U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES OFFICE

Research & Development Roadmap for Emerging Water Heating Technologies

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Prepared by Navigant Consulting, Inc.

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NOTICE

Preface

The U.S. 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 research and development (R&D) roadmap for water heating technologies. The initiatives identified in this report are Navigant's recommendations to BTO for pursuing in an effort to achieve DOE's energy efficiency goals. Inclusion in this roadmap does not guarantee funding; water heating initiatives must be evaluated in the context of all potential activities that BTO could undertake to achieve their goals.

BTO also manages the residential appliance and commercial equipment standards program; however these activities are separate. As part of the standards program, there are currently ongoing test procedure and standards rulemakings for residential and commercial water heating. To maintain the separation between emerging technologies activities and appliance standards activities, and to prevent undesirable interaction between the two, this roadmap does not cover the following topics:

- Test procedures for residential and commercial water heaters
- Energy efficiency descriptors
- Efficiency standards levels
- Grid-enabled water heating technologies

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List of Acronyms

A/C	Air-Conditioning
ACEEE	American Council for an Energy-Efficient Economy
AEO	EIA's Annual Energy Outlook report
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BTO	Building Technologies Office (Department of Energy), BTO
CBECS	EIA's Commercial Building Energy Consumption Survey
CCE	Cost of Conserved Energy
CEE	Consortium for Energy Efficiency
CO_2	Carbon Dioxide
DFM	Design for Manufacturing
DOE	Department of Energy
BTO	Department of Energy Building Technologies Office (part of EERE)
EF	Energy Factor
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EERE	DOE's Office of Energy Efficiency and Renewable Energy
FDD	Fault Detection and Diagnostics
FEMP	Federal Energy Management Program
FHR	First Hour Rating
GHG	Greenhouse Gas
GWP	Global Warming Potential
HVAC	Heating, Ventilation, and Air-Conditioning
HPWH	Heat Pump Water Heater
LEED	Leadership in Energy and Environmental Design
LBNL	Lawrence Berkeley National Laboratory
LPG	Liquefied Petroleum Gas
MYPPs	Multiyear Program Plans
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PEF	Primary Energy Factor
PNNL	Pacific Northwest National Laboratory
POU	Point-of-Use
P-Tool	BTO's Prioritization Tool
R&D	Research and Development
RECS	EIA's Residential Energy Consumption Survey
SWH	Solar Water Heating/Heater
WH	Water Heater

Executive Summary

The U.S. Department of Energy's (DOE) Building Technologies Office (BTO) within the Office of Energy Efficiency and Renewable Energy (EERE) works with researchers and industry to develop and deploy technologies that can substantially reduce energy consumption in residential and commercial buildings. BTO aims to reduce building-related primary energy consumption by 50% by the year 2030, relative to 2010 consumption. Specifically for water heating, BTO identified primary energy savings targets of 19% by 2020 and 37% by 2030.

This roadmap aims to advance BTO's energy savings goals by identifying research and development (R&D) initiatives for high efficiency water heating technologies that can be deployed in the marketplace within 5 years.

BTO R&D focuses on innovative initiatives that accelerate development of technologies. This includes those initiatives that produce near-term improvements, as well as those that advance development of next-generation or transformational technologies.

This roadmap does not address early stage science research that is more suitable for the Office of Science, or late-stage market development activities that may be more suitable for industry or for the commercial or residential building integration teams (separate from the emerging technologies group) within BTO.

To gather stakeholder input for this roadmap, BTO conducted one-on-one interviews and held a stakeholder forum on January 28, 2014. Stakeholders provided more than 40 unique ideas for initiatives, and in addition, voiced support for many overarching themes in water heating R&D, including:

- Simple and low-cost solutions
- Installer-focused and end-user-focused designs
- System-wide perspective that reflects understanding of the water/energy nexus

After characterizing and analyzing each initiative, BTO developed a prioritized list using a multivariate analysis with both qualitative and quantitative metrics. Table ES-1 shows the resulting tier 1 priority initiatives. They include both *direct-impact initiatives*, which address specific technical innovations to provide energy savings, as well as *enabling initiatives*, which indirectly aid improvements in energy efficiency via supplementrary technologies, processes, or knowledge advances.

Table ES-1: Tier 1 Priority Water Heating R&D Initiatives

Type	Initiative/Activity
Direct-Impact	Support late stage development and commercialization of gas-fired absorption HPWH
Direct-Impact	Support research and commercialization efforts for residential-scale thermoelectric HPWH
Direct-Impact	Develop smart controls for water heating and integrate WH into smart building control systems
Enabling	Establish a research program to conduct lab-based studies on energy and water use impacts of different system architectures on water use and WH energy consumption
Enabling	Conduct large-scale field studies mapping hot water and WH energy consumption in buildings
Enabling	Research advanced manufacturing techniques and components for cost-effective CO_2 HPWH

The report that follows provides detailed background on current R&D efforts in water heating, discussion of BTO's overall approach to water heating R&D, and clear articulation of the tier 1 priority initiatives. The report is organized as follows:

1. **Introduction/Background** – objectives, BTO role and current R&D
2. **Approach** – R&D roadmap development process steps
3. **Market Overview** – current state of technology and the water heating market
4. **R&D Roadmap** – detailed discussion of tier 1 and tier 2 initiatives, as well as general discussion of themes; tier 1 initiative discussion includes discussion of technical and market barriers, timelines and milestones, and stakeholder roles.

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1 Introduction

1.1 Background

1.1.1 BTO Role

BTO works with researchers and industry to develop and deploy technologies that can substantially reduce energy consumption in residential and commercial buildings. BTO aims to reduce building-related energy consumption by 50% by the year 2030, relative to 2010 consumption. Figure 1-1 shows the breakdown of building-related energy savings potential by end use as determined by BTO. The baseline data (shown as a solid black line) represents the EIA's projected energy consumption in buildings and each colored block represents BTO's projected portion that can be offset through the use of emerging energy saving technologies for each end-use.

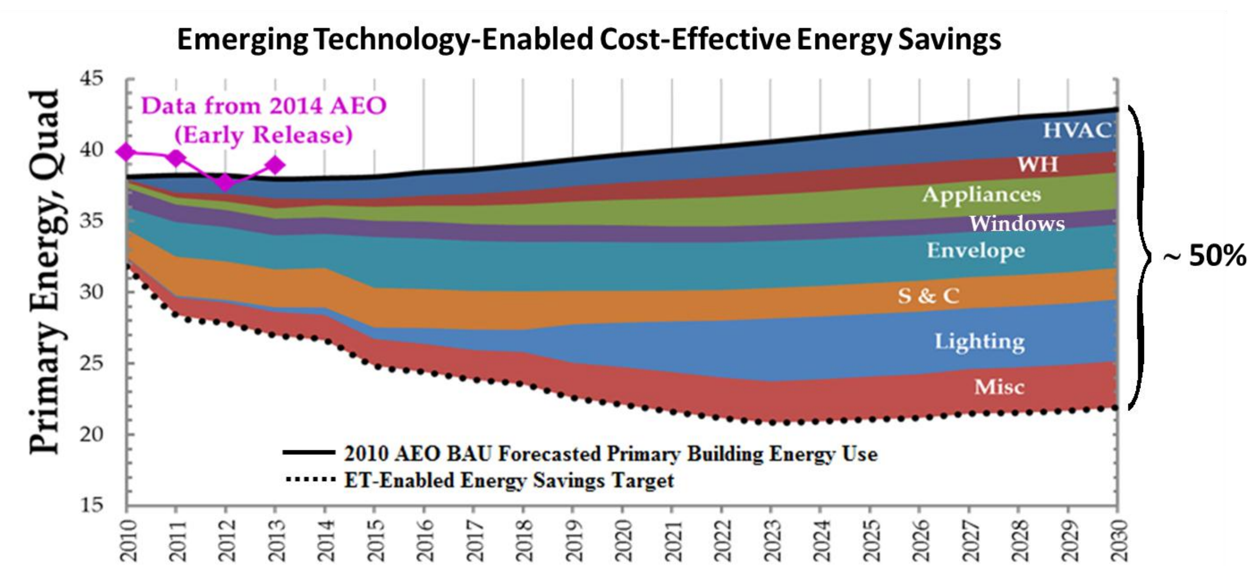
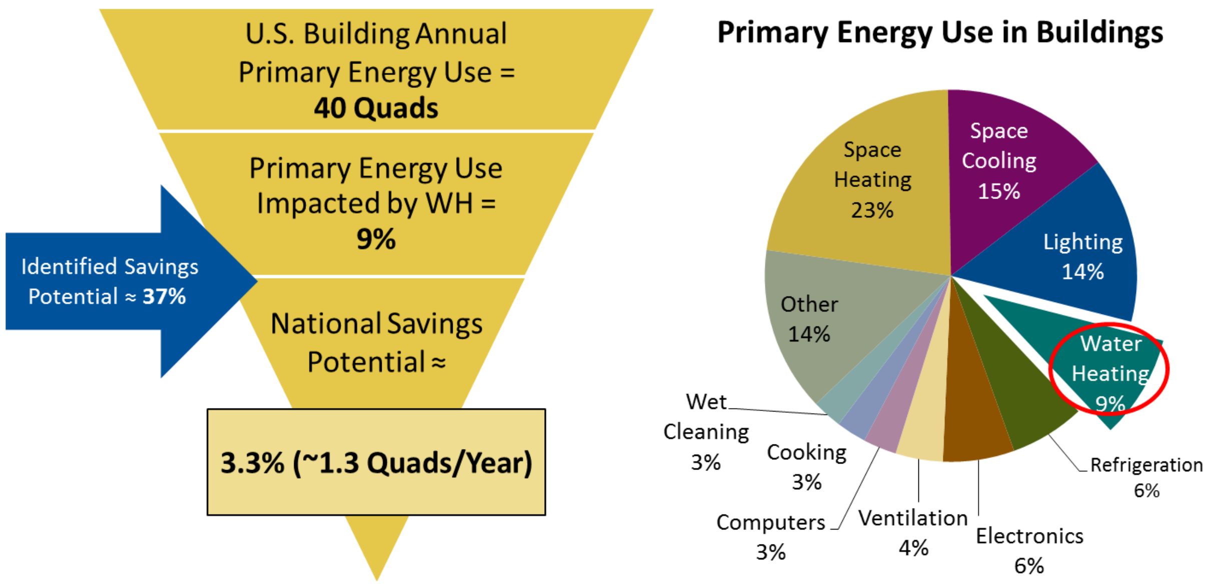


Figure 1-1: Energy Savings Potential Relative to EIA Annual Energy Outlook (AEO)

As part of the 50% target primary energy savings relative to 2010 consumption, BTO has identified water-heating-specific primary energy savings targets, including: 19% in the near-term (2020) and 37% in the long-term (2030).[1] Assuming 40 quads of total annual primary energy consumption in the United States, 9% of which is for water heating, 37% constitutes approximately 1.3 quads of primary energy savings per year (3.3% of total energy consumption). Figure 1-2 details these calculations.

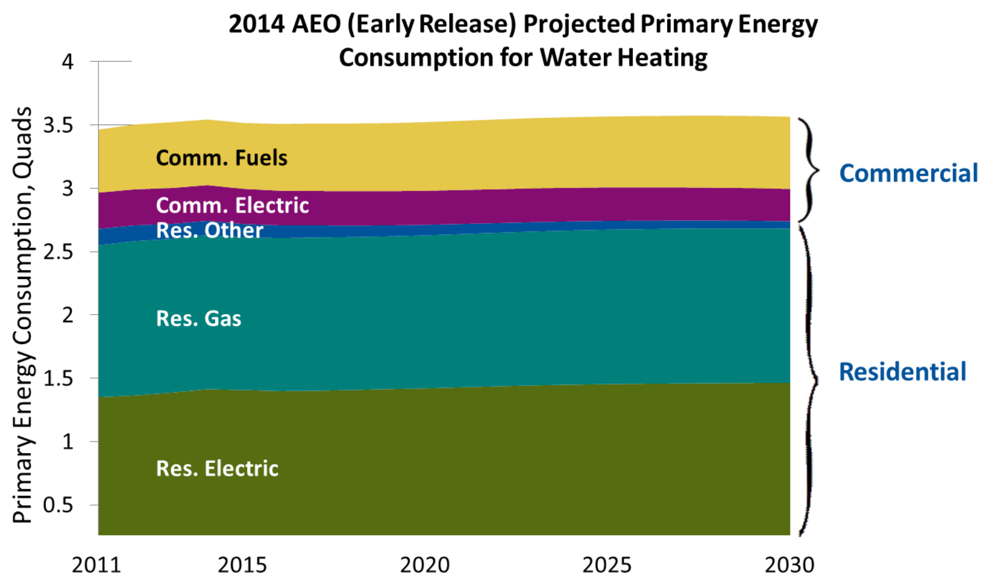
[1] BTO's target savings general information available at: www1.eere.energy.gov/buildings/technologies/index.html. Specific breakdown by end-use based on slide 3 of a presentation by Pat Phalen, Emerging Technologies program manager. (April 22, 2014) Accessed September 2, 2014: energy.gov/sites/prod/files/2014/05/f15/BTO_PeerReview_ET_Overview_042214.pdf.



Source: Buildings Energy Data Book tables 1.1.1 and 1.1.4. Savings estimated based on DOE Prioritization tool analysis.

Figure 1-2: Energy Savings Potential for Water Heating

The Energy Information Administration's (EIA) 2014 Annual Energy Outlook (AEO) provides a breakdown of primary energy consumption out to 2030 by both fuel source and sector for all water heating. Figure 1-3 shows that residential energy use for water heating constitutes nearly 80% of all water heating energy consumption. Within residential water heating, the fuels are split approximately evenly between gas and electric, with other (e.g., fuel oil, propane) representing only 5% of residential water heating energy consumption.



Source: Energy Information Administration's (EIA) Annual Energy Outlook (AEO)

Figure 1-3: Breakdown of Water Heating Consumption by Fuel and Sector

1.1.2 BTO Emerging Technologies Program Mission and Goals

It is the job of the Emerging Technologies Program to accelerate development of new technologies to help achieve such energy savings goals. As defined in its Multi-Year Work Plan (MYP), BTO's mission is to:

> Develop and promote efficient and affordable, environmentally friendly, technologies, systems, and practices for our nation's residential and commercial buildings that will foster economic prosperity, lower greenhouse gas emissions, and increase national energy security while providing the energy-related services and performance expected from our buildings.[2]

As part of this mission, BTO targets reducing building-related primary energy use by 50% by 2030, with a specific primary energy savings target of 37% for water heating (19% by 2020), as discussed in section 1.1.1, above.

In September 2011, BTO published a water heating research and development (R&D) roadmap, developed by Navigant, to provide a pathway to realizing their savings goals in water heating technologies.[3] As such, this report is an update to the 2011 report and includes new technology options that were not available at that time. BTO updates roadmaps periodically to ensure that they reflect the most up-to-date needs of the industry and appropriately reflect changes in their R&D portfolio. This roadmap update specifically incorporates three new key items:

- **Prioritization tool (P-Tool)** – BTO recently incorporated the P-Tool into their R&D planning process and uses it as a key point of comparison between all potential R&D options across all end uses. See section 2.2.2, for additional discussion.

- **New developments in key technology areas** – BTO identified four target areas in which they executed R&D activities since publication of the prior roadmap.

- **Recently developed/commercialized technologies** – heat pump technologies in particular have evolved rapidly in recent years, driving a need to reassess needs in the marketplace.

This roadmap also presents BTO's newly identified near-term efficiency and cost targets for four different water heating technology areas (based on analysis for the P-Tool):

- Non-CO_2 vapor compression heat-pump water heater (HPWH) – See Figure 1-4
- CO_2 vapor compression HPWH – See Figure 1-5
- Non-vapor compression HPWH – See Figure 1-6
- Gas-fired HPWH – See Figure 1-7

Each figure shows the efficiency using the primary energy factor, as opposed to the typical Energy Factor (EF) metric. The primary energy factor additionally accounts for the losses associated with generation/transmission/distribution of electricity for electricity-driven hot water

[2] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. "Building Technologies Program Multi-Year Work Plan 2011-2015." Accessed September 2, 2014: apps1.eere.energy.gov/buildings/publications/pdfs/corporate/myp11.pdf.

[3] "Research and Development Roadmap for Water Heating Technologies." Prepared for Oak Ridge National Laboratory by Navigant Consulting, Inc. (September 2011) Accessed September 2, 2014: btric.ornl.gov/pdfs/WaterHeatingTechnologiesRoadmap_9-30-2011_FINAL.pdf.

heaters. For example, a HPWH with an EF of 2.4 will have a primary energy factor of 2.4/3.096 or 0.77, where 3.0961 is the conversion factor between primary and site energy.[4] A conversion factor of 3.096 represents total energy conversion efficiency (including generation and distribution losses) of ~32% or 1/3.096. The figures show costs in installed cost premium (dollars per gallon of first-hour-rating, FHR), which is relative to the installed cost of a typical baseline model using the same fuel as the target technology. For gas-fired equipment, the baseline is a typical gas-fired storage unit with a FHR of 67 and an installed cost of $945. For electric equipment, the baseline is a typical electrical-resistance storage unit with a FHR of 50 and an installed cost of $600.[5]

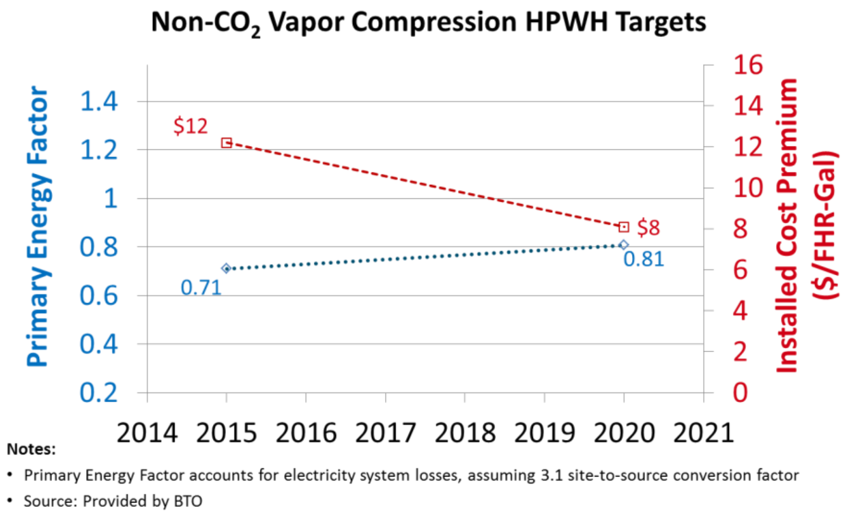


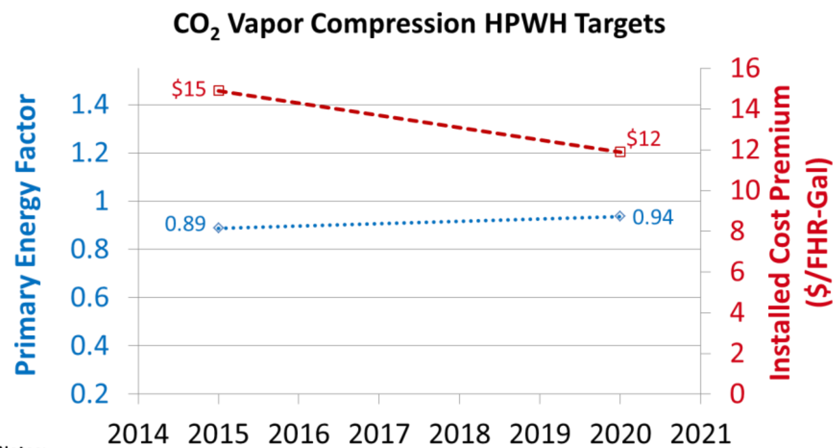
Figure 1-4: Cost and Efficiency Targets for Non-CO_2 Vapor Compression HPWH

Table 1-1 shows the underlying data for Non-CO_2 vapor compression HPWH targets.

Table 1-1: Underlying Data for Non-CO_2 Vapor Compression HPWH Targets

HPWH	Energy Factor (EF)	Installed Cost Premium	First Hour Rating (FHR)	Primary Energy Factor (PEF)	Installed Cost Premium /FHR
2015	2.2	$750	61.5	0.71	$12.20
2020	2.5	$500	61.5	0.81	$8.10
Source: BTO internal analysis, assuming $600 (installed cost) electric resistance storage model as baseline					

[4] The 3.1 primary-to-site energy conversion factor is used here for illustrative purposes only. The actual conversion factor for a given installation will depend on local factors such as generation fuel/technology mix.
[5] Baseline assumptions based on BTO analysis for P-Tool, using EIA data as the primary basis.



Notes:

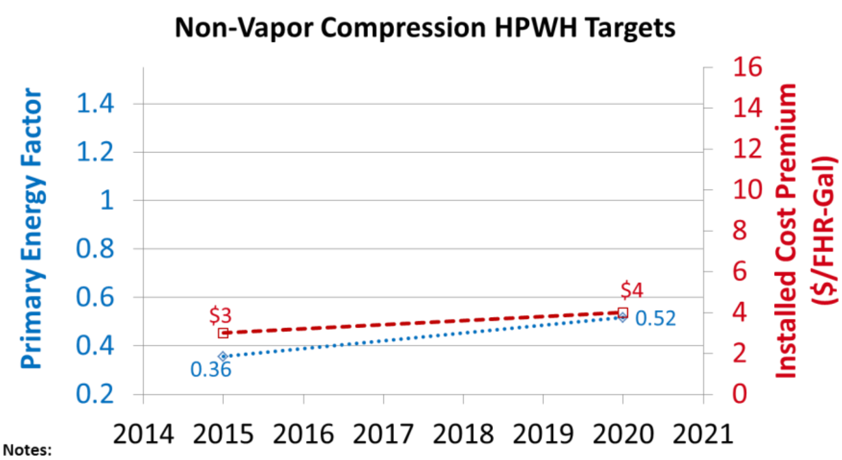
- Primary Energy Factor accounts for electricity system losses, assuming 3.1 site-to-source conversion factor
- Source: Provided by BTO

Figure 1-5: Cost and Efficiency Targets for CO_2 Vapor Compression HPWH

Table 1-2 shows the underlying data for CO_2 vapor compression HPWH targets.

Table 1-2: Underlying Data for CO_2 Vapor Compression HPWH Targets

CO2 Vapor Compression	EF	Installed Cost Premium	FHR	PEF	Installed Cost Premium /FHR
2015	2.75	$1000	67	0.89	$14.90
2020	2.9	$800	67	0.94	$11.90
Source: BTO internal analysis, assuming $600 (installed cost) electric resistance storage model as baseline					



Notes:

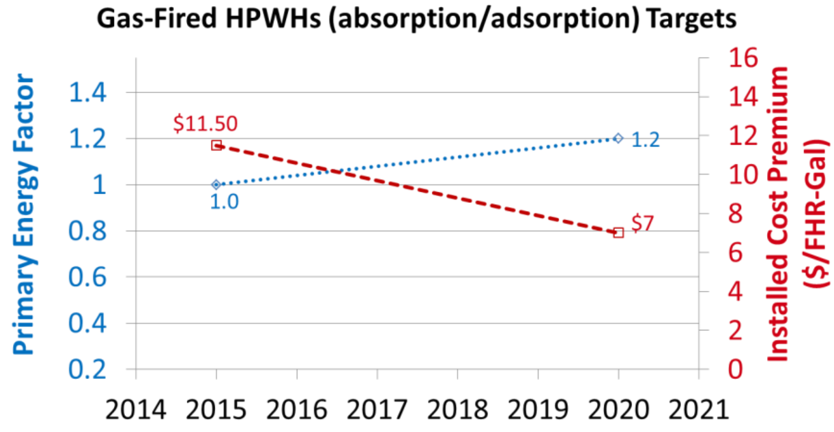
- Primary Energy Factor accounts for electricity system losses, assuming 3.1 site-to-source conversion factor
- Source: Provided by BTO

Figure 1-6: Cost and Efficiency Targets for Non-Vapor Compression Technologies

Table 1-3 shows the underlying data for non-vapor compression HPWH targets.

Table 1-3: Underlying Data for Non-Vapor Compression HPWH Targets

Non-Vapor Compression	EF	Installed Cost Premium	FHR	PEF	Installed Cost Premium /FHR
2015	1.1	$150	50	0.36	$3
2020	1.6	$200	50	0.52	$4
Source: BTO internal analysis, assuming $600 (installed cost) electric resistance storage model as baseline					



Source: Provided by BTO

Figure 1-7: Cost and Efficiency Targets for Gas-Fired HPWH

Table 1-4 shows the underlying data for gas-fired HPWH targets.

Table 1-4: Underlying Data for Gas-Fired HPWH Targets

Gas-Fired HPWH	EF	Installed Cost Premium	FHR	PEF	Installed Cost Premium /FHR
2015	1.2	$750	65	1	$11.50
2020	1.3	$500	70	1.2	$7.10
Source: BTO internal analysis, assuming $945 (installed cost) gas-fired storage water heater as baseline					

These targets represent a first-pass at determining realistically achievable goals in each technology area.

1.1.3 Recent and Current R&D Activities

BTO has been active in water heating R&D for many years; three of the most recent commercialized water heating technologies with which BTO has been involved include the GeoSpring electric heat pump water heater by GE, the Vertex residential gas condensing water heater by A.O. Smith, and the Emerson wireless water heater controller. Figure 1-8 describes each technology and documents the technologies' development statuses.

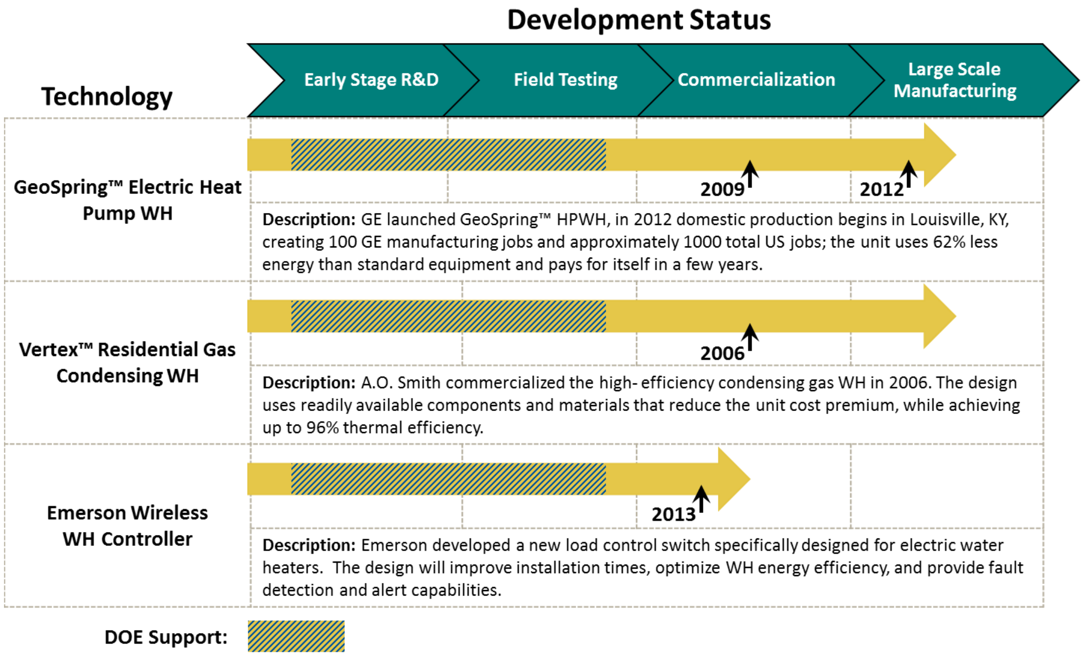
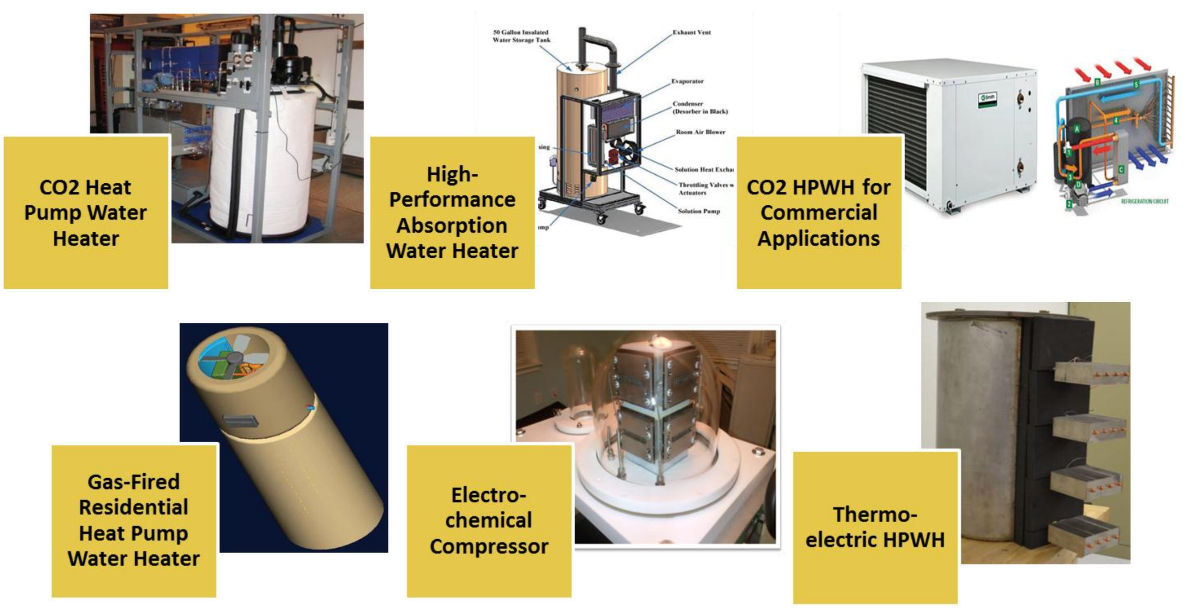


Figure 1-8: Water Heating Technologies Recently Commercialized with DOE Support

BTO has also supported many additional technologies that have not yet been commercialized, including many with ongoing work. Figure 1-9 shows a selection of these technologies.



Images Sources: http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/rd_breakthroughs.pdf , Introduction to Sheetak & Heat Pump Water Heaters (provided by DOE), DOE SBIR Xergy Presentation (provided by DOE)

Figure 1-9: Selection of BTO-Supported Water Heating Technologies

The following subsections describe some of the R&D conducted since BTO published the prior water heating roadmap.

1.1.3.1 Electrochemical Compressor

BTO awarded a Small Business Innovation in Research (SBIR) grant to the developer of electrochemical compressors for HPWH applications. Simulations of the product show a compressor COP of ~4 is achievable as compared to 2.5-3 for high-efficiency, commercially available HPWH compressors. In Phase I, the grant recipient developed the core technology for a 50 gallon unit. In Phase II (currently underway), they will create a prototype heat pump hybrid hot water heater using their electrochemical compressor.[6]

1.1.3.2 CO_2 Vapor Compression HPWH

The CO_2 HPWH projects, conducted under Cooperative Research and Development Agreements (CRADA), aim to create an ENERGY STAR-qualified CO_2 HPWH. By using CO_2 as the working fluid, instead of R-134a or other high-global warming potential (GWP) refrigerants, the equipment's vapor compression system will have a GWP of 1 and an ozone depletion potential (ODP) of zero. Further, CO_2 HPWHs have been shown to provide higher efficiencies and operate at lower ambient conditions than traditional HPWH in places like Japan where their use is more widespread.[7]

For commercial equipment, DOE funded a grant to develop a CO_2 HPWH with 20% better cycle efficiency than the baseline CO_2 HPWH. Further, this project aimed to develop control algorithms that would allow for continual use of the free cooling from the cold side of the heat pump. Restaurants, hotels, and hospitals benefit from such equipment due to typically year-round space cooling and water heating needs.[8]

1.1.3.3 Non-Vapor Compression

The thermoelectric HPWH project supports BTO efforts for non-vapor compression water heating. The targets for this project (currently a phase II SBIR grant) include a COP of 1.1 with a retail cost of less than $500 for a 50 gallon unit.[9]

1.1.3.4 Gas-Fired HPWH

BTO awarded a grant to work on a gas-fired HPWH in partnership with the National Energy Technology Laboratory (NETL). The target is an Energy Factor (EF, primary or source-fuel basis) that is 2.4 times higher than conventional gas storage water heaters and 2.1 times higher than conventional electric heat pump water heaters.[10]

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[6] More information available on the electrochemical compressor SBIR at: www.sbir.gov/sbirsearch/detail/408804 and energy.gov/eere/buildings/articles/small-businesses-receive-2-million-advance-hvac-technologies

[7] More information available on CO_2 HPWH work at: energy.gov/eere/buildings/carbon-dioxide-heat-pump-water-heater-research-project.

[8] More information available at: www.recovery.gov/arra/Transparency/RecoveryData/pages/RecipientProjectSummary508.aspx?AwardIdSur=113975&AwardType=Grants

[9] More information available at: aceee.org/files/pdf/conferences/hwf/2013/7A-pokharna.pdf and www.sbir.gov/sbirsearch/detail/408724.

[10] More information available at: www.recovery.gov/arra/Transparency/RecoveryData/pages/RecipientProjectSummary508.aspx?AwardIdSur=118923&AwardType=Grants%20 and aceee.org/files/pdf/conferences/hwf/2011/3B%20-%20Garrabrant.pdf.

DOE supports additional work on gas-fired HPWH through a CRADA between DOE, Oak Ridge National Laboratory and a CRADA manufacturing partner. They target an efficiency improvement of 40% over conventional gas-fired storage water heaters.[11]

1.2 Technology and Market Scope

BTO R&D focuses on innovative initiatives that accelerate development of technologies. However, in select cases, BTO also supports initiatives that can drive innovation broadly throughout the industry and enable future breakthroughs. We define these two types of technologies as follows, both of which we cover in this roadmap:

- **Direct-impact initiatives** – R&D that targets technical innovations in a specific component, system, or type of technology that will directly provide energy savings, e.g., development of improved heat exchangers for CO_2 HPWH. See section 4.2 for direct-impact technology initiatives.
- **Enabling initiatives** – R&D that indirectly aids improvements in energy efficiency through development of supplementary technologies (e.g., sensors) or through advances in processes (e.g., manufacturing) or knowledge (e.g., data collection) that benefits many types of technologies, e.g., development of modeling software. See section 4.3 for enabling technology initiatives.

This roadmap does not address early stage science research that is more suitable for the Office of Science, or late-stage market development activities that may be more suitable for industry or for the commercial or residential buildings groups (separate from the emerging technologies) within BTO.

This roadmap covers residential and commercial water heating systems, including the heating appliance/equipment (all fuel sources), the distribution system, the controls, and any associated components. Figure 1-10 shows a non-exhaustive overview of the various technologies covered in this roadmap in three different categories: Equipment, System Architecture, and Supporting Technologies.

[11] More information available on Gas-Fired HPWH research at: energy.gov/eere/buildings/gas-fired-absorption-heat-pump-water-heater-research-project and energy.gov/sites/prod/files/2013/12/f5/emrgtech10_gluesenkamp_040313.pdf.

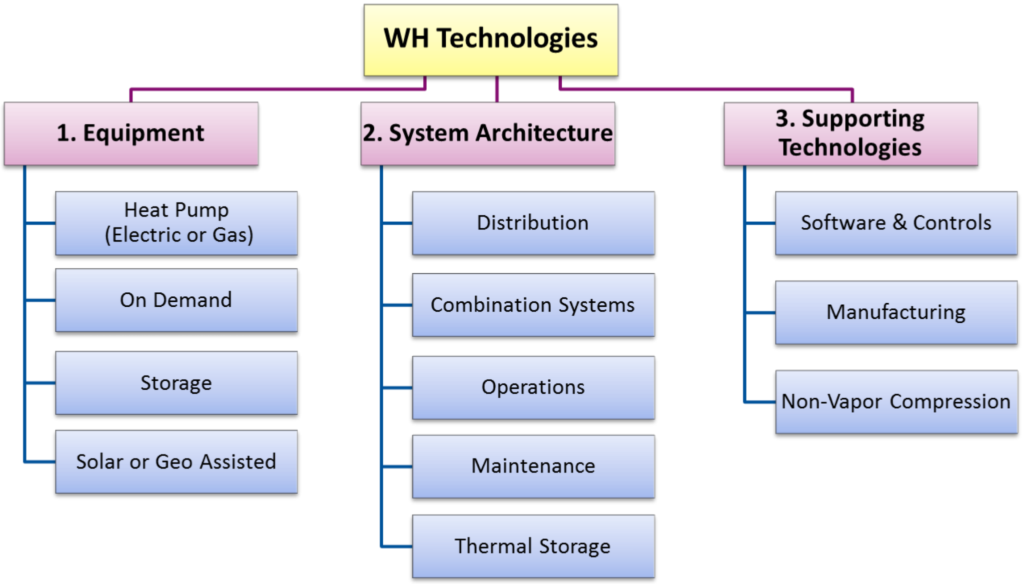


Figure 1-10: Water Heating Roadmap Technology Scope (Not Exhaustive)

While solar is included in this roadmap, we try to prevent overlap with BTO's report "Research and Development Needs for Building-Integrated Solar Technologies," published in January of 2014, so solar related activities are not heavily represented.[12]

1.3 BTO WH R&D Approach

In working to achieve the BTO energy savings goals (see section 1.1.1, above), BTO has developed a two pronged approach to support research in emerging water heating technologies, as illustrated in Figure 1-11. The two parallel pathways are:

1. **Low-Cost Efficiency** – Develop new cost-effective water heating solutions, targeting a price point that makes efficient water heating attractive to mass markets. E.g., support development of non-vapor compression heat pump water heater that is cost competitive with current baseline electric storage water heaters but with higher efficiency.
2. **Premium Efficiency** – Improve performance of ultra-high efficiency water heaters aimed at customers willing to pay a premium for high efficiency products. E.g., improve efficiency of heat-pump water heaters.

[12] William Goetzler et. al. "Research and Development Needs for Building-Integrated Solar Technologies." prepared for BTO by Navigant Consulting, Inc. January 2014. Accessed September 2, 2014: energy.gov/sites/prod/files/2014/02/f7/BIST_TechnicalReport_January2014_0.pdf.

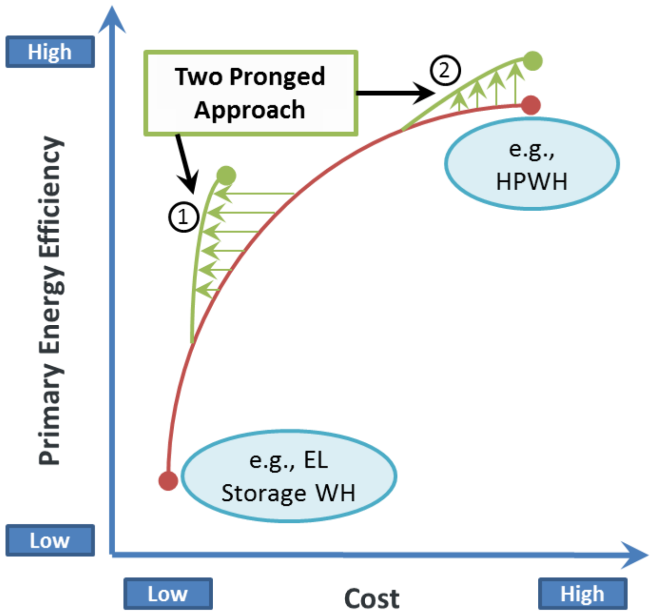


Figure 1-11: Efficiency and Cost Target Areas

BTO followed this two-pronged approach in recent R&D. For example, development of thermoelectric-based water heaters (see section 1.1.3.3, above) boosts efficiency of lower-cost equipment via pathway 1. At the same time, development of premium efficiency gas-fired HPWHs pushes the envelope of efficiency via pathway 2 (see section 1.1.3.4, above).

1.4 Objective of this Roadmap

The objective of this roadmap is to advance BTO's goal of reducing building-related energy consumption by identifying R&D initiatives in support of advancing high efficiency water heating technologies that can be deployed in the marketplace within 5 years.

This roadmap provides guidance on future research and development (R&D) activities by outlining the highest priority initiatives, which, if pursued, will have the greatest potential impact on reducing residential and commercial water heating energy consumption. These initiatives will aid in BTO's goal to achieve 50% energy savings relative to 2010 levels by 2030.

2 Roadmap Approach

Figure 2-1 outlines the three stages for developing this roadmap.

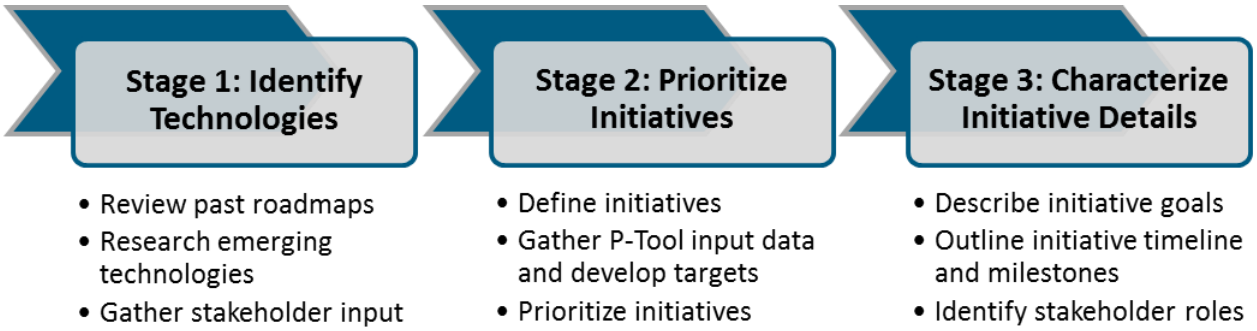


Figure 2-1: Roadmap Development Steps

2.1 Stage 1: Identify Technologies and Define Initiatives

To identify R&D initiatives, Navigant aggregated inputs from three different sources:

1. **Literature review** – research and analysis of the prior BTO water heating roadmap, academic papers, industry reports, and patent fillings regarding emerging water heating technologies.
2. **Stakeholder forum** – stakeholder input from the January 2014 water heating stakeholder forum at Navigant's Washington, D.C. office.
3. **One-on-one interviews** – detailed input from individual stakeholders and industry experts on emerging water heating technologies; included both forum attendees and non-attendees.

The stakeholder forum, held on January 28, 2014, brought together stakeholders and industry experts from around the nation to discuss barriers, new ideas and technologies, and strategic pathways towards helping achieve BTO's energy savings goals. The group consisted of 26 individuals representing manufacturers, academic researchers, national laboratories, gas and electric utilities, energy-efficiency organizations, and trade organizations. The 5-hour forum included a variety of opportunities to gather feedback and foster discussion around key challenges in water heating. In addition to group dialogue and brainstorming, the forum also utilized small break-out group discussions to generate intimate discussions in more specific topics areas, including:

- Water heating equipment
- System architecture (including distribution, operations and maintenance)
- Supporting technologies (including software and controls)

Participants voted on the initiatives generated throughout the forum based on their perceived impact and importance to the industry; these votes became inputs to the prioritization process (see section 2.2). After the forum, Navigant reviewed the list of initiatives and selectively conducted one-on-one interviews with stakeholders (both forum participants and non-participants) on topic areas that required additional clarification.

See "Appendix A – Water Heating Forum Summary Report" for additional details on the Water Heating Forum.

2.2 Stage 2: Prioritize Initaitves

To prepare for initiative prioritization, we developed a comprehensive list of suggested initiatives and refined the list to eliminate duplicates and combine those ideas that naturally fit together. The initiatives in this list fell into one of two categories: "enabling" or "direct-impact" (see discussion in Section 1.2, above). We labeled each initiative accordingly in anticipation of scoring.

In consultation with BTO, Navigant prioritized the initiatives to identify the most promising for BTO to pursue. We used the comprehensive prioritization process described below, which scores each initiative based on qualitative metrics and the votes from the stakeholder forum; in the case of "direct-impact" initiatives, we also evaluated initiatives using outputs from BTO's prioritization tool (P-Tool).

The prioritization approach was as follows:

1. Score and rank the selected initiatives using a qualitative prioritization process
2. Incorporate P-Tool inputs (Impact metric) for direct-impact initiatives only
3. Select a top tier of direct-impact initiatives and a top tier of enabling initiatives for deeper review and detailed characterization

2.2.1 Prioritization

The qualitative prioritization used five different metrics, each scored on a scale of 1 to 5. The weighted average of these scores determined the ranking. Table 2-1 shows the definitions of each metric.

Table 2-1: Initiative Scoring Metrics - Definitions

Metric	Definition
Impact (Direct-impact initiatives only)	**Impact on Energy Savings Potential** – P-Tool results for Staged Maximum Adoption Potential (see section 2.2.2)
Impact (Enabling initiatives only)	**Impact on Knowledge Gap or Adoption Barrier** – Expected impact on addressing a critical knowledge gap or overcoming a barrier to adoption of high-efficiency WH technologies
Fit with BTO Mission	Suitability of initiative (e.g., research stage and needs) to BTO's mission, goals, and capabilities (including the initiative's expected time to market)
Criticality of DOE Involvement	Criticality of DOE participation to the success of the initiative
Level of Risk	Funding level that may be expected for the initiative to be successful
Level of Required Investment	Expected investment risk based on the likelihood of the initiative achieving impact

Table 2-2 shows the scoring and weighting values. Impact scores for direct-impact initiatives were preliminary, and were later refined using the P-Tool; see Section 2.2.2 for discussion of the quantitative prioritization process for the direct-impact initiatives.

Table 2-2: Initiative Scoring Metrics - Scores

Metric	5	4	3	2	1	Wgt:
Impact (Direct-impact)	> 1,000 TBtu	1,000 – 500 TBtu	500 – 250 TBtu	250 – 10 TBtu	< 10 TBtu	30%
Impact (Enabling)	Significant	Semi-Significant	Moderate	Modest	Minimal	
Fit with BTO Mission	Core to mission	Semi-core to mission	Relevant to mission	Semi-relevant to mission	Outside scope / mission	20%
Criticality of DOE Involvement	Critical to success	Semi-critical to success	Beneficial to success	Semi-beneficial to success	Unnecessary for success	20%
Level of Risk	Low	Low-Moderate	Moderate	High-Moderate	High	10%
Level of Required Investment	< $1M	$1M - $3M	$3M - $5M	$5M - $10M	> $10M	20%

Two members of the roadmap team independently scored each initiative on the qualitative metrics. Averages of the scores determined the output score for each metric. In order to incorporate voting from the stakeholder forum (see section 2.1, above), we assigned an industry-input score (0-5) to each initiative, depending on the relative number of votes. Each point on the industry-input score corresponded to a boost in final score of 0.05 (applied after scoring of prioritization metrics from above). For example, an initiative with a prioritization score of 3 and an industry-input score of 4 would receive a final score of 3.20 (i.e.,$3 + (0.05)4 = 3.20$).

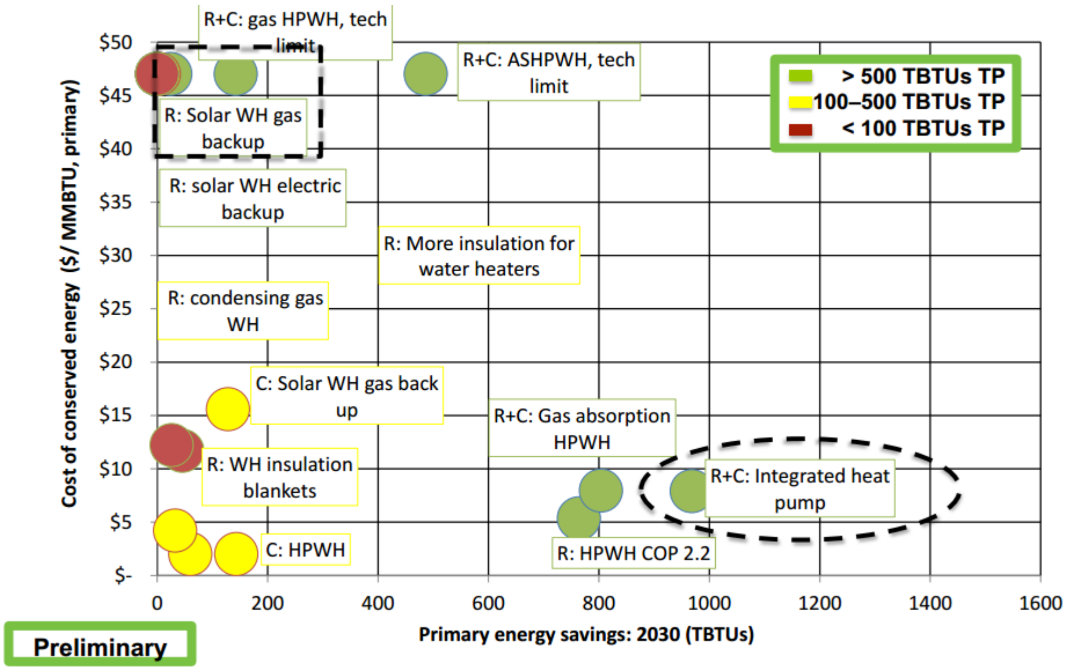
2.2.2 BTO Prioritization Tool – Direct-Impact Initiatives Only

To determine the Impact score for the direct-impact initiatives, we used BTO's P-Tool. The P-Tool compares investment opportunities across all of BTO to help inform decision making and goal/target development. The National Renewable Energy Laboratory (NREL) originally developed the tool and described it in more detail in their project report.[13] In brief, the tool uses inputs for energy measure performance, cost, market, and lifetime to analyze each measure both individually and as part of a full portfolio of measures. The tool produces three key outputs:

- **Technical Potential (TBtu):** The annual energy savings achieved if the new measure replaces all existing stock in the United States. This represents the theoretical maximum energy savings and does not account for any technical or market factors that might limit penetration.
- **Un-staged Maximum Adoption Potential (TBtu):** The portion of the technical energy savings potential achieved through deployment of the measure for all end-of-life replacements and new purchases by accounting for sales, disposals, and building stock growth. This is also referred to as the
- **Staged Maximum Adoption Potential (TBtu):** The portion of the un-staged maximum adoption potential achieved when accounting for competition among technologies, thereby avoiding double counting savings for measures with overlapping markets. The P-Tool attributes savings potential to competing technologies by prioritizing based on the cost of conserved energy (CCE), i.e., the technology with the lowest CCE is the first to capture its share of a given market. The P-Tool then attributes incremental savings potential to measures with higher cost of conserved energy and higher energy savings potential. The P-Tool determines staged maximum adoption potential on an individual market by market basis.

The P-Tool also presents results in other valuable ways, including calculating the cost of conserved energy (cost required to save a unit of energy by implementing an energy savings measure) and the expected primary energy savings in 2030. The example chart in Figure 2-2 compares a portfolio of technology options on both the cost of conserved energy and expected primary energy savings in 2030.

[13] Philip Farese, et. al. "A Tool to Prioritize Energy Efficiency Investments." National Renewable Energy Laboratory. (August 2012) Accessed September 2, 2014: www.nrel.gov/docs/fy12osti/54799.pdf.



Source: A. Abramson, "Building Technologies Office Prioritization Tool," April 2013[14]

Figure 2-2: Example P-Tool Output

Section 4.2 provides detailed P-Tool outputs for each direct-impact initiative and provides detailed discussion of the top tier of initiatives. These data enable BTO to further discern which water heating initiatives provide the greatest benefit relative to other investments across any end-use and help determine appropriate performance and cost targets.

2.3 Stage 3: Develop R&D Roadmap

Navigant developed detailed descriptions and workplans as a starting point for BTO to use in executing the top three direct impact initiatives and the top three enabling initiatives. The detailed recommendations include the following components:

- Define initiative purpose and goals
- Identify key technical challenges and hurdles
- Present 2025 cost and performance targets
- Outline initiative timeline and major milestones
- Discuss initiative's potential impact on existing market barriers
- Recognize key stakeholder roles and responsibilities

Section 1 contains the detailed recommendations and characterizations for each high-priority initiative.

[14] A. Abramson. "Building Technologies Office Prioritization Tool." BTO presentation (April 2013) Accessed September 2, 2014: energy.gov/sites/prod/files/2013/12/f5/ptool_overview_abramson_040213.pdf

3 Market Overview

3.1 Current Technological Landscape

3.1.1 Residential Equipment

Existing residential water heaters in U.S homes are primarily storage-tank type as opposed to tankless. The EIA found through the Residential Energy Consumption Survey that in 2009, only 2% of water heaters in the U.S. were tankless. They are most common in the northeast where they constitute 6% of the installed base.[15] Nationwide, 51% of water heaters use natural gas and 41% use electricity; propane (liquefied petroleum gas, LPG) and fuel oil make up 4% and 3%, respectively. Noteworthy exceptions include:

- Fuel oil in the northeast – 17% of homes in the northeast use fuel oil while quantities are negligible in other regions.
- Electricity in the South – 65% of homes in the south use electricity, while the northeast, Midwest, and west range from 20-30%.

On a regional basis, these data vary further, particularly due to fuel availability. Two key examples are the high concentration of electric water heaters in the Pacific Northwest where hydropower is the predominant electricity source, and in rural areas nationwide where natural gas is typically not available and electric water heaters are the typical choice. Figure 3-1 summarizes residential water heating fuel sources in the U.S.

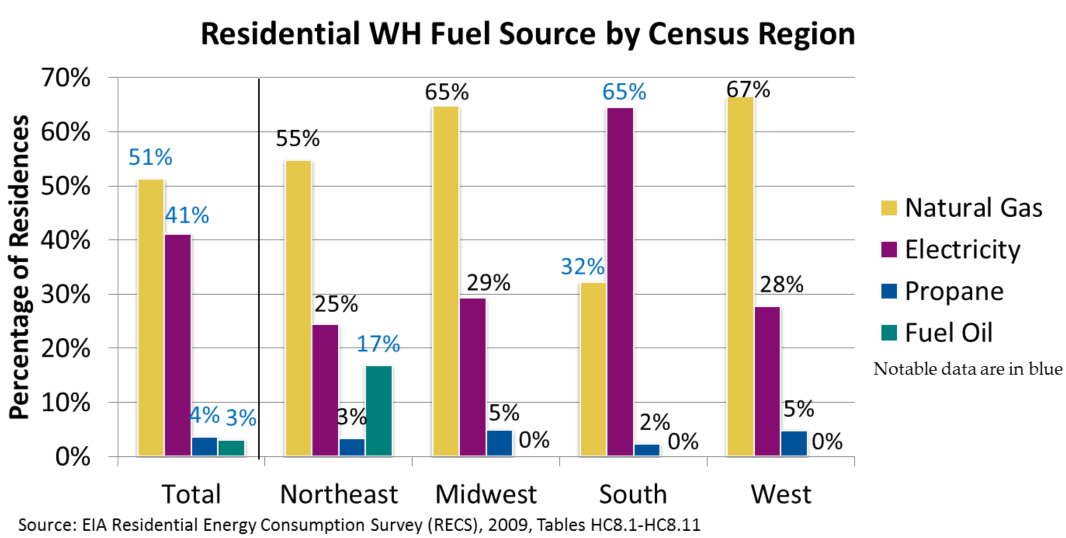


Figure 3-1: Residential Water Heat Fuel Type in U.S. Homes

[15] RECS 2009, Energy Information Administration, Table HC8.1, available: www.eia.gov/consumption/residential/data/2009/

3.1.2 Commercial Equipment

Figure 3-2, from the EIA's 2003 Commercial Building Energy Consumption Survey, shows that 55% of commercial buildings heat water with electricity while 42% heat with natural gas (trend reversed from residential buildings). Similar to the residential market, fuel oil only has a notable market share in the northeast where 14% of commercial buildings use oil for water heating. District heat and propane both have small single-digit market shares as fuel sources for water heating in all regions. However, when looking at total fuel consumption, as opposed to fuel source, the data differ, primarily due to differences in fuel use (and availability) by building size. 70% of water heating fuel use in commercial buildings nationwide is from natural gas. This is due to the fact that larger buildings are concentrated in urban areas where natural gas is more readily available. This trend is also apparent with district heat. Only 1% of buildings use district heat for water heating, but 9% of fuel consumption nationwide for water heating of commercial buildings is from district heat. Again, this is due to high concentrations of district heat in urban centers with many large buildings.

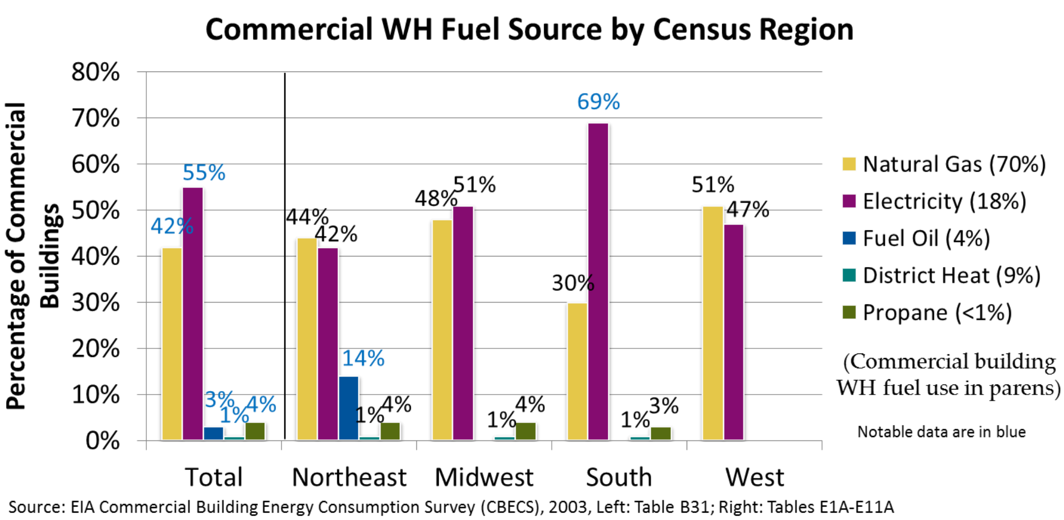


Figure 3-2: Commercial Water Heating Energy Consumption by Fuel and Region

As with residential applications, tankless water heaters are gaining some traction, particularly in small commercial buildings, such as restaurants. One or more tankless water heaters can be installed close to the load to provide an efficient overall solution. In large commercial buildings, such as offices, tankless point-of-use (POU) water heaters may be utilized for distributed system architectures where a single unit may serve a single restroom. However, tankless units are commonly used for large central systems in large buildings (small commercial buildings, such as restaurants, may utilize a bank of multiple tankless units in parallel to serve their load).

3.2 State of the Market – Equipment Trends

In recent years, consumers have exhibited a few notable trends, including growth in:

- **Heat pumps** – Multiple manufacturers have begun selling HPWHs in recent years, making them widely available as a high-efficiency alternative to traditional electric resistance water heaters. As recently as 5-8 years ago, HPWHs were not readily available in the US Market. Today's readily available products typically first or second generation products. ENERGY STAR-specified electric waters heaters must meet or exceed an EF of 2.0, which is currently achievable only with HPWHs. The EF of currently available ENERGY STAR qualified models ranges from 2.2 to 2.75 (approximately 30 different models available).[16]

- **Condensing technology** – Commercial, non-condensing, baseline storage water heaters typically have thermal efficiencies around 80%. However, condensing technologies can help achieve thermal efficiencies in the mid to upper 90% range. For residential applications, the typical baseline EF for non-condensing is ~0.6 and condensing is ~0.8. Condensing technology is available on natural gas and propane/LPG water heaters in both storage and tankless configurations. Select applications may be able to utilize condensing technology for fuel-oil-fired water heating, including indirect water heaters (fired from a condensing boiler), or condensing boilers with built-in tankless coils. While the price premium dissuades consumers looking for the lowest-cost technology, those with available capital (aided by utility or federal incentives) are increasingly looking to condensing options.
- **Solar** – Though solar and other renewable thermal water heating technologies (e.g., ground-source heat pumps, biomass) maintain a small market share (<1%), they have had increased attention from efficiency advocates.[17] The federal government's 30% residential renewable energy tax credit, which includes solar water heating, along with many state and utility incentive programs have boosted awareness and grown the industry. Increased attention at the state and regional level on renewable thermal technologies continues to spur the industry. Improvements in integrating solar hot water systems with solar space conditioning and thermal storage will boost the interest in this technology.

3.3 Barriers to Achieving Energy Savings

Table 3-1 lists some of the key barriers that the industry faces in trying to achieve greater energy savings in water heating systems. This list is not exhaustive and does not touch on issues such as availability of an experienced workforce as this topic is outside the scope of this roadmap; see the 2011 water heating roadmap for a comprehensive discussion.[18]

[16] ENERGY STAR water heating information available: www.energystar.gov/certified-products/detail/high_efficiency_electric_storage_water_heaters
[17] "Low-Cost Solar Water Heating Roadmap." NREL Technical Report TP-5500-54793. K. Hudon, et al. (August 2012) Accessed September 2, 2014: www.nrel.gov/docs/fy12osti/54793.pdf.
[18] "Research and Development Roadmap for Water Heating Technologies." Prepared for Oak Ridge National Laboratory by Navigant Consulting, Inc. (September 2011) pp. 19-20. Accessed September 2, 2014: btric.ornl.gov/pdfs/WaterHeatingTechnologiesRoadmap_9-30-2011_FINAL.pdf.

Table 3-1: Barriers to greater market penetration of high efficiency systems

Barrier	Description
Affordability	Many high efficiency products are available; however, their high-first costs inhibit their potential market penetration.
Retrofit-ability	Replacing equipment in existing homes can be complex and costly; issues may include the need for more space, a water drain, re-lining of chimneys or running a new direct-vent exhaust, or a larger gas service line.
Sales driven by emergency replacement needs	Hot water heaters are often sold on an emergency replacement basis; the energy savings discussion is therefore not always a part of the sales process. Further, the models that plumbers have readily available are therefore the options given to homeowners.
Human factors - Market acceptance	Commodity, baseline water heaters set high bars for consumer expectations in human factors. New products face basic challenges such as fan noises from heat pumps, as well as complex factors such as more complex interfaces and greater potential user-involvement requirements; to many users the added controls may be a selling point, but it is at the very least a substantial change in use from typical water heaters, which are designed for zero user involvement.
System efficiency	Inefficient distribution systems hinder the benefits available from high-efficiency water heaters. For example, a system with a high entrained hot water volume inherently has high distribution-related heat loss. Further, such systems have slow time-to-tap, which is further exacerbated by low-flow fixtures and reduces utility to consumers. If that system uses a HPWH, the impacts on space conditioning should also be considered.

4 Research & Development Roadmap

Stakeholder outreach efforts generated three different types of outputs described in the following sections:

- **Central themes** - Qualitative needs, generally associated with overarching concepts for inclusion in a variety of different R&D initiatives (see section 4.1)
- **Direct-impact initiatives** – Specific, traditional R&D initiatives with direct-impact on energy savings (see section 4.2)
- **Enabling initiatives** – Indirect energy-savings initiatives that impact secondary technologies or processes, which indirectly enable energy savings from WH systems (see section 4.3)

4.1 Central Themes

During the January, 28th stakeholder forum, and during additional one-on-one interviews, stakeholders voiced support for many overarching themes in water heating R&D in addition to suggestions on specific initiatives. These ideas fell into three general themes for R&D emphasis:

- Simple and low-cost solutions
- Installer-focused and end-user-focused designs
- System-wide perspective that reflects understanding of the water/energy nexus

Although these themes do not represent concrete research initiatives for DOE, they are valuable concepts that drive and shape the overall approach to R&D. Figure 4-1 provides examples of some of the feedback supporting these themes.

Qualitative Stakeholder Feedback Themes:

Simple & low-cost solutions

Stakeholder Feedback:
- Focus on reducing first costs and payback periods for high-efficiency WH
- Continue driving costs down for HPWH using conventional refrigerants
- Consider low-cost opportunities based on point-of-use equipment
- Consider ultra-low-cost electric WH solutions
- Leverage options for reducing size and weight of high efficiency WH
- Understand inherent challenges of greater complexity

Installer-focused & end-user-focused designs

Stakeholder Feedback:
- Remember human factors and usability issues (e.g. noise concerns), which present a barrier to mainstream acceptance
- Design products for limited interaction (operation & maintenance)
- Consider regular, periodic maintenance schedules if new equipment requires service; many people are used to systems that require almost no service.
- Designs should emphasize installation ease in existing buildings (replacements)

System-wide perspective that reflects understanding of the water/energy nexus

Stakeholder Feedback:
- Maintain a holistic system perspective, including space conditioning & system integration
- Focus on system efficiency, not just equipment efficiency
- Understand the relationship between water and energy consumption
- Explore alternate ways of doing tasks that use significantly less hot water

Figure 4-1: Qualitative Stakeholder Feedback Themes

4.2 Roadmap for Direct-Impact R&D Initaitives

This section details the tier 1 initiatives (3 of 9) in this category. Table 4-1 lists all 9 direct-impact initiatives identified during roadmap development.

Table 4-1: Prioritized List of Direct-Impact R&D Initiatives

ID	Activity/Initiative	Tier
1	Support late stage development and commercialization of gas-fired absorption HPWH	1

ID	Activity/Initiative	Tier
2	Support research and commercialization efforts for residential-scale thermoelectric HPWH	1
3	Develop smart controls for water heating and integrate WH into smart building control systems	1
4	Improve compressor technologies for HPWH	2
5	Support commercialization of grey-water-source HPWH	2
6	Develop advanced thermal storage tanks	2
7	Develop commercial HPWH with flexibility to meet base load demands, peak demands, and recovery time requirements	2
8	Develop optimal configurations for PV assisted HPWH by supporting lab testing and product development efforts	2
9	Develop commercially viable, non-sorption-based thermally driven HPWH	2

Figure 4-2 shows the prioritization score and savings potential values from the P-Tool for all nine initiatives (see section 2.2.2 for a discussion of each savings potential value). The savings potential values from the P-Tool analysis represent the projected savings for each technology compared to baseline water heaters. For example, the savings for "Improved HPWH Compressors" (ID #4) represent the savings of a HPWH with an advanced compressor compared to a baseline electric water heater, not compared to a HPWH with a conventional compressor. Table 4-2 summarizes the P-Tool assumptions (applicable building sectors and fuel sources) for each initiative and provides the resulting technical and staged adoption potential for each initiative. We assume that the applicable market for each technology is only the portion of the market using the same fuel as the target technology (i.e., we do not account for fuel switching opportunities).

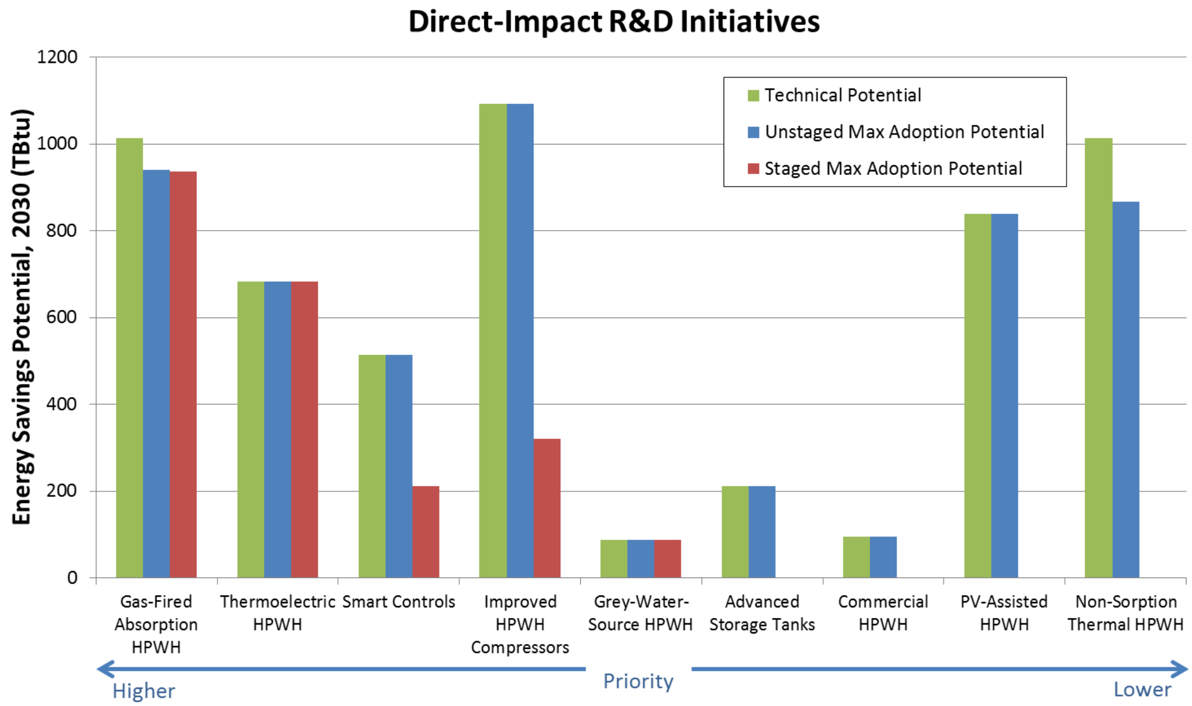


Figure 4-2: Direct-Impact Initiative Savings Potential

Table 4-2: Summary of Inputs to P-Tool Analysis for Direct-Impact Initiatives

ID	Activity/Initiative	Applicable Building Sectors	Applicable Fuel Sources	Technical Potential (TBtu)	Staged Max Adoption Potential (TBtu)
1	Gas-Fired Absorption HPWH	Residential & Commercial	Natural Gas	1014	936
2	Thermoelectric HPWH	Residential	Electric	682	682
3	Smart Controls	Residential & Commercial	Electric & Natural Gas	513	211
4	Improve HPWH Compressor	Residential & Commercial	Electric	1092	320
5	Grey-Water-Source HPWH	Commercial	Electric	88	88
6	Advanced Storage Tanks	Residential & Commercial	Electric & Natural Gas	212	1
7	Commercial HPWH	Commercial	Electric	96	2

ID	Activity/Initiative	Applicable Building Sectors	Applicable Fuel Sources	Technical Potential (TBtu)	Staged Max Adoption Potential (TBtu)
8	PV-Assisted HPWH	Residential[19]	Electric & Natural Gas[20]	839	0
9	Non-Sorption Thermal HPWH	Residential & Commercial	Natural Gas	1014	0

Although initiatives 8 and 9 do not have any staged adoption potential, they do have very high technical and un-staged adoption potential. Therefore these initiatives are worth pursuing because with further R&D they could lead to commercially viable solutions with significant staged adoption potential.

The following subsections provide detail on the tier 1 initiatives.

4.2.1 Support Late Stage Development & Commercialization of Absorption HPWH

Gas-fired absorption HPWH technologies are in prototype stage and need further product development, lab and field testing, design for manufacturing, and commercialization support. Under this initiative, BTO would support the R&D steps necessary to address key barriers and develop commercially viable gas-fired HPWH for residential and commercial building applications.

Absorption cycle heat pumps use thermal energy to drive a chemical compression cycle capable of pumping heat from one source to another. Some large industrial operations already use absorption-based systems, primarily for large, scale process cooling and refrigeration; however, cost-effectively scaling the technology down for smaller capacity heating applications proved to be challenging. The primary benefit of a gas-fired absorption HPWH is that it can achieve a primary energy COP above 1.0. Being gas-fired, they are not subject to transmission and generation losses that electric HPWH experience. These systems can utilize a range of different architectures and chemistries including ammonia-water (NH_3-H_2O) and water-lithium bromide-water (H_2O-LiBr) absorption cycles. Figure 4-3 shows two different absorption HPWH concepts that are both in prototyping stages today. Most of these designs use similar configurations to electric HPWH, consisting of a large water storage tank with a heat pump module attached to it, and a backup heating source.

[19] The P-Tool analysis only applies to the portion of the gas and electric residential WH markets that are appropriate candidates for rooftop PV installations. We assume 35% of residences are capable of having the required rooftop PV array installed, based on consultation with Navigant subject matter experts and on "Rooftop Photovoltaics Market Penetration Scenarios", NREL, available at http://www.nrel.gov/docs/fy08osti/42306.pdf

[20] The PV-assisted HPWH initiative includes HPWH connected directly to PV panels (using DC electricity) with either electric (grid tied) or gas back up heating elements, therefore these systems are applicable for residential customers with either gas or electric water heaters. The P-Tool analysis accounts for the impact of PV-assisted HPWH on the residential gas-fired WH market and on the residential electric WH market, however, it does not account for fuel switching between fuel sources.

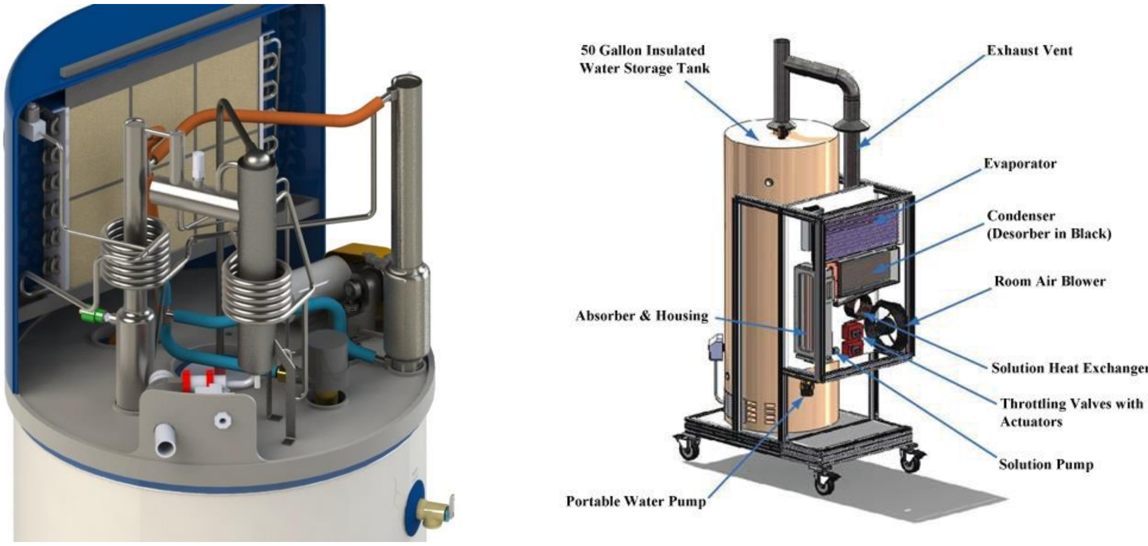


Figure 4-3: Absorption HPWH Architectures (left: NH_3-H_2O cycle, right: H_2O-LiBr cycle)[21]

Absorption HPWH have promising energy savings potential, although they currently face many technological and market barriers including, high first costs, slow recovery times, consumer apprehension due to chemical contents, and limitations due to building code issues. Table 4-3 and Table 4-4 describe these technical challenges and market barriers, respectively.

Table 4-3: Technical Challenges – Gas-Fired Absorption HPWH

Technical Barrier	Description
High First Cost	Current cost estimates, based on absorption HPWH prototypes, are fairly expensive relative to conventional alternatives. The first cost of absorption HPWH will have to come down significantly to compete in mass markets.
Reliability	Lack of proof that absorption HPWHs are robust and reliable enough for long-term use in residential and commercial building applications
LiBr Crystallization	Traditional H_2O-LiBr absorption cycle heat pumps can experience crystallization/solidification of the LiBr solution, which limits efficiency.[22]
Large Footprint	Traditional absorption heat pumps are very large and require a substantial footprint. To be competitive, absorption HPWH will have to occupy nearly the same footprint as conventional WH.

[21] Image Sources: aceee.org/files/pdf/conferences/hwf/2013/6A-garrabrant.pdf ; apps1.eere.energy.gov/buildings/publications/pdfs/corporate/rd_breakthroughs.pdf
[22] Energy Saving Absorption Heat Pump Water Heater information available: web.ornl.gov/adm/partnerships/factsheets/10-G01078_ID2389.pdf

Table 4-4: Market/Deployment Barriers – Gas-Fired Absorption HPWH

Market Barrier	Description
Consumer Apprehension	Consumers may be hesitant to install absorption HPWH in their homes because of the chemical solutions they contain.
Perceived Reliability	Even if the technological barrier of proving reliability (described above) is overcome, consumer sentiments about a perceived lack of reliability may still need to be addressed.
Building Code Issues	Some building codes limit the amount of certain chemicals (e.g. ammonia) that appliances can contain within homes or buildings; as a result, some units, (especially at larger capacities) may require special safeguards or be designed for outdoor installation.
Lack of trained workforce	Innovative systems require new and different expertise for installation and servicing. Absorption systems will be entirely new to plumbers, inspectors, and contractors.
Space conditioning impacts	As with vapor compression HPWHs, gas-fired absorption HPWH will remove heat from the ambient environment to heat the water.
Lack of trained salesforce	Uneducated salesforce can create disincentive to purchase new and unknown equipment because they will not vouch for it and advocate its advances.

Residential and small commercial scale gas-fired absorption HPWH designs are still in development, and different designs are at different stages. In general, prototype designs for ammonia-water cycle HPWH are further along in the R&D process than prototypes for H_2O-LiBr HPWH, but each technology still requires significant effort to bring to it to market.

Researchers of ammonia-water absorption HPWHs have developed initial residential prototypes and have started field testing. However, developers still need to complete a significant amount of performance and reliability testing to verify long-term performance and reliability. Following this testing, ammonia-water HPWH developers will need to continue refining HPWH designs to ensure they can meet consumers' performance demands at a reasonable installed cost and with a minimal equipment footprint. Designers also need to optimize absorption HPWH designs for large scale manufacturing to reduce production costs and allow them to compete in mass markets.[23]

H_2O-LiBr absorption HPWH researchers are working on earlier stage R&D activities. These include testing new liquid desiccants to overcome issues with crystallization or solidification of the H_2O-LiBr solution (one of the challenges with traditional H_2O-LiBr systems) and incorporating advanced membrane technologies into prototypes to improve performance and reduce system size and weight. After completing these investigations, H_2O-LiBr absorption HPWH system designers will move on to developing advanced prototypes, conducting lab-based and field testing, and refining system designs for commercial production.

[23] Based on interviews with absorption HPWH researchers and designers.

Stakeholders voiced support for continuing work on both absorption cycles and, as such, this initiative aims to continue developing both technologies. Figure 4-3 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to bring these technologies to market.

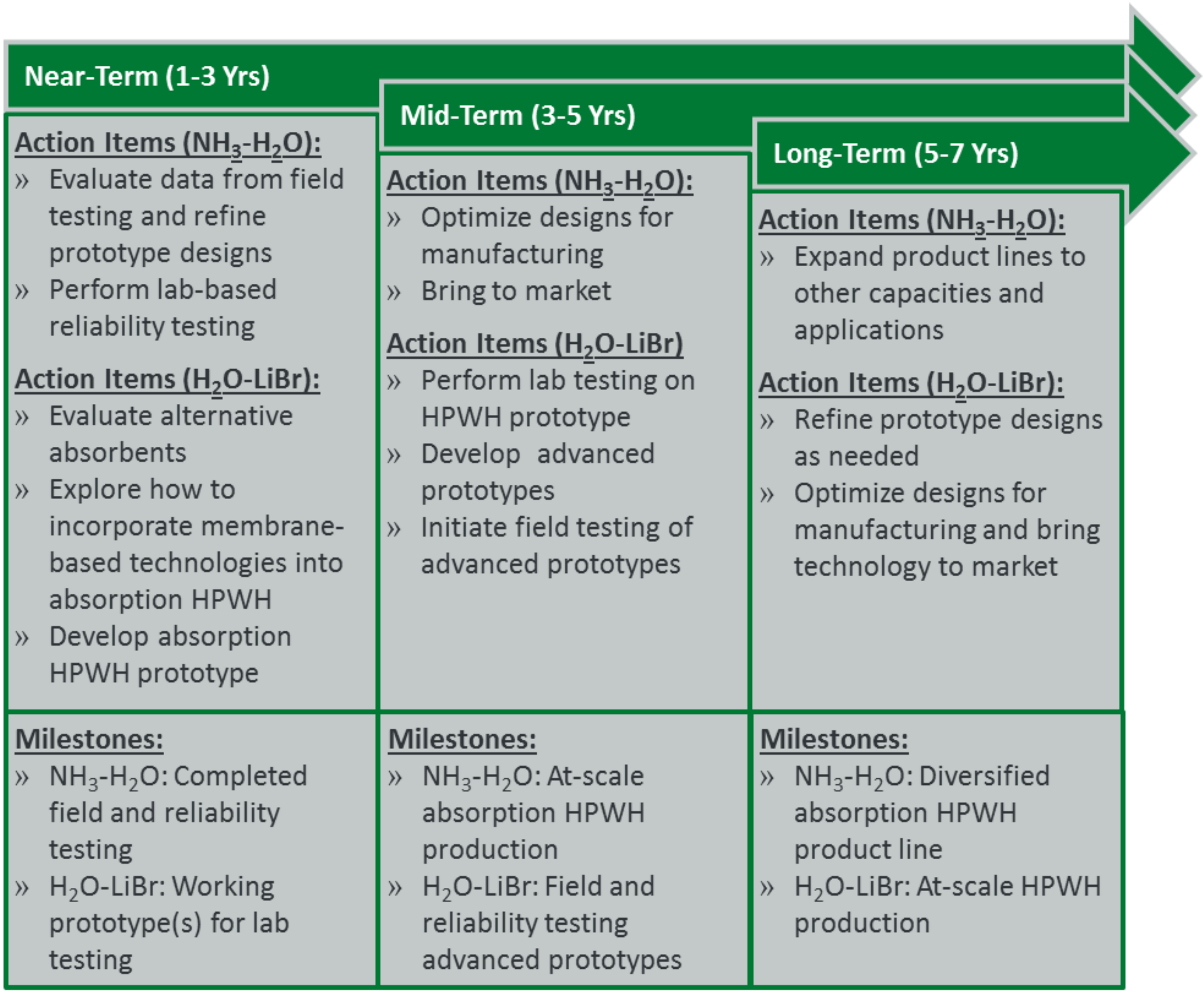


Figure 4-4: Timeline and Milestones – Gas-Fired Absorption HPWH

Table 4-5 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-5: Stakeholder Involvement – Gas-Fired Absorption HPWH

Tasks	Key Stakeholders
R&D	» Independent research firms – prototyping, scientific evaluation » National laboratories – prototyping, design/field support » Universities – research support
Validation and Testing	» Primary: National laboratories, independent testing facilities, manufacturers » Secondary: Utilities, energy efficiency organizations
Deployment	» Manufacturers – Product roll-out, technician training, marketing » DOE – commercialization support
Codes and Standards	» DOE – Minimum efficiency standards and test procedures » EPA – Evaluation for ENERGY STAR inclusion » State/Local Regulators – incorporation in building codes for safe installation/operation

Figure 1-7, above, shows the relevant cost and performance targets for a gas-fired absorption HPWH.

4.2.2 Support Research & Commercialization of Residential Thermoelectric HPWH

Under this initiative, BTO would address key technological and market barriers for residential-scale thermoelectric HPWH. Specifically, this initiative focuses on supporting testing, product development, and commercialization of thermoelectric HPWH technologies with the goal of developing a commercially viable residential HPWH.

Thermoelectric materials produce a temperature gradient when a voltage is applied across the material; this gradient can be used for heating and cooling purposes. Thermoelectric HPWH use this temperature gradient to pump heat from the ambient environment into a storage water heater. Thermoelectric heat pumps are historically used in small capacity cooling devices such as electronics coolers or wine chillers. However, recent advancements in thermoelectric production techniques have opened the doors to larger capacity thermoelectric heat pump technologies, including residential WH. A residential scale thermoelectric HPWH may not exceed the efficiency of a high-efficiency vapor compression HPWH; however, thermoelectric HPWHs could potentially be significantly cheaper while still providing better performance than a traditional electric resistance or gas-fired storage WH. Figure 4-5 shows a thermoelectric HPWH prototype with four thermoelectric heat pump modules mounted on the side of the tank (left), and a rendering of a next generation concept WH with the thermoelectric heat pump modules mounted underneath the storage tank.

Source: Low Cost Heat Pump Water Heaters, presentation at ACEEE, aceee.org/files/pdf/conferences/hwf/2013/7A-pokharna.pdf

Figure 4-5: Thermoelectric HPWH (left: prototype, right: rendering of concept HPWH)

Thermoelectric materials are relatively inexpensive for small capacity heating or cooling applications, however scaling them up cost-effectively to provide enough heating capacity for residential WH is challenging. Researchers and thermoelectric manufacturers continue to work on improving production methods to reduce material and manufacturing costs. In order to develop a commercially viable residential WH, designers will need to improve the performance of thermoelectric HPWH further by addressing some of the key technological barriers, such as limited heating capacity, slow recovery time, and inefficient AC to DC power conversion. Table 4-6 and Table 4-7 describe the technological challenges and market barriers facing thermoelectric HPWH.

Table 4-6: Technical Challenges – Thermoelectric HPWH

Technical Barrier	Description
High First Cost	Although thermoelectric HPWH are expected to be less expensive than vapor compression HPWH they will still be more expensive than traditional electric resistance WH.
Heating Capacity and Slow Recovery Time	Thermoelectric elements need to deliver enough heating capacity to meet consumers' performance demands, while still maintaining efficiency and affordability. The limited heating capacity of thermoelectric HPWH also slows the recovery time for the storage WH.
AC/DC Conversion Efficiency	Thermoelectric heat pumps using DC power can lose approximately 10% of incoming energy in the AC/DC power conversion.

Table 4-7: Market/Deployment Barriers – Thermoelectric HPWH

Market Barrier	Description
Lack of familiarity	Thermoelectric elements have not been used on this scale previously. Consumer education will be required to assure acceptance.
Space conditioning impacts	As with vapor compression HPWHs, thermoelectric HPWHs will remove heat from the ambient environment to heat the water (also related to consumer education, see above).
Lack of trained workforce	Innovative systems require new and different expertise for installation and servicing. Thermoelectric systems will be entirely new to plumbers, inspectors, and contractors.
Lack of trained salesforce	Uneducated salesforce can create disincentive to purchase new and unknown equipment because they will not vouch for it and advocate its advances.

Researchers have developed thermoelectric HPWH prototypes, but in order to make this technology commercially viable, thermoelectric HPWH developers need to address the barriers listed above to a market-ready level. Researchers need to focus on:

- Designing advanced control packages and strategies to improve the operation and performance of the individual thermoelectric heat pump modules and the HPWH as a whole system
- Identifying low-cost, high-efficiency power conversion systems and integrating them into thermoelectric HPWH
- Working with WH manufacturers to refine designs for manufacturability and develop any necessary manufacturing technologies.

Figure 4-6 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to bring this technology to market.

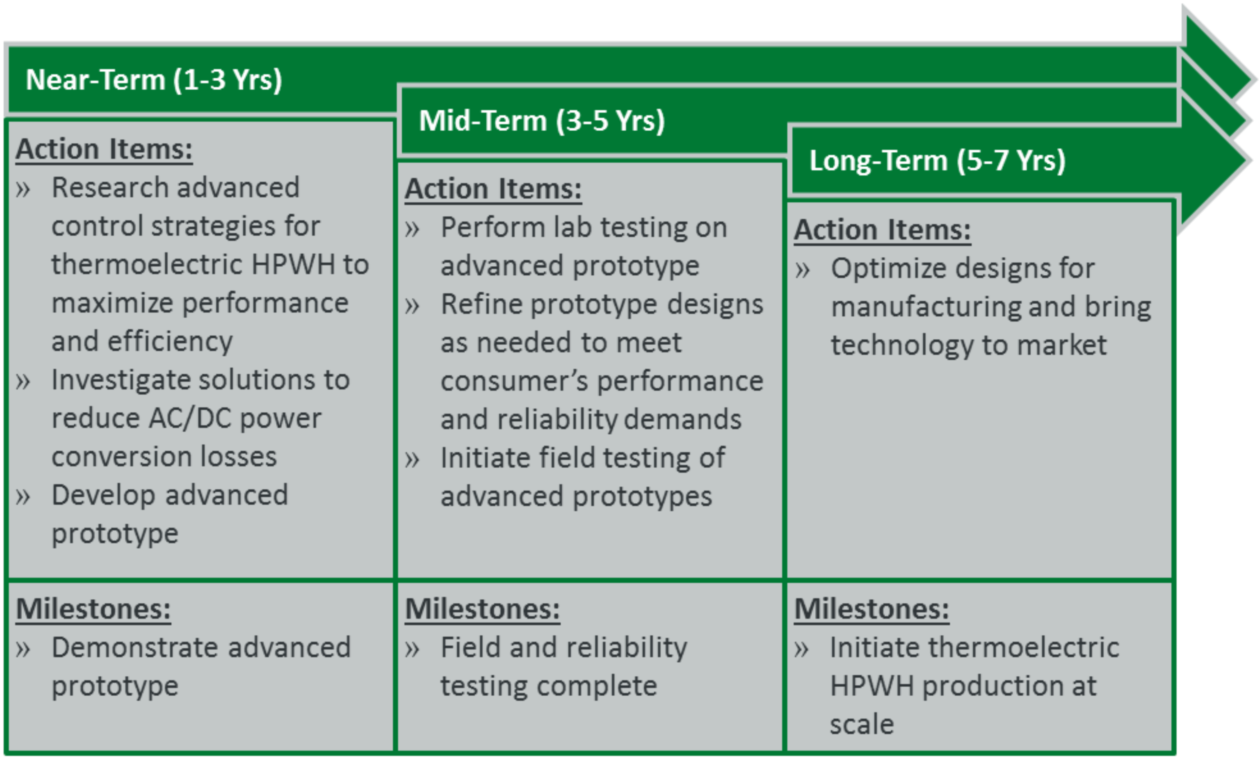


Figure 4-6: Timeline and Milestones – Thermoelectric HPWH

Table 4-8 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-8: Stakeholder Involvement – Thermoelectric HPWH

Tasks	Key Stakeholders
R&D	» Independent research firms – prototyping, scientific evaluation » National laboratories – prototyping, design/field support » Universities – research support
Validation and Testing	» Primary: National laboratories, independent testing facilities, manufacturers » Secondary: Utilities, energy efficiency organizations
Deployment	» Manufacturers – Product roll-out, technician training, marketing » DOE – commercialization support
Codes and standards	» DOE – Minimum efficiency standards and test procedures » EPA – Evaluation for ENERGY STAR inclusion

Figure 1-6, above, shows the relevant cost and performance targets for a thermoelectric HPWH.

4.2.3 Develop Smart Controls & Integrate into Smart Building Control Systems

Under this initiative, BTO would support continued development and commercialization of smart controls systems for WH. The primary tasks include testing and validating control algorithms, designing a well packaged system for easy installation and operation, and commercializing this technology.

WH systems need smarter controls to use WH energy more effectively and improve WH system efficiency. Smart building controls have become more popular with HVAC systems; however, few commercially available smart WH control systems exist. Smart WH controls need to be capable of learning usage patterns, raising or lowering the water temperature accordingly, and activating re-circulation loops as needed. These controls may require better sub metering systems and improved communication between devices. Future smart WH controls should incorporate fault detection & diagnostic (FDD) capabilities, intuitive interfaces, predictive and adaptive algorithms, and be able to integrate seamlessly with other smart building systems.

The predictive algorithms behind smart control systems are reasonably well understood. The significant challenges for researchers are to validate that these algorithms can work effectively across a wide range of building types, WH types, and usage patterns, and to develop control packages that are easy to install and operate.

Table 4-9 and Table 4-10 describe the technological challenges and market barriers, respectively, facing smart WH control technologies.

Table 4-9: Technical Challenges – Smart Controls

Technical Barrier	Description
Effective control for all building and WH types	Smart WH controllers should be capable of operating effectively with a range of different building and WH types, and usage patterns
Reliable WH service	Control systems must aim to reduce unnecessary WH energy consumption while still providing hot water service that meets consumers' performance and reliability demands
Easy installation and operation	Smart WH controls need to be packaged in hardware that is easy to install and provides an intuitive user interface

Table 4-10: Market/Deployment Barriers – Smart Controls

Market Barrier	Description
Complexity	Complexity will limit distributor, contractor, plumber, and other's interests in purchasing the equipment
Marketing and Consumer Education	Water heating requires limited or no consumer involvement, added complexity will require educating/marketing to customers to convince them of the benefits

The National Renewable Energy Laboratory has developed initial predictive control algorithms for WH and has studied the energy savings of these technologies. NREL's simulations indicated that energy savings of up to 20% were feasible when used with a HPWH (baseline assumed to be HPWH without controls).[24] Researchers need support to evaluate predictive WH control algorithms, such as the one NREL has developed, validate them in real building applications, and develop them into commercially viable products.

Figure 4-7 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to bring this technology to market.

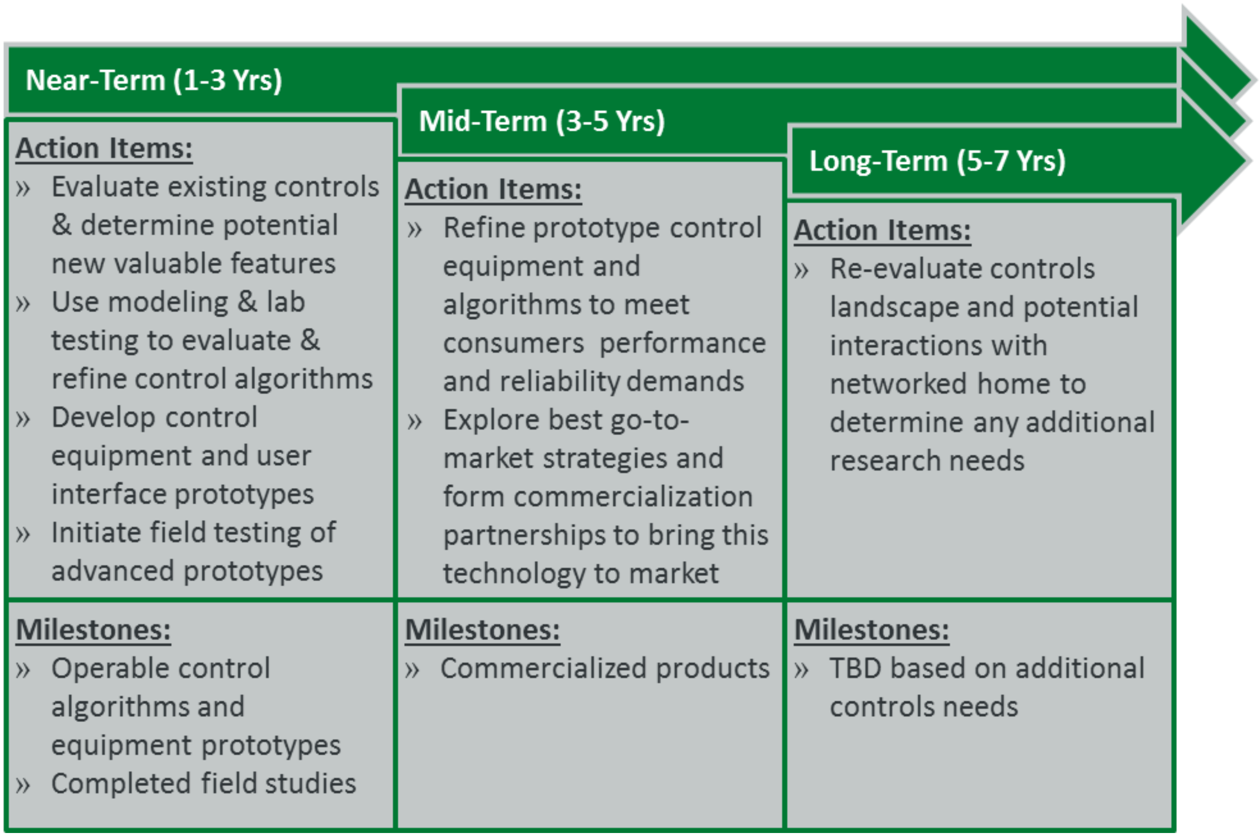


Figure 4-7: Timeline and Milestones – Smart Controls

Table 4-11 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-11: Stakeholder Involvement – Smart Controls

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» Independent research firms – prototyping, algorithm evaluation

[24] Predictive Control of Hot Water Heaters, NREL, Information available at: techportal.eere.energy.gov/technology.do/techID=1181; this source does not state a baseline for the 20% savings claim, but we assume that it is a HPWH without controls.

Tasks	Key Stakeholder Roles and Responsibilities
	» National laboratories – prototyping, design/field support » Universities – research support
Validation and Testing	» Primary: National laboratories, independent testing facilities, manufacturers, consultants » Secondary: Utilities, energy efficiency organizations
Deployment	» Component manufacturers – product roll-out » System manufacturers – technician training, marketing » DOE – commercialization support

4.2.4 Tier Two Direct-Impact Initiatives

The following initiatives, though not articulated in-depth like the tier 1 initiatives, are also valuable opportunities to further BTO energy savings goals and should be considered for future action.

4.2.4.1 (ID #4) Improve compressor technologies for HPWH

Manufacturers can improve system efficiencies by using purpose-built compressors that operate in HPWH-specific operating conditions. Current low-cost compressor options are generally best-fit options, selected from compressors designed for other HVAC applications. Alternative, non-electromechanical-based options may provide innovative solutions in the long term.[25]

4.2.4.2 (ID #5) Support commercialization of grey-water-source HPWH

Similarly to some commercial geothermal heat pump applications, HPWHs can utilize unique heat sources, such as greywater and/or wastewater systems, to improve efficiencies (particularly in cold climates) and scalability for large buildings. Such systems have been demonstrated previously, but success of a cost-effective package requires additional work to refine architectures/designs and facilitate manufacturing and commercialization.[26]

4.2.4.3 (ID #6) Develop advanced thermal storage tanks

Research and develop advanced storage tanks that promote longevity and reduce heat loss. R&D should focus on advanced strategies to control water stratification within tanks, improved insulation materials (including PCM), long-life tank materials, and new storage tank architectures.

[25] A similar initiative was identified during development of the Geothermal Heat Pump Roadmap to optimize compressors for specific applications; William Goetzler et. al. "Research and Development Roadmap: Geothermal (Ground-Source) Heat Pumps." prepared for BTO by Navigant Consulting, Inc. (October 2012) Accessed September 2, 2014: www1.eere.energy.gov/buildings/pdfs/ghp_rd_roadmap2012.pdf.

[26] A similar initiative was identified during development of the Geothermal Heat Pump Roadmap to help support grey-water-source Geothermal Heat Pumps. See footnote 26.

4.2.4.4 (ID #7) Develop commercial HPWH with flexibility to meet base load demands, peak demands, and recovery time requirements

Support R&D to improve the hot water capacity and recovery time of HPWH without substantially impacting cost or efficiency. Commercial HPWHs need to have significant hot water capacity and short heat recovery time to meet the large peak demand and rapid changes in hot water demand of commercial buildings that have large water heating loads (restaurants, hotels, hospitals, etc...). Current products may not fully meet the needs of many commercial applications and have limited penetration.

4.2.4.5 (ID #8) Develop optimal Configurations for PV Assisted HPWH by supporting lab testing and product development efforts

Conduct studies to determine the most cost-effective configurations for solar electric water heating. Recent price reductions in PV modules may enable new solar electric water heating methods. PV systems coupled directly to heat pump water heaters may become cost competitive with traditional solar thermal solutions. These technologies eliminate much of the balance-of-system and labor costs associated with traditional solar thermal systems.[27]

4.2.4.6 (ID #9) Develop commercially viable, non-sorption-based thermally driven HPWH

Support additional R&D and testing efforts and foster commercialization partnerships between researchers and large industry players that can facilitate rapid production scale up. Non-sorption-based thermally driven heat pumps include any water heating technologies that use alternative heat pump cycles or architectures (such as a Vuilleumier cycle HP). Some of these technologies have high theoretical COPs in heating applications and represent potentially low-cost, scalable WH solutions. Current non-sorption-based systems are still in the prototype stage and require support to refine these prototypes and conduct thorough reliability testing, to prepare for large-scale manufacturing, and to bring the technology to market.

4.3 Roadmap for Enabling Technology R&D Initiatives

As discussed in section 1.2, enabling initiatives indirectly improve energy efficiency of water heaters and water heating systems. Through the roadmap development process, some key enabling initiatives surfaced that can be key drivers of energy savings. This section details the tier 1 initiatives (3 of 10) in this category. Table 4-12 lists all 10 enabling initiatives identified during roadmap development.

[27] Also identified during development of the Building-Integrated Solar Technologies research report as Initiative #1; William Goetzler et. al. "Research and Development Needs for Building-Integrated Solar Technologies." prepared for BTO by Navigant Consulting, Inc. (January 2014) Accessed September 2, 2014: energy.gov/sites/prod/files/2014/02/f7/BIST_TechnicalReport_January2014_0.pdf.

Table 4-12: Prioritized List of Enabling R&D Initiatives

ID	Activity/Initiative	Tier
1	Establish a research program to conduct lab-based studies on energy and water consumption impacts of different system architectures on water use and WH energy consumption	1
2	Conduct large-scale field studies mapping hot water and WH energy consumption in buildings	1
3	Research advanced manufacturing techniques and components for cost-effective CO_2 HPWH	1
4	Research low-cost, advanced smart metering techniques for water and energy consumption	2
5	Develop open source simulation tools for technology design and testing	2
6	Demonstrate commercial-scale fuel cells and CHP in WH applications	2
7	Conduct detailed energy analyses and field demonstrations on high-efficiency combination systems (HVAC and WH)	2
8	Research the best ways to design WH systems for easy installation in retrofit applications, and develop best practices guide for retrofit WH technologies	2
9	Educate installers, designers, & consumers on the benefits high-efficiency water heating via field demonstrations & development of associated education & training materials	2
10	Update hot water system design resources and sizing processes, and develop updated training programs for installers	2

Enabling initiatives do not have a specific energy savings tied to them. Instead, they provide pathways to achieving energy savings via the systems they support or relate to. Enabling initiatives therefore cannot be compared on a quantitative basis with the direct-impact initiatives (see section 2.2.1). DOE therefore cannot compare them with other potential R&D investments, across all potential building technology opportunities, using the P-tool. The following sections document the details of recommended enabling initiatives, including barriers, action items, and stakeholder roles and responsibilities.

4.3.1 Water/Energy Use Research Program

Stakeholders voiced concerns that the WH industry needs better data and knowledge about the performance of WH systems as a whole (rather than just individual pieces of equipment) and about the interactions between water consumption and water heating energy consumption. Under this initiative, BTO would establish a lab-based research program that studies these interactions in depth and enables WH manufacturers and WH system designers to make more informed decisions when developing high-efficiency WH systems.

This research program will focus on testing the performance of WH equipment, components, and system architectures and characterizing their impact on water and energy consumption. The outputs from this research should include:

- Overview reports for classes of WH equipment and best practices for designing them into water systems
- Detailed analytical reports on each piece of equipment or system component tested
- Advanced design guides that recommend optimal system configurations and allow system designers to estimate the WH system efficiency with different architectures and combinations of components

This program should be designed to work hand-in-hand with the field study initiative (see section 4.3.2) to exchange findings and better guide each program's research goals.

Some example tasks to conduct under this program include study of:

- The energy impacts of distributed WH vs centralized WH
- The system efficiency, cost, and performance of a HPWH with no central backup only distributed booster heating
- The impact of smart recirculation control strategies on energy and water consumption
- The impacts of separating storage tanks and heating elements on system efficiency, cost and reliability
- The interactions between components in a hot water system, including, pumps, fixtures, mixing valves, etc.
- Low-flow fixtures and reduced water consumption impact on system architecture
- Ultra-low-cost approaches to POU WH

Figure 4-8 outlines an approximate timeline for this initiative and identifies the major action items and milestones associated with establishing this research program.

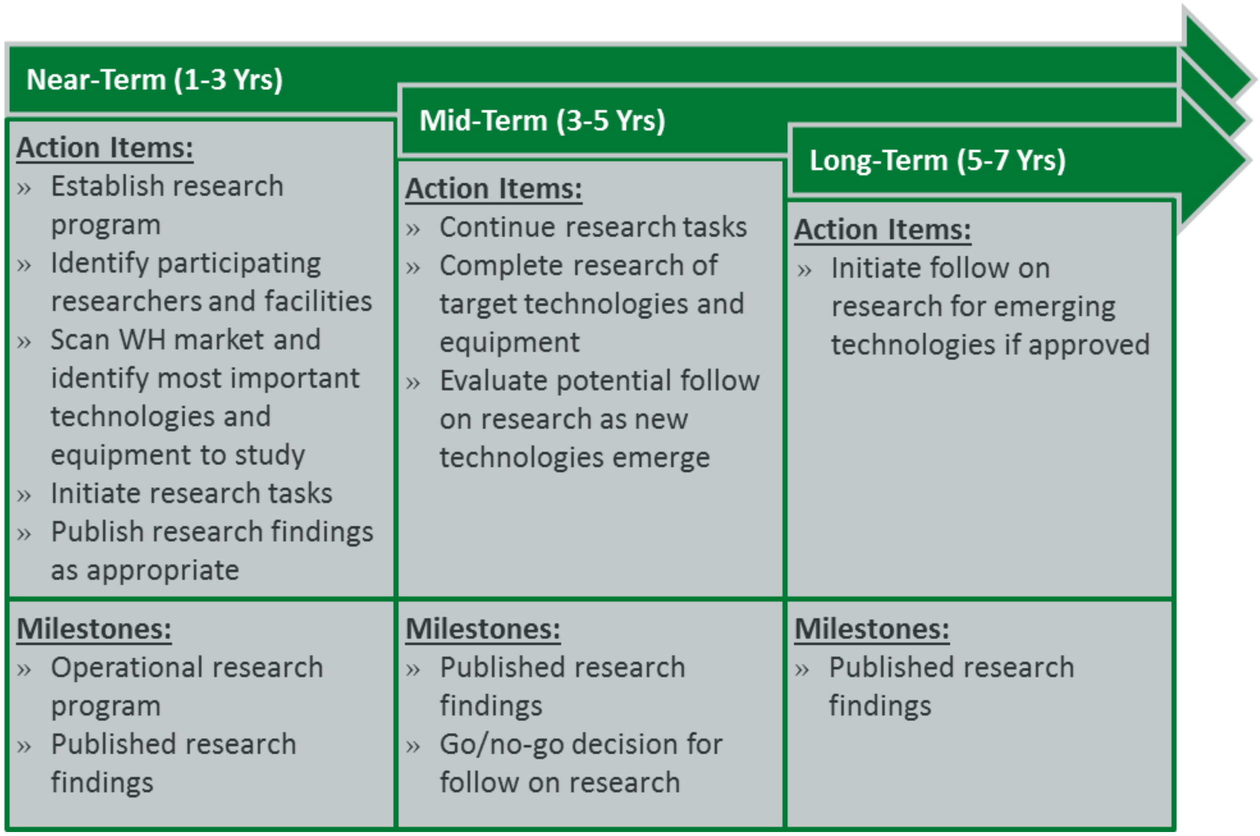


Figure 4-8: Timeline and Milestones – Water/Energy Use Research Program

Table 4-13 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-13: Stakeholder Involvement – Water/Energy Use Research Program

Tasks	Key Stakeholders
Program management	» National laboratories » BTO and/or BTO subcontractor
Research and testing	» Independent testing facilities – Laboratory testing » Independent research firms – testing protocols and testing » National laboratories/Universities – equipment/architecture selection support

This initiative will enable WH manufacturers and systems designers to better tailor systems and installation architectures to optimize efficiency. Table 4-14 identifies the impact that the initiative will have on key market barriers in the WH industry.

Table 4-14: Market Impact – Water/Energy Use Research Program

Relevant Market Barrier	Initiative's Impact
Lack of system performance data	Provides comprehensive system performance testing data to industry
Lack of water/energy nexus understanding	Studies relationship between water and energy consumption to deepen industry understanding of the water/energy nexus

4.3.2 Large-Scale Field-Based Consumption Study

The WH industry needs large-scale, detailed field studies of WH energy use in real buildings. Under this initiative, DOE would sponsor multiple field studies with varying degrees of granularity and detail. The resulting data will help WH system designers, manufacturers, and regulators make more informed decisions based on accurate water and energy consumption data from the field.

Current WH system designs and regulations are based on outdated and inaccurate water consumption data. In order to gather sufficient data, we need to study a broad selection of buildings across the U.S. representing different building sectors, types, ages, climates, and functions. Stakeholders suggest that many hundreds of buildings should be included in this analysis. This type of field research is typically precompetitive, and is therefore unlikely to be a cost effective endeavor for an individual manufacturer to pursue on its own; however, such an activity will receive collaborative support from across the industry, assuming that DOE takes a lead role.

This initiative should include three levels of field studies:

1. **Consumer Survey -** The WH consumer survey would be directed at building owners, similar to building surveys (such as the US Energy Information Administration's Residential Energy Consumption Survey, RECS), and consist of questions regarding the building owner's WH equipment, system design, and consumption habits. This survey data will provide a broad view of WH systems across the country.

2. **Onsite WH System Audits –** WH system audits involve sending trained technicians to buildings to conduct audits of their WH systems by measuring and recording a detailed account of the WH system. The audit will characterize details about the WH systems including, WH type, building type, number and location of fixtures, and the type of plumbing (material, configuration, approximate lengths). It will be important to maintain consistency in audit practices so that the data can be complied and used for future analysis. In order to facilitate these audits a data recording system, such as a web-based app for a technician's mobile device and a set of physical tools (e.g., tape measure, flow meter, infrared camera, etc.) should be provided to auditors. A procedure will also need to be developed describing how to conduct the audit. The procedure will have to be developed, tested and refined before it can be deployed and technicians will need to be trained in conducting proper audits to ensure consistency across auditors.

3. **Detailed End Use Study** – End use studies are the most granular of the three types of field studies, and it will gather a much deeper level of information, but only on a sample of representative, audited buildings. These studies require installing monitoring equipment for temperature and water flow on fixtures in a building's water distribution system. The monitoring equipment will track the data for an extended period covering different seasons and capturing the data at short intervals. In order to reduce the burden of conducting these detailed studies, new metering equipment should be explored, such as non-intrusive water flow and temperatures sensing technologies, which are significantly cheaper and easier to install than conventional metering systems.

Finally, all of the data collected through these three types of field studies will be compiled analyzed and published for the public. Figure 4-9 outlines an approximate timeline for this initiative and identifies the major action items and milestones associated with conducting these field studies.

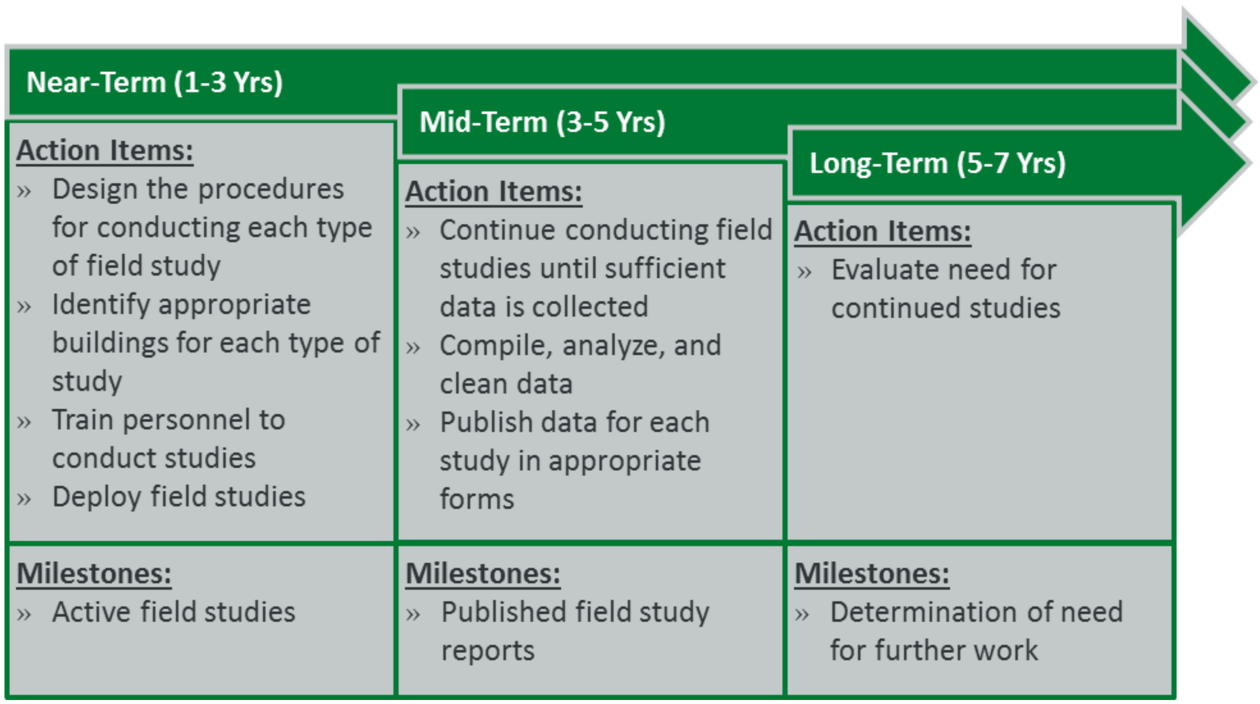


Figure 4-9: Timeline and Milestones – Large-Scale Field Studies

Table 4-15 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role(s).

Table 4-15: Stakeholder Involvement – Large-Scale Field Studies

Tasks	Key Stakeholder Roles and Responsibilities
Program management	» National laboratories » BTO and/or BTO subcontractor
Field studies, data analysis, and report publication	» Independent research firms – protocols, field test design » National laboratories/Universities – Survey design, end-use knowledge/support » Surveying organizations – survey design and execution

This initiative will enable manufacturers and systems designers to better tailor systems and installations to optimize efficiency. Table 4-16 identifies the key market barriers addressed by this initiative and the associated impact.

Table 4-16: Market Impact – Water/Energy Use Research Program

Relevant Market Barrier	Initiative's Impact
Lack of field performance data	Provides comprehensive field performance testing data to industry and WH regulators
Lack of WH system census data	Provides a nationwide account of WH system types, equipment, and architectures

4.3.3 Advanced Manufacturing for CO_2 HPWH

European and Japanese companies currently sell CO_2-based HPWH. Under this initiative, DOE would research advanced manufacturing techniques and capture best practices used in international WH industries for large-scale CO_2 HPWH production.

Japan and Europe are leading the industry in CO2 HPWH technology; by 2010, Japan had over 5 million units installed, representing roughly 10% of their residential WH market.28 US manufacturers can improve cost-effectiveness by refining their design-for-manufacturing (DFM), manufacturing approaches, and assembly processes. Current Japanese models utilize more complex controllers, variable speed compressors and pumps, and electronic expansion valves. U.S. manufacturers need to develop methods to incorporate these advanced components into CO2 HPWH designs without imposing significant cost premiums on these units. This initiative supports studies of best practices used in Europe and Japan to reduce manufacturing costs for CO2 HPWH and development of new manufacturing techniques to incorporate advanced heat pump components. Figure 4-10 outlines an approximate timeline for this initiative and identifies the major action items and milestones that it aims to achieve.

[28] The CO_2 Heat Pump Water Heater as a New Countermeasure Against Global Warming: Drastic Improvement in Energy Efficiency in Three Years Since Its Debut. Accessed September 2, 2014: aceee.org/files/proceedings/2006/data/papers/SS06_Panel1_Paper25.pdf.

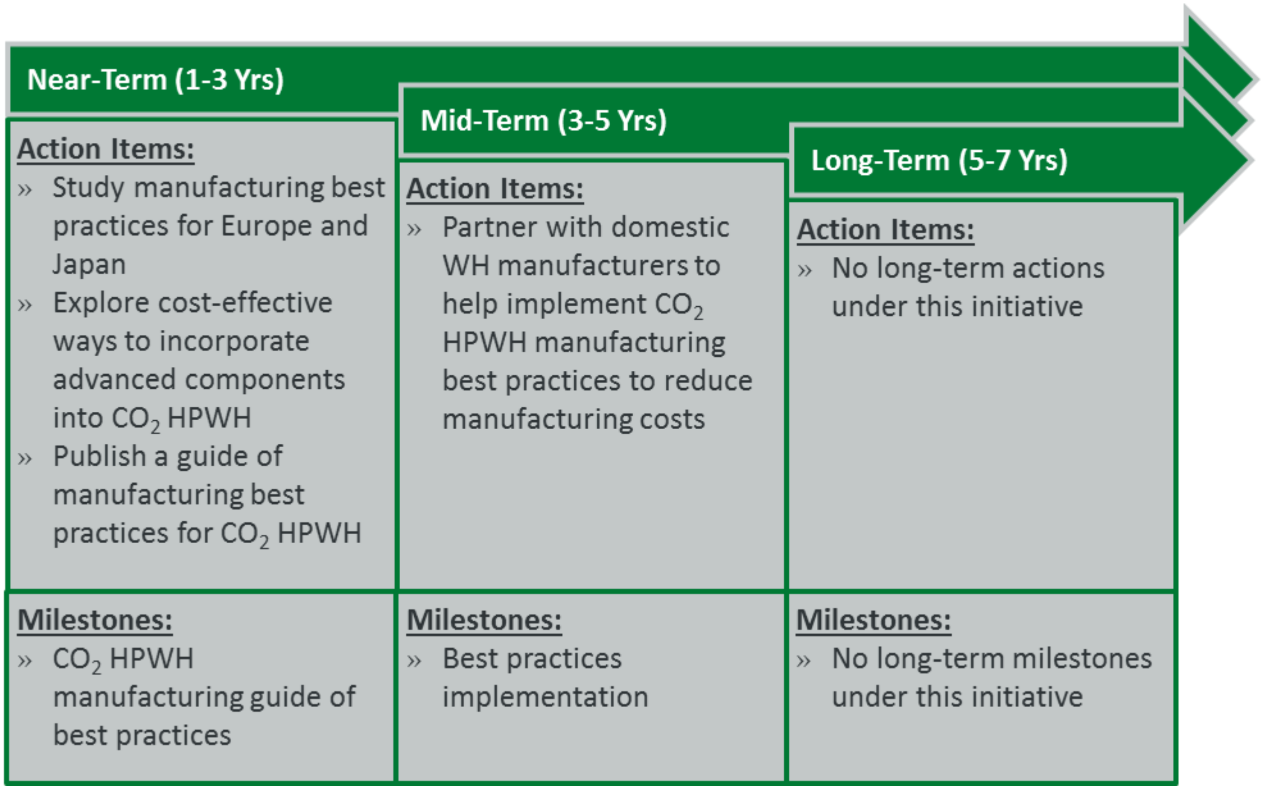


Figure 4-10: Timeline and Milestones – Advanced Manufacturing for CO_2 HPWH

Table 4-17 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role(s).

Table 4-17: Stakeholder Involvement – Advanced Manufacturing for CO_2 HPWH

Tasks	Key Stakeholder Roles and Responsibilities
Best practices research	» Academic researchers, consultants – international outreach and research » Manufacturers – focus area expertise
Deployment	» Manufacturers – implementation in facilities » Industry consultants – implementation and process guidance/facilitation

This initiative will enable manufacturers and systems designers to develop higher efficiency CO_2 water heaters at lower costs by leveraging manufacturing improvements. . Table 4-16 identifies the key market barriers addressed by this initiative and the associated impact.

Table 4-18: Market Impact – Advanced Manufacturing for CO_2 HPWH

Relevant Market Barrier	Initiative's Impact
Lack of cost-effective manufacturing methods for CO_2 HPWH	Provides guide of best practices to domestic WH manufacturers
Lack of cost-effective advanced HPWH components	Researches manufacturing techniques for developing and integrating advanced components into CO_2 HPWH

4.3.4 Tier Two Enabling Technology Initiatives

The following initiatives, though not articulated in-depth like the tier 1 initiatives, are also valuable opportunities to further BTO energy savings goals and should be considered for future action.

4.3.4.1 (ID#4) Research low-cost, advanced smart metering techniques for water and energy consumption

Analyze approaches to, and develop solutions for, cost-effective smart water and energy metering. To be cost effective, research should focus on non-flow-meter-based sensing technologies, potentially akin to the algorithm-based electricity meters. Such meters should aim to monitor all fixtures in a building or home with as little required infrastructure as possible. Similar electricity systems recognize signatures of various end-use products at a single monitoring point to identify when specific appliances or products are in use. The data can be used to inform building owners regarding potential retrofit opportunities or drive consumers to change their water use behavior. These meters need to be inexpensive, easy to install, and integrate well with smart control systems to present data in real-time via intuitive displays or interfaces.

4.3.4.2 (ID #5) Develop open source simulation tools for technology design and testing

Support development of open-source simulation tools to facilitate and accelerate design and testing processes. Such tools would aid in rapid analysis of various product configurations and certification of products through rapid performance simulation. Current building simulation models are adequate, but WH simulation in these models is considered to be not very accurate. Most building simulation models operate on a fixed 1-hour time step. However changes in a WH system are based on the behavior of the operator and can occur very rapidly. These rapid changes and the intermittency of hot water draws can have a surprisingly large impact on WH efficiency (especially on tankless WH), and these impacts cannot be easily captured by simulation models with long fixed time steps. WH simulation models will first need to be designed as standalone software models; although over time it would be ideal if they could be integrated into complete building modeling software packages. These models should ideally incorporate water consumption behavioral data to validate and confirm results. Ultimately, simplified versions with a distinct end-user interface could be developed to assist contractors and sales people. Platforms already exist that could be used as the basis for this tool.

4.3.4.3 (ID #6) Demonstrate commercial-scale fuel cells and CHP in WH applications

Develop integrated fuel cell and CHP-driven water heaters. As opportunities for fuel cell and CHP systems grows, so too will opportunities to leverage these systems for use with water heating. Integrated approaches that optimize thermal output in conjunction with water heating use profiles will provide the most cost effective solutions. Similar solutions have been successful in Europe and Japan – such success stories should be showcased and repeated in the US.

4.3.4.4 (ID #7) Conduct detailed energy analyses and field demonstrations on high-efficiency combination systems (HVAC and WH)

Support commercialization and awareness efforts for residential and commercial combination systems, starting with energy analysis and field demonstrations to gather data. Many combination system configurations and architectures are based on established technologies, however they need still thorough energy analyses and field demonstrations to prove their performance in real world applications and to identify which combination systems work best in which building types. While the benefits of various configurations of combination system are understood in the industry, adoption is very low. For a building owner to consider a combination system, typically their HVAC or WH (or both) must be retired early – a major barrier to penetration. Specific analysis needs may best be identified through partnership with ASHRAE 124 (Test method for combination space and water heating appliances) group.

4.3.4.5 (ID #8) Research the best ways to design WH systems for easy installation in retrofit applications, and develop best practices guide for retrofit WH technologies

Support efforts to increase penetration of high efficiency water heating technologies in existing buildings by optimizing system for retrofit installations, which represent the vast majority of installations. Many high efficiency technologies require unique installation requirements that differ from incumbent systems. Improving the ease of installation through focused design and sharing of best practices can reduce installation costs and remove barriers to market growth.

4.3.4.6 (ID #9) Educate installers, designers, & consumers on the benefits high-efficiency water heating via field demonstrations & development of associated education & training materials

Conduct field demonstrations to facilitate education of installers, designers, and consumers. Installers and plumbers that are not educated on the benefits of high-efficiency technologies will be unlikely to promote them with their customers. Development of comprehensive education and training materials for all points in the value chain will enable greater comfort with the technology and greater acceptance among designers, installers, and consumers. Included should be a best-practices guide for each high-efficiency technology explaining in what applications the technology can be used and how it should be installed. This guide should include case studies proving the technology works in the field. These field demonstrations should cover all geographic regions, climate zones, and building types.

4.3.4.7 (ID #10) Update hot water system design resources and sizing processes, and develop updated training programs for installers

Coordinate with training and industry trade organizations to update system design resources. Commonly used sizing and design methodologies could be updated to account for newly developed technologies and distribution systems. The data that engineers use to design WH systems is based on the ASHRAE handbook (developed using data about hot water consumption gathered in the 1960's). This handbook should be updated using current data. In addition, Hunter's curves (system sizing charts from the 1920s, etc.) need to be updated with both energy and water consumption in mind. This initiative should include development of updated training programs for WH installers to educate installers on new technologies, such as the difference between installing a HPWH in an insulated vs. uninsulated space.

4.4 Water Heating R&D Portfolio Review

The prioritized initiatives align well with BTO's two-pronged approach to water heating R&D (see Section 1.3, above, for discussion of BTO R&D approach).

1. **Low-Cost Efficiency –** Initiatives serve this prong via leap-frog technologies (e.g., thermoelectric HPWH), cost-reducing initiatives (e.g., advanced manufacturing techniques), and via the many enabling initiatives aimed at providing better data for efficient product and system design and installation.
2. **Premium Efficiency –** The direct-impact initiatives are weighted more towards the this prong, but do have a distinct cost-effectiveness element throughout that will help maintain focus on the longer-term goal of bringing these premium-efficiency products to the masses through cost-reduction efforts.

Further, the prioritized initiatives align well with BTO's previously determined savings target areas (see Section 1.1.2, above, for discussion of existing BTO water heating targets). The following initiatives support BTO's target areas (initiative titles abbreviated for brevity, and repeated where appropriate):

Non-Vapor Compression HPWH – 1 aligned initiative:

- Research/commercialization for residential-scale thermoelectric HPWH (Direct ID#2)

CO_2 Vapor Compression HPWH – 2 aligned initiatives:

- Compressor technologies for HPWH (Direct ID#4)
- Advanced manufacturing techniques for CO_2 HPWH (Enabling ID#3)

Non-CO_2 Vapor Compression HPWH – 4 aligned initiatives:

- Optimized PV assisted HPWH (Direct ID#8)
- Compressor technologies for HPWH (Direct ID#4)
- Grey-water-source HPWH (Direct ID#5)
- Flexible commercial HPWH to meet base load demands, peak demands, and recovery time requirements (Direct ID#7)

Gas-Fired HPWH – 3 aligned initiatives:

- Development/commercialization of gas-fired absorption HPWH (Direct ID #1)
- Compressor technologies for HPWH (Direct ID#4)
- Non-sorption-based thermally driven HPWH (Direct ID#9)

Supporting all four target areas above – 7 aligned initiatives:

- Smart controls for water heating and integration with building controls (Direct ID#3)
- Advanced thermal storage tanks (Direct ID#6)

- Research program on energy and water consumption impacts of different system architectures on water use and WH energy consumption (Enabling ID#1)
- Large-scale field studies mapping hot water and WH energy use (Enabling ID#2)
- Low-cost, advanced smart metering for water and energy consumption (Enabling ID#4)
- Open source simulation tools for technology design and testing (Enabling ID#5)
- Retrofit-focused water heating design – best-practices guide (Enabling ID#8)

Four additional initiatives support activities that are independent of the four target areas and can support high efficiency water heating via other avenues, including:

- Commercial-scale fuel cells and CHP demonstrations for water heating (Enabling ID#6)
- Analyses and field demonstrations of combination space/water heating systems (HVAC/WH) (Enabling ID#7)
- Field demonstrations for consumer awareness & development of associated education & training materials (Enabling ID#9)
- Hot water system design resources and sizing process update (Enabling ID#10)

The initiatives discussed in this roadmap are programmatically independent and require no critical-path sequencing. However, depending on implementation, some activities may be best coordinated from the start. For example, Enabling initiatives #1 (energy/water consumption research) and #2 (field studies), may be able to leverage knowledge between the two initiatives for efficient use of resources. In this example, program implementers may actually consider a delayed start for enabling initiative #2, but it is not required.

During execution of the initiatives in this roadmap, BTO should consider secondary benefits that could be gained for other end-use equipment, namely space conditioning and refrigeration. Table 4-19 lists the end uses that benefit from the roadmap initiatives.

Table 4-19: Initiatives to Leverage for Innovations in Other End-Uses

Benefitting End-Use	Water Heating Initiatives
Space Heating	» Direct #1 – Gas-fired absorption HPWH » Direct #5 – Grey-water-source HPWH » Direct #6 – Advanced thermal storage tanks » Direct #7 – Flexible commercial HPWH to meet base load demands, peak demands, and recovery time requirements » Enabling #3 – Advanced manufacturing techniques for CO_2 HPWH » Enabling #6 – Fuel cell and CHP demonstrations for water heating » Enabling #7 – Analyses and demo of combo systems (HVAC/WH) » Enabling #9 – Field demonstrations for consumer awareness & development of associated education & training materials
Space Cooling	» Direct #8 – PV-assisted HPWH » Enabling #3 – Advanced manufacturing techniques for CO_2 HPWH » Enabling #7 – Analyses and demo of combo systems (HVAC/WH)

Benefitting End-Use	Water Heating Initiatives
Refrigeration	» Enabling #3 – Advanced manufacturing techniques for CO_2 HPWH » Enabling #7 – Analyses and demo of combo systems (HVAC/WH)

While this table is a high level review of cross-cutting benefits from WH R&D, the individual benefits will vary by implementation. For each initiative, including those not in Table 4-19, above, BTO should consider how it may be used as a stepping stone for advances in HVAC and refrigeration technologies. Water heating advances lend themselves well to furthering improvements in space conditioning due to the similarities, yet greater complexity in space heating and cooling. Refrigeration, though more similar in complexity to space cooling, has an increasing amount in common with water heating as HPWH become a primary focus for advances.

5 Appendix A – Water Heating Forum Summary Report

United States Department of Energy Research and Development Roadmap for Emerging Water Heating Technologies
January 28, 2014

Stakeholder Forum Summary – Navigant's Washington D.C. Office

Summary

On January 28, 2014, Navigant Consulting, Inc., on behalf of the U.S. Department of Energy's (DOE) Building Technologies Office (BTO), hosted a stakeholder forum to identify research and development (R&D) needs and critical knowledge gaps related to emerging water heating (WH) technologies. This forum covered WH equipment, hot water distribution systems, and enabling technologies such as software and advanced controls. BTO is the office through which DOE funds research to support emerging building technologies. BTO aims to reduce total building-related energy consumption by 50% by the year 2030. As one component of DOE's strategy to reach this goal, DOE is targeting a 37% reduction in WH-related energy consumption by 2030. By supporting R&D activities for emerging WH, DOE hopes to reduce barriers to greater market penetration of high efficiency WH solutions.

DOE held the forum at Navigant's Washington D.C. office. Twenty six stakeholders participated, including academics, researchers from national laboratories, industry manufacturers, and representatives from efficiency advocacy groups. A list of attendees and their affiliations is included in the Appendix.

Objective

The objective of this forum was twofold: 1) Engage participants in a discussion on the key R&D technologies and processes that have the potential to reduce barriers to greater market penetration of high-efficiency WH; and 2) Gather a prioritized list of potential R&D activities that can aid BTO in achieving their goals and that industry stakeholders believe will reduce barriers to greater adoption of these highly efficient technologies.

Process and Results

Discussions at the forum included both large group brainstorming sessions, as well as smaller breakout-group sessions. Each attendee participated in two breakout sessions based around the three following topic areas:

- WH Equipment
- System Architecture
- Enabling Technologies

These discussions generated a total of 41 potential R&D initiatives for DOE. At the conclusion of the forum, Navigant posted all of the topics on the wall and asked the participants to prioritize the topics by voting on the ones that they felt were most promising for DOE to undertake. Each participant received 3 high priority votes and 3 medium priority votes to disperse among the different initiatives as they saw fit. Navigant then recorded the resulting data, weighted the medium and high priority votes accordingly, and divided the initiatives into three priority levels:

high, medium, and low. The following tables show the prioritized initiative list. These prioritizations are one component in BTO's decision making process for determining which activities to pursue.

High Priority	
Topic Area	**Initiative/Activity**
Enabling Tech	Conduct large-scale field studies mapping WH energy consumption in buildings
Enabling Tech	Study and develop best practices guidance on the relationship between water use and WH energy consumption
Enabling Tech	Develop smart controls for water heating & integrate WH into smart building controls
Enabling Tech	Explore smart metering of water and energy consumption
Enabling Tech	Develop open-source simulation tools for technology design and certification
System Architecture	Research optimal high-efficiency combination system configurations (HVAC/WH)
System Architecture	Research how low-flow fixtures and reduced water consumption impact system architecture
System Architecture	Support solar WH plug-&-play systems and integration with conventional WH systems
WH Equipment	Demonstrate commercial-scale fuel cells and CHP in WH applications
WH Equipment	Support new technologies that can be easily installed in retrofit applications
WH Equipment	Develop commercial HPWH with flexibility to meet both base load and peak demands, and recovery time requirements
WH Equipment	Research improved insulation materials
WH Equipment	Identify ways to create a low-cost HPWH with conventional refrigerants
WH Equipment	Develop a Cost-Effective CO2 HPWH

Medium Priority	
Topic Area	**Initiative/Activity**
Enabling Tech	Develop easy to use design tools for contractors and installers
Enabling Tech	Develop tools to help consumers understand WH energy usage and drive behavioral changes
Enabling Tech	Support identification and analysis of the best refrigerants and blowing agents
Enabling Tech	Develop simple retrofit audit tools
System Architecture	Research the impact of smart recirculation control strategies on energy and water consumption
System Architecture	Study and compare the energy impacts of distributed WH vs centralized WH, including systems with point-of-use (POU) heating and/or storage
System	Study the system efficiency, cost, and performance of a HPWH with no

Architecture	central backup only distributed booster heating
System Architecture	Study the interactions between components in a hot water system, including, pumps, fixtures, mixing valves, etc.
WH Equipment	Develop PV assisted HPWH
WH Equipment	Research which is better for a range of building types and applications, CHP or absorption HPWH
WH Equipment	Study the impacts of separating storage tanks and heating elements on system efficiency, cost, and reliability
WH Equipment	Support commercialization of gas-fired absorption HPWH
WH Equipment	Reduce size and weight of high-efficiency water heaters
WH Equipment	Develop advanced thermal storage tanks

Low Priority	
Topic Area	**Initiative/Activity**
Enabling Tech	Improve hot water system design, layout, and sizing processes, and update ASHRAE handbook data
System Architecture	Reduce first costs for POU WH
System Architecture	Research best opportunities for waste heat recovery and storage
WH Equipment	Support field demonstrations of high efficiency gas and electric WH to educate consumers on their benefits
WH Equipment	Focus on reducing first costs, and achieving reasonable payback periods for high-efficiency WH
WH Equipment	Improve compressor technologies for HPWH
WH Equipment	Develop long-life tank materials
WH Equipment	Research advanced control strategies for non-CO2 HPWH
WH Equipment	Consider human factors and usability (e.g. noise concerns) in high efficiency WH
WH Equipment	Develop ultra-low-cost electric WH solutions
WH Equipment	Develop better training and best practices guidance for installers and contractors
WH Equipment	Design equipment for limited homeowner interaction in terms of maintenance and operation
WH Equipment	Research opportunities for grey water-source HPWH

Next Steps

Navigant, in consultation with BTO, will continue to refine and develop these R&D initiatives though additional research and follow-up interviews with individual stakeholders who were unable to attend the forum. Navigant will combine any duplicate or overlapping initiatives to ensure that all initiatives are unique. We will use a combination of qualitative and quantitative methods in developing final recommendations of the top R&D initiatives DOE to consider. The qualitative prioritization will consider some or all of the following criteria:

- Technical savings potential
- Fit with DOE mission
- Criticality of DOE involvement
- Technical and market risks
- Market Readiness
- Level of required DOE investment
- Stakeholder input (including voting results)

The quantitative prioritization will be based on cost and benefit outputs from BTO's Prioritization Tool. DOE will consider for funding the recommended outputs of these prioritization processes in parallel with other priorities in other end-use areas. Therefore, no recommended output from this road-mapping process is guaranteed to receive DOE support. The roadmap will serve as a guide for DOE and its partners in advancing the goal of reducing building energy consumption, while maintaining the competitiveness of American industry.

Forum Attendees

Navigant and DOE wish to thank all of the forum participants. The suggestions, insights, and feedback provided during the forum are critically important to developing a useful water heating R&D roadmap.

The R&D roadmap forum brought together 26 individuals representing a range of organizations across the industry. The following table lists all the attendees and their affiliations.

Attendee Name	Organization
Gary Klein	Affiliated International Management, LLC
Frank Stanonik	Air-Conditioning, Heating, and Refrigeration Institute
Harvey Sachs	American Council for an Energy-Efficient Economy
Patrick Phelan	DOE Building Technologies Office
Tony Bouza	DOE Building Technologies Office
Ammi Amarnath	Electric Power Research Institute
John Bush	Electric Power Research Institute
Gary Connett	Great River Energy
Phillip Stephens	Heat Transfer Products (HTP)
Christopher Lindsay	IAPMO
Omar Abdelaziz	Oak Ridge National Laboratory
Van Baxter	Oak Ridge National Laboratory
Edward Vineyard	Oak Ridge National Laboratory
Scott Baker	PJM Interconnection
Troy Trant	Rheem Water Heating
Karen Meyers	Rheem Water Heating
Joel Dickinson	Salt River Project
David Seitz	Seisco International Limited, Inc.
Joe Shiau	Southern California Gas Company
Don Brundage	Southern Company Services

Attendee Name	Organization
Chris Gray	Southern Company Services
Chuck Foster	Steffes Corporation
Matthew Carlson	Sunnovations
Arnoud van Houten	Sunnovations
Reinhard Radermacher	University of Maryland
Bill Hines	WFH Consulting

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For more information, visit: energy.gov/eere/buildings/building-technologies-office

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