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

BUILDING TECHNOLOGIES OFFICE

Research & Development Roadmap for Next-Generation Appliances

W. Goetzler, T. Sutherland, K. Foley

October 2014

Prepared by Navigant Consulting, Inc.

(This page intentionally left blank)

Available electronically at www.osti.gov/home/

Preface

The Department of Energy's (DOE) Building Technology Office (BTO), a part of the Office of Energy Efficiency and Renewable Energy (EERE) engaged Navigant Consulting, Inc., (Navigant) to develop this research and development (R&D) roadmap for next-generation appliances. The initiatives identified in this report are Navigant's recommendations to DOE/BTO for pursuing in an effort to achieve DOE's energy efficiency goals. Inclusion in this roadmap does not guarantee funding; next-generation appliance initiatives must be evaluated in the context of all potential activities that DOE/BTO could undertake to achieve their goals. DOE/BTO also manages the residential appliance and commercial equipment standards program; however these activities are separate from BTO's R&D initiatives.

Prepared for:
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Building Technologies Office
www.eere.energy.gov/buildings

Prepared by:
Navigant Consulting, Inc.
77 South Bedford Street, Suite 400
Burlington, MA 01803

William Goetzler
Timothy Sutherland
Kevin Foley

List of Acronyms

AHAM	Association of Home Appliance Manufacturers
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BTO	Building Technologies Office
CCE	Cost of Conserved Energy
CES	Center for Energy Studies
DOE	Department of Energy
EER	Energy Efficiency Ratio
EF	Energy Factor
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	Electrostatic Precipitator
GE	General Electric
HVAC	Heating, Ventilation, and Air-Conditioning
IR	Infrared
MCE	Magneto-Caloric Effect
NBS	National Bureau of Standards
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PERC	Propane Education and Research Council
PU	Polyurethane
R&D	Research and Development
TSD	Technical Support Document
VIP	Vacuum-Insulated Panel

Executive Summary

The Building Technologies Office (BTO) within the Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy is responsible for developing and deploying technologies that can substantially reduce energy consumption in residential and commercial buildings. The BTO has a critical stake in supporting the development, evaluation, and widespread implementation of advanced home appliance technologies. The mission of the BTO is as follows:

> *Develop and promote efficient, affordable, and 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.*[1]

Residential appliances such as refrigerator/freezers, dishwashers, laundry equipment, and cooking equipment account for over 12 percent of U.S. residential sector primary energy consumption. The appliance sector has seen substantial innovation in recent years; however, energy efficiency measures, while significant, have generally involved incremental improvements to meet new DOE efficiency standards. Little research has focused on radical innovations that might dramatically reduce energy consumption. By leveraging resources, the appliance industry may be able to work cooperatively with the DOE to develop and commercialize products and technologies that could make significant improvements feasible. In order to guide such activities and ensure the best possible outcomes, a research & development (R&D) roadmap is necessary.

The objective of this roadmap is to advance DOE's goal of reducing the energy consumption of residential appliances by accelerating the commercialization of high-efficiency appliance technologies, while maintaining the competitiveness of American industry.

DOE retained Navigant Consulting Inc. (hereafter, "Navigant") to develop this roadmap as a follow-on to a similar report written in 2012.[2] This roadmap reflects the current state of the industry in 2014 and describes advances that have been made since the 2011 roadmap.

This roadmap targets high-priority R&D, demonstration, and commercialization activities that, if pursued by DOE and its partners, could significantly reduce residential appliance energy consumption. The roadmap prioritizes those technologies with the highest energy savings potential and greatest likelihood of being embraced by both manufacturers and consumers. The schedule of proposed activities ranges from near-term activities in the 1-year to 3-year frame, to

[1] Building Technologies Program Multi-Year Work Plan, 2011-2015. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/myp11.pdf.
[2] http://www1.eere.energy.gov/buildings/pdfs/next_generation_appliances_roadmap.pdf.

mid-term activities in the 3-year to 5-year frame, to longer-term research initiatives that may span 5-10 years.

This R&D roadmap focuses on the following residential appliances: **refrigerator/freezers**, **clothes washers**, **clothes dryers**, **cooking equipment,** and **cross-cutting** appliance technologies. This roadmap does not cover HVAC systems, water heaters, or building envelope components. These technologies are covered by other roadmap reports published by the BTO.

Table 1 summarizes the recommended R&D activities for each high-priority technology option. Specifically, for each technology, the table provides the following:

- Summary of current status
- Identification of key technical challenges and hurdles
- Identification of key market barriers
- Outline of initiative timeline and major milestones

Table 1: Summary of Results for Each High Priority Appliance Technology Options

Technology Option	Summary of Current Status	Technical Barriers	Market Barriers	Near-Term R&D Milestones [Years 0-2]	Medium-Term R&D Milestones [Years 2-5]	Long-Term R&D Milestones [Years 5-10]
Refrigerator/ Freezer: ***Advanced compressor technologies***	High efficiency linear compressors exist on the market, but could benefit from improved design, materials, and lubricants. An electrochemical compressor prototype has been developed for a hybrid heat pump hot water heater. Current prototypes only work with non-fluorinated refrigerants. No current developments for residential refrigerator applications.	● Reducing or eliminating the need for lubricating oil to further improve efficiency and performance ● Addressing compatibility with fluorinated refrigerants or next-generation refrigerants to be used in residential refrigerators ● Reducing cost ● Improving reliability ● Demonstrating feasibility for residential refrigerator applications	● Higher initial cost	● Further developments on reducing/removing oil from linear compressors ● Mostly lab-based prototypes of electrochemical compressors addressing reliability issues and reducing manufacturing cost	● Successful development of oil-free linear compressors for residential refrigerators ● Electrochemical compressor prototypes demonstrating feasibility in a residential refrigerator application	● Linear compressors implemented in wider range of product applications ● First demonstrations of electrochemical compressors implemented in residential-sized refrigerator ● First full-sized residential refrigerators using electrochemical compressors brought to market, likely in high-end products
Refrigerator/ Freezer: ***Vacuum insulation panels***	VIPs are currently commercially available and are used in some high-end residential refrigerators. Research is ongoing in reducing the cost, reliability, and longevity of VIPs. Research is also ongoing to investigate improved, more robust materials with better insulation properties.	● Reducing manufacturing cost ● Improving VIP reliability and longevity ● Maintaining optimal installation procedures on high-volume manufacturing lines	● Higher initial cost ● VIP manufacturers must ramp up production to meet an increase in demand	● Continued progress on determining root causes of issues with reliability and longevity ● Continued progress identifying new, more optimal core materials	● Improved VIPs brought the market, and improved manufacturing methods	● Improved VIPs implemented in wider range of residential refrigerators
Refrigerator/ Freezer: ***Magnetic refrigeration***	Proof of concept prototype has been developed in laboratory settings. Current prototypes are large, and only have the cooling capacity to chill one bottle of fluid, and are fairly noisy. Current prototypes also do not incorporate all the other components of a refrigerator system that would need to be included in a fully-functional product.	● Reducing manufacturing cost ● Reducing the size to fit within the small space constraints of a residential refrigerator ● Increasing the cooling power to handle the cooling load for a full-sized refrigerator ● Reducing the noise levels associated with the valves and pumps required to operate the magnetic system ● Making magnetic refrigerators as reliable as conventional alternatives	● Higher initial cost ● Increasing demand and decreasing production of rare-earth magnets ● Educating the consumer about the benefits (including non-energy-related benefits)	● Demonstration of cooling capacity of typical residential refrigerator ● Demonstration of equivalent performance using iron-base alloy	● Demonstration of prototype residential-sized magnetic refrigerator	● Development of full-size magnetic refrigerator that can be brought to market ● Testing of full-sized magnetic refrigerator in residential settings
Clothes Dryer: ***Heat pump (electric only)***	Heat pump clothes dryers are currently commercially available in Europe, but have been unable to penetrate the U.S. market despite showing significant energy savings. A few manufacturers have stated they plan on releasing heat pump clothes dryers on the U.S. market in late 2014.	● Reducing manufacturing cost ● Reducing the longer drying time assoicated with heat pump drying ● Improving reliability inherent with more complex systems than traditional clothes dryers	● Higher initial cost ● Longer drying times may decrease consumer uptake ● Educating the consumer about the benefits (including non-energy-related benefits)	● Completed test program to verify energy savings	● Revised ENERGY STAR specification for clothes dryers	● Ongoing support of ENERGY STAR specification
Cross-Cutting Technologies: ***Integrated energy and water recovery & transfer between appliances***	Oak Ridge National Laboratory has developed a pre-fabricated wall to which all kitchen and laundry appliance would be connected, including major bathroom fixtures.	● Reducing manufacturing cost ● Unproven technical feasibility ● Unproven energy savings ● Current standards and test procedures are appliance-specific and would not accommodate energy-sharing between appliances ● Numerous regulatory issues need to be considered	● Requires total redesign of kitchen/laundry room layouts. ● Feasible for new construction only. Likely only feasible for smaller pre-fabricated housing. ● Added expense of custom wall system ● May require changes to appliance usage patterns ● This concept would represent a radical departure from the current industry distribution model, where appliances are stand-alone products that can be purchased individually at large home improvement stores	● Replication of the ORNL prototype wall system ● Tested prototype wall system	● Optimized prototype system for pre-fabricated residential dwellings ● Optimized prototype tested in pre-fabricated residential dwellings	● Optimized integrated kitchen system brought to market

Table of Contents

(This page intentionally left blank)

1 Introduction

1.1 Background

Residential appliances such as refrigerator/freezers, dishwashers, laundry equipment, and cooking equipment account for over 12 percent of U.S. residential sector primary energy consumption. The appliance sector has seen substantial innovation in recent years; however, energy efficiency measures, while significant, have generally involved incremental improvements to meet new Department of Energy (DOE) efficiency standards. Little research has focused on radical innovations that might dramatically reduce energy consumption. By leveraging resources, the appliance industry may be able to work cooperatively with the DOE to develop and commercialize products and technologies that could make significant improvements feasible. In order to guide such activities and ensure the best possible outcomes, a research & development (R&D) roadmap is necessary.

Most recently, particular attention has been focused on energy savings potential in existing buildings, because the impacts are more immediate due to the slow turnover of the residential building stock. Because appliances are less expensive and are replaced more regularly than heating, ventilation, and air-conditioning (HVAC) systems or building envelope components, they present an opportunity for near-term energy savings.

1.2 DOE Building Technologies Office Mission and Goals

The Building Technologies Office (BTO) within the Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy is responsible for developing and deploying technologies that can substantially reduce energy consumption in residential and commercial buildings. The BTO has a critical stake in supporting the development, evaluation, and widespread implementation of advanced home appliance technologies. The mission of the BTO is as follows:

> *Develop and promote efficient, affordable, and 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.*[3]

The BTO Multi-Year Work Plan for 2011-2015 articulates BTO's mission and program goals, which include the following[4]:

- Promote efficiency
- Promote affordability (cost reduction)

[3] Building Technologies Program Multi-Year Work Plan, 2011-2015. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/myp11.pdf.
[4] Ibid.

- Promote “environmentally friendliness”
- Lower greenhouse gas emissions
- Conduct R&D to advance innovative technologies for appliances
- Conduct R&D for integrated buildings approaches
- Accelerate adoption of new products on the market
- Increase private sector collaboration in developing new technologies

Part of the BTO’s strategy is to develop and implement technology roadmaps that drive market transformations, and more specifically, to develop innovations in key technology areas such as home appliances.

1.3 Objective of This Roadmap

The objective of this roadmap is to advance DOE’s goal of reducing the energy consumption of residential appliances by accelerating the commercialization of high-efficiency appliance technologies, while maintaining the competitiveness of American industry.

DOE retained Navigant Consulting Inc. (hereafter, “Navigant”) to develop this roadmap as a follow-on to a similar roadmap published in 2012.[5] This roadmap reflects the current state of the industry in 2014. Advances have been made since the 2011 roadmap, as described in the following section.

This roadmap targets high-priority R&D, demonstration, and commercialization activities that, if pursued by DOE and its partners, could significantly reduce residential appliance energy consumption. The roadmap prioritizes those technologies with the highest energy savings potential and greatest likelihood of being embraced by both manufacturers and consumers. The schedule of proposed activities ranges from near-term activities in the 1-year to 3-year frame, to mid-term activities in the 3-year to 5-year frame, to longer-term research initiatives that may span 5-10 years.

1.4 Technology and Market Scope

This R&D roadmap focuses on the following residential appliances: **refrigerator/freezers**, **clothes washers**, **clothes dryers**, **cooking equipment,** and **cross-cutting** appliance technologies. This roadmap does not cover HVAC systems, water heaters, or building envelope components. These technologies are covered by other roadmap reports published by the BTO.

DOE/BTO R&D focuses on innovative initiatives that accelerate development of technologies. However, in select cases, DOE/BTO also supports initiatives that can drive innovation broadly

[5] http://www1.eere.energy.gov/buildings/pdfs/next_generation_appliances_roadmap.pdf.

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 magnetocaloric cooling technology for residential refrigerators. See secion 5.1 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 integrated heat and water recovery across multiple household appliances. See section 5.2 for enabling technology initiatives.

1.5 Overview of Home Appliance Energy Consumption

Table 1-1 lists the residential appliances considered in this R&D roadmap. The table indicates the estimated annual unit energy consumption and annual operating costs according to the Buildings Energy Data Book. Annual energy consumption estimates for ovens and cooktops were obtained from the Technical Support Document (TSD) accompanying the most recent Final Rule for the DOE energy conservation rulemaking for residential cooking products (DOE, 2009).

Table 1-1: List of Appliances, Including Estimated Annual Energy Consumption and Annual Cost

Appliance	Estimated Annual Unit Energy Consumption [a,b]		Annual Cost [a,b] ($/year)
	Electric (kWh/year)	Gas (MMBtu/year)	
Refrigerator/Freezers	660	--	$63
Ovens	305	1.6	$29 (electric) $20 (gas)
Cooktops	234	3.4	$22 (electric) $42 (gas)
Microwave Ovens	131	--	$13
Dishwashers	120	--	$12
Clothes Washers	110[c]	--	$10
Clothes Dryers	1,000	4.0	$96 (electric) $52 (gas)

[a] Source: 2011 Buildings Energy Data Book, most current version (BEDB, 2011).
[b] Source for ovens: DOE Technical Support Document (DOE, 2009).
[c] Excludes electricity for water heating and clothes drying.

Table 1-2 shows the estimated installed base of each appliance type.

Table 1-2: Estimated Installed Base of each Appliance Type

Appliance	Estimated Installed Base [a,b] (million units)
Refrigerator/Freezers	**117.1**
Ovens (Total)	**103.9**
Ovens (Electric)	63.2
Ovens (Gas)	40.7
Cooktops (Total)	**104.7**
Cooktops (Electric)	59.1
Cooktops (Gas)	45.6
Microwave Ovens	**78.0**
Dishwashers	**63.6**
Clothes Washers	**86.6**
Clothes Dryers (Total)	**76.9**
Clothes Dryers (Electric)	61.9
Clothes Dryers (Gas)	15.0

[a] Calculated as average product lifetime x average annual shipments
[b] Source: Appliance Magazine - U.S. Appliance Shipment Yearly Statistics (Appliance, 2012) and Appliance Design – U.S. Appliance Shipment Yearly Statistics (Appliance Design, 2014).

Table 1-3 shows the estimated national energy consumption of each appliance type. This includes the sum of source electrical energy consumption and site gas consumption.

Table 1-3: Estimated National Annual Source Energy Consumption of each Appliance Type

Appliance	Estimated National Source Energy Consumption [a,b] (TBtu/year)
Refrigerator/Freezers	**804**
Ovens (Total)	**266**
Ovens (Electric)	201
Ovens (Gas)	65
Cooktops (Total)	**299**
Cooktops (Electric)	144
Cooktops (Gas)	155
Microwave Ovens	**106**
Dishwashers	**79**
Clothes Washers	**99**
Clothes Dryers (Total)	**704**
Clothes Dryers (Electric)	644
Clothes Dryers (Gas)	60

[a] For gas appliances, calculated as annual unit energy consumption x installed base
[b] For electrical appliances, calculated as annual unit energy consumption x 3412 Btu/kwh x installed base x 3.05 (3.05 = site-to-source energy conversion factor)

Figure 1-1 shows the relative ranking of each appliance type according to its estimated national source energy consumption.

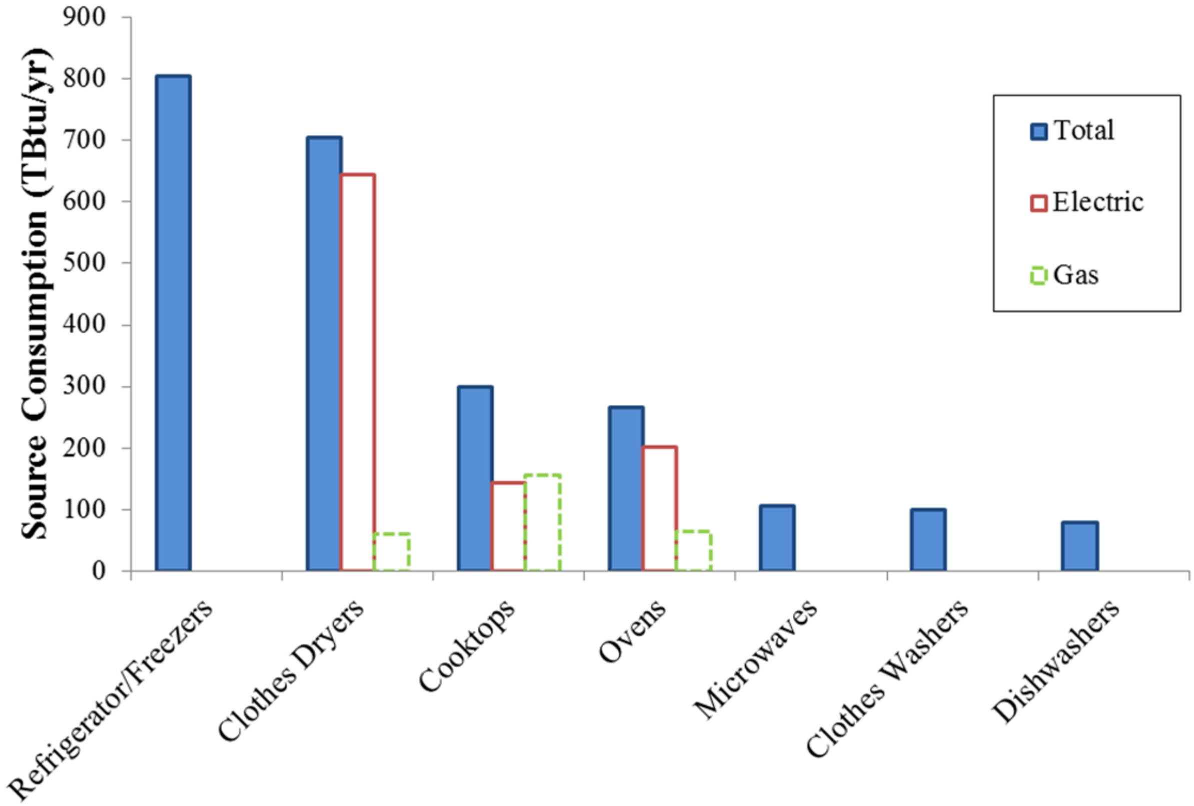


Figure 1-1: Source Energy Consumption of Each Appliance Type

Figure 1-1 shows that the appliances with the most energy consumption, and thus, highest energy savings potential, are refrigerator/freezers and clothes dryers. Refrigerator/freezers and clothes dryers consume 34 percent and 30 percent, respectively, of the total energy consumption of the seven residential appliances considered in this R&D roadmap.

2 Roadmap Approach

Figure 2-1 summarizes the approach used to identify and prioritize the R&D initiatives recommended in this report. The approach used for this report is similar to the approach used for other recent BTO reports and technology roadmaps for topic areas including water heating technologies, geo-thermal heat pumps, and building-integrated solar technologies.[6] The following sections provide additional details about each stage of the process.

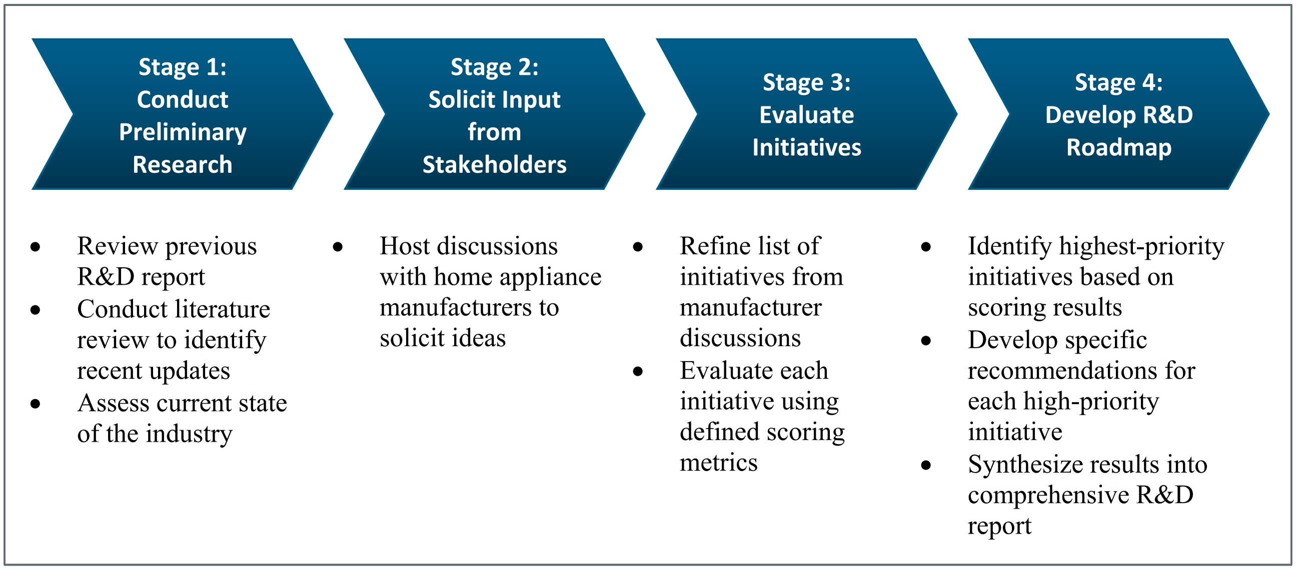


Figure 2-1: Roadmap Development Steps

2.1 Stage 1: Conduct Preliminary Research

We conducted a preliminary assessment through literature searches and discussions with industry experts of next-generation appliances. We reviewed any major changes in legislation or regulations, R&D initiatives, and new product deployments that have occurred since the 2012 roadmap. The information gathered during this stage provided a comprehensive overview of the current state of the market.

2.2 Stage 2: Solicit Input from Home Appliance Manufacturers

We conducted a series of one-on-one discussions with major home appliance manufacturers to review the technologies that we identified as "high priority" in the 2012 roadmap. Due to the sensitive nature of R&D programs, private discussions with manufacturers were conducted under non-disclosure agreements.

[6] BTO publications available at: http://www1.eere.energy.gov/library/default.aspx?page=2.

2.3 Stage 3: Evaluate Initiatives

Based on the preliminary assessment and stakeholder feedback, Navigant made adjustments to the list of technologies identified in the 2012 roadmap. In consultation with DOE/BTO, Navigant updated the prioritization of the initiatives to identify the most promising for DOE/BTO to pursue. We used the comprehensive prioritization process described below, which scores each initiative based on qualitative metrics. In the case of "direct-impact" initiatives, we also evaluated the highest-priority initiatives using outputs from DOE/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 estimates 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

2.3.1 Prioritization

The qualitative prioritization used four 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	Impact on energy savings potential, using the P-Tool results for Unstaged Maximum Adoption Potential (see section 2.3.2).
Fit with DOE/BTO Mission	Suitability of technology to DOE/BTO's mission, goals, and capabilities. A technology option is considered a very strong fit with DOE/BTO mission if: • The technology is much more likely to achieve success, or likely to achieve success much faster, with DOE/BTO support • The technology's technical risk is moderate to high, rather than low or extremely high • The technology, once developed, is likely to be embraced by major industry stakeholders and would likely achieve consumer acceptance
Cost/Complexity	The first cost of the technology option and the added complexity to the installation, operation and maintenance of the technology option, compared to typical technologies currently on the market.
Non-Energy Benefits	The potential for the technology option to provide benefits other than energy savings, including but not limited to: water savings, improved product utility, simplified maintenance, and reduced noise/vibration.

Table 2-2 shows the scoring and weighting values. See section 4 for a summary of the quantitative prioritization results for the direct-impact initiatives.

Table 2-2: Initiative Scoring Metrics - Scores

Metric	1	2	3	4	5	Wgt:
Impact (Direct-impact)	< 100 TBtu/yr	100 – 199 TBtu/yr	200 – 299 TBtu/yr	300 –399 TBtu/yr	≥ 400 TBtu/yr	**35%**
Impact (Enabling)	Minimal	Modest	Moderate	Semi-Significant	Significant	
Fit with DOE/BTO Mission	Very weak fit	Moderately weak fit	Neither strong nor weak fit	Moderately strong fit	Very strong fit	**35%**
Cost/Complexity	Much higher cost/ complexity	Moderately higher cost/ complexity	Slightly higher cost/ complexity	Potential for similar cost/ complexity	Potential for lower cost/ complexity	**15%**
Non-Energy Benefits	Potential negative effects	Provides few or no benefits	Likely to provide some modest benefits	Potential for significant benefits, but not well understood	Provides extensive, quantifiable benefits	**15%**

2.3.2 DOE/BTO Prioritization Tool – Direct-Impact Initiatives Only

To determine the "Impact" score for the direct-impact initiatives, we used DOE/BTO's P-Tool. The P-Tool compares investment opportunities across all of DOE/BTO to help inform decision-making and the development of program goals and targets. The National Renewable Energy Laboratory (NREL) originally developed the tool and describes it in more detail in their project report.[7] In brief, the tool uses inputs to characterize the performance, cost, market, and lifetime to analyze each technology 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 technology 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 technology for all end-of-life replacements and new purchases by accounting for sales, disposals, and building stock growth.
- **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 technologies 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 technologies with higher cost of conserved energy and higher energy savings

[7] Philip Farese, et. al., "A Tool to Prioritize Energy Efficiency Investments," National Renewable Energy Laboratory, August 2012, available: www.nrel.gov/docs/fy12osti/54799.pdf.

potential. The P-Tool determines staged maximum adoption potential on an individual market by market basis.

We used the Unstaged Maximum Adoption Potential for the "Impact" score in the scoring matrix because it provides a more realistic energy savings potential compared to using the Technical Potential. Generally, the Staged Maximum Adoption Potential can provide even further refinement of the estimated energy savings potential; however, generating these results from the P-Tool requires more rigorous estimates of projected costs, energy savings, and development timelines for all the technologies considered for each appliance type. Because many of the technologies identified in the roadmap are in early-stage development, a high level of uncertainty would have been associated with the required inputs to the P-Tool, leading to less meaningful outputs.

2.4 Stage 4: Develop R&D Roadmap

Based on the results of the evaluation, Navigant developed detailed descriptions and workplans as a starting point for DOE/BTO to use in accelerating the commercialization of the five high-priority technology options. The detailed recommendations include the following components:

- Define initiative purpose and goals
- Identify key technical challenges and hurdles
- Identify key market barriers
- Outline initiative timeline and major milestones
- Recognize key stakeholder roles and responsibilities

Section 5 contains the detailed recommendations and characterizations for each high-priority technology option.

3 Current Research and Development Initiatives

In June 2014, DOE announced funding for 15 R&D projects to support technologies that will contribute to advancing early-stage, breakthrough energy-efficient solutions for buildings and homes. Four of the 15 technologies fall within the scope of this report – one for refrigerators and three for clothes dryers.[8] These four projects, which are distinct from the R&D initiatives recommended in this report, are described below.

3.1 Refrigerator Using Rotating Heat Exchanger as an Evaporator

This project is a collaboration among Oak Ridge National Laboratory (ORNL), Sandia National Laboratories, and University of Maryland College Park. The project will demonstrate the first refrigerator using the Sandia Cooler as an evaporator. Oak Ridge National Laboratory (ORNL), University of Maryland, and Sandia National Laboratories will collaborate on the design, testing, and further optimization of the new air-bearing heat exchanger for a residential refrigerator evaporator. ORNL's accelerated frost accumulation testing has showed that the rotating heat exchanger has resistance to frost accumulation, which could eliminate the need for a defrosting cycle and increase refrigerator energy efficiency. As a crystal grows on the surface of the rotating blades, centrifugal force becomes large enough to break it. The rotating heat exchanger can thus be used as an evaporator in a refrigerator to reduce or eliminate the need for the defrost cycle. In addition, cold frost particles can be collected to cool the refrigerant leaving the condenser. This technology potential could produce energy savings of at least 13%.

3.2 Ultrasonic Clothes Dryer

This project is a collaboration between ORNL and GE Appliances. The project seeks to address BTO's goal of developing a new clothes dryer technology that can increase the energy factor (EF) from 3.7 to 5.43 lb/kWh without increasing drying time by more than 20% over baseline units. The goal of this project is to develop a clothes dryer prototype, using ultrasonic transducers, with an EF above 10 lb/kWh. Drying time is predicted to be around 20 minutes. Direct-contact ultrasonic drying is a novel, transformative drying technology that is completely different from conventional systems. It has the potential to reduce both energy consumption and drying time significantly and provides a quieter drying process. Because a high airflow rate of hot air is not needed, lint production would be minimized. This dryer technology has the technical potential for 0.4 quad of energy savings.

3.3 Infrared Heating and Electrostatic Precipitator Clothes Dryer (electric only)

For this project, GE Global Research seeks to develop a novel, high-efficient, electric residential clothes dryer. The proposed dryer is a ventless system, utilizing mid-wave infrared (IR) heating and a unique electrostatic precipitator (ESP) for humidity removal. The EF of the proposed dryer will be in excess of 4.04. This project seeks to design, demonstrate, and optimize the proposed

[8] DOE press release available at http://energy.gov/eere/articles/energy-department-invests-14-million-innovative-building-efficiency-technologies.

ESP and IR heater subassemblies. Once optimized, the subcomponents will be integrated into a modified residential dryer for demonstration of the program EF goal.

The proposed technology completely changes the current clothes dryer paradigm. The IR heating approach directly delivers the radiant energy to the clothes and water at a wavelength optimized for the water absorption, thus, saving energy and time. The ventless approach is made possible by the ESP, which separates water vapor from the exhaust stream while capturing and transferring the latent heat. This allows the warm dry air to be recirculated directly back into the drum. The ESP, in addition to separating out the water, collects fine lint particulates and sends them to the drain. The combination of the IR heating and ESP decreases drying times while meeting the required EF of greater than 4.04. It is anticipated that the proposed dryer will have an energy savings of 20 to 60%, similar to that of a heat pump condensing dryer, but a much lower cost increment of 20%, when compared to conventional electric vented dryers.

3.4 Thermoelectric Clothes Dryer

This project is a collaboration between ORNL and Sheetak, Inc. The project will demonstrate a proof-of-concept prototype dryer utilizing thermoelectric heat pump technology. The prototype will be able to meet a target efficiency level of an EF greater than 6 lbs/kWh. This project aims to develop a novel dryer that uses low-cost solid state heat pumps. It is targeted to have efficiency comparable to vapor-compression heat pump dryers on the market today, but at a substantially lower cost, allowing much greater adoption by consumers. This project is based on a concept from ORNL that uses thermoelectric modules integrated into the dryer drum. A conservative estimate is that the proposed technology can dry clothes with an EF of at least 6 lb/kWh, resulting in 38% less electricity than the 2015 minimum standard for vented electric dryers. This would yield a technical energy saving potential of 356 TBtu/year.

4 Summary of Prioritization Results

To re-prioritize the technology options from the 2012 report, we investigated the current state of technology development and updated our understanding of the impacts, potential benefits, and potential costs of each technology. The team rescored the "high priority" technologies identified in the 2012 roadmap, as well as any new technology options not considered in the prior report, using the scoring metrics described in section 2.3.1.

For the medium- and low-priority technology options, we revisited the scores from the 2012 roadmap, and made adjustments where needed. Table 4-1 shows the updated scoring results of each technology option. Table 4-2 shows a comparison of the updated priority rankings and the 2012 roadmap rankings.

Table 4-1: Scoring of Each Appliance Technology Option

Appliance	Technology Option	Impact	Fit with DOE	Cost / Complexity	Non-Energy Benefits	Weighted Score
High Priority						
Refrigerator/Freezer	Advanced compressor technologies	4	5	3	4	**4.2**
Refrigerator/Freezer	Vacuum insulation panels	3	5	4	2	**3.7**
Cross-Cutting Technologies	Integrated energy and water recovery and transfer between appliances	4	4	1	2	**3.6**
Refrigerator/Freezer	Magnetic refrigeration	2	5	3	4	**3.5**
Clothes Dryer	Heat pump (electric only)	5	3	2	1	**3.3**
Medium Priority						
Clothes Dryer	Mechanical steam compression	3*	4	2	3	**3.2**
Refrigerator/Freezer	Thermoelastic refrigeration	3*	4	3	2	**3.2**
Clothes Washer	Polymer bead cleaning	4*	3	1	4	**3.2**
Refrigerator/Freezer	Thermoelectric refrigeration	2*	4	4	2	**3.0**
Clothes Dryer	Inlet air preheat	2*	4	4	2	**3.0**
Low Priority						
Refrigerator/Freezer	Stirling cycle refrigeration	2*	4	3	2	**2.9**
Clothes Washer	Sanitizing agents	4*	2	1	4	**2.9**
Clothes Dryer	Indirect heating	2*	4	2	3	**2.9**
Cross-Cutting Technologies	"Smart" appliances	1	4	3	4	**2.8**
Cooking Equipment	Specialized cookware	1*	4	3	3	**2.7**
Clothes Dryer	Microwave (electric only)	2*	4	3	1	**2.7**
Cooking Equipment	Induction cooktops	1*	3	3	3	**2.3**

*The Impact metric for these technology options represents the "Technical Potential" energy savings, which is the metric used in the 2012 report, rather than the "Un-staged Maximum Adoption Potential."

Table 4-2: Updated Priority Rankings for Each Appliance Technology Option

Updated Priority Ranking	2012 Roadmap Priority Ranking	Resulting Change
High Priority		
Refrigerator/Freezer: Advanced compressor technologies	Medium	↑
Refrigerator/Freezer: Vacuum insulation panels	High	No change
Cross-Cutting Technologies: Integrated heat and water recovery	High	No change
Refrigerator/Freezer: Magnetic refrigeration	High	No change
Clothes Dryer: Heat pump (electric only)	High	No change
Medium Priority		
Clothes Dryer: Mechanical steam compression (electric only)	Medium	No change
Refrigerator/Freezer: Thermoelastic refrigeration	Low	↑
Clothes Washer: Polymer bead cleaning	Medium	No change
Refrigerator/Freezer: Thermoelectric refrigeration	Low	↑
Clothes Dryer: Inlet air preheat	Medium	No change
Low Priority		
Refrigerator/Freezer: Stirling cycle refrigeration	Low	No change
Clothes Washer: Sanitizing agents	Low	No change
Clothes Dryer: Indirect heating	Low	No change
Cross-Cutting Technologies: "Smart" appliances	N/A	N/A
Cooking Equipment: Specialized cookware	Medium	↓
Clothes Dryer: Microwave (electric only)	Low	No change
Cooking Equipment: Induction cooktops	Medium	↓

5 Research & Development Roadmaps

This section provides the R&D roadmaps developed for both direct-impact and indirect-impact initiatives.

5.1 Roadmap for Direct-Impact R&D Initiatives

This section details the high-priority technologies in this category. Table 5-1 lists all 15 direct-impact technologies identified during roadmap development. Appendix A provides additional details on each of the direct-impact technologies.

Table 5-1: Prioritized List of Direct-Impact Technologies

Technology/Initiative	Priority
Refrigerator/Freezer: Advanced compressor technologies	High
Refrigerator/Freezer: Vacuum insulation panels	High
Refrigerator/Freezer: Magnetic refrigeration	High
Clothes Dryer: Heat pump (electric only)	High
Clothes Dryer: Mechanical steam compression (electric only)	Medium
Refrigerator/Freezer: Thermoelastic refrigeration	Medium
Clothes Washer: Polymer bead cleaning	Medium
Refrigerator/Freezer: Thermoelectric refrigeration	Medium
Clothes Dryer: Inlet air preheat	Medium
Refrigerator/Freezer: Stirling cycle refrigeration	Low
Clothes Washer: Sanitizing agents	Low
Clothes Dryer: Indirect heating	Low
Cooking Equipment: Specialized cookware	Low
Clothes Dryer: Microwave (electric only)	Low
Cooking Equipment: Induction cooktops	Low

5.1.1 Advanced Compressor Technologies

The compressor is the primary energy-consuming component in a refrigerator, refrigerator-freezer, or freezer. Therefore, technologies that can advance compressor efficiency have a significant effect on overall product efficiency. Residential refrigeration products use positive-displacement compressors in which the entire motor-compressor is hermetically sealed in the welded steel shell. Two types of compressors have historically been used in residential refrigeration products—reciprocating and rotary. Currently, reciprocating compressors are the most predominant type in U.S. products. High-efficiency compressors are in development and some are already incorporated in residential refrigerators currently on the market. The high-efficiency compressor technologies that we identified for this roadmap are linear compressors and electrochemical compressors.

Linear Compressors

Linear compressors employ a different design than either reciprocating or rotary compressors and are potentially more efficient than both. These compressors use a linear rather than rotary motor, thus eliminating the crankshaft and linkage that converts the rotary motion to the linear motion of the piston of a reciprocating compressor. Elimination of the mechanical linkage reduces friction and side-forces. The linear motor requires power electronics and a controller to assure proper piston throw. Most linear compressor designs use a free piston arrangement and can be controlled for a range of capacities through adjustment of piston displacement. Early work on the concept suggested that the compressors can operate without the use of oil, which could provide additional energy benefit by improving heat transfer in the evaporator. Refrigerator noise levels can also be reduced by operating most of the time at low capacity, similar to how variable-speed compressors are used.

A leading manufacturer has developed a linear compressor for household refrigerators that does require use of oil. The manufacturer claims that its linear compressor technology is up to 20 percent more efficient than reciprocating designs, and emits lower noise levels.[9] It reports the efficiency of its linear compressors only at "Reference Conditions," which are significantly different than the ASHRAE rating conditions. Under ASHRAE conditions, compressors are rated with evaporating and condensing temperatures of -10 degrees Fahrenheit and 130 degrees Fahrenheit, respectively, while the "Reference Conditions" are based on evaporating and condensing temperatures of -14.8 degrees Fahrenheit and 100.4 degrees Fahrenheit, respectively. The manufacturer does not provide the liquid and suction vapor temperatures, which also impact capacity and power input. Factoring in these modified test conditions, its linear compressor may be about 9% more efficient than the best current-technology rotating-shaft reciprocating compressors.

A compressor manufacturer has developed an oil-free compressor for home appliances, as seen in Figure 5-1.[10] Instead of using oil, the only moving part uses the refrigerant gas itself as lubrication. The manufacturer claims the product is smaller and quieter than other compressors used in refrigerators, as well as 20% more efficient than the most efficient refrigerator compressors.[11] These oil-free compressors have not yet been introduced to the U.S. refrigerator market.

[9] http://www.lg.com/us/kitchen/refrigerator/energy-efficient-refrigerator.jsp
[10] Image source: http://www.coolingpost.com/world-news/oil-less-linear-compressor-launched/
[11] http://www.hydrocarbons21.com/articles/embraco_s_new_wisemotion_to_revolutionise_domestic_refrigeration

Figure 5-1: Example oil-free compressor for home appliances

Electrochemical compressors

Electrochemical compressors are currently under development. An electrochemical compressor incorporates membrane-electrode-assemblies separated by proton exchange membranes in series to reach higher pressures. When a current is passed through the membrane-electrode-assemblies, protons and electrons are generated at the anode. The protons are electrochemically driven across the membrane to the cathode, after which they combine with the rerouted electrons to form hydrogen, which is fed to the hydrogen compressor to be oxidized at the anode of each cell to form protons and electrons. When the reactions are complete, the fluid is at a higher pressure than when the fluid entered the system.

A U.S. company has developed an electrochemical compressor that uses non-fluorinated refrigerants, as seen in Figure 5-2.[12] The company claims its electrochemical compressor reduces energy used in refrigeration cycles by at least 20 percent, and reduces noise when compared to traditional refrigerator compressors. The compressor is still in prototype form. The first planned application of this compressor is in residential water heating applications, after which it may be further developed for other products.

[12] Image source: http://aceee.org/files/pdf/conferences/hwf/2013/7A-bahar.pdf

Figure 5-2: Electrochemical compressor prototype

Table 5-2 and Table 5-3 describe the technical challenges and market barriers associated with advanced compressor technologies.

Table 5-2: Technical Barriers – Advanced Compressor Technologies

Technical Barrier	Description
High First Cost	The current costs of electrochemical prototypes will need to decrease for it to be commercially-viable.
Removing Oil	One company has recently developed an oil-free compressor, but it has not been applied in U.S. residential refrigerators. Challenges remain for other compressor companies to follow suit.
Non-fluorinated Refrigerants	Current electrochemical compressors use non-fluorinated refrigerants, and all mainstream refrigerants for residential refrigerators are fluorinated. Either electrochemical compressors will need to accommodate fluorinated refrigerants, or residential refrigerators will need to be able to function using non-fluorinated refrigerants, in order for electrochemical compressors to be applied in refrigerators.
Feasibility	Electrochemical prototypes have been designed for water heating applications. Challenged remain in demonstrating feasibility for residential refrigerator applications.
Reliability	Electrochemical compressors will need to be as reliable as conventional refrigerator compressors.

Table 5-3: Market/Deployment Barriers – Advanced Compressor Technologies

Market Barrier	Description
High Upfront Cost	Consumers may not accept higher upfront costs without a strong value proposition for purchasing the new technology.

Figure 5-3 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.

Near-Term (1-3 Yrs)	Mid-Term (3-5 Yrs)	Long-Term (5-10 Yrs)
Action Items: » Identify ways of reducing/removing oil from linear compressors » Address reliability issues and reduce manufacturing cost of electrochemical compressors » Publish research findings as appropriate	**Action Items:** » Develop oil-free linear compressor for residential refrigerator » Refine electrochemical compressor prototypes as needed » Develop electrochemical compressor prototypes demonstrating feasibility in a residential refrigerator application	**Action Items:** » Implement linear compressors in a wider range of product applications » First demonstrations of electrochemical compressors in a residential refrigerator
Milestones: » Developments on reducing/removing oil from linear compressors » Lab-based electrochemical compressor prototypes addressing reliability issues and reducing cost » Published research findings	**Milestones:** » Successful development of oil-free linear compressor for a residential refrigerator » Demonstration of feasibility of electrochemical compressor prototype in a residential refrigerator » Published research findings	**Milestones:** » Linear compressors implemented in wider range of product applications » First residential refrigerators with electrochemical compressors brought to market

Figure 5-3: Timeline and Milestones – Advanced Compressor Technologies

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

Table 5-4: Stakeholder Involvement – Advanced Compressor Technologies

Tasks	Key Stakeholders
R&D	» Independent research firms – prototyping, scientific evaluation » National laboratories – prototyping, design/field support » Universities – research support » Manufacturers – prototyping, design/field support
Validation and Testing	» Primary: National laboratories, independent testing facilities, manufacturers, DOE-BTO » Secondary: Utilities, energy efficiency organizations
Deployment	» Manufacturers – product roll-out, technician training, marketing » DOE – commercialization support » Retailers – sales, product display

5.1.2 Vacuum Insulation Panels

Vacuum-insulated panel (VIP) technology is based on the reduction in conductivity that occurs in a low vacuum. Typical VIPs generally consist of a core material and an airtight envelope. The intermolecular spacing within the core material increases at low vacuum levels, which causes an interference with the molecular mean free path; thus reducing the material's conductivity. The core material also provides rigid support to prevent the panel from collapsing. VIPs can be foamed in place between the cabinet liner and wrapper. They are available in a variety of geometries (e.g., flat, curved, cylindrical) with added features (e.g., holes, cut-outs). Some VIPs also include an absorber to absorb gas that leaks through the envelope.[13] VIPs have a thermal resistance about 10 times higher than that of equally thick conventional polystyrene boards used in refrigerators.[14]

VIPs are currently used in some high-end residential refrigerators on the market. Although they are commercially available, research is ongoing to reduce the cost and longevity of VIPs. ORNL analyzed three composite VIPs and measured only a five-percent reduction in overall thermal resistance over a three-year period. ORNL demonstrated that this reduction in thermal resistance was less than the corresponding reduction for a panel without any VIPs, i.e., panels consisting only of polyurethane (PU) foam insulation.[15]

---

[13] United States Department of Energy. Final Rule Technical Support Document: Refrigerators, Refrigerator-Freezers, and Freezers. August 25, 2011: http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrig_finalrule_tsd.pdf.

[14] "Vacuum insulation panels – From research to market": http://www.sciencedirect.com/science/article/pii/S0042207X07003727.

[15] Vineyard, E.A., Stovall, T.K., Wilkes, K.E., and Childs, K.W. "Superinsulation in Refrigerators and Freezers," ASHRAE Transactions, 1998, Vol. 104, Pt.2.

Several core materials have been used in the manufacture of VIPs, including polystyrene, open-cell PU, silica powder, and glass fiber. Research sponsored by the European Commission has evaluated these core materials based on their cost and characteristics, including density and manufacturing time. Additionally, ORNL also has evaluated the performance of three types of VIPs: a silica powder filler encapsulated in a polymer barrier film; a fibrous glass insulation filler encapsulated in a stainless steel barrier; and an undisclosed insulation filler encapsulated in a stainless steel barrier.[16]

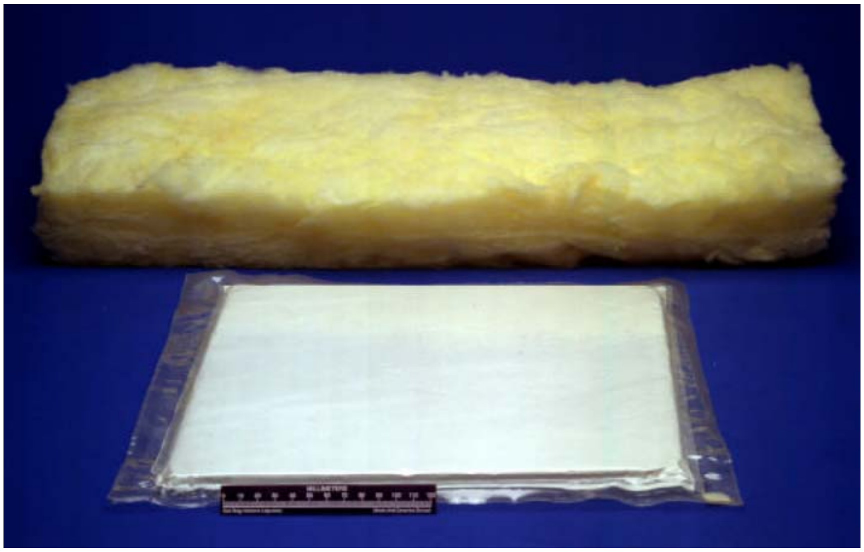


Figure 5-4: Top – typical insulation used in residential refrigerators; Bottom – vacuum panel insulation

Of significant concern for VIPs is their long-term thermal conductivity integrity and cost. VIP thermal conductivity increases dramatically as the pressure within the VIP exceeds 100 Pa (1 mbar). Pressure increases in the VIP can occur over time due to several factors, including: residual gases in the VIP after vacuum, degassing from the VIP core material, and gas diffusion through the envelope pores. Improved envelopes and absorbers have been developed to prevent pressure increases from occurring in VIPs. Additionally, VIPs are more difficult to manufacture than polyurethane foams or mineral wools, and strict quality control of manufacture of the membranes and sealing joins is important if a panel is to maintain its vacuum over a long period of time.

To accelerate the usage of VIPs, manufacturers will need to address some of the key technological barriers, such as high manufacturing cost and reliability and longevity. Table 5-5 and Table 5-6 describe the technological challenges and market barriers facing VIPs.

[16] United States Department of Energy. Final Rule Technical Support Document: Refrigerators, Refrigerator-Freezers, and Freezers. August 25, 2011: http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrig_finalrule_tsd.pdf.
Image source: http://web.ornl.gov/~webworks/cpr/pres/102936.pdf

Table 5-5: Technical Challenges – Vacuum Insulation Panels

Technical Barrier	Description
High Manufacturing Cost	The materials that are needed to make VIPs are inexpensive, but the technology requires more costly manufacturing methods.
Reliability and Longevity	Pressure increases in the VIP due to residual gases in the VIP after vacuum, degassing from the VIP core material, and gas diffusion through envelope pores can dramatically increase thermal conductivity.
Installation Procedures	Refrigerator manufacturers must maintain optimal installation procedures on high-volume manufacturing lines.

Table 5-6: Market/Deployment Barriers – Vacuum Insulation Panels

Market Barrier	Description
High Upfront Cost	Consumers may not accept upfront costs with little or no perceived higher value.
Supply Chain	Refrigerator manufacturers have expressed concern about the ability of VIP suppliers to ramp up production to meet an increase in demand.

By improving reliability and lowering the cost, these recommended programs would significantly increase the prevalence of this technology option in the residential refrigerator/freezer market. Because VIPs have the potential to significantly improve energy efficiency in the short-term, this is a high-priority technology option that DOE should continue to support over the next several years. Figure 5-5 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to improve this technology.

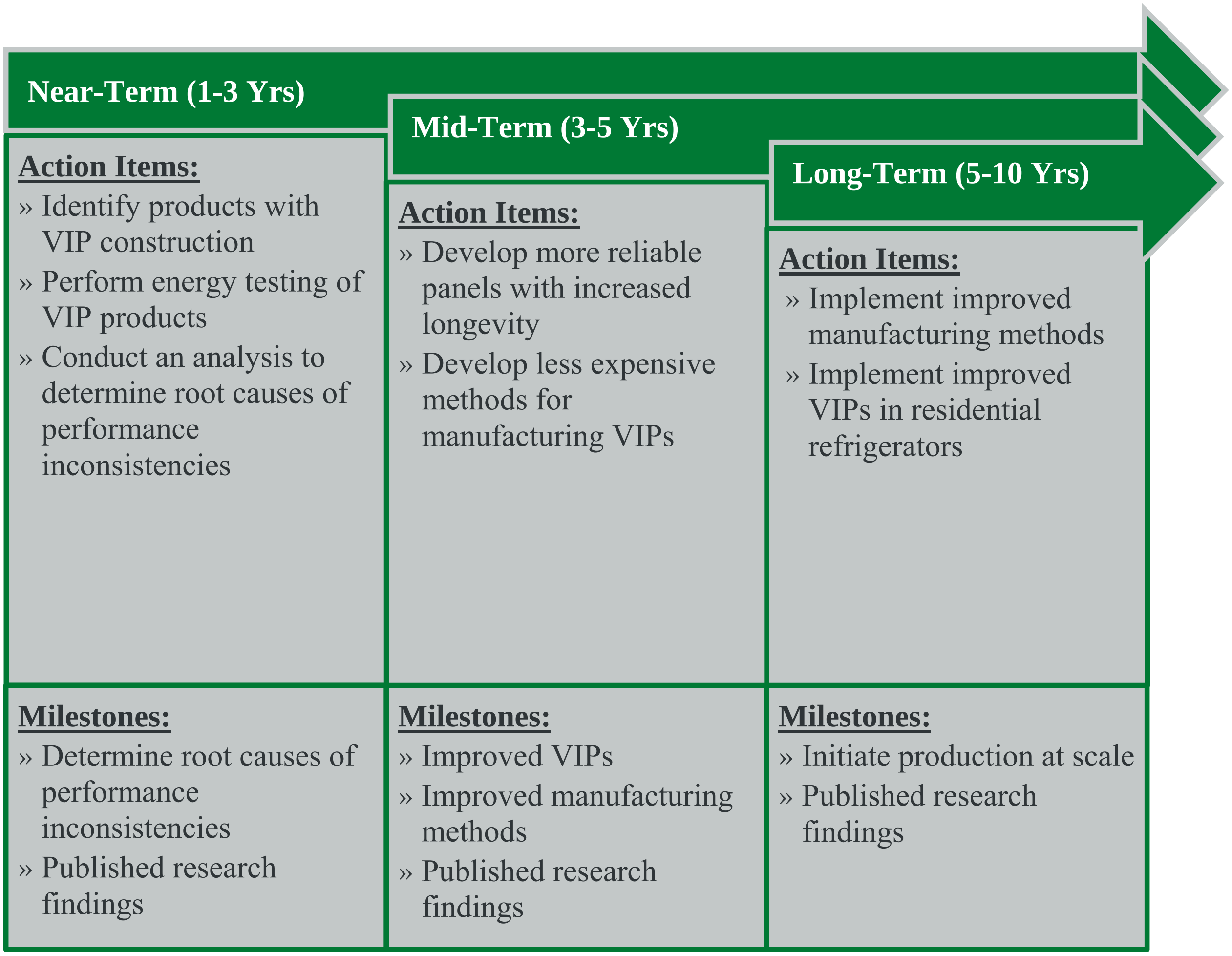


Figure 5-5: Timeline and Milestones – Vacuum Insulation Panels

Table 5-7 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 5-7: Stakeholder Involvement – Vacuum Insulation Panel

Tasks	Key Stakeholders
R&D	» Independent research firms – scientific evaluation » National laboratories – design/field support » Manufacturers – Product roll-out, technician training, marketing
Validation and Testing	» Primary: National laboratories, independent testing facilities, manufacturers » Secondary: Utilities, energy efficiency organizations
Deployment	» Manufacturers – product roll-out, sales training, marketing » Retailers – sales, product display

5.1.3 Magnetic Refrigeration

Magnetic refrigeration is based on the magneto-caloric effect (MCE). MCE is a magneto-thermodynamic phenomenon in which a reversible change in temperature of a paramagnetic material is caused by exposing it to a changing magnetic field. In the magnetic refrigeration cycle, randomly oriented magnetic spins in a paramagnetic material are aligned via a magnetic field, resulting in a rise in temperature. This heat is removed from the material to ambient air. Upon removal of the magnetic field, the magnetic spins return to a randomized state, which cools the material to below ambient temperature. The material is then used to absorb heat from the refrigerated volume, thus cooling that space and returning the paramagnetic material to its original state, after which the cycle starts again. For room temperature applications, materials are needed that have a Curie temperature (the temperature above which ferromagnetic materials lose their permanent magnetism) around 295 K. Gadolinium and Gadolinium alloys have a large MCE around this temperature range and they are among the most widely investigated materials for room temperature refrigeration and space cooling applications.[17]

An early working prototype was developed at the Ames Laboratory. Figure 5-6 shows an early-stage prototype that demonstrated a temperature span of 38 K, and a maximum cooling power of 600 Watts. Two of the biggest technical barriers remaining for this prototype were its large size and high strength of the magnetic field.[18]

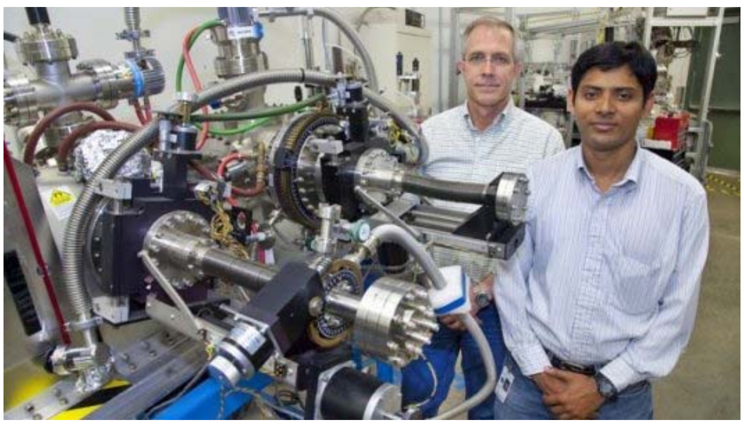


Figure 5-6: Magnetic refrigeration prototype at Ames Laboratory

General Electric (GE) and Oak Ridge National Laboratory (ORNL) have developed a more refined working prototype, as seen in Figure 5-7.[19] The system uses a water-based fluid to transfer heat from inside the refrigerator and achieve the cooling process. The GE and ORNL prototype can reduce the temperature of the water-based fluid by 80 degrees Fahrenheit and provide 60W of cooling, with the ultimate goal of reducing the temperature by 100 degrees Fahrenheit and providing 100W of cooling.[20] Although this prototype is much smaller than

[17] "The Magnetocaloric Effect" http://magnetocaloric.web.ua.pt/mce.html.
"Magnetocaloric effect and magnetic cooling near a field-induced quantum-critical point" http://www.pnas.org/content/108/17/6862.full.pdf.
[18] "Magnetic Refrigeration" http://www.che.cemr.wvu.edu/publications/projects/prod_design/magnetic_refrigerator.pdf.
Image source: http://www.gizmag.com/giant-magnetocaloric-effect-in-fridges/15624/.
[19] Image source: http://www.gizmag.com/ge-magnetocaloric-refrigerator/30835/
[20] "Your next fridge could keep cold more efficiently using magnets" http://www.gizmag.com/ge-magnetocaloric-refrigerator/30835/.

earlier prototypes, further size reductions would be required to incorporate this into a residential system. The current prototype is about 20 percent more efficient than typical residential refrigeration systems, and GE is aiming to release a working residential magnetic refrigerator with the next five years.[21]

Figure 5-7: GE magnetic refrigeration prototype

A French firm announced it will launch a magnetic "compressor replacement unit" for use in a retail integrated cold counter in the latter part of 2014, as seen in Figure 5-8.[22] The company's commercial magnetic refrigeration system is currently in production. It claims energy savings of up to 50 percent, although these claims have not been substantiated in the field.[23]

In 2013, a Cambridge, England based company stated it was in advanced field trials with a major U.S. manufacturer for the production launch of a residential magnetic refrigerator in Europe within the next two years. The product would use an iron-based alloy to provide the magnetic charge in the system, which would reduce the price of the technology considerably compared to current magnetic refrigerator prototypes that use expensive rare-earth permanent magnets.[24] The

---

"GE's magnetic fridge could reinvent refrigeration in just 5 years" http://www.geek.com/science/ges-magnetic-fridge-could-reinvent-refrigeration-in-just-5-years-1587808/.

[21] "From Ice Block to Compressors to Magnets: The Next Chapter in Home Refrigeration" http://pressroom.geappliances.com/news/from-ice-blocks-to-compressors-to-magnets:-the-next-chapter-in-home-refrigeration

[22] "The View of Europe: The attraction of magnetic refrigeration" http://www.multibriefs.com/briefs/exclusive/view_magnetic_refrigeration.html#.U-vUqPldU8Q.
Image source: http://www.cooltech-applications.com/magnetic-refrigeration-system.html.

[23] Cooltech website: http://www.cooltech-applications.com/magnetic-refrigeration-system.html.

[24] "New Directions in Refrigeration" http://www.achrnews.com/articles/124702-new-directions-in-refrigeration.

company claims its magnetic refrigeration system will be twice as efficient as a typical European residential refrigerator.[25]

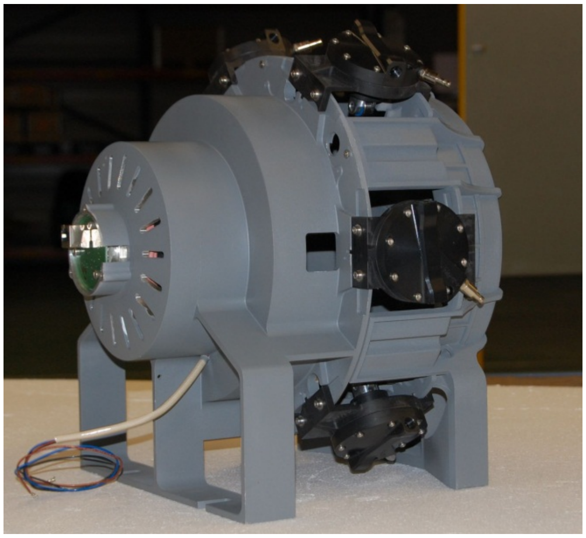


Figure 5-8: Magnetic refrigeration system for commercial applications

Researchers and refrigerator manufacturers continue to work on refining working laboratory prototypes. In order to develop a residential magnetic refrigerator, the technology will need to demonstrate equivalent cooling capacity as a typical residential refrigerator. In addition, the technology must be further reduced in size to fit within the internal space constraints of a residential refrigerator. Table 5-8 and Table 5-9 describe these technical challenges and market barriers, respectively.

Finally, geo-political factors may represent a barrier hindering the use of rare earth magnetic materials, since most of these materials used in the U.S. are imported. Additionally, demand for these metals has increased in recent years as the number of applications that they are used in increases, e.g. smartphones, wind turbines, and electric vehicles.[26]

[25] "The View of Europe: The attraction of magnetic refrigeration" http://www.multibriefs.com/briefs/exclusive/view_magnetic_refrigeration.html.
[26] "Your Next Refrigerator Could be a Magnet" http://www.smartplanet.com/blog/bulletin/your-next-refrigerator-could-be-a-magnet/.

Table 5-8: Technical Barriers – Magnetic Refrigeration

Technical Barrier	Description
High First Cost	Current cost estimates, based on prototypes from GE research, are four times more expensive relative to conventional alternatives.[27] The first cost of magnetic refrigeration will need to come down significantly to compete in mass markets. BTO's 5-year target for non-vapor compression system is an installed cost premium of $285.[28]
Large Footprint	Prototype magnetic refrigeration systems are large and require a substantial footprint compared to vapor-compression systems. To be feasible in a residential refrigerator, the size of magnetic refrigeration systems will need to be substantially decreased to fit inside a residential refrigerator.
Cooling Capacity	Current prototypes do not demonstrate the cooling capacity required for a residential refrigerator.
Reliability	Magnetic refrigerators will need to be as reliable as conventional alternatives.
Noise Levels	Current prototypes exhibit increased noise levels associated with the valves and pumps required to operate the magnetic system

Table 5-9: Market/Deployment Barriers – Magnetic Refrigeration

Market Barrier	Description
High Upfront Cost	Consumers may not accept higher upfront costs without a strong value proposition for purchasing the new technology.
Rare-Earth Magnet Availability	Political factors are affecting market stability, and demand for permanent magnets is increasing from other sectors (hybrid vehicles, electronics, and wind turbines).
Lack of trained salesforce	Lack of salesforce training can create market barriers if sales associates are unable to vouch for the new technology and advocate its benefits to potentially skeptical consumers.

The recommended R&D activities include a multi-year program to demonstrate the required cooling capacity of a residential refrigerator/freezer, demonstrate equivalent performance using iron-based alloy, and develop a system small enough to fit in a typical residential refrigerator. In the long-term, magnetic refrigeration shows the potential to be a viable replacement for

[27] Source of current cost estimate: http://www.geek.com/science/ges-magnetic-fridge-could-reinvent-refrigeration-in-just-5-years-1587808/.
[28] http://energy.gov/sites/prod/files/2014/05/f15/BTO_PeerReview_ET_Overview_042214.pdf.

traditional vapor-compression systems, with greater energy efficiency. Therefore, this is a high-priority technology option that DOE should continue to support over the next several years. Figure 5-9 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.

Near-Term (1-3 Yrs)	Mid-Term (3-5 Yrs)	Long-Term (5-10 Yrs)
Action Items: » Identify ways to improve the cooling capacity of prototype systems » Further investigate the use of iron-based alloys » Develop full-system prototypes that incorporate all the other components of a residential refrigerator » Publish research findings as appropriate	**Action Items:** » Refine prototype designs as needed » Develop a system exhibiting the required cooling capacity and small enough to fit in a typical residential refrigerator	**Action Items:** » Develop full-size magnetic refrigerator that can be brought to market » Test full-size magnetic refrigerator in residential settings
Milestones: » Demonstration of cooling capacity of typical residential refrigerator » Demonstration of equivalent performance using iron-based alloy » Published research findings	**Milestones:** » Demonstration of prototype residential-sized magnetic refrigerator » Published research findings	**Milestones:** » Completion of field testing » Expansion of the number and types of products that can use magnetic refrigeration

Figure 5-9: Timeline and Milestones – Magnetic Refrigeration

Table 5-10 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 5-10: Stakeholder Involvement – Magnetic Refrigeration

Tasks	Key Stakeholders
R&D	» Independent research firms – prototyping, scientific evaluation » National laboratories – prototyping, design/field support » Universities – research support » Manufacturers – prototyping, design/field support
Validation and Testing	» Primary: National laboratories, independent testing facilities, manufacturers, DOE-BTO » Secondary: Utilities, energy efficiency organizations
Deployment	» Manufacturers – product roll-out, technician training, marketing » DOE – commercialization support » Retailers – sales, product display

5.1.4 Heat Pump Clothes Dryers

Heat pump dryers function using a refrigeration-dehumidification system to remove moisture from the air, and then recirculating the exhaust air back to the dryer. A heat pump dryer is essentially a dryer and a dehumidifier packaged as one appliance. The warm and damp exhaust air of the dryer enters the evaporation coil of the dehumidifier, where it cools down below the dew point, and sensible and latent heat are extracted. The heat is transferred to the condenser coil by the refrigerant and reabsorbed by the air, which is moving in a closed air cycle. A drain is required to remove the condensate; however, one is usually available since clothes washers and dryers are typically located side by side.

Research conducted on both heat pump dryers and conventional vented dryers on the European market showed that heat pump dryers consumed about 50 percent less energy than conventional dryers. The heat pump dryers tested had energy efficiency values between 0.32 and 0.40 kWh/kg laundry (with 70 percent initial moisture, measured according to test standard EN 61121), whereas conventional dryers had values between 0.6 and 0.8 kWh/kg laundry. Another benefit noted by this research was that the leakage of water vapor into the room was around 20 percent, which is significantly lower than conventional dryers. A life-cycle cost analysis showed that the combined sale price and electricity costs of a conventional dryer over 15 years is around 2300 Euros, compared to 1900 Euros for a heat pump dryer—a savings of 400 Euros over the expected lifetime of the product.[29]

Heat pump dryers have yet to penetrate the U.S. market despite showing significant energy savings. The major issues for heat pump dryers have been cost and performance. Heat pump dryer cycle times are typically significantly longer than those associated with standard U.S. electric dryers. More maintenance will likely be required for a heat pump dryer than for a conventional dryer. The traditional heating element is replaced by equipment found in a small

[29] United States Department of Energy. Final Rule Technical Support Document: Residential Clothes Dryers and Room Air Conditioners. April 21, 2011. Chapter 3, Market and Technology Assessment: http://www.regulations.gov/#!documentDetail;D=EERE-2007-BT-STD-0010-0053.

room air conditioner— a condenser, evaporator, compressor, expansion valve, etc. Installation costs, though, may be less than for a conventional electric dryer because the heat pump dryer may not require an exhaust vent as does a conventional dryer (although some heat pump dryers may still use a vent). However, heat pump dryers require access to a drain for removal of condensate.

A technology development firm and a leading U.S. manufacturer developed a high efficiency, high-performance heat pump clothes dryer prototype intended for the U.S. market. This different approach to the heat pump system maximized the output capacity and temperature from the heat pump. This design has shown 40 to 50 percent energy savings on large loads along with 35 degree Fahrenheit (°F) lower fabric temperatures and similar drying times as conventional dryers. For delicate loads, the design reduced fabric temperature by 10–30 °F and provide up to 50 percent energy savings and 30–40 percent drying time savings. The heat pump dryer designed by the two companies also exhibited improved fabric temperature uniformity as well as robust performance across a range of vent restrictions in a partially open-loop design.[30]

A major Asian appliance manufacturer has publically stated that it plans on releasing a heat pump clothes dryer on the market in the summer of 2014. The company claims that it will be up to 50 percent more efficient than standard clothes dryers. The price will be similar to that of high-end models currently on the market.[31] A major U.S. manufacturer has also stated that it plans on releasing a heat pump clothes dryer to select U.S. markets in the fourth quarter of 2014, and will expand to other U.S. markets in early 2015.[32]

Table 5-11 and Table 5-12 describe the technological challenges and market barriers, respectively, facing heat pump clothes dryers.

Table 5-11: Technical Challenges – Heat Pump Clothes Dryer

Technical Barrier	Description
High Manufacturing Cost	The materials and processes that are needed to make heat pump clothes dryers are more expensive than traditional clothes dryers. Heat pump clothes dryers are generally more complex than traditional clothes dryers, which adds to the manufacturing cost.
Longer Drying Times	Cycles that use the heat pump to aid in drying require longer drying times.
Reliability	Because heat pump clothes dryers are more complex than traditional clothes dryers, reliability may be an issue once they enter the market.

[30] Ibid.
[31] http://www.consumerreports.org/cro/news/2014/01/lg-s-new-dryer-saves-energy-and-money/index.htm.
[32] http://investors.whirlpoolcorp.com/releasedetail.cfm?ReleaseID=860720.

Table 5-12: Market/Deployment Barriers – Heat Pump Clothes Dryer

Market Barrier	Description
High Upfront Cost	Consumers may not be willing to pay the higher upfront cost of a heat pump clothes dryer despite the potential lifetime energy savings.
Longer Drying Times	Consumers may not be willing to buy a heat pump clothes dryer if the drying time is longer than a traditional dryer.
Lack of Trained Salesforce	Lack of salesforce training can create market barriers if sales associates are unable to vouch for the new technology and advocate its benefits to potentially skeptical consumers.

Figure 5-10 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to fully commercialize this technology.

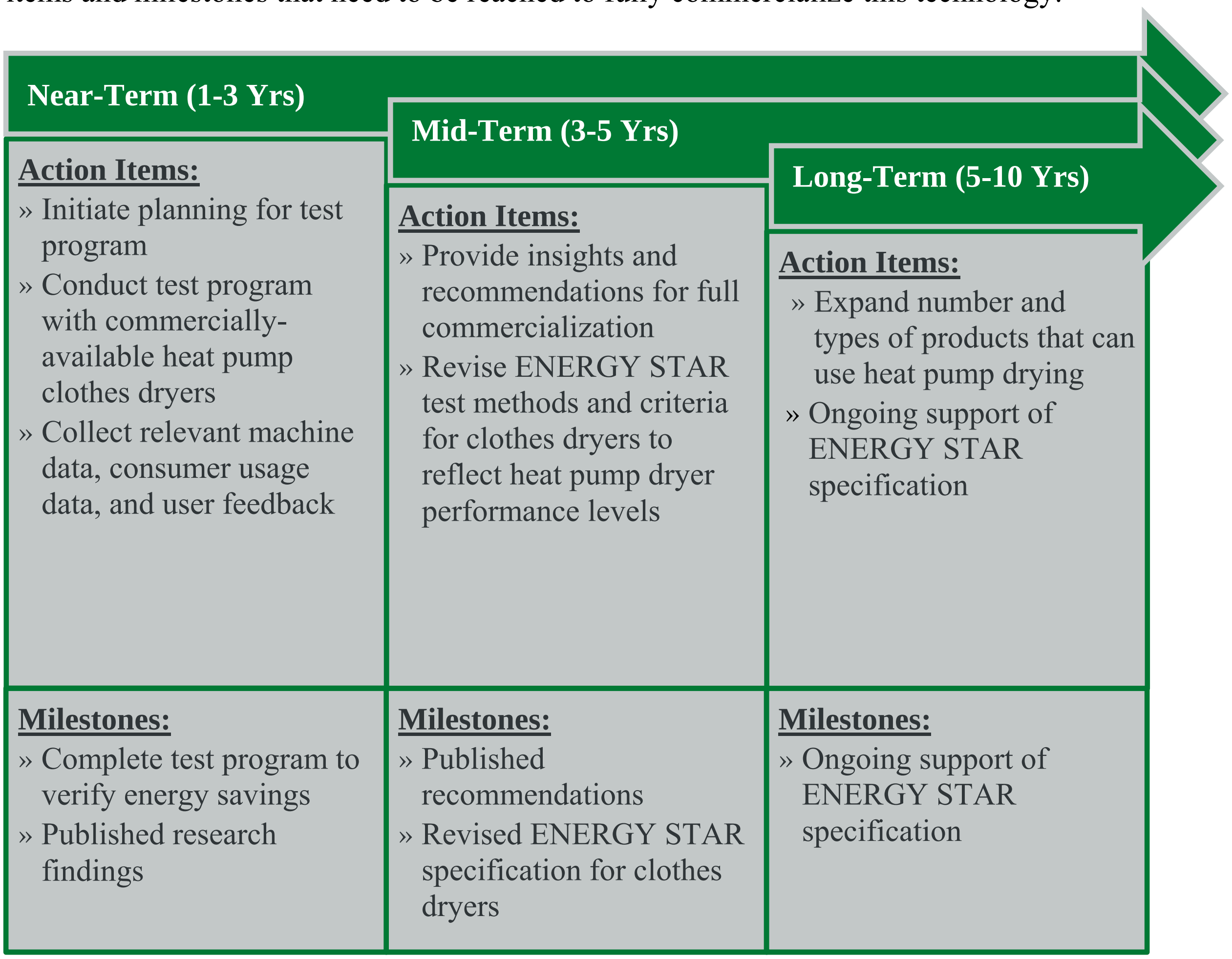


Figure 5-10: Timeline and Milestones – Heat Pump Clothes Dryers

Table 5-13 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 5-13: Stakeholder Involvement – Heat Pump Clothes Dryers

Tasks	Key Stakeholder Roles and Responsibilities
Validation and Testing	» Primary: National laboratories, independent testing facilities, manufacturers, consultants » Secondary: Utilities, energy efficiency organizations
Specification Development	» Environmental Protection Agency – specification development » DOE – test procedure and verification support

5.1.5 Medium and Low Priority Direct-Impact Technologies

The following technologies, though not articulated as in-depth as the high-priority technologies, also represent opportunities for energy savings and could also be considered for future R&D activities. Appendix A provides additional details on each technology.

5.1.5.1 Mechanical steam compression clothes dryers (electric only)

The Center for Energy Studies (CES) in Paris, France has developed a super-heated steam dryer concept using mechanical steam compression. The CES has completed preliminary performance testing on a compressor that could be used in such a system. Computer simulations have been conducted to model the performance of a complete working system; however, we are unaware of any fully-assembled working laboratory prototype.

The recommended R&D program includes development of the remaining components required in the system, integration into a fully functional prototype, and preliminary energy performance testing. Because the laboratory developing this technology is located in France, a cooperative research agreement would need to be reached with a national laboratory or academic institution in the U.S.

5.1.5.2 Thermoelastic refrigeration

Thermoelastic cooling is based on a thermoelastic shape memory alloy that releases heat when compressed and returns to its original shape when heated. Researchers are developing a 0.01-ton prototype with the goal of establishing the commercial viability of thermoelastic cooling.

The recommended R&D program includes refining individual components to improve the cooling capacity. Many years of research will be required to create a full-size residential refrigerator/freezer using thermoelastic cooling technology.

5.1.5.3 *Polymer bead cleaning for clothes washers*

Polymer bead cleaning technology is currently in development by a company in the United Kingdom. The company has successfully installed this technology in various commercial-scale dry cleaning settings and other industrial laundry settings in the U.S. Development is ongoing to create prototypes for residential use.

To accelerate the development of this technology for residential application, we recommend creating a cooperative research agreement with the manufacturer to support the ongoing development of a residential prototype that would be relevant to the U.S. laundry consumers. This R&D effort would culminate in the demonstration of a residential prototype under laboratory conditions. In addition, we recommend investigating any environmental or human health and safety risks associated with the usage and disposal of polymer beads in a residential setting.

5.1.5.4 *Thermoelectric refrigeration*

Thermoelectric cooling occurs when a current is passed across the junction of two dissimilar metals. One side of the device becomes hot and the other becomes cold. Several compact refrigerators and wine coolers using thermoelectric cooling are currently available on the market, including several models offered by a U.S. appliance manufacturer. However, their efficiency is lower than traditional vapor-compression models, and the technology is not yet suitable for standard-size residential refrigerator-freezers. One potential area for development would be to use thermoelectric cooling in conjunction with traditional vapor-compression systems. For example, a residential refrigerator could achieve most of its cooling needs using vapor compression, while using thermoelectric cooling for enhanced features within the refrigerator (i.e. to provide more precise temperature control of the food drawers). Such a hybrid system could be more efficient than using vapor compression or thermoelectrics individually.

The recommended R&D program includes development of a full-sized prototype, energy performance testing, and additional design and development based on preliminary test results.

5.1.5.5 *Inlet air preheating for clothes dryers*

One company has developed a heat recovery wheel that provides dryer inlet air preheating in a commercial laundry setting. Limited testing has been performed to provide energy savings estimates in a commercial setting. We are unaware of any adaptations of this technology for use with residential clothes dryers.

The recommended R&D program includes developing a smaller-scale version of the heat recovery wheel that could be applied to residential clothes dryers. The external cabinet of a residential clothes dryer would be modified with an air inlet to be compatible with the heat wheel. The prototype system would be tested to determine the energy savings potential of heat wheel technology in a residential setting. Further design work could be performed to investigate the feasibility of installing the heat exchange system inside the dryer cabinet.

5.1.5.6 *Stirling cycle refrigeration*

A Stirling cycle machine is a device that operates on a closed regenerative thermodynamic cycle, with cyclic compression and expansion of the working fluid at different temperature levels. The flow of the working fluid is controlled by volume changes, so that there is a net conversion of heat to work, or vice versa. A Stirling refrigeration cycle compresses and expands an inert gas in a single cylinder. Heat is rejected at one end of the cylinder and absorbed at the opposite end. In the absence of all thermodynamic losses, the efficiency could be higher than for vapor compression systems. Various technical difficulties have so far limited the use of Stirling cycle cooling to small prototype residential refrigerators.

Stirling cycle technology is well known, but has not been shown to be more efficient than vapor compression. Thus, manufacturers have not pursued this technology. The recommended R&D program includes developing and testing a full-sized residential prototype.

5.1.5.7 Sanitizing agents for clothes washers

Certain sanitizing agents, such as chemical or ionic compounds, can be added to the incoming cold wash water to reduce the need for hot water washing. A clothes washer using such sanitizing agents could offer cooler wash cycles that provide sanitization of the clothing; such wash cycles typically require hot water temperatures up to 140°F.

One example of a sanitizing agent is the addition of silver ions to the cold wash water. Silver is a natural disinfectant and can provide sanitization during a cold water wash. A leading Asian appliance manufacturer previously introduced this technology to the market. However, concerns about potential health and environmental risks arose after these clothes washers entered the market. This technology has since been withdrawn from the market.

The recommended R&D program includes assessing the environmental and human health risks associated with silver ion and other sanitizing agents that may be added to the wash water. The assessment would include an investigation of the risks associated with sanitizing agents in wastewater discharge. This recommended research program could alleviate concerns associated with various sanitizing agents and could help promote the usage of cold water wash cycles.

5.1.5.8 Indirect heating for clothes dryers

A U.S. company has developed a hydronic heating system for electric dryers. The company claims that its clothes dryer uses 50 percent less energy compared to a conventional clothes dryer; however, there are three models that are certified on the market that show similar energy savings when compared to other high-efficiency clothes dryers. The hydronic dryer may benefit from back-to-back laundry cycles, which are not accounted for in the DOE energy efficiency test procedure.

The recommended program involves conducting testing to evaluate the energy savings potential of this technology when back-to-back laundry cycles are conducted. This testing program would resolve specific questions that arose during the most recent energy efficiency standards rulemaking for clothes dryers. In addition, an assessment would be made of any potential safety risks associated with the clothing cool-down period. Lack of an adequate cool-down period could pose a fire hazard.

5.1.5.9 Specialized cookware

Cookware modified with fins or grooves along the bottom surface have been shown to significantly increase gas cooktop efficiency. Heat-up times are substantially reduced and production capacities increased. A U.S. company has developed two unique pot designs that use aluminum fins to increase the surface area exposed to the burner flame, thereby increasing the rate of heat transfer to the bottom of the pot. This type of cookware may also be well-suited for commercial cooking applications, where larger quantities of food are prepared and the annual energy consumption of the cooking equipment is much more substantial.

The recommended program involves quantifying the energy efficiency potential of specialized cookware in a residential setting, and supporting the development of an ENERGY STAR specification for specialized cookware.

5.1.5.10 Microwave clothes dryer (electric only)

Previous research by the Electric Power Research Institute (EPRI) led to the development and testing of prototype microwave dryers. Serious safety concerns were raised due to electrical arcing between metallic objects in the microwave dryer. EPRI investigated some approaches to mitigating the risk of arcing; however, the persistence of safety concerns has resulted in the abandonment of any major R&D activities related to microwave drying.

The recommended R&D program includes investigating techniques for eliminating the major safety concerns associated with microwave clothes drying, such as through the use of advanced sensors or by creating a hybrid system that combines microwave drying with traditional drying. If the major safety concerns can be resolved, R&D efforts would continue with the development of demonstration units that could be tested in a pilot test program in residential settings.

5.1.5.11 Induction cooktops

Induction cooktops use an inductor and the creation of magnetic fields to generate heat from specialized cooking vessels. Induction cooktops are currently available on the market, but the technology is currently not accommodated by the DOE test procedure for cooking equipment. DOE has an ongoing rulemaking to develop a test procedure for induction cooktops. Although induction cooktops were originally considered much more energy-efficient than traditional electric cooktops, analysis during the DOE test procedure development shows that induction cooktops do not provide a significant efficiency improvement over conventional smooth electric cooktops.

The recommended activities include finalizing a test method to incorporate into the DOE test procedure, and supporting the development of an ENERGY STAR rating for residential cooktops.

5.2 Roadmap for Enabling Technology R&D Initiatives

As discussed in section 1.4, enabling technologies indirectly improve energy efficiency of appliances. Table 5-14 lists the two enabling technologies identified during roadmap development. Appendix A provides additional details on each of the enabling technologies.

Table 5-14: Prioritized List of Enabling Technologies

Technology/Initiative	Priority
Cross-Cutting Technologies: Integrated heat and water recovery	High
Cross-Cutting Technologies: "Smart" appliances	Low

Enabling technologies 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 technologies therefore cannot be compared on a quantitative basis with the direct-impact technologies (see section 5.1). DOE therefore cannot compare them with other potential R&D investments, across all potential building technology opportunities, using the P-Tool. The following section document the details of the recommended enabling technologies, including barriers, action items, and stakeholder roles and responsibilities.

5.2.1 Integrated Heat and Water Recovery Across Multiple Appliances

A variety of technologies have been proposed in the home appliance space that would enable energy savings across multiple residential appliances. These proposals and concepts consider residential appliances as an interconnected system rather than individual, distinct appliances.

A major U.S. manufacturer has proposed an integrated kitchen design concept, shown in Figure 5-11, where waste water and heat would be captured from one appliance and re-used by another. The system would capture heat from the refrigerator's compressor and use it to pre-heat the dishwasher water. It estimates that 60% of the water in the integrated system could be captured, sanitized, and then stored in an external water tank under the sink. This water could then be used for the dishwashing cycle. The manufacturer estimates that savings would result in 7 liters (1.8 gallons) of water per cycle and up to 20% savings of electricity with the same washing performance. The refrigerator would be compartmentalized into drawers to prevent cold air from spilling out when the doors are opened. In total, the manufacturer estimates this concept could increase water and energy efficiency by up to 70%.[33]

[33] http://www.whirlpoolcorp.com/about/design/green_kitchen/
Image source: http://cubeme.com/whirlpools-green-kitchen-concept/

Figure 5-11: Prototype integrated kitchen

Another concept, the Propane Energy Pod from the Propane Education & Research Council (PERC), is intended to serve as a new energy model for homes. PERC describes it as a research-based solution for home construction that treats five areas of energy use in a home: space heating, water heating, cooking, clothes drying, and fireplaces, all as part of a whole-home energy package. The model is designed for significant reductions in energy consumption and carbon emissions when compared to homes with standard appliances and mechanical systems. The Propane Energy Pod includes mechanical systems with high-efficiency amenities, such as on-demand hot water, professional-grade cooktops, and switch-on fireplaces. According to a study by Newport Partners, a home built using the Propane Energy Pod model can save homeowners about $285 in annual energy costs.[34]

Additionally, ORNL has developed a ZEHcor Interior Utility Wall concept, as seen in Figure 5-12. The ZEHcore wall concept is a pre-fabricated wall to which all kitchen and laundry appliances would be connected, including major bathroom fixtures. The wall would be built off-site in a controlled environment. It is designed to reduce hot water distribution losses and enable a high level of integration between appliances that could not otherwise be accomplished reliably on-site. The ZEHcore wall could also be integrated with an external foundation heat exchanger.[35]

[34] http://www.propanecouncil.org/PressReleases.aspx?id=3864&pressreleaseId=6732
[35] http://e2s2.ndia.org/pastmeetings/2009/tracks/Documents/8240.pdf.

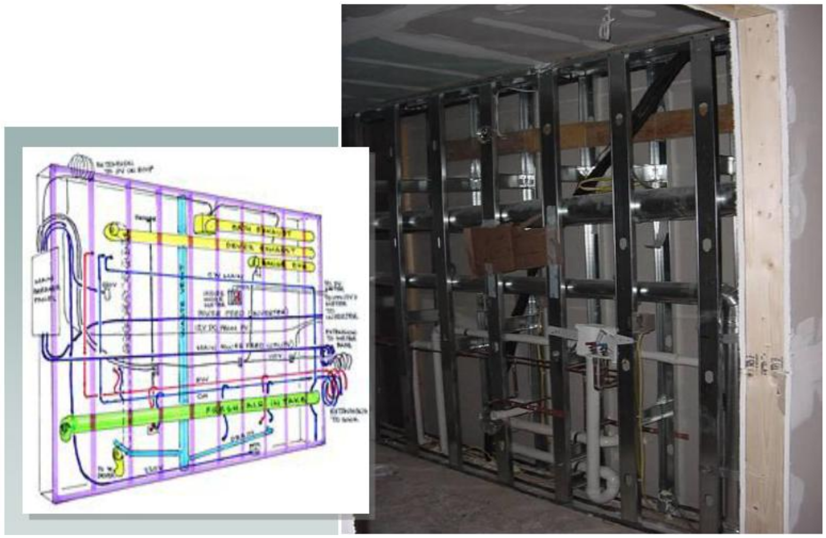


Figure 5-12: ZEHcor Interior Utility Wall designed by ORNL

The integrated kitchen design concept and Propane Energy Pod are conceptual in nature only and would require long-term investments in R&D to bring the concepts to fruition. The ZEHcor wall concept has been prototyped and is further along in development; however it, too, would require a long development time frame to be fully implementable in a residential setting.

Table 5-15 and Table 5-16 describe the technological challenges and market barriers, respectively, facing cross-cutting technologies.

Table 5-15: Technical Challenges – Cross-Cutting Technologies

Technical Barrier	Description
High Manufacturing Cost	This concept would require changes to manufacturing processes and additional hardware to allow energy and water transfer between appliances. This will increase the manufacturing cost of typical kitchen appliances.
Unproven Feasibility	Energy and water recover and transfer concepts have not been proven in laboratory settings or the real world.
Unproven Savings	Energy and water savings have not been proven in laboratory settings or the real world.
Manufacturing Changes	This concept would require changes to manufacturing processes to allow appliances to recover and transfer energy and water.
Regulatory Codes	Numerous regulatory issues would need to be considered, including: building codes, UL, NSF, DOE standards.

Table 5-16: Market/Deployment Barriers – Cross-Cutting Technologies

Market Barrier	Description
High Upfront Cost	Integrated energy and water recovery and transfer between appliances would require a total redesign of typical kitchen appliance layouts. Consumers may not be willing to pay this high upfront cost.
New Construction versus Retrofit	Because integrated energy and water recovery and transfer systems require a total redesign of a typical kitchen layout, this type of system is only viable for new construction only and not retrofits.
Consumer Acceptance	Consumers may not accept the integrated kitchen if it required different usage patterns. Consumers may also be reluctant to reuse waste water.
Homebuilder Acceptance/Promotion	Due to the revolutionary nature of this technology, its adoption is likely to be limited initially to niche homebuilders that focus on high-performance “eco-friendly” homes. The broader homebuilder industry would be unlikely to embrace this technology until it is well-proven and the broader market demonstrates sufficient demand for the technology.
Marketing Changes	Marketing changes may be required to shift away from a single-appliance focus.

Figure 5-13 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.

Near-Term (1-3 Yrs)	Mid-Term (3-5 Yrs)	Long-Term (5-10 Yrs)
Action Items: » Replicate or revisit ZEHcore prototype wall system » Test prototype system under typical usage » Characterize heat transfer and water recovery performance » Modify and optimize prototype based on preliminary test results	**Action Items:** » Perform follow-on testing of prototype energy and water recovery/transfer system to measure performance improvements » Install optimized prototype system in pre-fabricated residential dwellings » Measure energy and water consumption for a period of one year	**Action Items:** » Support the development of systems that can be brought to market » Initiate production at scale
Milestones: » Test integrated kitchen prototype » Published research findings	**Milestones:** » Complete testing of optimized prototype in residential dwellings » Published research findings	**Milestones:** » Bring system to market

Figure 5-13: Timeline and Milestones – Cross-Cutting Technologies

Table 5-17 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 5-17: Stakeholder Involvement – Cross-Cutting Technologies

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» Independent research firms – prototyping, scientific evaluation » National laboratories – prototyping, design/field support » Universities – research support » Manufacturers – research support
Validation and Testing	» Primary: National laboratories, independent testing facilities, manufacturers » Secondary: Utilities, energy efficiency organizations
Deployment	» Manufacturers – product roll-out, sales training, marketing » DOE – commercialization support » Retailers – sales, product display

5.2.2 Medium and Low Priority Enabling Technologies

The following technology, though lower priority, could also be considered for future R&D activities.

5.2.2.1 "Smart" appliances

The Association of Home Appliance Manufacturers (AHAM) defines smart appliances as appliances that monitor, control and protect their electrical energy usage in response to customer needs. The appliance control and interface software may enable the appliances to participate in demand response and time-based rate programs with the local utility. Alternatively, the appliances may connect to the internet through smartphone applications, which may enable additional energy-saving and other non-energy benefits.

One of the primary benefits of "smart grid" technologies is to shift loads from peak times to off-peak times. Smart appliances may demonstrate the following demand-response capabilities:

- A refrigerator could shift its energy-intensive defrost cycle to non-peak times.
- A clothes dryer could encourage the end-user to delay usage until off-peak hours.
- A water heater could pre-heat water during off-peak hours.
- An air conditioner could automatically reduce its load during peak hours.

Examples of energy-saving features enabled by smart appliances include:

- A refrigerator could be easily (or automatically) switched into "vacation mode," suspending the ice maker and auto-defrost feature until the user returns home.
- A refrigerator could send an alert to a user's smartphone to indicate that the door has been left open.
- A clothes dryer could send an alert to a user's smartphone to indicate a clogged dryer vent, which would decrease the efficiency of the dryer.

Smart appliances will play an essential role in the smart grid by facilitating large-scale residential demand response. By shifting residential appliances' usage from peak to off-peak periods, peak electricity usage will be reduced. Lower peak loads will improve the health and stability of the power grid and will reduce long-term investments in expensive generation.

Appliances with smart grid capabilities exist on the market today. Major U.S. manufacturers have platforms that allow the user to monitor and manage their smart appliances through a mobile phone app or online.[36] A major Asian manufacturer also has a line of appliances that allows customers to monitor and control their appliances through a mobile phone app. These appliances are also smart grid ready, allowing the appliance to communicate with the local utility to participate in demand response scenarios.[37]

As currently implemented, the features available on "smart" or connected appliances are largely limited to consumer convenience features. Demand-response and other smart-grid capabilities are given secondary consideration in manufacturer advertising material. While smart-grid features may help improve the overall stability of the electric power grid, the potential for smart appliance features to enable energy savings is limited.

[36] https://mysmartappliances.com/.
[37] http://www.lg.com/us/discover/smartthinq/thinq.

Appendix A – Description of Appliance Technology Options

This appendix provides detailed descriptions of each technology option, including current development status and links to relevant source information. The order of technology descriptions corresponds to the order in which the technologies are presented in the final report above.

A.1 Refrigerator/Freezers

A.1.1 Advanced Compressor Technologies

The compressor is the primary energy-consuming component in a refrigerator, refrigerator-freezer, or freezer. Therefore, technologies that can advance compressor efficiency have a significant effect on overall product efficiency. Residential refrigeration products use positive-displacement compressors in which the entire motor-compressor is hermetically sealed in the welded steel shell. Two types of compressors have been used in residential refrigeration products over the years—reciprocating and rotary. However, predominantly reciprocating compressors are now used in U.S. products. High-efficient compressors are in development and some are already incorporated in residential refrigerators currently on the market. The high-efficient compressor technologies that we identified for this roadmap are linear compressors and electrochemical compressors.

Linear compressors employ a different design than either reciprocating or rotary compressors and are reportedly more efficient than both. These compressors use a linear rather than rotary motor, thus eliminating the crankshaft and linkage which converts the rotary motion to the linear motion of the piston of a reciprocating compressor. Elimination of the mechanical linkage reduces friction and side-forces. The linear motor requires power electronics and a controller to assure proper piston throw. Most linear compressor designs use a free piston arrangement and can be controlled for a range of capacities through adjustment of piston displacement. Early work on the concept suggested that the compressors can operate without requiring oil, which could provide additional energy benefit by improving heat transfer in the evaporator. Refrigerator noise levels can also be reduced by utilizing linear compressors in the same way that this can be done with variable-speed compressors, by operating most of the time at low capacity.

A leading Asian appliance manufacturer has developed a linear compressor for household refrigerators which does require use of oil. It claims that its line of linear compressors is up to 20 percent more efficient than reciprocating designs, and emits lower noise levels. The manufacturer reports the efficiency of its linear compressors only at “Reference Conditions,” which are significantly different than the ASHRAE rating conditions. Under ASHRAE conditions, compressors are rated with evaporating and condensing temperatures of -10 degrees Fahrenheit and 130 degrees Fahrenheit, respectively, while the “Reference Conditions” are based on evaporating and condensing temperatures of -14.8 degrees Fahrenheit and 100.4 degrees Fahrenheit, respectively. It is not clear what the liquid and suction vapor temperatures for the manufacturer conditions are - these temperatures also impact capacity and power input. As a result, its linear compressor may be about 9% more efficient than the best current-technology rotating-shaft reciprocating compressors.

A compressor manufacturer has developed an oil-free compressor for home appliances, as seen below. Instead of using oil, the only moving part uses the refrigerant gas itself as lubrication. The manufacturer claims the product is smaller and quieter than other compressors used in refrigerators. Press releases claim the product is 20% more efficient than the most efficient refrigerator compressors. These oil-free compressors have not yet been introduced to the U.S. refrigerator market.

Electrochemical compressors are currently under development, and use a proton-pump to drive compression and a refrigerant. An electrochemical compressor incorporates membrane-electrode-assemblies separated by proton exchange membranes in series to reach higher pressures. When a current is passed through the membrane-electrode-assemblies, protons and electrons are generated at the anode. The protons are electrochemically driven across the membrane to the cathode, after which they combine with the rerouted electrons to form hydrogen, which is fed to the hydrogen compressor to be oxidized at the anode of each cell to form protons and electrons. When the reactions are complete, the fluid is at a higher pressure than when the fluid entered the system.

A U.S. company has developed an electrochemical compressor that uses non-fluorinated refrigerants. It claims their electrochemical compressor reduces energy used in refrigeration cycles by at least 20 percent, and reduces noise when compares to traditional refrigerator compressors. The compressor is still in prototype form. The company plans on first using its compressor in residential water heating applications, before moving along to other products.

Sources:
1. United States Department of Energy. Final Rule Technical Support Document: Refrigerators, Refrigerator-Freezers, and Freezers. August 25, 2011. Available online at http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrig_finalrule_tsd.pdf
2. LG product website: http://www.lg.com/us/kitchen/refrigerator/energy-efficient-refrigerator.jsp
Accessed August, 2014.
1.Embraco website: http://www.embraco.com/Default.aspx?tabid=40
Accessed August, 2014.
4. Xergy Inc. website: http://www.xergyinc.com/
Accessed August, 2014.

A.1.2 Vacuum Insulation Panels

Vacuum-insulated panel (VIP) technology is based on the reduction in conductivity that occurs in a low vacuum. Typical VIPs generally consist of a core material and an airtight envelope. The intermolecular spacing within the core material increases at low vacuum levels, which causes an interference with the molecular mean free path; thus reducing the material's conductivity. The core material also provides rigid support to prevent the panel from collapsing. VIPs can be foamed in place between the cabinet liner and wrapper. They are available in a variety of geometries (e.g., flat, curved, cylindrical) with added features (e.g., holes, cut-outs). Some VIPs also include an absorber to absorb gas that leaks through the envelope. VIPs have a thermal resistance about 10 times higher than that of equally thick conventional polystyrene boards used in refrigerators.

Of significant concern for VIPs is their long-term thermal conductivity integrity. VIP thermal conductivity increases dramatically as the pressure within the VIP exceeds 100 Pa (1 mbar). The pressure increase in the VIP over time is related to several factors, including: residual gases in the VIP after vacuum, degassing from the VIP core material, and gas diffusion through the envelope pores. Improved envelopes and absorbers have been developed to prevent pressure increases from occurring in VIPs. Oak Ridge National Laboratory (ORNL) analyzed three composite VIPs and measured only a five-percent reduction in overall thermal resistance over a three-year period. ORNL demonstrated that this reduction in thermal resistance was less than the corresponding reduction for a panel without any VIPs, i.e., panels consisting only of PU foam insulation.

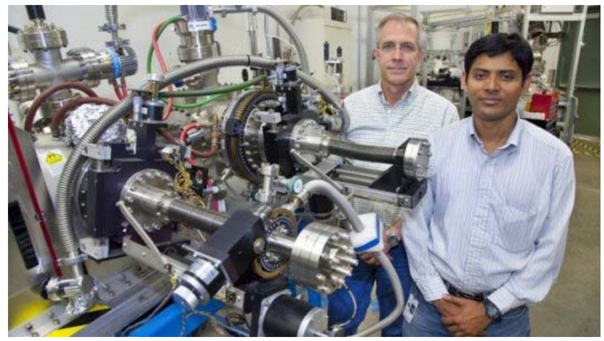
VIPs are currently commercially available, but research is ongoing in reducing the cost and longevity of VIPs. Several core materials have been used in the manufacture of VIPs including polystyrene, open-cell PU, silica powder, and glass fiber. Research sponsored by the European Commission has evaluated these core materials based on their cost and characteristics, including density and manufacturing time. Additionally, ORNL also has evaluated the performance of three types of VIPs: a silica powder filler encapsulated in a polymer barrier film; a fibrous glass insulation filler encapsulated in a stainless steel barrier; and an undisclosed insulation filler encapsulated in a stainless steel barrier.

Sources:

1. *United States Department of Energy. Final Rule Technical Support Document: Refrigerators, Refrigerator-Freezers, and Freezers. August 25, 2011. Available online at* http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrig_finalrule_tsd.pdf
2. *"Vacuum insulation panels – From research to market." Last accessed August 2014.* http://www.sciencedirect.com/science/article/pii/S0042207X07003727.

A.1.3 Magnetic Refrigeration

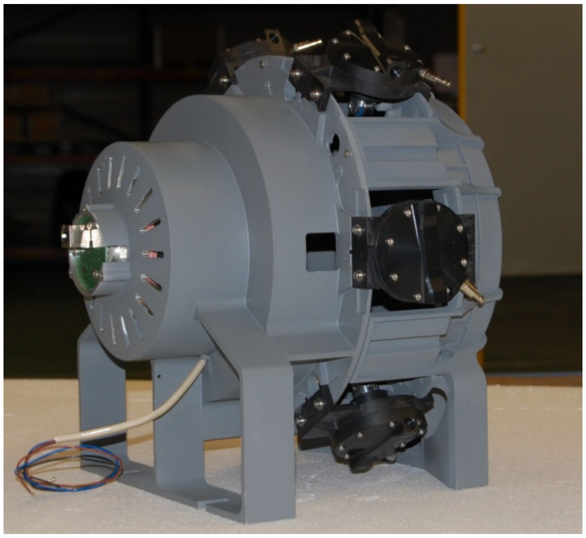
Magnetic refrigeration is based on the magneto-caloric effect (MCE). MCE is a magneto-thermodynamic phenomenon in which a reversible change in temperature of a paramagnetic material is caused by exposing it to a changing magnetic field. In the magnetic refrigeration cycle, randomly oriented magnetic spins in a paramagnetic material are aligned via a magnetic field, resulting in a rise in temperature. This heat is removed from the material to ambient by means of heat transfer. Upon removal of the magnetic field, the magnetic spins return to a randomized state, which cools the material to below ambient temperature. The material is then used to absorb heat from the refrigerated volume, thus cooling that space and returning the paramagnetic material to its original state, after which the cycle starts again. For room temperature applications, materials are needed that have a Curie temperature (the temperature above which ferromagnetic materials lose their permanent magnetism) around 295 K. Gadolinium and Gadolinium alloys have a large MCE around this temperature range and they are among the most widely investigated materials for room temperature refrigeration and space cooling applications.



A working prototype has been developed at the Ames Laboratory that demonstrated a temperature span of 38 K, and a maximum cooling power of 600 Watts. However, due to the high magnetic field, the system is not applicable for use at home.

GE and Oak Ridge National Laboratory (ORNL) have also developed a working prototype about the size of a cart, as seen below. The system uses a water-based fluid rather than a chemical refrigerant such as Freon to transfer heat from inside the refrigerator and achieve the cooling process. The GE and ORNL prototype can reduce the temperature of the water-based fluid by 80 degrees Fahrenheit and provides 60W of cooling, with the ultimate goal of reducing the temperature by 100 degrees Fahrenheit and provide 100W of cooling. The current prototype is about 20 percent more efficient than typical residential refrigeration systems, and GE is aiming to release a working residential magnetic refrigerator with the next five years.

In 2013, a French firm announced it will launch a magnetic "compressor replacement unit" for use in a retail integrated cold counter that year, as seen below. According to the firm's website, their commercial magnetic refrigeration system is currently available, with claims of energy savings of up to 50 percent. Also in 2013, a Cambridge, England based company stated it was in advanced field trials with a major U.S. manufacturer for the production launch in Europe of a residential magnetic refrigerator inside two years. They claimed to have developed an iron-based alloy to provide the magnetic charge in the system, which will bring the price of the technology down considerably. This is because current magnetic refrigerator prototypes use expensive rare-earth permanent magnets. China, one of the largest producers of rare-earth metals, has officially cited resource depletion and environmental concerns as the reasons for a decrease in rare-earth metal production. Additionally, there has been an increase in demand for these metals in recent years as the number of applications that they are used in increases, e.g. smartphones, wind turbines, and electric vehicles. They also claim their magnetic refrigeration system will be twice as efficient as a typical European residential refrigerator.



Sources:
1. *United States Department of Energy. Final Rule Technical Support Document: Refrigerators, Refrigerator-Freezers, and Freezers. August 25, 2011. Available online at* *http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrig_finalrule_tsd.pdf*
2. *Idea Connection, July 2010.* *http://www.ideaconnection.com/new-inventions/magnetic-refrigeration-03730.html*
5. *"Magnetic Refrigeration."* *http://www.che.cemr.wvu.edu/publications/projects/prod_design/magnetic_refrigerator.pdf*.
6. *"Your Next Fridge Could Keep Cold more Efficiently Using Magnets." Gizmag. Last accessed August 2014.* *http://www.gizmag.com/ge-magnetocaloric-refrigerator/30835/.*
7. *"From Ice Block to Compressors to Magnet: The Next Chapters in Home Refrigeration" GE website. Last accessed August 2014.* *http://pressroom.geappliances.com/news/from-ice-blocks-to-compressors-to-magnets:-the-next-chapter-in-home-refrigeration.*
8. *"The View of Europe: The attraction of magnetic refrigeration." Multibriefs website. Last accessed August 2014.* *http://www.multibriefs.com/briefs/exclusive/view_magnetic_refrigeration.html#.U-vUqPldU8Q.*
9. *Cooltech website. Last accessed August 2014.* *http://www.cooltech-applications.com/magnetic-refrigeration-system.html.*
10. *"New Directions in Refrigeration." Last accessed August 2014.* *http://www.achrnews.com/articles/124702-new-directions-in-refrigeration*.

A.1.4 Stirling Cycle Refrigeration

A Stirling-cycle machine is a device that operates on a closed regenerative thermodynamic cycle, with cyclic compression and expansion of the working fluid at different temperature levels, and where the flow is controlled by volume changes, so that there is a net conversion of heat to work or vice versa. "Regenerative" refers to the use of an internal heat exchanger, the regenerator, which is an essential part of the Stirling cycle. A Stirling refrigeration cycle compresses and expands an inert gas in a single cylinder. Heat is rejected at one end of the cylinder and absorbed at the opposite end. In the absence of all thermodynamic losses, the efficiency could be higher than for vapor compression systems. Various technical difficulties have so far limited the use of Stirling-cycle cooling to small prototype domestic refrigerators. There is no circulating refrigerant fluid and the hot and cold heat areas are relatively small, which creates heat exchange challenges for any but the lowest-capacity systems.

Source: United States Department of Energy. Final Rule Technical Support Document: Refrigerators, Refrigerator-Freezers, and Freezers. August 25, 2011. Available online at http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrig_finalrule_tsd.pdf

A.1.5 Thermoelastic Refrigeration

Thermoelastic cooling is based on a thermoelastic shape memory alloy (SMA) that releases heat when compressed and returns to its original shape when heated. Two or three alloys are combined in precise proportions that permit them to take on two different internal structures, depending on their temperature and pressure. Thermoelastic cooling occurs when an SMA is strained or stretched, resulting in a solid phase change of the material. This phase change is accompanied by a nearly-reversible temperature rise in the material. The material rejects heat to its surroundings in its strained state. When the SMA is relaxed from its strained state, a solid phase change occurs back to its initial phase. This phase change is accompanied by a nearly-reversible temperature drop. In the relaxed state, the SMA absorbs heat from a temperature source.

The efficiency of the thermoelastic cooling process is high, with a coefficient of performance (COP) estimated at 11.8, which is double that of state-of-the-art vapor compression technology. This technology, however, has drawbacks in its current preliminary form; these include a relatively low latent heat (~12 kJ/kg) and a limited fatigue life.

The University of Maryland, collaborating with General Electric Global Research and the Pacific Northwest National Laboratory, is developing a 0.01-ton prototype with the goal of establishing the commercial viability of thermoelastic cooling.

Sources:
1. *Quick, Darren. "'Thermally-elastic' metal to cut summer CO2 emissions and electricity bills". Gizmag July, 2010.* http://www.gizmag.com/thermally-elastic-smart-metal/15793/
2. *"Thermoelastic Cooling". Degrees.* http://www.reece.com.au/degrees/2011/Apr/thermoelastic.html
3. *"Smart Metals for Solid-State Cooling Nix Greenhouse Gases". Smarter Technology.* http://www.smartertechnology.com/c/a/Technology-For-Change/Smart-Metals-for-SolidState-Cooling-Nix-Greenhouse-Gases/
4. *"SBIR Phase I Award Abstract". NSF.* http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=1143093
5. *"Refrigeration Machines".* http://www.machine-history.com/Refrigeration%20Machines
6. *New 'Smart' Metal Could Mean Cool Cash for Consumers, Less CO2". July 15, 2010.* http://www.newsdesk.umd.edu/vibrant/release.cfm?ArticleID=2198

A.1.6 Thermoelectric Refrigeration

Thermoelectric cooling occurs when a current is passed across the junction of two dissimilar metals. One side of the device becomes hot and the other becomes cold. Semiconductor materials have relatively recently been developed that have allowed for the use of this type of cooling in some applications. Thermoelectric cooling devices have no moving parts and have extremely long lifetimes. There are several compact refrigerators and wine coolers using thermoelectric cooling that are currently on the market, including several models offered by a U.S. appliance manufacturer. However, their efficiency is lower than traditional vapor-compression models, and the technology is not yet suitable for standard-size residential refrigerator-freezers.


DOE tested a thermoelectric refrigerator from another U.S. appliance manufacturer, model HRT02WNC, a 1.7 cubic foot all-refrigerator. Testing revealed that the thermoelectric module energy efficiency ratio (EER) was 0.9 at a temperature lift of at most 33 °F, an order of magnitude less than is achieved by conventional technology.

Sources:
1. United States Department of Energy. Final Rule Technical Support Document: Refrigerators, Refrigerator-Freezers, and Freezers. August 25, 2011. Available online at http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrig_finalrule_tsd.pdf
2. Avanti Products, August 2014. http://www.avantiproducts.com/superconductor

A.2 Clothes Washers

A.2.1 Polymer Bead Cleaning

This technology is currently in development by a company in the United Kingdom. Polymer bead cleaning uses the absorbent properties of nylon polymer beads to clean clothes. The nylon beads are added to the wash drum with a small amount of water and detergent to loosen the dirt or stains on the clothing. The clothes are tumbled with the polymer beads for around 45 minutes. The polarity of the nylon polymer attracts stains from the clothing. Under humid conditions, the polymer becomes absorbent. Dirt is attracted to the surface and then absorbed into the center of the bead. At the end of the cycle, the polymer beads are separated from the clothing through an inner drum/outer drum rotation process.

Research conducted in the United Kingdom has shown that this technology would reduce water consumption by up to 80% compared to a traditional clothes washer. This technology can also reduce hot water energy and detergent use by 50%.

According to the manufacturer's website, it has successfully concluded two field trials in the United Kingdom. One field study was in a commercial-scale dry cleaning setting and the other was in a commercial-scale industrial setting. The manufacturer has also partnered with a hotel, athletic club, and commercial laundry services in the U.S. The athletic club was able to reduce water consumption by 75% with using the polymer bead washer. Additionally, development is ongoing to create prototypes for residential use. The company is open to exploring R&D partnership opportunities.

Source: Xeros, Ltd. March 2012. http://www.xerosltd.com/xeros-marketing.htm

A.2.2 Sanitizing Agents

Sanitizing agents, such as chemical or ionic compounds, can be added to the incoming cold wash water to reduce the need for hot water washing. Clothes washers using such sanitizing agents could offer cooler wash cycles that provide sanitization of the clothing; such wash cycles typically require hot water temperatures up to 140°F.

One example of a sanitizing agent is the addition of silver ions to the cold wash water. Silver is a natural disinfectant and can provide sanitization during a cold water wash. A leading Asian manufacturer previously offered silver ion injection as an alternative to the traditional hot water sanitization cycle in a line of front-loading residential clothes washers; however, clothes washers with this feature are no longer available on the market. With this feature, silver is electrolyzed during the wash and rinse cycles, and, according to the manufacturer, the released silver ions penetrate into the fabric, killing bacteria and sanitizing the clothes. The manufacturer also states that the silver ions eradicate bacteria and mold from inside the clothes washer, disinfecting the drum and other internal parts.

Because the silver ion injection feature can be used for sanitization in cold water, energy savings can be achieved compared to a hot water or steam sanitization cycle. The sanitization of the machine may also eliminate the need for period self-cleaning cycles commonly recommended for front-loading clothes washers.

The long-term health effects of human and environmental exposure to nanoscale silver particles are unknown. In September 2007, the U.S. Environmental Protection Agency (EPA) issued a *Federal Register* notice in which it determined that clothes washers will be regulated as pesticides if the machines contain silver or other substances, and if they generate ions of those substances for express pesticidal purposes. According to this decision, a manufacturer would be required to register a clothes washer with EPA as a pesticide if the product is marketed with claims that it will kill bacteria on clothing. In May 2008, a group of advocacy organizations sued the EPA asking the agency to issue new rules regulating products containing nanoscale silver particles. The petition claimed that EPA failed to adequately regulate products containing or using nanoscale silver particles. The petition asks EPA to: (1) classify nanoscale silver as a new pesticide; (2) require detailed product registration and data submissions under the Federal Insecticide Fungicide and Rodenticide Act; and (3) analyze the potential environmental, health, and safety risks of nanoscale silver.

Sources:

1. *United States Department of Energy. Draft Final Rule Technical Support Document: Residential Clothes Washers. April, 2012.*
2. *Samsung 2010. "Silver Nano Health System – Frequently Asked Questions." Samsung website. Accessed August, 2014.* *http://www.samsung.com/my/consumer/learningresources/silvernano/silvernano/index_faq_popup.html*.
3. *"Ions and Free Radicals." Appliance Magazine, September 2007. Accessed online at http://www.appliancemagazine.com/editorial.php?article=1820&zone=1&first=1.*
4. *EPA Announcement. "Pesticide Registration: Clarification for Ion Generating Equipment." September 21, 2007. Accessed online at http://www.epa.gov/oppad001/ion_gen_equip.htm.*

5. *Monica, John C. "EPA Sued Over Nanoscale Silver." Nanotechnology Law Report. May 3, 2008. Accessed online at http://www.nanolawreport.com/2008/05/articles/epa-sued-over-nanoscale-silver.*

A.3 Clothes Dryers

A.3.1 Heat Pump Clothes Dryer

Heat pump dryers function by recirculating the exhaust air back to the dryer while moisture is removed by a refrigeration-dehumidification system. A heat pump dryer is essentially a dryer and a dehumidifier packaged as one appliance. No heating element is needed. The warm and damp exhaust air of the dryer enters the evaporation coil of the dehumidifier where it cools down below the dew point, and sensible and latent heat are extracted. The heat is transferred to the condenser coil by the refrigerant and reabsorbed by the air, which is moving in a closed air cycle. A drain is required to remove the condensate; however, one is usually available since clothes washers and dryers are typically located side by side.

Heat pump dryers have been unable to penetrate the U.S. market despite showing significant energy savings. The major issue for heat pump dryers has been cost and performance. Heat pump dryer cycle times are typically significantly longer than those associated with standard U.S. electric dryers. More maintenance will probably be required for a heat pump dryer than for a conventional dryer. The traditional heating element is replaced by equipment found in a small room air conditioner— a condenser, evaporator, compressor, expansion valve, etc. Installation costs, though, may be less than for a conventional electric dryer because the heat pump dryer does not require an exhaust vent as does a conventional dryer (although some heat pump dryers may still use a vent). However, heat pump dryers require access to a drain for removal of condensate.

Research conducted on both heat pump dryers and conventional vented dryers on the European market showed that heat pump dryers consumed about 50 percent less energy than conventional dryers. The heat pump dryers tested had energy efficiency values between 0.32 and 0.40 kWh/kg laundry (with 70 percent initial moisture, measured according to test standard EN 61121) whereas conventional dryers had values between 0.6 and 0.8 kWh/kg laundry. Another benefit noted by this research was that the leakage of water vapor into the room was around 20 percent, which is significantly lower than conventional dryers. This research performed a cost comparison of heat pump dryers versus conventional dryers, which showed that the combined sale price and electricity costs over 15 years was about 1900 and 2300 Euros, respectively.

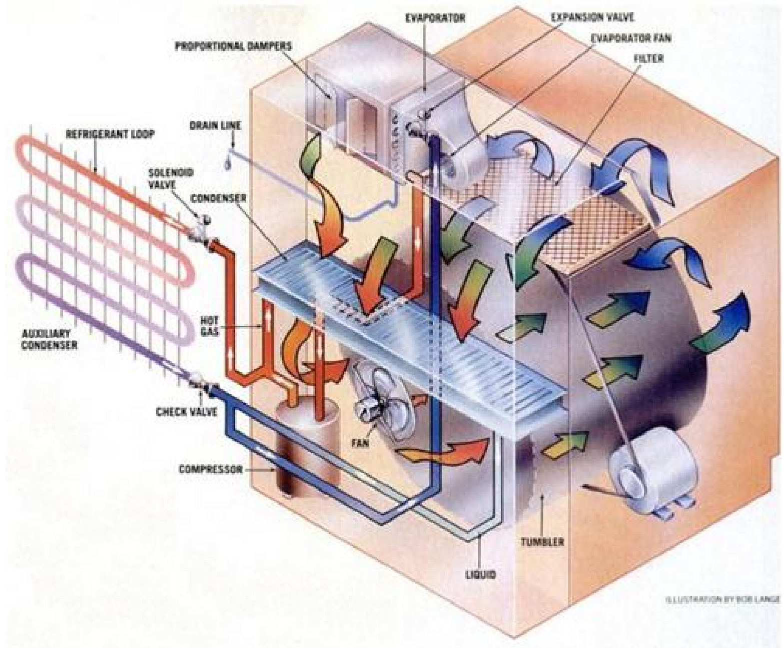
According to the DOE technical support dryer for the clothes dryer energy conservation standards, a heat pump dryer has been developed by a U.S. company which has successfully tested several prototypes and found energy savings of 68 percent as compared to energy use by a conventional electric clothes dryer. The estimated retail cost is approximately twice that of a conventional electric dryer. Drying times were essentially the same as for the conventional dryer, and the dryer operates on standard 120 V line power. The prototype uses a disposable filter to reduce lint in the air system. One inch of polyisocyanurate insulation was used to avoid condensation of water vapor in the recirculated air. In addition, the extension on the back of the prototype dryer to accommodate the added refrigeration components was estimated to be about the same depth as a vent duct, so the cabinet may fit in the same space as a conventional dryer.

Research sponsored by technology development firm and a leading U.S. manufacturer developed a high efficiency, high-performance heat pump clothes dryer for the U.S. market. This different approach to the heat pump system maximized the output capacity and temperature from the heat pump. This design has shown 40 to 50 percent energy savings on large loads along with 35 degree Fahrenheit (°F) lower fabric temperatures and similar drying times as conventional dryers. For delicate loads, the design reduced fabric temperature by 10–30 °F and provide up to 50 percent energy savings and 30–40 percent drying time savings. The heat pump dryer designed by the two companies also exhibited improved fabric temperature uniformity as well as robust performance across a range of vent restrictions in a partially open-loop design.

In order to maximize the air inlet temperature and airflow into the dryer's drum, the companies replaced the standard refrigerant, R-22, with R-134a in an R-22 air conditioner/heat pump compressor, shifting evaporating and condensing temperatures by 30 °F while maintaining similar operating pressures and power input. The companies were also able to maximize the capacity of the heat pump system by redesigning the heat exchanger components to optimize space utilization and increasing the airflow in the system as compared to typical dryers.

A key issue in the design was the venting options of the heat pump dryer. The moisture in the air exiting the drum is removed by the evaporator. This air can then be recirculated back into the drum, which removes the need for a vent. However, some form of heat rejection is required since the heat pump generates more heat than cooling in steady state operation. The researchers used a partially open-loop design in which a portion of the process air is vented outdoors to remove excess heat. In this design, all of the process air is recirculated through the dryer until the system has fully warmed, at which point the exhaust is opened and a portion of the total flow is vented to the outside.

In the late 1980s, a U.S. company developed a ventless heat pump dryer, funded through a grant with the Department of Energy. The dryer reportedly used two-thirds less energy than a traditional electric dryer and operated on a 110-volt circuit, rather than the typical 220-volts required by traditional electric dryers. The estimated retail cost was approximately $800, around twice the cost of a conventional dryer at the time. The dryer used a chlorofluorocarbon-based refrigerant loop with a coefficient of performance of approximately 2.6. Drying times were essentially the same as with a conventional dryer. The dryer used a disposable filter to reduce the lint in the air system. Insulation was also used to avoid condensation of water vapor in the recirculated air.



According to DOE dryer rulemaking documents, the prototypes were constructed by modifying a conventional electric dryer. The unit resembled a conventional dryer except that it contained the refrigerant system in the rear of the cabinet, which usually houses the electric heater. The extension on the back of the dryer was approximately the same depth as a vent duct, so the cabinet could fit within the same space as a conventional dryer.

The U.S. company had arranged for an offshore manufacturer to make the heat pump dryers, but economic problems that developed had prevented commercial units from being made.

A major Asian appliance manufacturer has publically stated that they plan on releasing a heat pump clothes dryer on the market in the summer of 2014. The company claims that it will be up to 50 percent more efficient than standard clothes dryers. The price will be similar to that of high-end models currently on the market. A major U.S. appliance manufacturer has also stated that it plans on releasing their own heat pump clothes dryer to select U.S. market in quarter four of 2014, and will expand to other U.S. markets in early 2015.

Sources:
1. United States Department of Energy. Direct Final Rule Technical Support Document: Residential Clothes Dryers and Room Air Conditioners. April 21, 2011. Available online at *http://www1.eere.energy.gov/buildings/appliance_standards/residential/residential_clothes_dryers_room_ac_direct_final_rule_tsd.html*
2. E. Bush and J. Nipkow. 2006. Tests and Promotion of Energy-Efficient Heat Pump Dryers. Report Prepared for International Energy Efficiency in Domestic Appliances & Lighting Conference '06.
3. P. Pescatore and P. Carbone. 2005. High Efficiency High Performance Clothes Dryer. Final Report to Department of Energy.
4. V. Elaine Gilmore. November 1989. "Heat-pump clothes dryer." Popular Science. pp.124-126.
5. "LG's new dryer saves energy and money." Consumer Reports. Accessed August 2014. *http://www.consumerreports.org/cro/news/2014/01/lg-s-new-dryer-saves-energy-and-money/index.htm.*
6. Whirlpool website. Accessed August 2014. *http://investors.whirlpoolcorp.com/releasedetail.cfm?ReleaseID=860720.*

A.3.2 Indirect Heating (Hydronic) Clothes Dryer

For indirect heating, the clothes dryer heat energy is derived from an external heating system such as the home's hydronic heating system, or a stand-alone supplementary hydronic system. This technology option uses a hydronic heating system to heat water which then flows through a heat exchanger in the dryer, heating the air entering the drum. To use a home's existing heating system, significant plumbing would be required to circulate heated water through the heat exchanger in the dryer. There are three models that are certified on the market that show similar energy savings when compared to other high-efficiency clothes dryers.

A U.S. company has developed a built-in hydronic heating system for electric dryers. In the system, a heat transfer fluids is heated using an immersion element similar to a water heater. The heated fluid passes through a heat exchanger, where the heat is transferred to the air entering the drum, and is then pumped back to the hydronic heater. The company claims that their clothes dryer uses 50 percent less energy compared to a conventional clothes dryer. However, it appears that this estimate refers to the fact that the hydronic heating system draws 2,500 Watts of power, versus a typical electric heater that draws around 5,000 Watts. It is unclear whether the total cumulative energy consumption over a complete cycle is less than a conventional clothes dryer, because the cycle time for the hydronic system may be longer. The website also claims that because the system utilizes a proprietary heat transfer fluid that retains its heat between loads much longer than a gas or electric clothes dryer's heating system can, more energy can be saved when drying back-to-back loads. The dryer is also marketed as safer than a traditional electric dryer because of the reduced risk of lint fires.

Source: Hydromatic Technology Corporation. *http://www.safe-mates.com/products.html*

A.3.3 Inlet Air Pre-Heating

For this technology option, a heat exchanger is used to recover exhaust heat energy and to preheat inlet air. This system should be feasible for both gas and electric dryers since none of the exhaust air re-enters the dryer. Energy savings are achieved either by a faster drying time or by reducing the required heater input power.

A limitation of this technology option is that a large surface area is required to achieve sufficient heat transfer, and that lint may accumulate on these heat transfer surfaces. Although every dryer is equipped with a lint filter, considerable lint is still contained in the exhaust air. This lint can foul the heat exchanger, decreasing its effectiveness. Additionally, to overcome the increased resistance to airflow, an extra blower is needed at the fresh air inlet or a stronger blower in the exhaust air duct is required.

Manufacturers have also expressed concern that any decrease in exhaust temperature will lead to moisture condensation in the exhaust duct, which could result in damage to the exhaust duct and dryer, as well as water leakage into the home. Water leakage into the home could lead to the health risks from the development of mildew and/or mold.

One example of a technology for recovering dryer exhaust heat is the heat recovery wheel, manufactured by a U.S. company**.** Half of the heat recovery wheel is exposed to the dryer air inlet, while the other half is exposed to the dryer exhaust inlet. The wheel is constructed of alternate layers of flat and corrugated aluminum, as shown in the figure below. As the heat wheel spins, heat is extracted from the exhaust outlet and transferred to the colder dryer inlet air. A case study featured on the company website claims a fuel reduction of 44-51% using the heat recovery wheel.

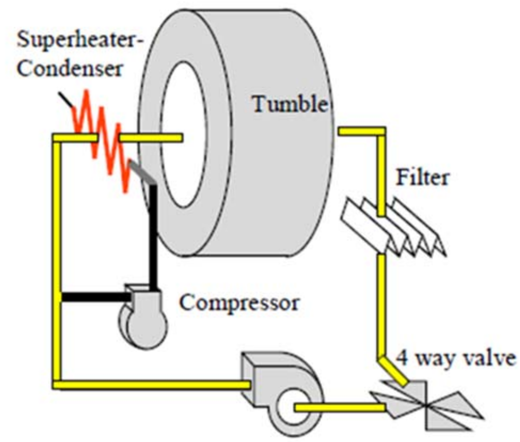
Source: Rototherm Corporation. http://www.rototherm.net/index1.html

A.3.4 Mechanical Steam Compression

The Center for Energy Studies has developed a super-heated steam dryer using mechanical steam compression. Instead of using hot air to dry the clothing, mechanical steam compression dryers use water recovered from the clothing in the form of steam.

First, the tumbler and its contents are heated to the boiling point of water at 100°C/212°F. The resulting wet steam purges the system of air, and the internal atmosphere is now pure water vapor. As wet steam exits the tumbler, it is mechanically compressed to extract water vapor and transfer the heat of vaporization to the remaining gaseous steam. The extracted water is drained from the compression chamber, and the pressurized gaseous steam is allowed to expand and be superheated before being injected back into the drum. Back in the drum, heat from the super-heated steam causes more water to vaporize from the clothing, creating more wet steam and restarting the cycle.

The considerably higher temperatures used in mechanical steam compression dryers result in a one-hour drying time, roughly half as long as the drying time for a heat pump dryer. The energy consumption of a mechanical steam compression dryer is roughly 55% less than a traditional electric dryer.



The Center for Energy Studies has completed preliminary performance testing on a compressor that could be used in such a system. Computer simulations have been conducted to model the performance of a complete working system; however, a working laboratory prototype has not yet been built.

Source: Palandre and Clodic. "Comparison of Heat Pump Dryer and Mechanical Steam Compression Dryer" http://www-cep.ensmp.fr/francais/innov/pdf/ICR0143SLV%20_IIR_IIF%20Conf.pdf

A.3.5 Microwave Clothes Dryer

Microwave energy can be absorbed by water, thereby heating the water enough to cause evaporation. This would be a direct and efficient manner to remove moisture from clothes. Instead of the conventional method of passing warm air over the clothes, microwave energy can be directly absorbed by water retained in the clothing, thereby heating the water enough to cause evaporation. Microwave drying uses the principle of dielectric heating, in which electromagnetic energy is radiated into the dryer drum where it is absorbed by water molecules which have a higher dielectric loss factor than most common fabric materials. Most fabric materials are also relatively transparent to microwave energy, so that the microwaves can penetrate the fabric's interior to heat the water molecules directly. This allows the fabric in a microwave dryer to stay cooler—below 115 °F—as compared to conventional dryers which heat air to approximately 350 °F, with fabric surfaces reaching 150 °F.

Microwave dryer prototypes have been shown to consume about 17 to 25 percent less energy as well as to dry clothes about 25 percent faster than conventional electric dryers.

Early conceptualization of this technology began in the mid-1960s; however, product development was not pursued because of high manufacturing costs and difficulties in overcoming hazards relating to arcing and overheating of clothing. In 1997, the Electric Power Research Institute (EPRI) focused on developing a compact countertop dryer based on economic feasibility and market surveys. EPRI market studies and the development of prototypes for in-house evaluation have led to negotiations for technology licensing and indications of serious product development for a residential microwave clothes dryer.

Because of the interaction between the metallic sensor contacts and the electromagnetic field, microwave dryers are incapable of using contact moisture sensors as in conventional dryers. EPRI investigated using sensors to detect the microwave electric field strength and the fabric temperature, which both correlate well with the moisture content. As evaporation nears completion, both measured signal slopes begin to rise in a predictable manner, so that the dryer can be shut off automatically and avoid wasted energy in over-drying clothes.

Microwave drying also introduces a safety concern related to arcing. Arcing is caused by an electric field which induces a voltage differential between metal objects, allowing current to flow within them. The resultant heating and sparking of the metal objects may ignite a fire in the load. EPRI has developed a rapid-response gas sensor to detect small amounts of gaseous by-products of combustion in the exhaust stream. Upon detection, the drying cycle can be shut down immediately, preventing safety hazards and damage. Another technique to avoid arcing is to switch to electric resistance heaters when the clothes are almost dry.

Sources:
1. Ashley, Steven. 1998. "Energy-Efficient Appliances." Mechanical Engineering. Vol. 120, No. 3, pp. 94–97.
2. J. Gerling. 2003. "Microwave Clothes Drying – Technical Solutions to Fundamental Challenges." Appliance Magazine. April 2003.
3. EPRI. "Microwave Drying of Textile Products." October 1999.
http://my.epri.com/portal/server.pt?space=CommunityPage&cached=true&parentname=ObjMgr&parentid=2&control=SetCommunity&CommunityID=404&RaiseDocID=000000000001006118&RaiseDocType=Abstract_id

A.4 Cooking Equipment

A.4.1 Induction Cooktops

Induction cooktops use a solid-state power supply to convert 60 hertz alternating line current into a high-frequency (approximately 25 kilohertz) alternating current. This high-frequency current is supplied to an inductor. The inductor is a flat spiral winding located underneath a glass-ceramic panel. The high-frequency current, which is supplied to the inductor, causes it to generate a magnetic field, which passes through the glass-ceramic panel unaffected and produces eddy currents in the bottom of the cooking vessel. The vessel must be made of ferromagnetic material, and the eddy currents that are generated within it cause it to heat up. Thus, the vessel essentially becomes the heating element.

A sensor is placed between the inductor and the glass-ceramic panel, providing a continuous temperature measurement of the vessel bottom. Sensors also enable the inductor to only heat objects of at least 4 inches in diameter. This prevents any small metal objects, such as forks or spoons, from accidentally being heated. In addition, since the glass-ceramic panel is unaffected by the magnetic field, it remains relatively cool, reducing the potential for accidental burns.

The primary advantages of induction elements are their fast response and control of the heat source, their ease of cleaning, and their ability to heat vessels that are not flat. Because these features have usually been associated with gas burners, induction elements are being marketed in competition to them.

As noted above, the cooking vessel used with an induction element must be made from a ferromagnetic material. Since aluminum is not a ferromagnetic material, the current DOE test procedure, which specifies an aluminum test block, cannot be used to rate this equipment. In 1978, the National Bureau of Standards (NBS), now called National Institute of Standards and Technology (NIST), developed a proposed method of measuring the energy consumption of induction cooktops. The method is a modification of the current DOE test procedure. Energy use is determined by attaching a ferromagnetic material to the bottom of the aluminum test block.

There is an ongoing rulemaking to develop a DOE test procedure for induction cooktops. Although induction cooktops were originally considered much more energy-efficient than traditional electric cooktops, analysis during the DOE test procedure development for induction cooktops shows that there is not significant efficiency improvement over conventional smooth electric cooktops.

Sources:

1. *United States Department of Energy. Final Rule Technical Support Document: Residential Dishwashers, Dehumidifiers, Cooking Products, and Commercial Clothes Washers. Residential Clothes Dryers and Room Air Conditioners. April 8, 2009. Available online at [http://www1.eere.energy.gov/buildings/appliance_standards/residential/cooking_products_final_rule_tsd.html.](http://www1.eere.energy.gov/buildings/appliance_standards/residential/cooking_products_final_rule_tsd.html)*
2. *United States Department of Energy. Notice of Proposed Rulemaking Technical Support Document: Conventional Cooking Products Test Procedure. January 30, 2013. Available online at http://www1.eere.energy.gov/buildings/appliance_standards/rulemaking.aspx/ruleid/57.*

A.4.2 Specialized Cookware

Cookware modified with fins or grooves along the bottom surface have been shown to significantly increase cooktop performance. Heat-up times are substantially reduced and production capacities increased. Energy performance is also significantly improved. By simply using an advanced pot design, the 25–30% energy efficiency of a standard, gas-fired range top can be raised to more than 40%. When used on a range top with energy efficiency in the low 30s, the number can approach 60%.

A U.S. company has developed a line of cooking vessels that use aluminum fins to increase the surface area exposed to the burner flame, thereby maximizing the amount of heat transferred to the bottom of the pot.

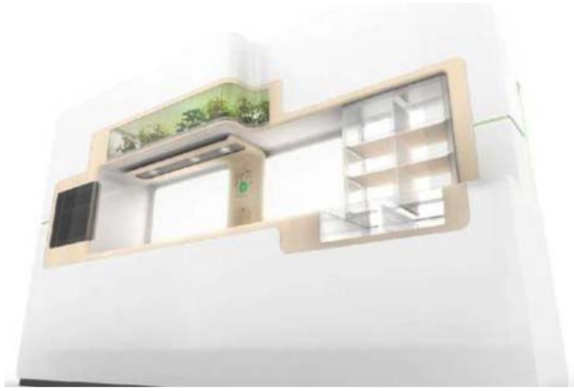
Sources:

1. *Appliance Magazine, August 2009.*
http://www.appliancemagazine.com/ae/editorial.php?article=2257&zone=215&first=1
2. *Eneron, Inc website: http://www.turbopot.com/ Accessed August, 2014.*

A.5 Cross-Cutting Technologies

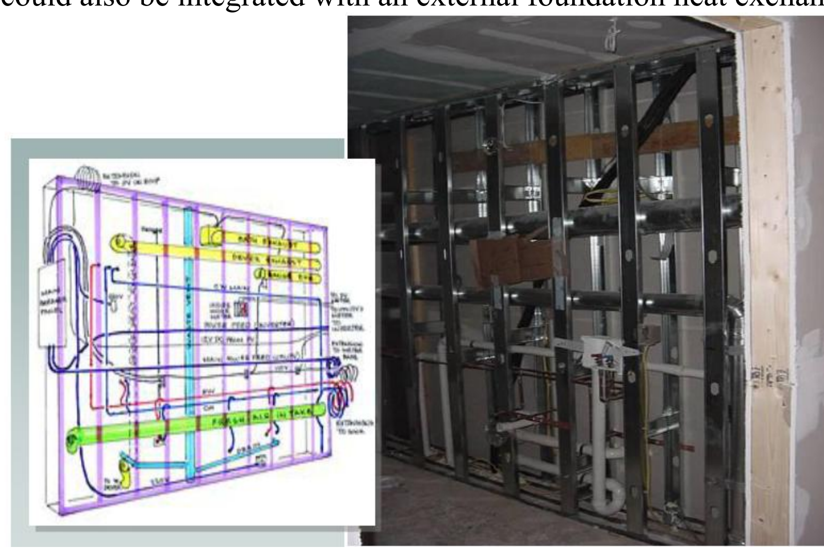
A.5.1 Integrated Heat & Water Recovery

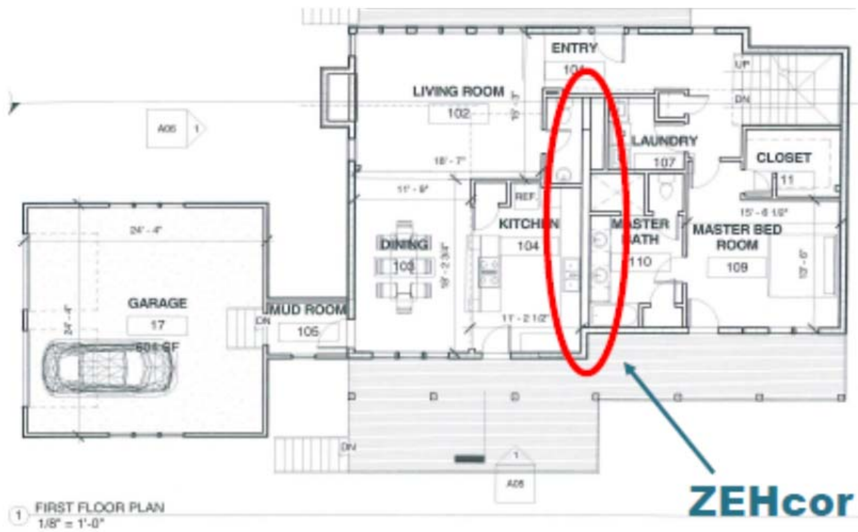
A major U.S. appliance manufacturer has designed a prototype integrated kitchen design concept where wasted water and heat are re-used from one appliance by another. The system captures heat from the refrigerator's compressor and uses it to pre-heat the dishwasher water. 60% of the water in the integrated system is captured, undergoes anti-bacterial treatment and then stored in an external water tank under the sink. This water can be used for the dishwashing cycle. The refrigerator is compartmentalized into drawers to prevent cold air from spill out when the doors are opened. The manufacturer estimates that savings would result in 7 liters (1.8 gallons) of water per cycle and up to 20% savings of electricity with the same washing performance. In total, the concept claims to increased water and energy efficiency by up to 70%.



Another concept, the Propane Energy Pod from the Propane Education & Research Council (PERC), is intended to serve as a new energy model for homes. PERC describes it as a research-based solution for home construction that treats five areas of energy use in a home: space heating, water heating, cooking, clothes drying, and fireplaces, all as part of a whole-home energy package. The model is designed for significant reductions in energy consumption and carbon emissions when compared to homes with standard appliances and mechanical systems. The Propane Energy Pod includes mechanical systems with high-efficiency amenities, such as on-demand hot water, professional-grade cooktops, and switch-on fireplaces. According to a study by Newport Partners, a home built using the Propane Energy Pod model can save homeowners about $285 in annual energy costs.

Additionally, ORNL has developed a ZEHcor Interior Utility Wall concept. The ZEHcore wall concept is a pre-fabricated wall to which all kitchen and laundry appliances would be connected, including major bathroom fixtures. The wall would be built off-site in a controlled environment. It is designed to reduce hot water distribution losses and enable a high level of integration between appliances that could not otherwise be accomplished reliably on-site. The ZEHcore wall could also be integrated with an external foundation heat exchanger.





Sources:
1. Whirlpool, August 2011. http://www.whirlpool.co.uk/discover-whirlpool/sustainability/green-kitchen.content.html
2. Appliance Magazine, June 2011.
Source: http://www.appliancemagazine.com/news.php?article=1497114&zone=0&first=101
3. Images: http://www.treehugger.com/files/2008/03/kitchen-design-whirlpool.php
4. Thomas King. May 2009. "Addressing the Future Energy Challenges Through Innovation." Oak Ridge National Laboratory. Presentation available at http://e2s2.ndia.org/pastmeetings/2009/tracks/Documents/8240.pdf

A.5.2 "Smart" Appliances

The Association of Home Appliance Manufacturers (AHAM) defines smart appliances as appliances that monitor, control and protect their electrical energy usage in response to customer needs. The appliance control and interface software may enable the appliances to participate in demand response and time-based rate programs with the local utility. Alternatively, the appliances may connect to the internet through smartphone applications, which may enable additional energy-saving and other non-energy benefits.

One of the primary benefits of "smart grid" technologies is to shift loads from peak times to off-peak times. Smart appliances may demonstrate the following demand-response capabilities:

- A refrigerator could shift its energy-intensive defrost cycle to non-peak times.
- A clothes dryer could encourage the end-user to delay usage until off-peak hours.
- A water heater could pre-heat water during off-peak hours.
- An air conditioner could automatically reduce its load during peak hours.

Examples of energy-saving features enabled by smart appliances include:

- A refrigerator could be easily (or automatically) switched into "vacation mode," suspending the ice maker and auto-defrost feature until the user returns home.

- A refrigerator could send an alert to a user's smartphone to indicate that the door has been left open.
- A clothes dryer could send an alert to a user's smartphone to indicate a clogged dryer vent, which would decrease the efficiency of the dryer.

Smart appliances will play an essential role in the smart grid by facilitating large-scale residential demand response. By shifting residential appliances' usage from peak to off-peak periods, peak electricity usage will be reduced. Lower peak loads will improve the health and stability of the power grid and will reduce long-term investments in expensive generation.

Appliances with smart grid capabilities exist on the market today. Major U.S. manufacturers have platforms that allow the user to monitor and manage their smart appliances through a mobile phone app or online. A major Asian manufacturer also has a line of appliances that allows customers to monitor and control their appliances through a mobile phone app. These appliances are also smart grid ready, allowing the appliance to communicate with the local utility to participate in demand response scenarios.

Sources:

1. *"Arrival of Smart Appliances is a Milestone on the Path to the Smart Grid." IEEE website, accessed August, 2014. http://smartgrid.ieee.org/newsletter/october-2011/415-arrival-of-smart-appliances-is-a-milestone-on-the-path-to-the-smart-grid.*
2. *"Smart Appliances: What to Expect." GreenTech Efficiency website, accessed August, 2014. http://www.greentechmedia.com/articles/read/smart-appliances-what-to-expect.*
3. *Whirlpool's "Smart Appliances" website, accessed August, 2014. https://mysmartappliances.com/.*
4. *LG's "Smartthinq" website, accessed August, 2014. http://www.lg.com/us/discover/smartthinq/thinq.*

U.S. DEPARTMENT OF
ENERGY

Energy Efficiency &
Renewable Energy

For more information, visit: buildings.energy.gov

DOE/EE-1146 • October 2014