methane concentration. Emissions from operating combustion equipment were taken as measurement of dilute exhaust (CO_2 and CH_4) with a Picarro G2132 analyzer. The product of the fractional enhancement of CH_4 relative to CO_2 in exhaust times gas input (based on nameplate or repeated gas meter readings) provided the total methane emission rate during steady-state operation. Ignition and extinguishment transients were estimated for three tankless water heaters but not included in total estimates.

The measurements of combustion efficiency during steady operation showed zero emissions from over half of the equipment measured, while equipment with emissions generally showed ΔCH_4: ΔCO_2 enhancement rations between 0.015% and 0.5%. Estimated total statewide emissions of 13.3 Gg CH_4/year, were an order of magnitude higher than 2015 California inventory estimates for residential natural gas combustion, with pilot lights contributing nearly 30% to total appliance emissions. Transient emissions were not included in the estimate and would likely increase appliance emissions further. Total emissions including quiescent house leakage and equipment operation were estimated to be 35.7 Gg CH_4/yr, equivalent to about 0.5% of California's residential NG consumption.

Recommendations for emission reductions related to equipment included modernization of combustion equipment to move toward electronic ignitions and improved manufacturer design to minimize CH_4 emissions during startup and shutdown.

Unburned Methane Emissions from Residential Natural Gas Appliances, 2019 [Merrin, 2019]

For a 2019 publication from the University of Illinois, Champaign, researchers measured space heating, water heating, and cooking equipment emissions from 100 homes in the Boston and Indianapolis area, including transient emissions. For field measurements, the research team directly measured dry exhaust composition (CO_2, CH_4) using a modified Picarro G3401. The exhaust rate was calculated from combustion stoichiometry, excess air, and rated fuel consumption (maximum rated input assumed) and combined with measured CH_4 concentration to calculate the CH_4 emission rate. To calculate exhaust flow during ignition and extinction transients, no excess air was assumed during initial ignition phase and linear decrease in exhaust flow rate was assumed when deactivating the unit.

The appliance results were combined with appliance usage and prevalence assumptions to estimate ~30 Gg CH_4/yr of emissions from U.S. residential natural gas appliances, or about 0.038% of natural gas consumed (see Figure 52). Emissions for equipment such as furnaces, storage water heaters, and boilers typically demonstrated a pattern of emission peaks during ignition and extinction of the burner, with low concentrations of CH_4 during steady state. Ovens and some tankless water heaters displayed cycling behavior during operation, leading to higher per unit emissions. Stove burners and numerous tankless water heaters exhibited non-trivial emissions during steady-state operation.

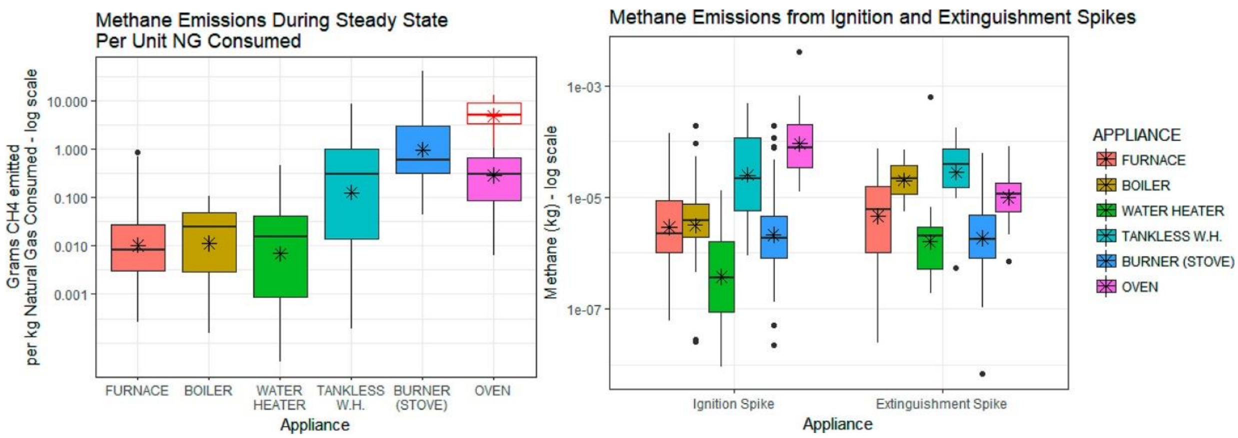

Figure 52: Steady-state and On/Off Pulse Emissions for Residential Appliances [Source: Merrin, 2019]

Quantifying Methane Emissions from Natural Gas Water Heaters, 2020 [Lebel, 2020]

A 2020 field study published by researchers at Stanford University examined water heater emissions from 35 northern California homes and characterized daily usage patterns from 46 homes. Results were scaled to estimate nation-wide emissions from tankless and standard water heaters of 82.3 [73.2, 91.5] Gg CH_4/yr, roughly 0.40% of natural gas delivered to the appliance. Tankless water heaters emitted an average of 0.93% of their gas consumed and storage water heaters 0.39%. Emissions were measured by collecting the exhaust of the water heaters into the controlled airstream of a Minneapolis Duct Blaster with a known flow rate. The concentration of CH_4 within the airflow was measured at the end of a flexible duct to ensure the sample was well mixed using a Cavity Ring-Down Spectrometer G2210-i (Picarro Inc.). The concentration enhancement over background CH_4 concentration was multiplied by the temperature corrected flow rate to determine emission rates. This method allowed for measurement of emission rates for a variety of operating states: steady-state off (includes pilot light emissions and local leakage), as the appliance turned on or off, and steady-state operation as shown in Figure 53.

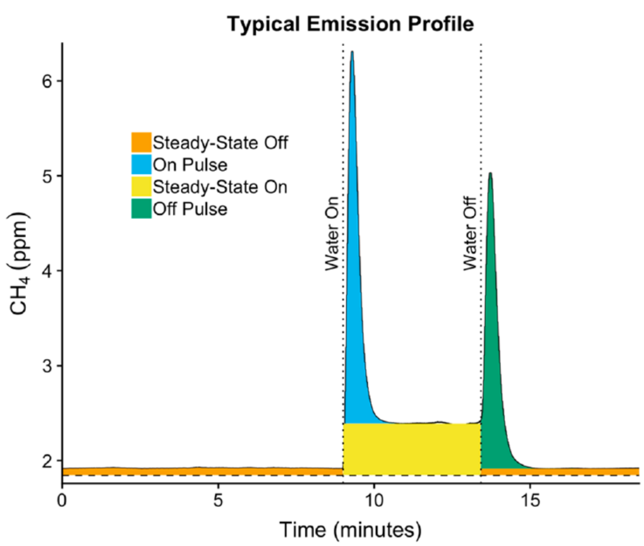

Figure 53: Typical Concentration Plot for a Water Heater Run Cycle [Source: Lebel, 2020]

A key insight from this paper is that the distribution of methane emissions from various equipment types is significantly different, providing opportunities to target specific design and operation elements to mitigate emissions. As seen in Figure 54, emissions from storage water heaters are dominated by steady-state off emissions, likely from incomplete combustion of pilot lights or nearby pipe leaks. In contrast, tankless water heater emissions are primarily from on/off pulses. These pulses were, on average, much larger than those for storage water heaters. Also, daily usage the storage water heater activated an average of only 3.9 times per day compared to the 31.9 times per day of the tankless water heater.

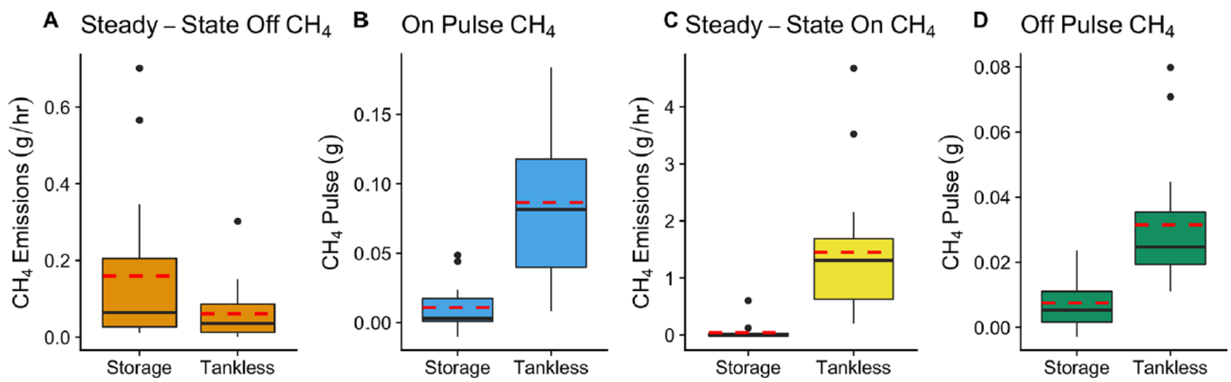

Figure 54: Boxplot of Emission Measurement for Storage and Tankless Water Heaters During Different Operating Modes [Source: Lebel, 2020]

Mitigation recommendations from this paper include increased adoption of electronic ignitions to reduce storage water heater steady-state off emissions as well as closer evaluation of tankless water heater design to reduce on/off pulse emissions, either through equipment design or by redesigning triggering of hot water demand to reduce daily activations, especially for short draws that may not result in hot water to the tap.

GTI Energy Laboratory Quantification of Methane from End Use Appliances [Bonetti, 2020 and forthcoming]

GTI Energy has a series of projects ongoing in their laboratories to quantify the amount and determine the conditions under which residential appliances emit CH_4. The projects will develop representative emission factors under specific operating conditions and representative use patterns. Laboratory testing of TWHs completed in 2020 measured emissions for steady-state, modulating, and 24-hr simulated use cases from which determinations of energy efficiency are based.[67] This work used direct flue measurements of exhaust constituents. To address the challenge of large range, two analyzers were utilized: a rack-mounted flame ionization analyzer with higher range and short response time to capture peaks, and a cavity ring down spectroscopy analyzer (Los Gatos Research Ultra-portable Greenhouse Gas Analyzer) with ppb resolution to capture steady-state low sources. Since a mass balance approach was used to calculate steady-state emissions, gas input was measured with a high-resolution gas meter. Exhaust gas mass flow rate was calculated based on gas input and exhaust gas composition for combustion periods, while direct exhaust flow measurement using a pitot tube was utilized to understand the flow patterns during transient periods. Measured CH_4 concentration combined with calculated exhaust flow rate provided the CH_4 emission rate.

67 10 CFR Appendix E to Subpart B of Part 430 – "Uniform Test Method for Measuring the Energy Consumption of Water Heaters".

Rather than a large field study, the laboratory work sought to provide a more detailed investigation of the effect of TWH design, selecting three TWHs representing a variety of burner and control strategies as shown in Table 14.

Table 14: Tankless water heater design and control details

TWH	Burner Details	Other
1	Cartridge Style – 3 modules, three-port staged gas valve, 3 igniters	Non-condensing, up-fired, constant speed combustion air blower
2	Mesh Style burner, staged gas valve, single point ignition	Condensing, down-fired, tight control of excess air
3	Mesh/flameholder style - two primary stages (solenoids) with single modulating gas valve, 2 igniters	Condensing, down-fired, tight control of excess air

Understanding that the number of daily activations will play a significant role in the final emission factor, the 24-hr simulated use test results (see Table 15) are between 0.27% and 0.36% of fuel consumed by the appliance emitted as methane, with between 73% and 100% of emissions due to transient, cycling behavior [Bonetti, 2020].

Table 15: 24-hr Simulated Use Test for TWH: High-usage case, 14 draws, 84 gal

TWH	Ignition Avg. (mg)	Extinction Avg. (mg)	Steady State (mg/min)	Daily Percent of NG (% v/v/)
1	153	21	30	0.36%
2	96	67	0	0.27%
3	89	62	20	0.32%

Results indicated the following general principles:

- All TWHs examined exhibited "puffs" of methane at both ignition and extinction of the burner, regardless of design.
- Burner modulation showed only increased methane emissions when it involved ignition or extinction of stages, whereas modulation within a stage maintained steady-state or near steady-state emission levels.
- Steady-state emission levels were dependent on burner design and firing rate.
- Some TWHs had methane emissions during periods of no firing.
- Emission factors are highly specific to the firing pattern assumed due to the significant contribution of ignition/extinction emissions.

Further testing was recently completed at GTI Energy using similar methods to test four residential natural gas furnaces. Additionally, laboratory measurements of large commercial and industrial furnaces, water heaters, and boilers is ongoing, measuring full-cycle methane emissions during duty cycles at various firing rates and excess O_2, including start-up and shut-down transient emissions.

Methane and NOx Emissions from Natural Gas Stoves, Cooktops, and Ovens in Residential Homes, 2022 [Lebel, 2022]

A further publication from Stanford University released in 2022 quantified methane emissions from stove use in 53 homes, again covering steady-state off, steady-state on, and transient emissions. Without a dedicated exhaust, emissions from cooking equipment can be difficult to measure in the field. The researchers used a room chamber method, sealing the space around the appliance and measuring the change in concentration of methane in the chamber with a Picarro G-2210i cavity ring-down spectrometer over various operating modes. The estimated emissions from natural gas stoves was 0.8 to 1.3% of the natural gas supplied to the appliances, with more than a quarter from steady-state off (see Figure 55). This operating mode includes all leaks within the chamber, which may include pipe leaks from home piping to the appliance, valve bypass, or pilot light emissions.

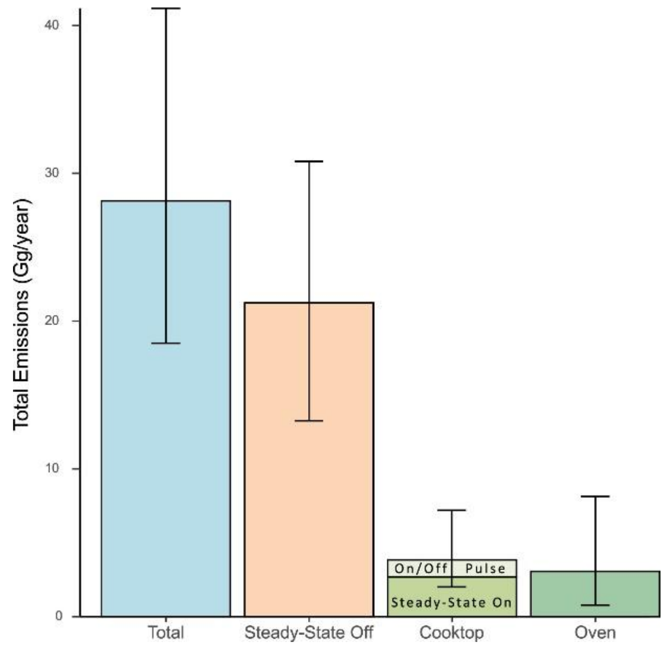

Figure 55: Total Methane Emissions by Source Scaled Up to National Estimate [Source: Lebel, 2022]

A few important observations come from this study.

- These results are long-tailed skewed for each one of the burner operational states, with the top 10% of all observations responsible for 47% of total emissions. The high emitters were identified as cooktops ignited with pilot lights.
- Emissions from cooktop use, excluding steady-state off emissions, are similar in order of magnitude to previous studies that included measurement of cooktop emissions [Merrin, 2019 and Fischer, 2018].
- This study suggests that steady-state off emissions provide the largest source of natural gas leakage in homes.

GFO-21-505 - Improve Characterization of CH_4 Emissions from California's Residential Sector[68]

Recognizing the challenges with quantification of methane emissions from residential equipment and correct attribution in inventories, the California Energy Commission awarded a research grant to Lawrence Berkeley National Lab in early 2022 to further characterize methane emissions and develop residential sector mitigation methods for methane leakage. To fully

68 https://www.energy.ca.gov/solicitations/2021-11/gfo-21-505-improve-characterization-methane-emissions-californias-residential Accessed November 2022.

characterize the necessary variables for estimating building stock emissions, the study will characterize both transient and steady-state emissions, assess the impact of super-emitters, and draw from a representative sample of California's housing stock. The study will characterize the magnitude and distribution of residential methane emissions in California to inform building decarbonization policy and implementation by providing an improved basis for accounting for methane emissions reductions associated with residential decarbonization.

Technology Pathway Outlook

With methane measurement and mitigation from end-use equipment still in early stages, a number of key research pathways clearly emerge:

- **Develop Sampling and Testing Protocols:** Working with gas-fired appliance manufacturers, researchers and academia, regulatory stakeholders, and other interested bodies, the industry should prioritize establishing common sampling and laboratory testing protocols for methane emissions from gas-fired appliances. To date, sampling and testing methodologies used have been ad hoc, leading to challenges in comparing results across studies. Using existing sampling and laboratory test methods for quantifying other air pollutants from gas-fired appliances as a guide, the industry should seek to reach consensus on sampling and testing methodologies for quantifying these methane emissions.
- **Expanded Quantification of Appliance Methane Emissions:** Building on prior, initial studies, the industry should also prioritize expanding data collection of methane emissions from the primary appliance categories. Quantification of emissions, through in-situ field measurements and laboratory-based testing, should leverage emerging industry protocols and facilitate generalization across appliance use cases. A key aspect of this effort is development of representative use patterns.
- **Develop and Deploy Cross-cutting Methane Mitigation Solutions:** For appliance categories or use cases where mitigation is necessary, the industry should support the development and deployment of cross-cutting methane mitigation solutions. These may range from design changes to existing products to application of after-market emissions control technologies.

Thus far, the natural gas industry's response to methane emissions have been sector-specific and responsive to external pressures applied by environmental stakeholders through regulatory channels and public perception. A collaborative research program, inclusive of all sectors of the natural gas industry, would be well-positioned to undertake a pro-active response in terms of establishing a sound baseline and then a measured plan to achieve reasonable methane emission reduction goals over time.

References for Methane Emissions Section

- Bonetti, E., "Methane Emissions from Tankless Water Heaters," Presented at the 2020 ACEEE Hot Water Forum.
- California Air Resources Board. Inventory Updates Since the 2018 Edition of the Inventory: Supplement to the Technical Support Document. August 2019. https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2017/ghg_inventory_00-17_method_update_document.pdf
- Fischer, Marc L., Wanyu Chan, Seongeun Jeong, and Zhimin Zhu. Lawrence Berkeley National Laboratory. 2018. Natural Gas Methane Emissions From California Homes. California Energy Commission. Publication Number: CEC-500-2018-021.
- Li, H. et al. 2019. "Atmospheric Methane Emissions Correlate with Natural Gas Consumption from Residential and Commercial Sectors in Los Angeles." Geophysical Research Letters 46.
- Kosar, D., Glanville, P., and Vadnal, H. "Residential Water Heating Program - Facilitating the Market Transformation to Higher Efficiency Gas-Fired Water Heating - Final Project Report", CEC Contract CEC-500-2013-060, 2013.
- Lebel, E. et al. Quantifying Methane Emissions from Natural Gas Water Heaters", Environmental Science & Technology 2020 54 (9), 5737-5745, DOI: 10.1021/acs.est.9b07189.
- Lebel, E. et al. Methane and NO_X Emissions from Natural Gas Stoves, Cooktops, and Ovens in Residential Homes. Environmental Science & Technology 2022, 56 (4), 2529-2539, DOI: 10.1021/acs.est.1c04707.
- Merrin, Z. and Francisco, P. Unburned Methane Emissions from Residential Natural Gas Appliances, Environmental Science & Technology 2019, 53 (9), 5473-5482, DOI: 10.1021/acs.est.8b05323.
- Saint-Vincent, P. and Pekney, N. Beyond-the-Meter: Unaccounted Sources of Methane Emissions in the Natural Gas Distribution Sector. *Environmental Science & Technology* 2020, 54 (1), 39-49.
- U.S. Environmental Protection Agency. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2020. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020
- U.S. Environmental Protection Agency, "AP-42: Compilation of Air Emissions Factors", Table 1.4-2. Accessed 2022, https://www3.epa.gov/ttnchie1/ap42/ch01/final/c01s04.pdf