U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

R&D Opportunities for Natural Gas Technologies in Building Applications

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Preface

The Department of Energy's (DOE) Building Technology Office (BTO), a part of the Office of Energy Efficiency and Renewable Energy (EERE) engaged Navigant Consulting, Inc., (Navigant) to develop this report characterizing research & development (R&D) activities for the advancement of natural gas technologies.

The activities identified in this report are Navigant's recommendations to BTO for pursuing to achieve DOE's energy efficiency goals. Inclusion in this report does not guarantee funding; activities must be evaluated in the context of all potential activities that BTO could undertake to achieve their goals.

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Nomenclature or List of Acronyms

Acronym	Description
A/C	Air conditioning
AMI	Advanced metering infrastructure
BTO	Building Technologies Office (Department of Energy, part of EERE)
CC-GAHP	Cold-climate gas absorption heat pump
CCHP	Combined cooling, heat, and power (aka trigeneration)
CHP	Combined heat and power (aka cogeneration)
DHW	Domestic hot water
DOE	Department of Energy
EERE	DOE's Office of Energy Efficiency and Renewable Energy
ESTCP	Environmental Security Technology Certification Program (Department of Defense)
EUI	Energy use intensity
FMEA	Failure modes and effects analysis
GAHP	Gas absorption heat pump
GHG	Greenhouse gases
GHP	Gas (engine) heat pump
HP	Heat pump
HPWH	Heat pump water heater
HVAC	Heating, Ventilation, and Air-Conditioning
LPG	Liquefied petroleum gas
NG	Natural gas
NILM	Non-intrusive load monitoring
NREL	National Renewable Energy Laboratory
MYPP	Multi-year program plan
S-CO_2	Supercritical CO_2
SPY-A	Single-packaged year-round air conditioners
TPV	Thermophotovoltaic
R&D	Research and development
VRF	Variable refrigerant flow

Executive Summary

The U.S. Department of Energy's (DOE) Building Technologies Office (BTO) within the Office of Energy Efficiency and Renewable Energy (EERE) seeks to reduce building energy consumption by 30%, relative to 2010 consumption levels, by 2030.

DOE retained Navigant Consulting Inc. (hereafter, "Navigant") to recommend innovative natural gas (NG) technologies that can assist BTO in achieving its 2030 goal. This report identifies research and development (R&D) activities across several building applications where further investigations could result in impactful savings. While this report uses the term natural gas throughout for simplicity, the analysis also covers products that operate on propane (liquified petroleum gas, LPG).

One-on-one interviews, as well as a stakeholder workshop, hosted at the DOE's headquarters in Washington D.C., helped guide and inform the findings of this report. Key themes emerged from that outreach, including:

- Condensing technologies have brought traditional, direct-fired NG equipment efficiencies to the upper 90% range, so few additional opportunities exist for incremental performance increases without embracing transformative technologies like absorption heat pumps.
- Stakeholders have broad interest in improving natural gas system efficiency through system-level improvements, not just through improved combustion efficiency. Areas of interest include waste-heat recovery from one end-use for application in another, innovative controls, and low-cost sensors that enable data-driven operations.
- Interest in low-cost, innovative multi-function NG products is increasing, including the more common combination space heat and hot water systems, as well as more exotic products like combined cooling, heating, and power systems (CCHP, or trigeneration). Combining discrete systems into multi-function systems enables mutually beneficial solutions to increase performance and reduce heat losses.
- Interest in CHP and related technologies is increasing, particularly among utility stakeholders. Small applications, like light commercial and large residential (both single family and multi-family) have historically been of little interest to the CHP industry due to cost and complexity concerns. At the workshop, Stakeholders discussed at length the potential opportunities to overcome these hurdles in order to open up a new market for CHP with high-reliability, low-maintenance products.
- NG technologies face increased competition from all-electric, renewable-enabled building systems, which is motivating increased focused on new and innovative NG solutions. This has increased interest among utilities in NG-based equipment to displace electric loads (e.g., cooling, refrigeration, on-site generation).

Navigant aggregated and refined the findings from the stakeholder outreach and identified the top 10 activities for DOE to consider based on their potential impact, relevance to DOE's goals, the criticality of DOE's involvement in their development, and their level of interest amongst select stakeholders. Table ES-1 lists these activities along with their score (1-5, where 5 is best); they are discussed in further detail in Section 3 of this report.

Table ES-1: Top 10 R&D Activities

Rank	Category	Description	Score
1	Gas heat pumps	Development of reversible cycle absorption HP (GAHP) appliances with high efficiency cooling (to enable year-round use and better competition with electric A/C)	3.6

Rank	Category	Description	Score
2	CHP	Development of connected, controllable CHP systems (~100-500 kW) with optimized control strategies to enable rapid-response operation (including electrical and thermal storage).	3.5
3	Boilers & Furnaces	Development of energy recovery solutions to boost NG equipment efficiencies and resiliency through electric generation.	3.5
4	Manufacturing	Development of equipment designs and/or manufacturing methods for cheaper manufacturing of NG equipment (e.g. gas fired HP heat exchanger mfg.).	3.45
5	CHP	Development of improved and/or lower cost combined cooling, heat, and power (CCHP) systems (aka Trigeneration)	3.45
6	Materials	Development of novel materials or processes to improve cost-effectiveness of regenerating desiccants using natural gas	3.4
7	Gas heat pumps	Development of new or improved gas HP absorption cycles to improve efficiency in cold climates	3.4
8	Boilers & Furnaces	Development of improved multi-fuel/hybrid systems that optimize for cost and emissions	3.3
9	Heat & heat/mass exchange	Development of membrane-based heat and mass exchangers with higher throughput of fluid	3.1
10	CHP	Improve performance of small natural gas engines for microCHP and small GHP applications (improved efficiency, longer useful life, and fewer servicing requirements)	3.1

The following report further characterizes each of these activities, as well as the challenges they face and seek to overcome. Section 3 contains a comprehensive list of all activities identified during develop of this report.

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1 Introduction

1.1 Background

The U.S. Department of Energy's (DOE) Building Technologies Office (BTO) within the Office of Energy Efficiency and Renewable Energy (EERE) seeks to reduce building energy consumption by 30%, relative to 2010 consumption levels, by 2030. To meet this goal, BTO seeks to develop next-generation technologies that dramatically improve efficiency and/or provide substantial cost reductions for existing high-efficiency equipment.

BTO's mission is to:

> Develop, demonstrate, and accelerate the adoption of technologies, techniques, tools, and services that are affordable, as well as to enable high-performing, energy-efficient residential and commercial buildings in both the new and existing buildings markets.

DOE views natural gas technologies as a unique opportunity to improve primary energy efficiency and help achieve the 2030 goals and further BTO's mission. DOE has previously funded natural gas technology R&D but seeks to determine what further early stage R&D opportunities

1.2 Report Objective

With this report, BTO seeks to determine the greatest opportunities for research and development (R&D) of natural-gas building equipment and appliances and to characterize those activities that are well suited to BTO support. This objective includes two elements:

1. Understand the landscape of innovative natural gas technologies
2. Characterize future BTO opportunities for natural gas technology R&D

The characterization of the emerging natural gas technology landscape and the development of the activities described in this report, provide DOE with a wide array of paths to pursue. Each activity is a focused topic area with specific objectives but is defined sufficiently broadly that potential BTO funding recipients can propose and compete on the merits of their own specific technology solutions. That is, activities in this report are not specific projects – the details of any individual project must be determined by the proposing organization (performer).

1.3 Report Scope

The following is an overview of the applications of interest to DOE for this report – it is not exhaustive; their inclusion was the basis for research and information gathering.

- Furnaces & boilers – space heating
- Water heaters & boilers – water heating water heating
- Natural gas heat pumps – space heating, water heating, space cooling (including both gas absorption heat pumps [GAHP] and gas engine heat pumps [GHP])
- Combination ("combi") systems – space and water heating
- Appliances – clothes dryers, cooking equipment

- Combined heat and power (CHP) – Residential and commercial CHP systems (aka cogeneration), including MicroCHP (aka µCHP), and combined cooling, heating and power (CCHP)
- Gas combustion components – Burners and controls technologies
- Fuel distribution systems (behind the meter) – Metering, piping, pressure management
- Heat exchangers – specifically for use with natural gas systems
- Venting and emissions management – materials and products for safely venting one or more products to the exterior of the building while meeting all relevant emissions standards

DOE did not seek to cover this list of applications equally with new research opportunities, so the characterized activities in Section 3 are not intended to be exhaustive; they only cover those areas in the list above in which one or more stakeholders specifically raised topics of interest.

This report, as with the BTO, covers all residential and commercial buildings. Industrial applications that are not also applicable to commercial applications (e.g., multi-megawatt CHP) are excluded. Though we refer to all the relevant technologies in this report as operating on natural gas for simplicity, this analysis also pertains to those that operate on propane (liquified petroleum gas, LPG) as well.

1.4 R&D History

To understand the broader context of the R&D opportunities described in section 3 and to promote development of high-quality, innovative ideas in the broader R&D community, the following subsections provide a brief history of the natural gas R&D for both gas-fired heat pumps and CHP. DOE and other organizations have been conducting R&D on both equipment categories for many years. BTO seeks for future early-stage R&D to learn from these past experiences to make further progress toward DOE goals.

1.4.1 Gas-Fired Heat Pumps

The concept of gas absorption systems has been around for more than 100 years but has historically been used in large commercial and industrial applications. Some niche products are also available for marine, or off-grid refrigeration and cooling. However, for broader viability for use in residential and commercial buildings in the US, gas heat pumps must overcome two key challenges: high cost and large footprint. Garrabrant et. al. note that the R&D for space conditioning applications (capacities of 36,000 – 100,000 Btu/hr.) has covered numerous cycles in research laboratories throughout the world. The authors of that report state that "In general, research has taken the path of embracing increasingly complex cycle configurations (e.g., double-, triple-, and even quadruple- effect cycles, generator absorber heat exchanger (GAX) cycles, Branched GAX cycles, and Vapor-Exchange GAX cycles) to improve system efficiencies.[1]" However, despite the exploration of these cycles and the incremental efficiency improvements that these efforts have yielded, the resulting solutions have still been prohibitively complex, large, and costly. In addition to complex system architectures, these systems also tend to have complex control systems that are difficult to implement, which is generally counter to long-term reliability in the field, even if lower costs can be achieved.

Gas heat pump efficiency has improved because of focused R&D, particularly in the 1990s. An NREL article from May 1995 highlights efficiency improvements in the preceding two decades and shows cooling COP of 0.8 to 1.4 and heating COP of 1.6 to 2.1 (depending on the cycle and operating conditions). These COPs are not far from the COP ranges of today's technology.[2] (See section 3.1.1 for additional discussion of absorption

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[1] Paraphrased from Garrabrant, Michael, et. al. "Development and Validation of a Gas-Fired Residential Heat Pump Water Heater - Final Report". United States. doi:10.2172/1060285. https://www.osti.gov/servlets/purl/1060285.
[2] "Thermally activated heat pumps". United States. doi:10.2172/72952. https://www.osti.gov/servlets/purl/72952.

heat pump cooling COP.) We have not seen major jumps in efficiency since the 1990's because most research since that time has focused on cost and complexity as they the biggest barriers to commercial viability.

Key advances in today's absorption heat pumps include the GAX cycle (boosts the efficiency of the unit by recovering the heat that is released when the ammonia is absorbed into the water), high-efficiency vapor separation, variable ammonia flow rates, and low-emissions, variable-capacity combustion of the natural gas.[3] DOE has supported R&D on absorption systems to further these technologies for both commercial and residential applications since the 1970s, including[4]:

- From 1981-1996, DOE funded a series of projects with Phillips Engineering to develop a GAX heat pump. Building on the original 1913 design by Altenkirch, Phillips Engineering created a prototype GAX absorption heat pump in 1984-85, with independent testing occurring in 1993. DOE hoped to partner with existing HVAC manufacturers to bring the heat pump to market, but there was little cooperation due to manufacturer concerns that the GAX heat pump would simply displace sales of their current absorption products.
- In 1998, DOE supported a joint-venture between gas utilities and manufacturers to commercialize a GAX heating and cooling heat pump under the name Ambian. Although the venture developed multiple prototypes, the incremental costs for the units prevented commercialization. Subsequently, TIAX estimated that a heating-only version of the GAX heat pump could reduce costs by 25-35%.
- With DOE support since the early 2000s, Rocky Research developed, but did not commercialize, a 5-ton reversible GAHP utilizing GAX technology, optimized controls, and other innovations such as specially designed generators, expansion valves, and solution pumps.
- In the late 1990s, the Italian company Robur worked with DOE and ORNL to develop and commercialize their GAX heat pumps leading to limited introduction into the European market. Currently, Robur is the leading GAHP manufacturer in Europe, and has offered products in the Northeast U.S. since the late 2000s.

Additional details on active R&D prior to 1981 are available via an ORNL report: "A Survey of Advanced Heat-Pump Developments for Space Conditioning".[5]

1.4.2 CHP

The U.S.'s first power plant, Edison's Pearl Street Station, was a CHP plant built in 1882 that provided district steam to local manufacturers. For the next nearly 100 years, CHP remained a solution for central power plants and industrial facilities. CHP for buildings did not develop until after the Public Utilities Regulatory Policies Act of 1978 and implementation of tax credits. This Act required utilities to interconnect with qualified facilities, opening the door for merchant generators and broader deployment of CHP. An ACEEE blog post (citing data from ICF), showed 15 GW of CHP capacity in the US in 1980, increasing more than 5-fold over 30 years to 80 GW by 2010.[6] Today, more than 65% of the installed capacity (55 GW) is still in large central plants larger than 100 MW each.[7] With its roots in these large industrial power generation applications, CHP

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[3] "Absorption Heat Pumps" DOE website, available: https://www.energy.gov/energysaver/heat-pump-systems/absorption-heat-pumps

[4] Goetzler, William, et. al. "Energy Savings Potential and Research, Development, & Demonstration Opportunities for Residential Building Heating, Ventilation, and Air Conditioning Systems". United States. doi:10.2172/1219929. https://www.osti.gov/servlets/purl/1219929.

[5] Phillip D. Fairchild, "A Survey of Advanced Heat-Pump Developments for Space Conditioning" Oak Ridge National Laboratory, available: https://www.osti.gov/servlets/purl/6590861

[6] ACEEE, "A brief history of CHP development in the United States," available: http://aceee.org/blog/2016/02/brief-history-chp-development-united, accessed May 2018.

[7] DOE CHP Technical Assistance Partnerships, "History of CHP Development in the US," available: http://www.midwestchptap.org/cleanenergy/chp/history.aspx

development for buildings in the last 30 years has focused on reductions in cost and complexity as systems are scaled down to the sub-MW scale and packaged for commercial use.

Building-scale systems require most of the same components, but without the economies of scale, so they suffer from increased costs – capital cost estimates vary, ranging from $1,400/kW for multi-MW-scale systems, up to nearly $3,200/kW or more for sub-100 kW systems.[8] Similarly, operations and maintenance costs (O&M) can range from $0.009/kWh to $0.024/kWh depending on size of the unit. The trend appears to be further accentuated for even smaller systems (sub-50 kW, aka microCHP) for use in light commercial and residential applications. In many markets with very high electricity prices and low gas prices (a high "spark spread"), these increased costs may not substantially hinder deployment, but for much of the country it is a major hurdle to broader market adoption.

In scaling down large gas turbine-based systems, microturbines emerged (1990s) as a viable option for sub-MW scale systems to compete with reciprocating engines of the same size, though they remain a minority of installed systems. The DOE's CHP installation database currently shows a total of 623 MW of CHP systems in the U.S. smaller than 1 MW. Of these, 11% are microturbines and 72% are reciprocating engines.[9] The smallest microturbines are in the range of 30 kW.

microCHP products first came to market in the early 2000s.[10] Their entrance to the market was precipitated by improvements to larger packaged products that could be installed at lower cost without extensive custom engineering for each customer. These products typically are targeted at large single-family homes (sub 10kW) or small multifamily residential and light commercial buildings (10-50kW) but can also serve larger applications with the use of multiple units. As with other R&D efforts, microCHP R&D has focused on lower costs, and increased maintainability and reliability. In 2003 the DOE published "The Micro-CHP Technologies Roadmap," which articulated a national strategy for the research, development, and demonstration (RD&D) of microCHP.[11] The roadmap articulates a vision for technology development where a packaged CHP unit is the "heart of a 'smart' household."

Indicative of the continued push for cost-effective, small CHP systems, DOE's Advanced Research Project Agency (ARPAe) announced $25MM in funding in 2015 for a program called Generators for Small Electrical and Thermal Systems (GENSETS), which seeks to "develop transformative generator technologies to enable widespread deployment of residential combined heat and power (CHP) systems." The program targets a unit capacity of 1 kW, which is applicable to most single-family homes in the US. They seek a high fuel-to-electricity generation efficiency, long life, low cost, and low emissions, within four different technology areas: Stirling engines, internal combustion engines, microturbines, and solid-state devices.[12]

Emissions R&D has also historically been an important component of CHP R&D programs, particularly so in California where emissions regulations, stricter than those in other parts of the country, dictate the need for lower-emissions products. California's air resources board regulate emissions from natural gas generation equipment, with specific standards for criteria emissions (primarily NOx and particulate matter [PM]). The California Energy Commission (CEC) has sponsored multiple emissions-related CHP R&D projects.[13] Work

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[8] Cost range by location (vary labor rates), vendor, equipment type, and many other variables. Anecdotal cost data suggests that in high cost areas of the country, some systems are as high as $4,000/kW for total installed cost. Cost data from DOE fact sheets for reciprocating engines and microturbines, available at: https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Recip%20Engines.pdf and https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Microturbines_0.pdf, respectively.

[9] U.S. DOE Combined Heat and Power Installation Database, available: https://doe.icfwebservices.com/chpdb/ percentages calculated as of June 2018.

[10] Loosely dated from: https://www.inspirit-energy.com/article/3042222-why-would-anyone-want-a-combined

[11] DOE, "The Micro-CHP Technologies Roadmap: Meeting 21st Century Residential Energy Needs," December 2003, available: https://www.energy.gov/sites/prod/files/2013/11/f4/micro_chp_roadmap.pdf

[12] GENSETS program description available: https://arpa-e.energy.gov/?q=arpa-e-programs/gensets

[13] One example project is documented in "Integrated CHP Using Ultra-=Low NOx Supplemental Firing" March 2013, final report to CEC, available: http://www.energy.ca.gov/2013publications/CEC-500-2013-043/CEC-500-2013-043.pdf

has covered both after-treatments for emissions (e.g, three-way catalysts and other multi-stage approaches), as well as combustion, controls, and heat-recovery advances that reduce generation of criteria emissions.

1.5 Methodology

Figure 1 summarizes the process for developing this report.

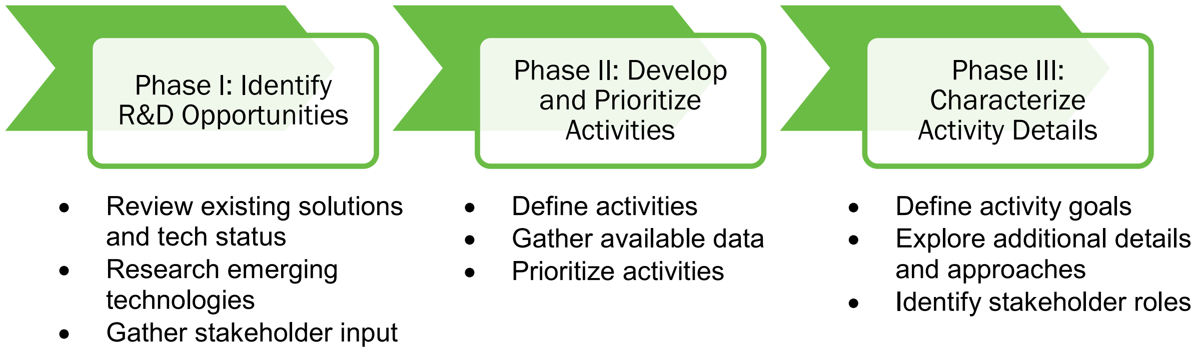

Figure 1: Report Development Process

1.5.1 Phase I: Identify R&D Opportunities

To identify potential research opportunities, we conducted a technology scan of research being undertaken. This research sought to uncover the overall trends, new emerging technologies, and barriers and challenges inhibiting adoption of these technologies. See Section 2 for a summary of key barriers and challenges. Phase I research lay the groundwork for detailed activity development.

To gather detailed inputs for activities, BTO hosted a stakeholder workshop on September 26, 2017 at the DOE's headquarters in Washington, D.C.[14] This event sought to capture inputs on early-stage research and development (R&D) needs and critical knowledge-gaps. We held a mix of large facilitated discussions with all participants as well as small breakout discussions with 10-12 people per discussion in order provide different avenues for all attendees to share their thoughts and respond to ideas suggested by others.

To help fill in gaps in information and ensure that we solicited information from a sufficiently broad stakeholder group, we conducted one-on-one interviews after the workshop. Interviewees include some workshop attendees with specific areas of expertise, interested stakeholders who were unable to attend the workshop, and select individuals who we identified after the workshop as having unique expertise who could help identify research opportunities in different or under-represented areas.

1.5.2 Phase II: Develop and Prioritize Activities

With the inputs from the foundational research and stakeholder workshops in Phase I, we developed a comprehensive list of R&D topics, which we refined into a preliminary activity list. This list aimed to broad reaching and mutually exclusive (but not necessarily exhaustive). To develop this list, we combined activities where there was overlap and added any activities that arose during stakeholder outreach that were not incorporated in the original list of R&D ideas.

[14] For more information on the outcomes of the workshop, refer to Appendix B – US Department of Energy's Workshop on Natural Gas Building Technologies

We evaluated each activity on the four metrics in Table 2 to identify the best opportunities, using the 1-5 scoring methodology described in Table 3.

Table 2. Activity Scoring Metrics – Definitions

Metric	Definition
Impact	Expected impact of the activity in addressing a critical knowledge gap or overcoming a key barrier to achieve significant energy savings in US buildings; savings may come directly from efficiency improvements or through cost reductions that enable broader adoption of high-efficiency technologies
Fit with BTO Mission	Suitability of activity (e.g., research stage and needs) to BTO's mission,[15] goals, and capabilities (including the activity's expected time to market) For example, high-risk, disruptive R&D is core to DOE's mission, while incremental, low-risk R&D is not.
Criticality of DOE Involvement	Criticality of BTO participation to the success of the activity
Stakeholder Interest	Level of interest based on stakeholder comments and votes from the stakeholder workshop. For activities that were combined due to overlap, the Stakeholder Interest score is the sum of the stakeholder votes from each of the initial individual activities.

Table 3. Activity Scoring Metrics – Scores

Metric	5	4	3	2	1	Weight
Impact	Significant	Semi-Significant	Moderate	Modest	Minimal	35%
Fit with BTO Mission	Core to mission	Semi-core to mission	Relevant to mission	Semi-relevant to mission	Outside scope / mission	35%
Criticality of DOE Involvement	Critical to success	Semi-critical to success	Beneficial to success	Semi-beneficial to success	Unnecessary for success	15%
Stakeholder Interest	> 20 votes	> 15 Votes	> 10 votes	> 5 votes	No Votes	15%

Members from the project team independently scored each activity based on the above, thereby resulting in a final list of activities, sorted by score.

1.5.3 Phase III: Characterize Activity Details

The process yielded a prioritized list of 30 activities. We selected the top 10 activities (scores greater than 3.1) as Tier I. For each of the Tier I activities, we further refined the objectives of the activity, outlined the potential impact on existing technical and market barriers, and recognized key stakeholder roles and responsibilities in pursuing the activity.

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[15] We considered activities not directly in BTO's purview but still relevant to DOE's mission as a fit with the mission. Additionally, activities with a broad idea related to BTO but specific functions in the domain of other offices also scored as a fit with the mission.

Section 3 describes each of the detailed activities.

2 Drivers and Challenges

Low-cost natural gas and an increased focus on alternatives to higher-emissions electric-generation fuels have increased the prominence of natural gas in recent years. Condensing equipment, introduced in the US only 10-15 years ago, has enabled a step change in efficiency for many types of equipment. While this has brought efficiency levels to 90+%, additional opportunities exist to improve efficiency beyond 100% (heat pumps) and to improve the efficiency of the distribution and controls systems. Section 2.1 and Section 2.2 discuss the technical and non-technical barriers, respectively.

2.1 Technical Barriers

Table 4 discusses some of the technical barriers that face many the innovative natural gas technologies.

Table 4. Technical Challenges.

Challenge	Description
Installation complexity Relevance: GHP/GAHP	Installation of a GHP/GAHP introduces new tasks that were not historically part of installing a hot water heater, boiler, or furnace. Further, some technologies will require involvement of multiple trades; for example, combi systems will require technicians for: HVAC (ducting, air handlers, and vapor compression systems), plumbing (piping, tanks, hydronic lines running outdoors), and for engine installation and commissioning for engine-driven heat pumps. As the product category grows, manufacturers may introduce standardized installation kits to reduce cost and complexity as they have done with electric heat pumps.
Ammonia toxicity Relevance: ammonia GAHP and HPWH	Ammonia is an ASHRAE class B2L refrigerant and is therefore toxic. Residential and light commercial products maintain safety by being fully sealed and using ammonia levels that are well within the allowable limits found in relevant mechanical codes. Most building products are also installed outdoors as an additional precaution. Larger commercial equipment is typically managed safely in a machine room with appropriate ventilation and other precautions. Absorption systems using lithium-bromide solutions do not encounter this problem.[16]
Field installation problems Relevance: Combi GHP/GAHP	The majority of combi products installed today are field-engineered to a certain degree, including many that are installed sub optimally. One key concern has been incorrect sizing of fan coils causing subpar performance.[17]
CHP/CCHP complexity Relevance: CHP and CCHP systems	CCHP and CHP systems are well established technologies in large commercial and industrial applications, but are not familiar to small commercial and residential building owners or the tradespeople that serve those sectors. The added complexity of the products means that most technicians will not be able to service these products without additional training. The most similar technology is backup power generation, but it is uncommon for service companies to be experienced in everything required for CHP/CCHP.

[16] Concerns for gas HPWH discussed briefly here: http://www.gastechnology.org/Expertise/Documents/ETP/Gas-Heat-Pump-Hot-Water-Heater-Technology-Snapshot-12-2016.pdf
[17] More information available at: http://www.etcc-ca.com/sites/default/files/nextgenhvac_final.pdf

Challenge	Description
Lack of contractor familiarity Relevance: CHP, GAHP/GHP, other new technologies	Innovative solutions to improve natural gas efficiency, such as absorption heat pumps, are very foreign to contractors because they rely on fundamentally very different principals of operation than traditional natural gas equipment. For broad adoption of the technologies, innovative R&D will have to consider solutions that are intuitive to maintain and service. While beyond the scope of this report, these innovative solutions will also require robust contractor education programs for them to be successful in the market.
Low COP for absorption cooling Relevance: GAHP	Absorption systems typically have low efficiency and to achieve high efficiency require substantial added complexity and cost. While non-reversible systems (heating only) may provide a successful path to market, many stakeholders expect that reversible systems will be more successful because they can operate year-round and ideally result in faster payback on high capital costs.
Limited resiliency of NG HVAC and water heating systems Relevance: all NG equipment	Natural gas water heating and HVAC equipment cannot operate in the event of a power outage. Natural gas infrastructure tends to be better protected from outages than electric infrastructure, but customers cannot take advantage of this fact since equipment also requires a separate electric supply. Resiliency is increasingly valued by customers and utilities, so resilient natural gas equipment could provide a valuable leg up on electric equipment.

2.2 Other Barriers

Innovative natural gas technologies also face barriers to successful development and deployment that are not technical, but instead relate to customer and contractor perceptions, supply chains, safety, and other issues that can impact how well a technology will be received by consumers.

Table 5 describes some of the key non-technical challenges.

Table 5. Non-Technical Challenges

Challenge	Description
Lack of contractor familiarity Relevance: GHP/GAHP	Contractors tend to promote the technologies they are most familiar with and, as with any substantially new technology, it will take training and encouragement to get the contractor community to embrace GHP/GAHP systems. Those contractors serving educated consumers that specifically request the product (a very small group) and are willing to install it, will charge a premium to do so.
Additional maintenance requirements Relevance: GHP – engine-driven only	Gas-engine driven heat pumps require all the maintenance of a vapor compression heat pump as well as all the maintenance requirements of a natural gas reciprocating engine. This increase in maintenance needs increases maintenance costs and increase the potential number of failure points in the system.
Cost premium Relevance: GHP/GAHP and CHP	The lack of familiarity by contractors (see above in this table) and introduction of new components and more complex systems will require extra labor and therefore added cost for each installation. Even in situations where the installation is straightforward, a contractor will charge a premium for the unknowns they encounter. The multiple trades required could introduce excessive premiums for installation of combi systems especially. Standardized installation kits (not yet available) could reduce cost and complexity as manufacturers done with electric heat pumps.

Challenge	Description
Btu/hr. as a sales specification Relevance: Commercial cooking equipment	Restaurant managers and chefs commonly specify some pieces of their cooking equipment, especially broilers, based on the Btu/hr. gas input instead of the cooking performance. Therefore, equipment that provides equivalent cooking performance but with lower gas input may not be considered sufficient.
Ammonia concerns Relevance: Absorption systems	Ammonia may be perceived as unsafe by customers due to its toxicity (ASHRAE class B2L refrigerant). See discussion of technical concerns in Table 4, above. Residential customers may not be comfortable with ammonia simply due to lack of familiarity. Contractors that are unfamiliar and voice safety concerns will also further inhibit adoption of the technology.
CHP competition Relevance: CHP	CHP faces lower-cost competition from incumbent technologies, most directly from well-vetted natural gas backup generators and (separately) gas heating equipment. Many manufacturers sell small-scale backup generators that are attractive to homeowners for resiliency. As a result, the key differentiator for CHP is efficiency – something that not all customers are willing to pay a premium for.
Interconnection, tariffs, and net metering Relevance: CHP and CCHP	Net metering regulations are inconsistent across the country; only 19 states allow net metering for CHP, though this may change over time.[18] Interconnection processes also differ by state and by utility, increasing hurdles for manufacturers and often increasing costs to customers. With time, tariffs may also change if CHP (and self-generation in general) becomes more accepted by utilities and regulators. Typical small units may be expected to operate 80-90% of the time but will not enable disconnection from the utility except in rare case (e.g., storage installed with CHP).

3 Research and Development Opportunities

The research and stakeholder outreach processes described in Section 1.5 resulted in identification and prioritization of 30 R&D activities. Table 6 summarizes the top 10 activities (scores greater than 3.1 out of 5). The following subsections provide additional details on each of these activities, including objectives of the activity, the potential impact on existing barriers, and key stakeholder roles and responsibilities in pursuing the activity. Key stakeholders include:

- Researchers – national laboratories, universities, R&D centers, etc.
- Contractors – customer-facing installers and technicians
- Suppliers – raw materials and component providers
- OEMs – original equipment manufacturers and their industry group representatives
- Utilities – gas, electric, and electric/gas utilities

Section 3.2 briefly discusses the tier II activities (scores less than 3.1).

3.1 Tier I Activities

Table 6 list each of the top tier activities along with a brief description and the final score from the prioritization process. See the following subsections for additional details.

[18] Data is from 2015: http://www.yanmar-es.com/news/net-metering-for-combined-heat-and-power-systems/

Table 6. Tier I Activities.

Rank	Category	Description	Score
1	Gas heat pumps	Development of reversible cycle absorption HP (GAHP) appliances with high efficiency cooling (to enable year-round use and better competition with electric A/C)	3.6
2	CHP	Development of connected, controllable CHP systems (~100-500 kW) with optimized control strategies to enable rapid-response operation (including electrical and thermal storage).	3.5
3	Boilers & Furnaces	Develop energy recovery solutions to boost NG equipment efficiencies and resiliency through electric generation	3.5
4	Manufacturing	Development of improved manufacturing methods for cheaper NG equipment (e.g. gas fired HP heat exchanger mfg.)	3.5
5	CHP	Development of improved and/or lower cost smaller-scale combined cooling, heat, and power (CCHP) systems (aka trigeneration)	3.5
6	Materials	Development of novel materials or processes resulting in more cost-effective methods for regenerating desiccants using natural gas	3.4
7	Gas heat pumps	Development of new or improved gas HP absorption cycles to improve efficiency in cold climates	3.4
8	Boilers & Furnaces	Development of improved multi-fuel/hybrid systems (e.g. NG and Elec) that optimize for cost and emissions	3.3
9	Heat & heat/mass exchange	Development of membrane-based heat and mass exchangers with higher throughput of fluid	3.1
10	CHP	Improve performance of small natural gas engines for microCHP and small GHP applications (improved efficiency, longer useful life, and fewer servicing requirements)	3.1

3.1.1 Reversible Cycle Absorption HPs

Table 7 shows the prioritization score, key stakeholders, barriers addressed, steps and outcomes for developing reversible cycle absorption HP appliances with high efficiency cooling.

Table 7. Development of reversible cycle absorption HP (GAHP) appliances with high efficiency cooling (to enable year-round use and better competition with electric A/C).

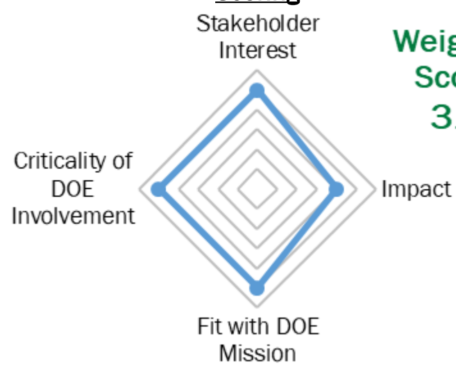
Development of reversible cycle absorption HP (GAHP) appliances with high efficiency cooling (to enable year-round use and better competition with electric A/C)

Stakeholders and Roles

Researchers – Research and development, lab testing, subject matter end-use expertise

Industry – Development of performance targets, commercialization partnerships, in-field knowledge of operational challenges

Scoring



Weighted Score: 3.6

Barriers Addressed

- Current absorption cooling systems have relatively low efficiency and struggle to compete with electric vapor-compression systems.
- The economics of GAHP equipment would benefit from higher year-round utilization, but many products are heating-only.

Steps		Outcomes
1	Characterize potential opportunities to improve absorption cooling performance and capacity	Collection of prioritized improvement opportunities relevant for further investment
2	Evaluate/model system efficiencies in the context of achievable improvements to determine efficiency and capacity targets	Comprehensive understanding of targets necessary to make reversible GAHPs cost-effective
3	Conduct R&D on high-efficiency reversible GAHPs	Enable the launch of more reversible GAHPs that operate efficiently year-round.

Absorption cooling systems require performance improvements to better compete with electric heat-pumps. Commercially available non-absorption products (i.e., GHPs), from manufacturers such as Yanmar and Intellichoice, include products that provide both heating and cooling using a multi-split (VRF capable) configuration, and serve a broad range of light commercial applications (10-30 tons); GHPs with 3-pipe systems that enable heat recovery and simultaneous heating and cooling; and rooftop units providing heating, cooling, and DHW. Workshop stakeholders indicated that, to remain competitive, gas cooling systems need a cooling COP of 1.3-1.4 or better (not accounting for potential benefit from heating or water heating), and COPs of greater than 1.5 for heating and cooling systems. Prototypical absorption cooling ranges in COP as follows:

- Single effect: 0.6-0.8 COP
- Double effect: 1.2-1.35 COP
- Triple effect: 1.7-1.9 COP

Currently, only one reversible gas absorption heat pump is known to be commercially available.[19] And overall, systems that do both heating and cooling typically have substantially higher heating capacity than cooling capacity, limiting the applications in which they can be the sole HVAC unit to colder climates. In warmer climates, the buildings would require additional cooling capacity from one or more separate units to handle the full cooling load. However, these products can benefit larger buildings in warm climates by serving the cooling baseload while electric heat pumps can supplement cooling during peak summer months. While expected annual-utilization rates are high given year-round operation, a cooling efficiency of only 60% with a substantial cost premium may not improve payback beyond that of a heating-only product.

Cooling efficiency improvements would reduce operating costs and could provide a more compelling value proposition for reversible GAHPs. Absorption systems are not a new technology, but for years the focus has been on large commercial and industrial applications. As interest has increased on smaller applications, more effort has been put into development of high efficiency in small packages, but the cooling efficiency has substantially lagged, thus the need for focus in this specific area. However, as discussed in section 1.4.1, above, efforts to improve cooling efficiency of absorption systems for residential applications have been underway, on and off, for more than 30 years. Accordingly, improvements should be highly innovative solutions for increased efficiency, or novel approaches to integrating current cycles into GAHPs that avoid pitfalls and leverage lessons-learned from prior research. Current improvement opportunities include: better fluids, better cycles, or climate-specific products (e.g., cold-climate) that enable improvements tailored to a specific range of operating temperatures.

Research to enable innovative improvements for absorption cycles should focus on specific, actionable R&D options that can enable increased efficiency on double- or single-effect systems, or simplify and reduce cost of triple-effect systems. Alternatively, R&D can focus on generating innovative approaches to boosting cooling performance that are outside of the traditional focus areas for GAHP research.

While cost is not specifically the focus of this activity, cost is a key concern for any GAHP product. Anecdotally, one example heating-only GAHP costs more than $11,000 (excluding shipping or installation).[20] So improvements in cooling performance will help to justify high incremental costs, but cost-reduction efforts must also be considered to enable widespread market viability.

3.1.2 Rapid-response CHP Systems

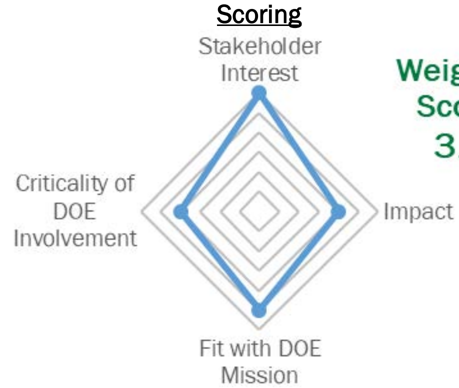
Table 8 shows the prioritization score, key stakeholders, barriers addressed, steps and outcomes for developing rapid-response CHP systems.

[19] Robur air-to-water reversible gas fired absorption heat pump, available at: https://www.roburcorp.com/heat_pumps/air_to_water_reversible_gas_absorption_heat_pump_gahp_ar

[20] "Combining Forces: Next Generation Space Conditioning and Water Heating Equipment," Presentation by P. Glanville, Gas Technology Institute, at the 2017 CA Emerging Technologies Summit. Available: https://www.etcc-ca.com/sites/default/files/nextgenhvac_final.pdf

Table 8. Development of connected, controllable CHP systems (~100-500 kW) with optimized control strategies to enable rapid-response operation (including electrical and thermal storage).

Development of connected, controllable CHP systems (~100-500 kW) with optimized control strategies to enable rapid-response operation (including electrical and thermal storage).

Stakeholders and Roles	Scoring
Researchers – Inter-industry R&D, evaluation of potential to adapt novel storage technologies Industry – Storage-solution integration, end-use expertise, collaboration to meet utility requirements Utilities – Product-specification document development (for utility-impacted elements), integration facilitation, commissioning and controls process development	 Weighted Score: 3.5

Barriers Addressed

- Lack of electrical storage and associated controls in many CHP systems limits operational flexibility and value to customers.

	Steps		Outcomes
1	Work with utilities and plant managers to evaluate/articulate specific opportunities for storage-integration improvements	→	Clear understanding of controls and integration needs for combined CHP and storage systems
2	Develop new or improved controls to optimize system outputs for customer and utility benefit.	→	Improved response time of CHP system and facilitate utility-wide renewables integration
3	Integrate thermal and electrical energy storage solutions into CHP systems	→	Fast-responding and performance-optimized CHP packages

CHP systems offer efficiency value to consumers and can provide a unique opportunity to provide demand response, and other ancillary services for utilities, but are still under-utilized in commercial and multi-family residential buildings. To maximize full value as a distributed energy resource, stakeholders indicated a greater need for operational flexibility and control – in particular, this hinged on improved integration of energy storage capabilities into CHP systems (and the associated controls) to enable improved resiliency, better integration with intermittent renewables, and fast, flexible response to utility dispatch signals. With the use of thermal and/or electrical energy storage, CHP systems can adjust their operating strategy to optimize their output for both the building owner and the utility. Historically, sub-megawatt CHP optimization has focused solely on optimizing electrical and thermal output for the building, with less concern for broader integration or responsivity to utility needs. Storage system(s) are the levers by which CHP systems can increase operational flexibility; the optimization is driven by:

- **Electricity pricing** – When electricity prices are high, the primary focus is on electric production, including, potentially discharging from battery storage. In times of medium or low electricity prices, the primary focus is on producing thermal energy to meet the heating demand and recharging batteries. Any additional electricity required on-site beyond that which is produced by the CHP in meeting the thermal load is likely best purchased from the utility.

- **Current storage levels** – With full electric-storage (i.e. batteries) or thermal storage reserves, the system can respond rapidly and with greater independence from external factors. When storage reserves get low, operational strategies must shift to rely primarily on real-time output until storage reserves can be replenished.
- **On-site demand** – Both electric and thermal demand can drive the CHP system sizing and operation. CHP systems with mismatched electric and thermal loads will require greater storage capacities to avoid system losses. Typically, systems are sized for thermal loads as this is considered a more efficient operating strategy than sizing for electric loads and discharging excess thermal production to the ambient environment (thereby reducing efficiency of the system). Optimization with on-site, intermittent generation, can provide additional value for resiliency and peak demand management.
- **System integration –** When electricity prices are high or when ancillary services are needed, it could be beneficial for system operators to provide power to the electricity system as opposed to storing any energy from excess electric capacity. Maintaining on-site electric storage reserves, however, allows for even further price optimization of ancillary services by adding additional time flexibility for battery discharge.

It is critical for efficiency that CHP systems have sufficient storage to capture excess production, rather than waste it. Capturing this excess production enables a reduction in coincident-peak demand, which is beneficial to both building owners and utilities.

Additional storage also has the benefit of speeding up the response time of CHP systems. For example, in times where the system is in standby (non-spinning reserve), a call for heat or electricity can be served promptly from storage without waiting for the system to start and ramp up to capacity.

Addressing the R&D challenges associated with incorporating further electrical and/or thermal storage into CHP systems can go a long way in increasing the efficiency, reliability, and profitability of CHP systems. These increased metrics would simultaneously boost the attractiveness of deploying CHP solutions for the end user and the utility. From the perspective of the end user, storage enabled CHP means greater operational flexibility and improved performance, yielding higher return on deployed assets. For the utilities, rapid-response CHP could play a critical role in managing intermittent distributed energy resources.

In February of 2018, DOE's Advanced Manufacturing Office (AMO) published a FOA for "Flexible combined heat and power for grid reliability and resiliency," which speaks to many of the same issues that stakeholders expressed for this activity. AMO's FOA, however, focuses on systems up to 20 MW for light industrial and manufacturing customers, while this activity focuses on commercial building or large multifamily residential applications.[21]

3.1.3 Waste-Heat-to-Power Opportunities

Table 9 shows the prioritization score, key stakeholders, barriers addressed, steps and outcomes for developing energy recovery solutions for NG equipment.

[21] DE-FOA-0001750: "Flexible Combined Heat and Power for Grid Reliability and Resiliency," published February 2018, available at: https://eere-exchange.energy.gov/default.aspx#FoaId584ea317-c588-4b85-bf33-6d21e94f1464

Table 9. Development of energy recovery solutions to boost NG equipment efficiencies and resiliency through electric generation.

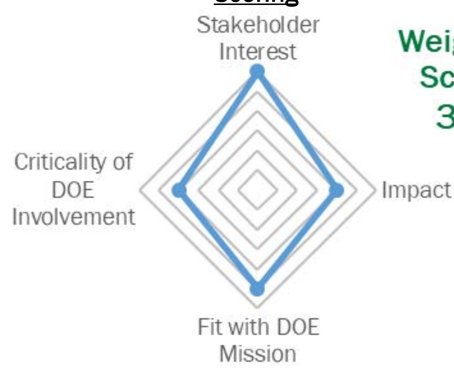
Development of waste-heat-to-power energy recovery solutions to boost NG system efficiencies and resiliency

Stakeholders and Roles

Researchers – Performance evaluation of existing energy recovery solutions, identification and development of advanced power-cycles, lab testing

Industry – Novel-solutions integration into existing systems, identification and resolution of barriers to adoption, end-use expertise

Scoring



Weighted Score: 3.5

Barriers Addressed

- NG systems experience suboptimal efficiency when waste heat is lost to the environment
- Most modern NG systems are not resilient to electrical outages since they cannot operate without constant electrical supply for electric blowers, ignitors, and other electronics

	Steps	Outcomes
1	Characterize NG system types and applications and prioritize based on achievable heat recovery	Detailed understanding of where the greatest opportunities exist for waste-heat recovery
2	Conduct R&D to improve performance of existing energy recovery solutions and to develop novel energy recovery solutions	New and improved solutions
3	Integrate solutions into existing/emerging technologies	Higher-efficiency equipment solutions achieved through energy recovery

Incorporation of Small-scale, waste-heat-to-power energy recovery solutions can increase building efficiency by leveraging waste heat from building components such as appliances, exhaust air or process water to generate power for auxiliary components and systems. Such solutions typically leverage innovative technologies, such as thermoelectrics or thermophotovoltaics. While the incremental efficiency improvement may be small in many cases, the resiliency benefits can be substantial. The following paragraphs discuss these two benefits separately:

1. Increase equipment efficiencies and reduce losses

Use of self-generation technologies within NG systems can recapture energy from thermal losses. This can be done via many methods, including but not limited to thermoelectric energy recovery from equipment exhaust. Further R&D needs to be conducted to determine the cost viability of performing such energy recovery with thermoelectrics. Another application that could benefit from increased R&D is improved energy recovery solutions to reduce transient thermal losses, in instantaneous water heaters, for example.

Transient thermal losses in water heaters are the losses that occur when the burner in a water heater turns off and the heat stored in the thermal mass of the equipment dissipates to the environment. These inefficiencies impact both tankless and tank water heaters. For instantaneous/tankless water heaters with small stored volumes of water, the losses are primarily from the thermal mass of the equipment itself and the small amount of water in the piping. These systems must warm up during the start of a draw and the whole unit comes up to temperature as the burner heats the water. Inefficiencies are particularly notable for draws with small outputs as the whole system still comes up to temperature, even for a very short draw. Transient losses are more significant in tanked water heaters but not negligible in tankless ones.

2. Increase resilience

Most NG equipment cannot run during a power outage; systems that can start and operate when utility-power is unavailable must 1) store enough electricity to restart when the power goes out, and then 2) be self-powered, by generating enough electricity during operation to power all electric components. Applicable solutions to generate electricity may include thermoelectrics and thermophotovoltaics, among others, where the optimal solution is, in substantial part, determined by the size and type of the NG equipment. For example, a natural draft water heat has much lower power requirements than a large condensing boiler with electronic draft inducers, ignitors, hot-water circulators, and more. It is conceivable that self-powered operation could be limited in duration to limit system cost, for example, to continue to provide heat to the building for a 24-hour outage. Alternatively, power generation could be sized with sufficient capacity to enable indefinite independent operation or oversized to provide additional electricity for the building. Some limited options are available on the market now, but only in select applications. One example is a "microCHP furnace" that claims to generate enough electrical power to "offer surplus power to the home" – its development is supported by multiple Canadian Gas Association (CGA) members and others.[22]

Self-powered NG systems can have a significant impact on health and safety concerns by maintaining livable conditions during a power outage (particularly those resulting from harsh weather conditions such as a blizzard). Maintaining heat in a building during a power outage not only enables safe living conditions for residents but can also reduce the overall burden on emergency facilities seeking to assist those in unlivable conditions. Outage-resiliency is an important feature that may help with adoption of higher efficiency systems, particularly in cold climates where extended outages of space heating can have real financial and safety impacts. These systems can also translate to economic benefits for end users by mitigating the risk for frozen and bursting pipes or similar infrastructure damages brought on by the lack of a heating source during inclement weather.

3.1.4 Improved Manufacturing Methods

Table 10 shows the prioritization score, key stakeholders, barriers addressed, steps and outcomes for developing improved manufacturing methods for NG equipment.

[22] Article with general overview available: https://www.proudgreenhome.com/news/hybrid-gas-furnace-that-generates-electricity-under-development/

Table 10. Development of equipment designs and/or manufacturing methods for cheaper NG equipment (e.g. gas fired HP heat exchanger mfg.).

Development of equipment designs and/or manufacturing methods for cheaper NG equipment (e.g. gas fired HP heat exchanger mfg.)

Stakeholders and Roles

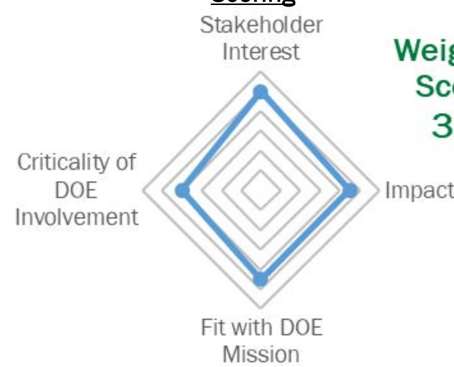
Researchers – evaluation of current technologies, feasibility assessment of adapting successful methodologies from other industries

Suppliers – identification by suppliers of emerging low-cost raw materials

Contractors – evaluation of equipment targets to meet customer and technician needs

OEMs – development of novel methods, execution, forecast of future equipment demand and cost reduction opportunities

Scoring



Weighted Score: 3.5

Barriers Addressed

- NG equipment is more expensive than electric equipment (e.g., electric vs. gas water heaters) due to the addition of parts that are costly to manufacture, such as heat exchangers

Steps		Outcomes
1	Evaluate current processes/materials limiting the manufacturability of technologies	Understanding of the barriers that currently impact manufacturing cost
2	Research potential manufacturing process and manufacturability solutions to address those barriers	Articulation of the best strategies for minimizing NG manufacturing costs
3	Develop new or improved manufacturing process or components with improved manufacturability	Manufacturing abilities or equipment designs that enable low-cost production of NG equipment and their components

Early stage R&D on manufacturability and manufacturing processes can reduce manufacturing costs of NG equipment. Stakeholders identified manufacturing costs as one of the biggest barriers to wide scale adoption and production of innovative high-efficiency natural gas equipment. Gas water heaters, even baseline efficiency models, are more expensive than electric water heaters due to added complexity. Numerous previously-funded DOE projects cite high manufacturing costs (often driven by system complexity, custom components, or low production volumes) as a primary barrier.[23] A case study analyzing the costs of manufacturing GHPs revealed a manufacturing cost on the order of 2-3 times the retail cost of an electric HP system.[24] Such figures highlight the need for cheaper manufacturing of NG equipment to remain cost competitive with conventional systems.

[23] https://energy.gov/sites/prod/files/2016/04/f30/31290_Schwartz_040616-1705.pdf
[24] http://hpc2017.org/wp-content/uploads/2017/05/P.4.7.4-Challenges-and-Opportunities-of-Gas-Engine-Driven-Heat-Pumps-Two-Case-Studies.pdf

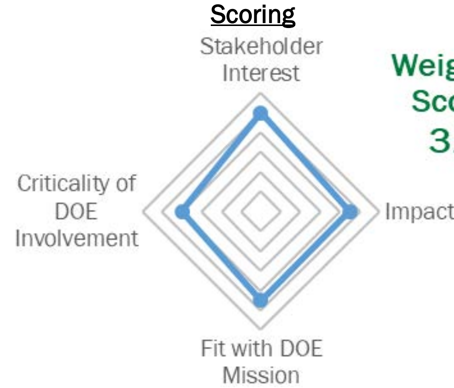
Early stage R&D can enable innovative methods of manufacturing. This is a particularly challenging proposition as manufacturing processes have been refined for decades specifically for this purpose. Nevertheless, some broadly-applicable emerging technologies may provide some value. Additive manufacturing (e.g. 3D printing), for example, has shown promise for printing gas turbine blades[25] and is expected to become a viable option for HVAC manufacturing.[26] 3D printing can also be used to print manufacturing molds, enabling cheaper manufacturing of parts at low volumes. Further R&D is required to optimize these solutions and/or identify additional solutions for low-cost NG equipment manufacturing.

Alternatively, or in combination with manufacturing process improvements, manufacturability R&D can also enable cost reductions by producing lower-cost systems. Stakeholders suggest that equipment designs of some NG products, such as GAHP heat exchangers, could be refined or entirely redesigned to suit the specific applications and thereby reduce manufacturing costs. Stakeholders did not specifically characterize the opportunities, so additional work would be needed to understand where the greatest opportunities exist for manufacturability improvements.

3.1.5 Smaller-Scale Combined Cooling, Heat, and Power

Table 11 shows the prioritization score, key stakeholders, barriers addressed, steps and outcomes for developing improved combined cooling, heat, and power systems.

Table 11. Development of improved and/or lower cost smaller-scale combined cooling, heat, and power (CCHP) systems (aka Trigeneration).

Development of improved and/or lower cost smaller-scale combined cooling, heat, and power (CCHP) systems (aka Trigeneration)	
Stakeholders and Roles Researchers – Evaluation of current CCHP technologies, lab testing of novel solutions Industry – Development of end users' system-performance-targets, identification of potential service challenges associated with increased system complexity, installation of innovative solutions OEMs – Characterization of barriers and opportunities for improvement	**Scoring**  Weighted Score: 3.5
Barriers Addressed • CCHP systems are complex, often resulting in high capital and maintenance costs and potentially minimizing the added benefit of year-round utilization	

[25] More information at: https://www.siemens.com/press/en/feature/2014/corporate/2014-03-3d-druck.php
[26] More information at: http://www.rehva.eu/publications-and-resources/rehva-journal/2017/032017/3d-printing-of-hvac-systems.html

Development of improved and/or lower cost smaller-scale combined cooling, heat, and power (CCHP) systems (aka Trigeneration)

	Steps	Outcomes
1	Evaluate current system components that negatively impact system cost or reliability	Understanding of most critical system-improvement opportunities
2	Conduct R&D to boost performance or reduce cost of target components	Lower-cost, higher-volume production, and improved performance of CCHP systems

Combined cooling, heating, and power (CCHP, aka trigeneration) systems provide increased utility relative to traditional CHP systems through the addition of cooling. CCHP systems enable higher year-round utilization rates versus CHP. The key concern is whether that higher utilization and associated energy savings is cost-effective given the increased system complexity.

During cooling season, a typical CCHP system may provide cooling by either using engine shaft power to drive a compressor, or more commonly, particularly for large systems, by using thermal output to drive an absorption heat pump cycle. During the heating season, the CCHP captures thermal output directly for heating (space and/or water heating) from both the exhaust and the engine's cooling system. Some technologies are specifically designed to simultaneously provide both heating and cooling, which can be valuable to many types of commercial building owners.

CCHP today is most common as multi-megawatt solutions for large C&I customers by installing absorption chillers alongside large CHP systems. Availability of smaller products is limited and generally costly. Multifamily residential and many commercial applications could be ideal applications for small-scale CCHP given the right cost and efficiency levels. In addition to increasing overall energy efficiency, this type of comprehensive energy appliance also provides an opportunity to reduce overall capital equipment cost for home/building owners by combining systems, much like combination heat and hot water heaters.

At least one micro-CCHP product exists, which has an electrical capacity of 5-10 kW and could serve single-family residential, small multi-family, or light commercial applications. One 2015 source stated an "initial price" of $26,000, which would limit its economically-viable market potential.[27] However, with 4-8 tons of heating and 2-10 tons of cooling capacity, it is possible that some of this cost could be offset by eliminating the need for other independent water heating and space conditioning equipment.[28] The added value of resiliency during power outages (assuming an islanding-capable system), also adds value that a home or building owner may be willing to pay for.

Further R&D can serve to improve reliability, increase year-round efficiency (particularly for cooling), or reduce system costs. Researchers could also consider if incorporation of storage (electrical or thermal) could provide additional value to CCHP, to better suit the target applications and strengthen the value proposition to building owners and operators. There is potential overlap of this activity with others characterized in this report; for example, reversible absorption HPs (see Section 3.1.1, above) or reducing engine-maintenance requirements (see Section 3.1.10) could greatly benefit CCHP.

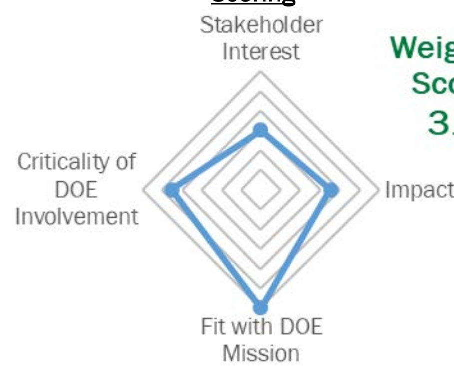
[27] Article with noted price available at: https://www.onehourheatandair.com/blog/eliminate-air-conditioning-and-heat-bills-with-micro-trigeneration
[28] Manufacturer provides all specifications as ranges; it is believed to imply multiple products in their lineup, but this is not clear in their literature. More information is available at: http://www.mtrigen.com/index.php/products/poweraire/specifications

3.1.6 Desiccant Regeneration

Table 12 shows the prioritization score, key stakeholders, barriers addressed, steps and outcomes for developing novel materials for regenerating desiccants.

Table 12. Development of novel materials or processes to improve cost-effectiveness of regenerating desiccants using natural gas.

Development of novel materials or processes to improve cost-effectiveness of regenerating desiccants using natural gas

Stakeholders and Roles	Scoring
Materials Researchers – R&D of novel materials, testing to evaluate the performance of those materials **HVAC Researchers** – Failure Modes and Effects Analysis to identify impact on overall system, validation of installed performance **Industry** – Identification of needs, addressing product integration barriers, performance/cost target characterization	 Weighted Score: 3.4

Barriers Addressed

- Current desiccant dehumidification systems are expensive due to the high cost of desiccant regeneration, which prohibits broader adoption across a range of climate zones.

	Steps	Outcomes
1	Evaluate performance of existing desiccants and desiccant systems in various applications	Detailed understanding of where limitations exist and what opportunities exist for improvement
2	Develop novel materials or processes for more efficient regeneration	Higher performing desiccants
3	Facilitate integration of novel regenerating materials or processes into equipment (e.g. reduce system component sizes)	More accessible desiccant regeneration

HVAC systems can use desiccants to manage latent heat load through moisture extraction. A typical application for these desiccants is in a desiccant wheel, wherein moist air is passed over a wheel lined with a desiccant that extracts moisture from the process air. Once the desiccant absorbs the moisture, it must be regenerated (or dried) before it can be used to extract more moisture. Regeneration is accomplished by running hot, dry air across the desiccant, which may come from a natural gas burner[29] or hot water coil heated by any type of heat source (including electricity, waste heat, or solar).[30] Using waste heat from NG equipment is of

[29] Advances in Desiccant Based Dehumidification; Trane, available at: https://www.trane.com/content/dam/Trane/Commercial/global/products-systems/education-training/engineers-newsletters/airside-design/admapn016en_0905.pdf

[30] A Review of Desiccant Dehumidification Technology; NREL, available at: https://www.nrel.gov/docs/legosti/old/7010.pdf

particular interest because of the improved utilization of the NG thermal output in a relatively simple setup that does not require a standalone gas-burner or electric-resistance coil.

The efficiency and efficacy of desiccant-dehumidification is directly impacted by the regeneration rate of the desiccants. In other words, the more effectively the desiccant regenerates, the more effectively the system can dehumidify. Alternative materials under development can regenerate desiccants at lower temperatures than standard desiccants, greatly improving the efficiency of regeneration and overall dehumidification performance. These materials, however, are too costly today for them to be cost-effectively integrated into most systems.

Stakeholders confirmed that cost-effectiveness has been the greatest barrier to integration of NG-driven desiccant dehumidification. The systems are most cost-effective in climates with high dehumidification loads, where the supply air requires substantial dehumidification, often done via overcooling and reheating to meet building set-points. Cost-reductions, however, could potentially increase the attractiveness of these dehumidification solutions in a broader range of climate zones. Cost-effective products will enable independent controls of latent and sensible loads, providing better comfort and better efficiency.

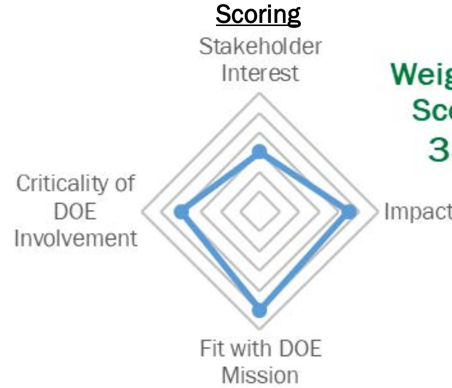
More R&D is needed to enable greater system efficacy, efficiency, and most importantly, lower costs. R&D activities can focus on several topics including but not limited to novel materials requiring less energy for regeneration, processes that can decrease the overall cost of regeneration, or novel equipment configurations that reduce equipment size while simultaneously keeping the adsorption area large.

3.1.7 Cold Climate HP Absorption Cycles

Table 13 shows the prioritization score, key stakeholders, barriers addressed, steps and outcomes for developing gas HP absorption cycles for cold climates.

Table 13. Development of new or improved gas HP absorption cycles to improve efficiency in cold climates.

<table>
<tr><th colspan="2">Development of new or improved gas HP absorption cycles to improve efficiency in cold climates</th></tr>
<tr><td><u>Stakeholders and Roles</u>
Researchers – Identification of cycle improvements for increased COP or capacity in cold climates

OEMs – Characterization of existing barriers to large-scale manufacturing, articulation of target performance metrics, integration of novel solutions</td><td><u>Scoring</u>


Weighted Score: 3.4</td></tr>
<tr><td colspan="2"><u>Barriers Addressed</u>
• HP Absorption cycles operate with degraded performance (both COP and capacity) in cold climates</td></tr>
</table>

Development of new or improved gas HP absorption cycles to improve efficiency in cold climates

	Steps		Outcomes
1	Conduct R&D to improve COP and capacities in cold climates	→	Cold Climate GAHPs with high COPs and Capacities at low ambient temperatures
2	Testing to validate installed performance in cold climates	→	Confirmation of system ability to achieve target performance metrics in installed cold-climate applications
3	Development of novel or improved system components to enable more cost-effective and scalable systems	→	Facilitated scale up and increased adoption of cold climate gas absorption HP technologies

Absorption HPs, as with all heat pumps, experience performance degradation in cold climates that generally reduces their attractiveness. Further R&D is required to minimize the extent of these capacity and efficiency losses and enable the cost-effective, year-round use of GAHPs in all climates. As has been done in recent years for many electric heat pumps, this effort should focus on boosting performance in cold climates while maintaining or improving efficiency in warmer climates. DOE has previously funded some activities related to GAHP efficiency losses in cold climates. This research yielded promising results for a single-effect absorption cycle, proving the potential value of the solution, but highlighting where further refinement may be required to bring to market a cost-effective solution for cold climates that maintains high COPs and capacities in cold climates. The concepts and lab trials produced by DOE's previous research show the potential of cold-climate GAHPs (CC-GAHP) to achieve COPs of ~1.3 at ambient temperatures as low as -25°C.[31] Further, at -25°C, the system performed at approximately 70% of the rated capacity (at 8.3°C). Industry generally considers capacities of 75% or higher at -25°C relative to their 8.3°C rated capacities to be indicative of well-performing cold-climate heat pumps.[32]

The technology requires further R&D focused on providing simple cycles and designs optimized for volume manufacturing. Furthermore, decreasing the overall system cost of CC-GAHP technologies will be necessary to achieve favorable payback periods. Anecdotally, one example GAHP costs more than $11,000 (excluding shipping or installation).[33] So improvements in cold-climate performance will help to justify high incremental costs, but cost-reduction efforts must also be considered in order to enable widespread market viability.

R&D to overcome the above challenges includes refinements to typical ammonia-water cycles, particularly ones that result in simpler cycles. Additional, R&D could focus on innovative changes that could substantially deviate from what is currently state-of-the-art.

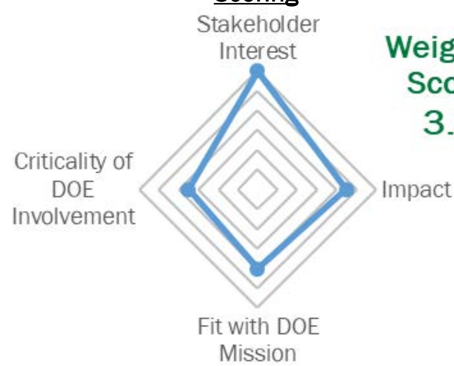
[31] Low-cost Gas Heat Pump for Building Space Heating, available at: https://energy.gov/sites/prod/files/2016/04/f30/312105_Garrabrant_040716-915.pdf
[32] Development of a Cold Climate Heat Pump using Two-Stage Compression, available at: http://web.ornl.gov/~jacksonwl/hpdm/Shen--2stageCCHP--2015ICR.pdf
[33] "Combining Forces: Next Generation Space Conditioning and Water Heating Equipment," Presentation by P. Glanville, Gas Technology Institute, at the 2017 CA Emerging Technologies Summit. Available: https://www.etcc-ca.com/sites/default/files/nextgenhvac_final.pdf

3.1.8 Multi-fuel/Hybrid Systems

Table 14 shows the prioritization score, key stakeholders, barriers addressed, steps and outcomes for developing improved multi-fuel/hybrid systems.

Table 14. Development of improved multi-fuel/hybrid systems that optimize for cost and emissions

Development of improved multi-fuel/hybrid systems that optimize for cost and emissions

Stakeholders and Roles	Scoring
Researchers – Evaluation of current technologies, solution development, lab testing Industry – Characterization of needs, end-use expertise	 Weighted Score: 3.3

Barriers Addressed

- Current multi-fuel/hybrid equipment has insufficient controls to enable dynamic utilization and optimization of systems

Steps		Outcomes
1	Develop and model algorithms and control mechanisms to forecast/act on real-time operational efficiencies by fuel source	Improved dynamic control optimization of multi-fuel/hybrid strategies for improved performance
2	Integrate, deploy, and validate these controls/algorithms	Understanding of performance of, value of, and areas of improvement for, hybrid systems
3	Leverage advances is NG/electric hybrid systems to develop novel renewables-integrated hybrid NG-equipment	More resilient, energy-efficient, hybrid systems

Multi-fuel NG equipment, also referred to as hybrid systems, enable the use of multiple fuels in the same system to optimize performance and minimize operating costs. Examples include:

- **Space conditioning:** Single-packaged year-round air conditioners (SPY-A), are a variant of packaged heat pumps and furnaces that use an innovative combination of natural gas and electricity. A typical packaged furnace/AC provides all the heating with natural gas. An SPY-A exclusively utilizes an electric vapor-compression cycle for cooling, but for heating, the unit uses the vapor compression system as a heat pump, or switches to natural gas depending on which system is most efficient at the given ambient temperature. The optimization of this switch is key to performance improvement and cost savings.

- **Water heating:** An electric HPWH with an instantaneous gas booster heater instead of an electric resistance backup element can use the electric heat pump to provide hot water in most low- to medium-usage periods and supplement with the gas booster heater during periods of very high usage. As with an SPY-A, the optimization driving the use of the gas burner is key to maximizing savings. The added cost and complexity of this concept is a barrier since it combines all the parts of two units into one.

This same multi-fuel/hybrid concepts can also apply to more complex systems. Integration of variable renewable energy sources, such as solar (electric or thermal) or wind power will require similar optimization capabilities to determine the appropriate storage capacities ensuring optimal hybrid-system performance even in times of low or no generation. While there are numerous iterations of hybrid systems, R&D topics addressing the following two research objectives can benefit the category as a whole:

1. Develop systems and control strategies to determine the optimal point at which it becomes more effective to utilize NG over electricity as well as how to optimize for storage of integrated renewables.
2. Evaluate the impacts and performance of this technology across various climates and use cases.
3. Conduct cost-reduction-focused R&D to enable broad market viability

Advances in the R&D topics above can enable any combination of renewable sources with natural gas systems to provide customers with improved system efficiencies and greater operational flexibility.

3.1.9 Membrane-based Heat and Mass Exchangers

Table 15 shows the prioritization score, key stakeholders, barriers addressed, steps and outcomes for developing membrane-based heat and mass exchangers.

Table 15. Development of membrane-based heat and mass exchangers with higher throughput of fluid.

Development of membrane-based heat and mass exchangers with higher throughput of fluid

Stakeholders and Roles

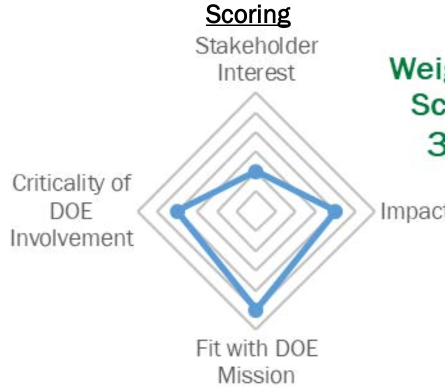
Membranes Researchers – Inter-industry R&D focused on identifying viable membranes utilized in other industries, research to develop novel membranes tailored for HMX applications

HVAC Researchers – Lab testing of emerging solutions, end-use expertise

Industry – Collaboration with the membranes industry to employ established best practices, development of a set of viable membranes from suppliers for integration into HMXs

OEMs – characterization of manufacturing challenges, specifications, and limitations, product integration

Scoring



Weighted Score: 3.1

Barriers Addressed

- Existing membrane-based heat and mass exchangers experience degraded performance from low fluid-throughput associated with required levels of selectiveness

Development of membrane-based heat and mass exchangers with higher throughput of fluid

	Steps	Outcomes
1	Define target metrics (e.g. flux, permeability, selectivity, etc.) defining the successful performance of a membrane-based HMX	Clear R&D goals focused on developing HMXs with the desired cost, size, and pressure drops for various applications
2	Develop new or improved membranes with higher permeability and equal (or improved) selectivity	Membranes meeting the previously defined fundamental performance-metrics
3	Conduct R&D to address physical integration challenges for inclusion of membranes in HMXs	Improved solutions for bonding, fastening, integrating, etc. membranes into HMXs
4	Assess performance in various building applications and determine opportunities for use of one membrane in many applications	A small number of solutions serving many applications with high-volume manufacturing

Membrane-based heat and mass exchangers (HMX), the enabling component in many energy recovery ventilation (ERV) applications, are emerging as a key method of providing both sensible and latent heat control for space conditioning. In such solutions, two airstreams (typically outdoor, supply air and exhaust air) are crossflowed. A membrane enables the exchange of heat and moisture between the two air streams. During cooling season, heat and moisture move from the supply air to the cooler and dryer building exhaust air. The reverse is true during heating season, wherein heat and moisture move from the exhaust air into the cool and dry incoming air. More advanced systems, such as the membrane HMX utilized in evaporative cooling technologies, can be complex, in this case consisting of alternating dry channels and wet, membrane-lined channels stacked to cross flow with each other. In such heat and mass exchangers an airstream flows through the heat exchanger where it separates into two airstreams: the working and the conditioned airstream. The working airstream wicks moisture off the wet membrane-lined channels, causing the membrane to evaporatively cool. The crossflowing conditioned airstream is thereby cooled by the membrane.[34] The resulting air is thereby dehumidified and evaporatively cooled. The systems can address up to 80% of a building's latent loads with a membrane; a comparatively small vapor compression cycle can then address the remaining sensible heat load.

One primary factor impacting HMX efficacy is the rate of fluid flow through the membranes. This property, also known as the flux, determines the overall performance of the system. Furthermore, the flux is governed by two critical membrane characteristics: selectivity and permeability. Increasing the permeability of a membrane increases the fluid throughput, but generally reduces selectivity. One strategy to increase flux while maintaining a high level of selectivity is to increase the surface area for membrane exchange. However, the increased surface area increases the difficulty of integration into membrane-enabled equipment, particularly those of the packaged variety. As such, there is a need for targeted R&D that can either improve membrane materials to simultaneously achieve improved permeability and selectivity or develop novel configurations resulting in higher surface area for heat and mass exchanges to occur, while maintaining a small overall

[34] Coolerado Cooler Helps to Save Cooling Energy and Dollars; Federal Energy Management Program, available at: https://www.nrel.gov/docs/fy07osti/40041.pdf

footprint within packaged equipment. Advances in either of these topics could enable high performing, compact, HMX designs with a significant impact on cost-effectively meeting a buildings latent loads.

BTO's report from October 2017, titled "R&D Opportunities for Membranes and Separation Technologies in Building Applications" provides additional detail on membrane research opportunities in greater depth.[35]

3.1.10 Engines for MicroCHP and Small-GHP applications

Table 16 shows the prioritization score, key stakeholders, barriers addressed, steps and outcomes for developing small natural-gas engines for microCHP and small GHP applications.

Table 16. Improve performance of small natural gas engines for microCHP and small GHP applications (improved efficiency, longer useful life, and fewer servicing requirements).

<table>
<tr><th colspan="2">Improve performance of small natural gas engines for microCHP and small GHP applications (improved efficiency, longer useful life, and fewer servicing requirements)</th></tr>
<tr><td><u>Stakeholders and Roles</u>
Researchers – Failure modes and effects analysis (FMEA), development of novel solutions, testing new solutions against existing ones

Industry – Development of system performance targets and targets to impact adoption rates, product integration

OEMs – characterization of existing barriers to improved performance</td><td><u>Scoring</u>
</td></tr>
<tr><td colspan="2"><u>Barriers Addressed</u>
• MicroCHP and GHP systems have high engine service requirements and suboptimal engine life due to a lack of application-optimized engine packages</td></tr>
</table>

[35] DOE report available online at: https://www.energy.gov/sites/prod/files/2017/11/f46/DOE-BTO%20Membranes%20Separations%20Report%20Nov%202017.pdf

Improve performance of small natural gas engines for microCHP and small GHP applications (improved efficiency, longer useful life, and fewer servicing requirements)

	Steps	Outcomes
1	Analyze available life-cycle test data for small gas engines to characterize resiliency and performance degradation	Understanding of failure mechanisms and their impact on the overall system
2	Conduct additional life-cycle testing for those engines deployed in specific CHP/GHP applications	Characterization of additional system challenges presented by the specific load profiles of GHP/CHP operations
3	Assess the potential of adapting innovations from other industry (e.g. hybrid vehicles)	Understanding of opportunities for innovation adaptation
4	Conduct R&D on targeted novel solutions for improving engine life and resilience	Application-optimized NG engines for use in small solutions

MicroCHP and GHP engines are often slightly (if at all) refined packages from other engine applications. microCHP/GHP engines are generally not produced at sufficient volume to warrant R&D to fully optimize the engines for the specific applications. As a result, the engines serve the needs acceptably, but have room for improvement in efficiency, life, and servicing requirements.

1. **Efficiency**: There have been limited R&D efforts to improve the performance of natural gas engines, particularly those in the 5-10 kW range. Historical innovation in this space typically sought to boost the performance of vehicle engines (>100 kW). GHP engines are commonly the same as those found in lawn mowers or generators, designed for intermittent use in those specific applications. When integrated into GHP or microCHP systems, however, they experience significant inefficiencies, running continually with efficiencies of approximately 25%.[36] Hybrid-vehicle engine optimization is a good example of how efficiency can be improved for a specific application; their designs enable high performance operation at specific operating conditions instead of at the wide range of operating conditions that a non-hybrid engine operates. Stakeholders indicated that lessons learned should be leveraged to boost the efficiency of CHP/GHP engines, targeting efficiency levels of more than 30 or 40%.

2. **Life**: Typical GHP and CHP solutions have very high run-time hours required to meet annual demands, creating a need for engines that last a long time. Most advanced vehicle engines have expected lifespans of 5,000-8,000 hours. The duty-cycle for commercial building CHPs may be conservatively 50% annually for 10 years, or 44,000 hrs., far surpassing the existing capabilities of most engines. As such, engine replacement is a common maintenance operation over the course of the system's effective useful life. Certainly, a motor vehicle engine used in a CHP system will last much longer than it would in a vehicle due to more consistent loading, but it is nevertheless lacking optimization that can produce a long-lasting, high-efficiency, low-maintenance system. Further R&D could enable reliable longer-life products that are more in line with electric heat pumps.

[36] Yanmar microchip with 28% efficiency, available at: https://aegischp.com/wp-content/uploads/5-kw-cut-sheet-1.pdf

3. **Service requirements**: As previously stated, GHP and microCHP engines can benefit from extended operations (e.g. target >10,000 hours) without maintenance interruptions such as oil changes or spark plug replacements. Sanyo has made substantial progress in this space, with engines requiring service every 10,000 hours or every 3 years; as compared with less-optimized solutions, which require servicing as often as every year. Further R&D devoted to decreasing service requirements for GHP and CHP systems can have a great impact on the total cost of operating these systems.

R&D focused at improving performance, life, and service intervals of CHP and GHP engines can greatly assist with adoption of these technologies.

3.2 Tier II Activities

The following subsections list each of the Tier II activities along with a short description and their final scores from the ranking process. Each subsection covers a different topic area.

3.2.1 Tier II Activities – Gas Heat Pumps

Table 17 lists each of the Tier II activities related to gas heat pumps.

Table 17. Tier II Activities – Gas Heat Pumps

Rank	Gas Heat Pump Activities	Score
11	Development of climate-hardened, engine-driven HPs that can withstand years of high performance in all climates	3.1
The objective of this activity would be to provide increased robustness and reliability for GHPs in harsh northern climates. Environmental Security Technology Certification Program (ESTCP) is conducting cold-climate testing of a commercially-available product with expected completion in 2019.[37] BTO/ET has a history of supporting cold climate heat pump research with multiple ongoing projects.[38] Stakeholders articulated two additional opportunities to increase robustness: 1. Reduce maintenance requirements (e.g., oil changes) while maintaining long-life. For residential applications, reducing maintenance needs through robust engineering design is a key enabler to increase market opportunity, reduce consumer anxiety, and ensure long product life. In commercial applications, reduced maintenance needs will help reduce operating costs, which is a key selling point. 2. Black-start capabilities to ensure reliable service during power outages (particularly important in northern climates). Incorporating packaged energy storage, GHPs could start and operate during outages to ensure heating is available during snow storms or to provide cooling in the aftermath of a hurricane.		

[37] Details available at: https://www.serdp-estcp.org/Program-Areas/Energy-and-Water/Energy/Conservation-and-Efficiency/EW-201515

[38] BTO projects with cold-climate performance requirements include Thermolift, which had targets for ambient temperatures down to -13F (see https://energy.gov/eere/buildings/downloads/natural-gas-heat-pump-and-air-conditioner) and Stone Mountain (see https://energy.gov/eere/buildings/downloads/low-cost-gas-heat-pump-building-space-heating).

<table>
<tr><th>Rank</th><th>Gas Heat Pump Activities</th><th>Score</th></tr>
<tr><td>14</td><td>Gas Absorption Heat Pump Water Heater (HPWH)</td><td>3.1</td></tr>
<tr><td colspan="3">Gas absorption heat pump water heaters (as well as space and water heating combi systems) have been part of DOE/BTO's R&D portfolio for many years and have overcome significant hurdles in that time.[39] Efficiencies have improved, configurations have been vetted in the field, and cost-effectiveness has been improved. However, products are still not commercially available and are expected to face many of the non-technical adoption hurdles as discussed in Section 2.2. Of key concern is the expected cost during low-volume production. At least one project expects to achieve at-volume costs that would provide a 2-5 year payback, but one stakeholder expressed concern with this, saying "unit sales would need to become very substantial before the cost objective could be met."[40]</td></tr>
<tr><td>15</td><td>Development of improved installation and maintenance processes for gas HPs</td><td>2.9</td></tr>
<tr><td colspan="3">Installation processes can vary widely between different installation sites and product configurations. To enable easier adoption by technicians, R&D could help characterize the challenges and improve product designs to simplify and standardize installation and maintenance processes as much as possible. One potential option could be standardized installation kits that work for multiple manufacturers' products.

For gas-engine GHPs, technicians will be least familiar with the engine, including specific commissioning and maintenance procedures, since the vapor compression system will be familiar to any technician that has worked with an electric HPWH. GAHPs will present different unfamiliar elements due to the absorption system. Development of robust systems that require little maintenance and establishment of easy, consistent processes for installation, commissioning, and maintenance can reduce costs and promote greater consistency and quality of installations.</td></tr>
<tr><td>21</td><td>Development of absorption HPs (GAHP) for commercial simultaneous heating and cooling</td><td>2.4</td></tr>
<tr><td colspan="3">Multiple manufacturers sell gas-engine GHPs with simultaneous heating and cooling via three-pipe architectures for heat-recovery. As mentioned in Section 3.1.1, one GAHP manufacturer sells a reversible heating/cooling product, but not for simultaneous heating/cooling applications.

Simultaneous heating and cooling technology is well-established in current VRV systems from many manufacturers, but has not yet been adopted by GAHP manufacturers. The specific challenges associated with this adaptation are unclear and require additional investigation.</td></tr>
</table>

3.2.2 Tier II Activities – CHP

Table 18 lists each of the Tier II activities related to CHP.

[39] DOE/BTO has funded multiple projects on absorption heat pump water heaters in the past (and continuing until at least 2020), including projects for commercial and residential applications with ORNL, Stone Mountain Technologies, Inc., and many other R&D partners as subcontractors. See additional information at BTO's website: https://energy.gov/eere/buildings/listings/water-heating-projects for water heating and https://energy.gov/eere/buildings/listings/heating-ventilation-and-air-conditioning-projects for space heating (and combi systems)

[40] DOE/BTO, "2016 Building Technologies Office Peer Review Report Appendix," Reviewer comments for project #312105, available: https://energy.gov/sites/prod/files/2016/12/f34/2016%20BTO%20Peer%20Review%20Report_Appendix.pdf

Table 18. Tier II Activities - CHP

Rank	CHP Activities	Score
12	Development of cheaper MicroCHP/MiniCHP "appliances" for light commercial applications	3.1
	The objective of this activity is to develop cost-effective, light commercial microCHP/MiniCHP systems for applications with a sizeable year-round thermal load, such as multi-family housing, workout facilities, smaller hotels (e.g. 50 rooms or fewer), and food services. The system should be designed as an appliance, i.e., with a compact form factor, packaged design, and simple controls. Stakeholders envisioned this technology being based on a platform design that could easily and cost-effectively be scaled down for residential applications. Stakeholders also noted that incorporation of cooling (CCHP) could enable higher year-round utilization and help improve cost effectiveness in residences (see Section 3.1.5 for an activity specifically on this topic). The primary market would be those homes with, or considering installing, backup generation.	
16	Development of standardized processes and hardware/design packages for CHP interconnection for simpler CHP installation	2.8
	Electric interconnection is commonly cited as a cost and time hurdle in CHP projects; development of a standardized, accepted system (hardware and processes) for interconnection would enable faster, lower-cost interconnection and approval by utilities and inspectors. IEEE has attempted to standardize practices governing the testing, performance, and operations of CHP interconnection hardware and software in the IEEE 1547. NYSERDA has also taken a programmatic approach to addressing CHP interconnection, which advocates for a "Catalog Approach" to CHP installations where use of pre-approved/pre-engineered CHP modules enables an accelerated process.[41] Even with this prescriptive approach, customers routinely encounter excessive hurdles and delays by inspectors (e.g., New York City's Electrical Advisory Board) due to ever-changing requirements and extensive backlogs that can delay inspections and approvals by many months. There is a need to establish standardized approaches at a national level that account for safe, reliable design while minimizing burden and cost on customers. The primary hardware R&D need is a standardized kit/package to facilitate the CHP interconnection process. Some utilities and regulatory bodies have published best-practices guides and identified preferred CHP providers, but there is little known activity on the development of hardware solutions.	

3.2.3 Tier II Activities – Heat and Heat/Mass Exchangers

Table 19 lists each of the Tier II activities related to heat and heat/mass exchangers.

[41] More on NYSERDA's Program (PON 2568) at https://portal.nyserda.ny.gov/CORE_Solicitation_Detail_Page?SolicitationId=a0rt0000000QnqyAAC

Table 19. Tier II Activities – Heat & Heat/Mass Exchange

<table>
<tr><th>Rank</th><th>Heat & Heat/Mass Exchange Activities</th><th>Score</th></tr>
<tr><td>13</td><td>Development of optimized heat recovery systems (for condenser heat, restaurant applications, etc.)</td><td>3.1</td></tr>
<tr><td colspan="3">Heat recovery systems that capture waste-heat from gas-fired equipment fundamentally provide opportunity to improve the overall efficiency of those gas systems. Waste heat in the form of hot air may include kitchen exhaust systems, HVAC exhaust, and air-cooled condensers on vapor-compression cooling and refrigeration equipment. Waste heat can also come in the form of hot water from condenser water from chillers or other water source cooling equipment and greywater from dishwashers, clothes washers, and sinks.

Stakeholders suggested that untapped opportunities exist for combining end-use equipment or developing coordinated controls and associated piping/ducting to leverage waste heat from one system in another for improved building efficiencies. Such research can improve efficiency of any thermal system using any fuel, not just natural gas, and therefore has broad applicability.

Effective use of advanced power cycles, such as the Supercritical CO2 (S-CO2) power cycle can be employed to increase system efficiency through waste-heat recovery, for example, from gas turbines in CHP systems. S-CO2 waste heat recovery systems can achieve high efficiencies with relatively compact system-components, a big benefit for small CHP systems.

Data centers, hospitals, and laboratories are among the buildings with the highest heat loads and with some of the greatest opportunities for heat recovery. Research opportunities may also exist related to how different buildings and businesses should be paired to optimize thermal energy. For example, an office that is located next to a data center may be able to provide space heating from the data center's waste heat. Research in this area would need to evaluate the tradeoffs of such building-pairing.</td></tr>
</table>

3.2.4 Tier II Activities – Data, Tools, and Modeling

Table 20 lists each of the Tier II activities related to data, tools, and modeling.

Table 20. Tier II Activities – Data, Tools, and Modeling

<table>
<tr><th>Rank</th><th>Data, Tools, & Modeling Activities</th><th>Score</th></tr>
<tr><td>17</td><td>Development of utility grade "macro-metering" tools for monitoring consumption at the utility scale</td><td>2.6</td></tr>
<tr><td colspan="3">Utility tools to monitor and understand gas consumption can assist utilities in better understanding their customers' loads and needs. Most tools encompass comprehensive software platforms that leverage utility smart-meter data. These systems have evolved since their inception about 10 years ago and some are quite advanced, including those from larger, established players. Typical solutions collect and process advanced metering infrastructure (AMI) data, and provide load analysis and analytics capabilities.

Workshop attendees suggested that additional R&D could be targeted to better understand how to convert these tools from passive natural gas monitoring solutions to data-driven, natural gas management solutions. Many utilities have amassed large amounts of data from their AMI, but do not leverage it for additional value to the company or their customers. Potential research areas include how the data can drive variable price schemes based on consumer load profiles, leak identification/solution deployment, or utility performance tracking.</td></tr>
</table>

<table>
<tr><th>Rank</th><th>Data, Tools, & Modeling Activities</th><th>Score</th></tr>
<tr><td>20</td><td>Development of consumer grade metering/monitoring tools for improved understanding of gas consumption (including sensors for performance tracking)</td><td>2.4</td></tr>
<tr><td colspan="3">A primary goal for this activity is more efficient (remote) data collection, consumption transparency, and improved customer engagement. Natural gas sub-meters are available for some applications, but further R&D is required to adapt these meters such that they are smaller and integrated directly into appliances (see micro-metering Activity 26 below in this table). One alternative is Non-Intrusive Load Monitoring (NILM), which enables disaggregation of consumption data collected by building-level utility meters to provide useful energy information to customers. For consumers, this enables a deeper understanding of energy use and therefore better, more informed decision making. Additionally, it provides a mechanism to identify degrading performance and can help promote equipment replacement or repair during non-emergency situations (which limits options and potentially efficiency improvement). These technologies also provide higher-level benefits such as enabling measurement and verification (M&V) for demand side management programs. Despite these benefits, such NILM solutions have not gained traction for natural gas equipment as they have (albeit in a limited fashion) for electric equipment.</td></tr>
<tr><td>24</td><td>Development of new or improved tools for equipment performance monitoring (e.g. steam trap monitoring, sand/silt level monitoring, FDD, etc.)</td><td>2.1</td></tr>
<tr><td colspan="3">Additional R&D is needed to make performance monitoring and FDD tools more impactful both from an efficiency and customer adoption standpoint; particularly through the development of connected equipment. Connected equipment represents the next major advancement in performance monitoring for natural gas equipment by enabling real-time data collection and alerts. Natural gas appliances have not seen the same level of R&D for connectivity as electrical appliances, despite very similar potential benefits. With data driven processes, consumers can ensure a continual state of optimal energy efficiency for their equipment.

Continuous, integrated monitoring capabilities for natural gas appliances can provide data to customers to make informed decisions about the proper use and maintenance of their appliances. Specific examples pertinent to natural gas appliances that were raised by stakeholders include steam trap monitoring and sediment (scaling/sludge) level monitoring in hot water heaters and boilers, but the opportunities extend far beyond this to include performance monitoring at a variety of points in each system.</td></tr>
<tr><td>25</td><td>Development of algorithms enabling district heating opportunity identification</td><td>2.0</td></tr>
<tr><td colspan="3">Analytical studies are required to develop an approach for identifying optimal district heating locations, sizes, and configurations across the country. Many of the district heating systems in the US are many decades old; new installations have been limited in recent decades. There are approximately 2,300 district heating systems in the US today. Meanwhile in northern Europe, district systems are much more common and are being increasingly used as an efficient way to reduce carbon emissions.[42]</td></tr>
<tr><td>26</td><td>Development of utility-grade "micro-meters" to enable equipment-level performance monitoring and reduce metering footprint and visual impacts</td><td>1.8</td></tr>
<tr><td colspan="3">Multi-family residential buildings that are not master metered typically utilize meter rooms or outdoor meter banks that occupy costly real estate and may be an eyesore for residents. Micro-metering equipment is the concept that instead of one meter per customer, individual, small, utility-grade meters could be installed for each piece of equipment. These small meters could be co-located with end-use equipment thereby eliminating the need for meter banks or rooms. Utility stakeholders suggested that some building developers forego natural gas in their developments because of visual and footprint concerns, so this solution could increase the market opportunity for natural gas in these buildings. Micro-metering would additionally enable an array of new services for customers, including performance management, automation, and natural-gas demand response.</td></tr>
</table>

[42] See additional information at: http://www.hpac.com/heating/why-district-energy-not-more-prevalent-us

Rank	Data, Tools, & Modeling Activities	Score
30	Development of tools (e.g., lifecycle analysis) to enable commensurate comparisons between gas HPs and electric heat pumps or other HVAC options	1.6
	Comparing performance of gas heat pumps to electric heat pumps is difficult, particularly when the differences must be conveyed to consumers or contractors who are unfamiliar with the technology. Unlike comparisons between two products using the same fuel (e.g., electric resistance and electric heat pump), more complex analyses are typically required to enable apples-to-apples comparisons between electric and gas products (e.g., lifecycle cost analyses). Comprehensive, but easy-to-use tools can enable contractors and manufacturers to more easily sell their products by more easily educating customers.	

3.2.5 Tier II Activities – Appliances

Table 21 lists each of the Tier II activities related to appliances.

Table 21. Tier II Activities - Appliances

Rank	Appliance Activities	Score
18	Development of novel methods to convert oil systems to operate on natural gas	2.5
	Simple solutions exist to facilitate a conversion from natural gas to/from propane; a similar, simple and uniform solution for oil conversions could increase adoption of natural gas equipment. However, converting from oil to natural gas is more challenging than from propane to natural gas. For a boiler, for example, changing fuel source would require a change of the burner assembly, a different nozzle/aperture, and installation of new natural gas piping. Given the numerous changes required, additional development could result in more packaged approaches. Preliminary research is required, however, to determine the value of such an activity. Gas burners in legacy oil equipment do not have the same efficiency as OEM-built natural gas equipment. Furthermore, old oil-fired equipment may be cost effectively replaced in full, negating the need for lower-cost conversion packages.	
22	Development of higher efficiency commercial cooking equipment	2.2
	Some commercial cooking equipment has seen efficiency improvements in recent years. Currently, ENERGY STAR covers fryers, griddles, hot food holding cabinets, ovens, and steam cookers. Notably absent are broilers, including under-fired products (aka charbroilers), over-fired broilers, and salamander/cheese-melter broilers. Broiler efficiency has been hindered by what some stakeholders consider to be an insufficient test procedure and by the way that broilers are purchased. Purchases are based on heat input rating (Btu/hr.), so a lower heat input is often seen as insufficient, as opposed to having potentially better efficiency with the same cooking performance. Opportunities for improvement (in broilers and other equipment) could include: • Charbroilers (under-fired broiler) or griddles with lids • Faster heat-up times to eliminate extended runtime before store opening • Auto turn-down ranges, griddles, or broilers (based on sensors that detect when food/cookware is present)	

3.2.6 Tier II Activities – Combustion and Emissions

Table 22 lists each of the Tier II activities related to combustion and emissions.

Table 22. Tier II Activities – Combustion and Emissions

Rank	Combustion and Emissions Activities	Score
19	Resolving selected venting issues for NG equipment	2.4
Venting issues for natural gas equipment arise in certain applications where condensing equipment is being retrofit into a building that previously only used non-condensing equipment. Condensing equipment cannot be vented through traditional masonry or double-wall metal chimneys, nor can they be common-vented in existing non-condensing equipment vents. As a result, dedicated PVC side-wall venting is commonly installed if the building site is suitable. One-pipe configurations are used where combustion air comes from within the building, while two-pipe (or pipe-in-pipe) configurations are used where combustion air must be drawn from outdoors. Alternatively, a sealed, dedicated vent can be run inside the existing chimney (the draft fan provides necessary static pressure to vent the exhaust). For additional discussion, see the detailed review of the challenges and potential solutions by ORNL in two reports, titled: "Condensing Furnace Venting Part 1: The Issue, Prospective Solutions, and Facility for Experimental Evaluation"[43] and "Condensing Furnace Venting Part 2: Evaluation of Same-Chimney Vent Systems for Condensing Furnaces and Natural Draft Water Heaters."[44]		
23	Development of standardized installation processes for condensing gas equipment	2.1
Installation processes for condensing gas equipment should be standardized, particularly with the goal of minimizing any follow-up work, which stakeholders suggest is more common than expected. The standardization of installations requires the development of tested processes in each of the four primary phases of system installations: pre-change out, installation, commissioning, and customer education. Each step contributes directly to the system's ability to achieve optimal performance. Many organizations have begun the process of identifying installation best-practices, including guides for installation covering field inspections, procedures, verification and testing, among others. Standardized solutions can take the form of specific guides to show uniform processes, such as the ACCA Standard 5 HVAC Quality Installation Specification, which describes standard methods for addressing common natural gas equipment challenges. Solutions can also take the form of hardware/tools, such as a commissioning tool that can verify the installed performance relative to the rated or expected performance. Further R&D is required to develop such tools.		

[43] Momen A., et. al. "Condensing Furnace Venting Part 1: The Issue, Prospective Solutions, and Facility for Experimental Evaluation," Oak Ridge National Laboratory, October 2014, available: http://web.ornl.gov/sci/buildings/docs/Condensing-Furnace-Venting-Part1-Report.pdf

[44] Momen A., et. al. "Condensing Furnace Venting Part 2: Evaluation of Same-Chimney Vent Systems for Condensing Furnaces and Natural Draft Water Heaters," Oak Ridge National Laboratory, February 2015, available: http://web.ornl.gov/sci/buildings/docs/Condensing-Furnace-Venting-Part2-Report.pdf

<table>
<tr><th>Rank</th><th>Combustion and Emissions Activities</th><th>Score</th></tr>
<tr><td>27</td><td>Development of ultra-low-NOx gas furnaces</td><td>1.8</td></tr>
<tr><td colspan="3">Ultra-low-NOx emissions standards, particularly those in place in California, have driven development of equipment that significantly reduces NOx and other emissions, even beyond that of low-NOx equipment. Ultra-low-NOx boilers and water heaters are more broadly available than for furnaces. Recent regulations have spurred the development of standard low (not ultra-low) NOx furnaces, allowing a grace period for manufacturers between 2009 (when there were no commercially available low-NOx furnaces) and 2015 to develop appropriate furnace technologies for commercial production. A similar R&D push is needed to close the gap between existing Low NOx furnace technologies and emerging ultra-low NOx ones. Established solutions exist to reduce burner NOx production, including: premixed combustion gasses, metal-fiber burners, and closely managed combustion air and fuel flows; these solutions need to be translated to furnace applications. In early 2018, one manufacturer introduced an ultra-low-NOx furnace, with claims of reducing NOx emissions by 65% relative to standard low-NOx furnaces.[45] The manufacturer describes the product as the first in a “new line of eco-efficient furnaces,” however this first model, with an AFUE of 80, has room for improvement with regards to efficiency. Low stakeholder interest and availability of products cause this activity to score low for the criticality of DOE involvement metric, but room still exists for additional R&D to improve efficiency (see section 1.5.2 for discussion of metrics).</td></tr>
<tr><td>28</td><td>Development of improved gas condensate neutralization methods (e.g., better integration with products, smarter sensors and sensor integration, etc.)</td><td>1.8</td></tr>
<tr><td colspan="3">Combustion condensate is produced at a rate of ~1 gallon/hr. for every 100,000 Btu of gas input.[46] Typical condensate has a pH of 3-4 and some local codes prohibit the introduction of acidic liquid into the sewer without treatment for corrosion prevention. Condensate is treated by introducing a media (commonly containing lime chips, or calcite in combination with magnesium oxide), which dissolves over time and must be replenished. Some products are modular and can be added in-line with the condensate drain line, while others have built-in neutralizer modules. When the neutralizer media runs out, it must be promptly replenished or the pH will again become acidic. Condensate management systems with sensors could notify homeowners or contractors of the need to replace the media. This activity did not garner strong support from stakeholders, aside from their noting that condensate management can be a challenging, and costly part of an installation and should be considered as a target for future innovation.</td></tr>
<tr><td>29</td><td>Development of Low NOx burners for high altitudes</td><td>1.7</td></tr>
<tr><td colspan="3">Low-NOx burners are available from multiple manufacturers for operation at typical elevations; at high altitudes (i.e. 5,000+ ft.), their emissions-performance degrades, so changes are required for products targeted for high-altitude markets.

Currently, this issue is addressed through air-dilution; the excess air cools down combustion temperatures enough to reduce the production of NOx gasses. This process is done by either:
1. Derating the equipment – The use of an orifice in the gas line reduces fuel input to boost the fuel-air-ratio.
2. Devaluing the fuel– gas utilities can add air to their fuel, thereby increasing the fuel to air ratio.

Derating the equipment is the most common and simplest way to achieve a proper fuel to air ratio, but this process does not necessarily optimize for air-dilution to achieve Low-NOx performance. Devaluing natural gas, on the other hand, makes it simpler to achieve optimal air-dilution. This solution, however, it is not as common and requires the utilities, rather than the building owner to take action. R&D is needed to refine today’s low-NOx burners to handle high altitudes while maintaining high efficiency levels.</td></tr>
</table>

[45] Manufacturer press release, available: https://www.prnewswire.com/news-releases/lennox-introduces-award-winning-sl280nv-gas-furnace-debut-model-in-industrys-first-line-of-ultra-low-nox-furnaces-300584021.html
[46] Assumes continuous operation; see https://www.weil-mclain.com/download/file/fid/3010

4 Conclusions

Through the course of our research and stakeholder outreach, themes emerged regarding the challenges facing the industry and the R&D opportunities that generated the most interest. Figure 2 shows an overview of these key themes.

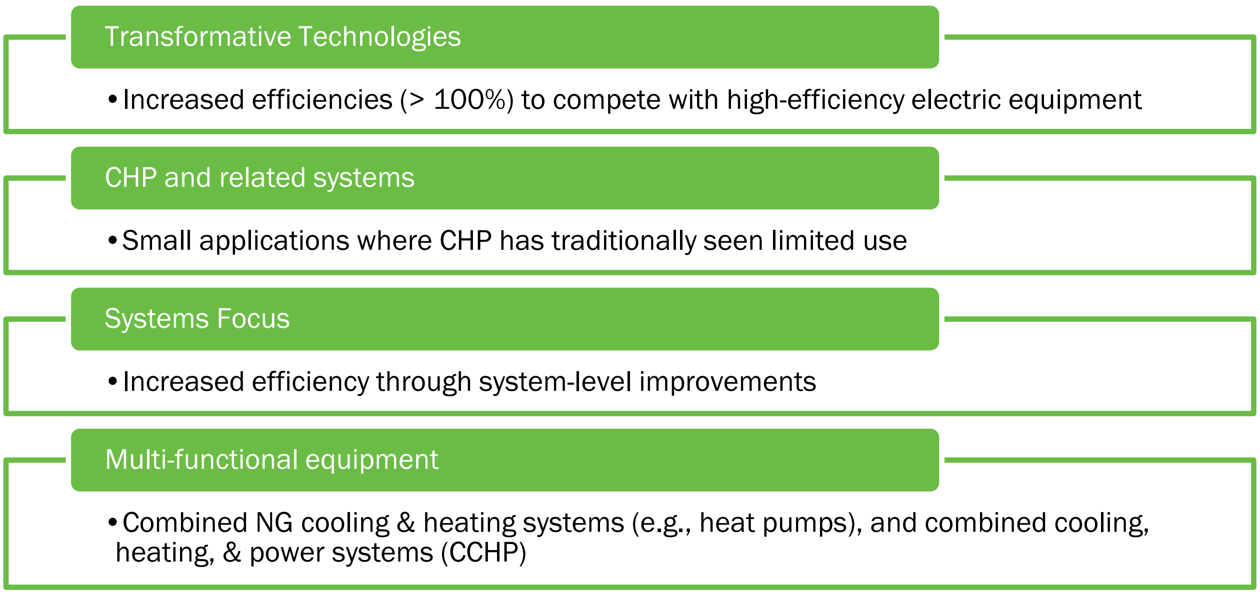


Figure 2: Key Identified Themes

The following list further elaborates on some of the themes:

Transformative technologies – Condensing NG equipment has gained market share in recent years, enabling efficiencies in the upper 90% range for many water heaters, boilers, and furnaces. While opportunities may exist to boost efficiency by 1-2%, the costs are presumed to be prohibitive for the resulting benefit. Therefore, stakeholders are increasingly looking to transformative innovations that can boost efficiencies to greater than 100%, with the natural focus on NG heat pumps. Absorption and adsorption NG heat pumps are not new concepts. In some applications, such as large chiller plants, absorption products are well established, though not common. However, in residential and light commercial applications, the introduction of NG heat pumps is just beginning.

Early products face significant cost premiums due to both complexity and low-volume production. In addition, the lack of contractor familiarity results in little exposure for emergency replacements and an overall lack of awareness of the value of NG heat pumps. Despite these challenges, stakeholders in our workshop expressed interest in multiple R&D opportunities for these technologies. Two activities reached the top tier: "Development of reversible cycle absorption HP (GAHP) appliances with high efficiency cooling" (See Section 3.1.1) and "Development of new or improved gas HP absorption cycles to improve efficiency in cold climates" (See Section 3.1.7). The former generated very high stakeholder interest with a score of 4 out of 5.

CHP and CCHP – Stakeholders express significant interest in CHP and related systems, particularly for smaller applications where CHP has traditionally seen low market penetration (less than 500 kW, with emphasis on applications for less than 100 kW). Three CHP-related activities made it into the top tier, with two more in the second tier. The top tier CHP activities included:

- Development of rapid-response CHP systems to enable control optimization (See Section 3.1.2)
- Development of improved and/or lower cost combined cooling, heat, and power (CCHP) systems (See Section 3.1.5)
- Improve performance of small natural gas engines for microCHP and small GHP applications (See Section 3.1.10)

Stakeholders spent a lot of time discussing cost and installation complexity as hurdles to small CHP applications and expressed interest in opportunities for CHP to reach appliance status in terms of reliability and prevalence. Such a vision places CHP, and therefore NG at the center of the home or business. Anecdotally, this vision appears to be most popular among utility stakeholders.

Systems focus – Stakeholders showed broad interest in improving natural gas system efficiency through system-level improvements, as exemplified to broad discussion and interest in non-widget-based research. Example opportunities included:

- Waste-heat recovery from one end-use for application in another
- Innovative and smart controls that optimize performance of NG equipment via modulating fan and burner controls and runtime management for improved comfort and energy savings
- Low-cost sensors that enable data-driven operations
- Piping and ducting layout

The resulting discussions enabled brainstorming of innovative solutions that, together with specific equipment-related R&D, provide a holistic set of opportunities for addressing NG efficiency in buildings.

Multi-functionality – Interest in low-cost, innovative multi-function NG products is increasing among the stakeholders we spoke with. Combination space heat and hot water systems, which are becoming more common in many markets, was of interest, but in addition, stakeholders discussed at length the value of combined heating and cooling systems (e.g., reversible NG heat pumps), and combined cooling, heating, and power systems (CCHP, or trigeneration). In these two applications, a core focus was enabling high-year-round utilization through the addition of space cooling to provide quicker returns on the investment. For these products high costs has been a key hurdle due to system complexities. Researchers hope that with focused investment on cost and complexity, the addition of cooling capabilities, which naturally adds more complexity, will enable development of a viable product. Further, the hope is that the products will be suitable for a broad array of residential and commercial applications enabling high-volume, low-cost manufacturing.

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