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Grid-Interactive Efficient Building Technology Cost, Performance, and Lifetime Characteristics

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Grid-Interactive Efficient Building Technology Cost, Performance, and Lifetime Characteristics

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Honeywell Inc.	Building Automation System
Johnson Controls International	Building Automation System
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Packetized Energy	Energy Management Software Systems
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Acronyms and Abbreviations

5G	Fifth-generation wireless technology	DOE	US Department of Energy
AC	Air conditioning	DR	Demand response
ACEEE	American Council for an Energy Efficient Economy	DVD	Digital versatile disc
AHRI	Air-Conditioning, Heating, and Refrigeration Institute	EERE	US DOE Energy Efficiency and Renewable Energy Division
AIA CZ	American Institute of Architects climate zone	EIA	U.S. Energy Information Administration
APS	Advanced power strip	EPA	Environmental Protection Agency
ASHRAE	American Society of Heating, Refrigerating & Air-Conditioning Engineers	EPCA	Energy Policy and Conservation Act
AV	Audio and video	ESTAR	ENERGY STAR
AWEF	Annual Walk-in Energy Factor	gal	Gallon
BAS	Building Automation System	GEB	Grid-interactive efficient buildings
BLS	Bureau of Labor Statistics	GSA	US General Services Administration
BTU	British thermal unit	hhp	Hydraulic horsepower
CCMS	Certification Candidate Management System	hr	Hour
CEF	Combined Energy Factor	HSPF	Heating seasonal performance factor
COP	Coefficient of Performance	HVAC	Heating, ventilation, and air conditioning
CPI	Consumer Price Index	IMEF	Integrated Modified Energy Factor
DDC	Digital direct control	IPLV	Integrated Part Load Value
DLC	DesignLights Consortium qualification	kBTU	Kilo-British thermal unit

Acronyms and Abbreviations

klm	Kilo-lumen	SHEMS	Smart home energy management system
kW	Kilowatt	SHGC	Solar heat gain coefficient
kWh	Kilowatt-hour	SME	Subject matter expert
lb.	Pound	Sq. ft	Square feet
LBNL	Lawrence Berkeley National Lab	SSL	Solid-state lighting
LED	Light emitting diode	TES	Thermal energy storage
lm	Lumen	TOU	Time-of-use
LTE	Long-Term Evolution wireless communication	TSD	Technical support document
NEEA	Northwest Energy Efficiency Alliance	TV	Television
NREL	National Renewable Energy Lab	UEF	Uniform Energy Factor
NYSERDA	New York State Energy Research and Development Authority	US	United States
ORNL	Oak Ridge National Lab	W	Watt
PC	Personal computer	WEF	Weighted energy factor
PCM	Phase change material	WH	Water heater
PNNL	Pacific Northwest National Lab	Wh	Watt-hour
PV	Photovoltaic	yrs.	Years
R&D	Research and development		
SEER	Seasonal energy efficiency ratio		

Table of Contents

Table of Contents

Overview and Objectives

- This study's objective is to develop current and projected performance, cost, and lifetime characteristics for residential and commercial building technologies and equipment with the potential to provide grid services.
- Enabling technologies for grid-interactive efficient buildings such as smart meters and distributed energy management software are out of scope for this report. Non-building technologies such as EV chargers and PV inverters were also out of scope.
- The list of technologies was developed based on data gathered from the DOE GEB Technical Report Series, ENERGY STAR Connected Certified Products, and input from researchers at LBNL and NREL.
- For each technology, characteristics are provided for a typical case and a connected or grid-interactive case. Where data was available, current DOE appliance standard levels are given. Definitions vary by technology and are provided with each data table.
- Current data is provided for 2020 and projections are available for 2030, 2040, and 2050.
- The data in this report will be used by LBNL as inputs to the Scout model to calculate potential energy and cost savings potential, though this data is public and may be used for other purposes.

Methodology

Data Collection

The methodology used for data collection is summarized below:

1. Collect public data

- ENERGY STAR and ENERGY STAR Connected products database
- Research public cost data from online retailers and/or research publications
- Review details from manufacturer specifications
- DOE EERE Appliance standards rulemaking data and Technical Support Documents
- CCMS Database
- RSMeans Data
- Price web-scraping from online retailers

2. Gather internal data

- Input and guidance from Guidehouse subject matter experts
- Internal data from previous Guidehouse studies

3. Contact manufacturers and distributors

- Providing non-public cost data, lifetime data, maintenance costs, and installation costs
- Provide case studies and typical applications
- Advising on projections over time including changes in manufacturing, adoption, product offerings, etc.
- Verifying and providing detail on demand response and connected capabilities

4. Contact researchers and subject matter experts

- Provide insights on ongoing research and technologies on the horizon
- Advise on projections and review

Methodology

Projections 2030-2050

The methodology used for developing projections is summarized below.

1. Gather current and historical data to establish trends*

- Use existing reports and analysis on smart/connected technologies
- Use standards data for typical case technologies
- *Many technologies are new to the market and do not have any historical trend data

2. Gather data on efficiency standards, R&D efforts/goals, and manufacturing

- Analyze the potential future performance, costs, and market changes
- Interviews with standards SMEs, researchers, and manufacturers

3. Gather data on utility DR programs and trends

- Interviews with utility and DR experts
- Available research reports/projections and information on regulation/policy impacts

4. Analyze historical trends and determine if future growth will be based on interviews and assumptions

- Use existing projections as available
- Analyze and summarize interview findings and record all assumptions
- Make assumptions on when typical become the connected

5. Review process for projections and assumptions

- Establish consensus on assumptions
- Adjust as needed

Key Data Sources

- DOE EERE Appliance Standards Technical Support Documents
  - Data available online: https://www.energy.gov/eere/buildings/standards-and-test-procedures
- EPA ENERGY STAR and ENERGY STAR Connected Databases
  - Data available online: https://www.energystar.gov/productfinder/
- CCMS Database
  - Data available online: https://www.regulations.doe.gov/certification-data/CCMS-All.html#q=Product_Group_s%3A*
- RSMeans by Gordian
  - Available (for purchase) online: https://www.rsmeansonline.com/
- Bureau of Labor Statistics (BLS) CPI Inflation Calculator
  - Available online: https://data.bls.gov/cgi-bin/cpicalc.pl
- Technology case studies and research reports
  - Details provided for each technology where relevant
- Common online retailers including:
  - Amazon, Best Buy, Lowes, Home Depot, AJ Madison, etc.
- Interviews and guidance from manufacturers, researchers, and technology subject matter experts

Note: The full list of sources for each technology is provided in the Appendix.

Notes and Assumptions

- Where market distributions or shipments were available, data is provided for the market weighted average efficiency level and capacity level.
- Where market distribution and shipments are not available, data is provided for a range of the 25 percentile to the 75 percentile of products available according to CCMS, ENERGY STAR databases, or other available sources.
- Prices are provided without utility incentives included, although many of these technologies may qualify for incentives in the region of purchase.
- Our projections generally assume that R&D funding, manufacturing, and consumer demand continue on current trends unless otherwise noted. No assumptions are made for new appliance standards, new technologies entering the market, or new utility program developments.
- Projections are based on expert guidance (manufacturers, internal Guidehouse SMEs, and researchers) and simplified assumptions. Research notes and interview findings are provided for each relevant technology.
- All prices are given in 2020 US dollars. Prices from older data sources were converted to 2020 US dollars using the BLS CPI Inflation Calculator.
- All technologies included in this report can be installed in new construction or existing buildings. No assumptions are made on how prices may differ for different applications.
- All reported energy savings are in site energy savings relative to baseline energy use.

Definitions

- **Typical:** The most common configuration of the technology available on the market, based on market distribution, shipments, available research reports, product databases, or expert guidance. This is generally included as a reference for comparison to other connected/grid-interactive products.
- **Current Standard:** The minimum DOE EERE appliance standard level in effect (or planned if rulemaking is final). This is included as a reference for comparison to typical and connected/grid-interactive products.
- **ENERGY STAR Connected:** Products certified by ENERGY STAR to meet the connected criteria specification. These products meet the ENERGY STAR criteria for efficiency and include requirements for communication, demand flexibility, and energy reporting. Specific definitions are noted for each technology.
- **Connected:** Technologies that include communication capability generally enabled through Wi-Fi or Bluetooth and remote control/management. Many include capabilities to automatically schedule use of the technology.
- **Grid-Interactive:** Technologies that include integrated communication and controls to enable demand flexibility by responding to grid signals. Grid-Interactive is used when there are no ENERGY STAR Connected products for the technology.
- **Passive:** Technologies such as phase-change materials and thermochromic glazing can provide passive energy savings and grid benefits, but do not include communication or controls.
- **Add-On Control:** Control device that can be added to typical technologies with integrated communication that enables demand flexibility.

Residential Technologies

Residential Central AC/Smart Thermostats

Data	2020			2030		2040		2050	
	Current Standard	Typical	ESTAR Connected Smart Thermostat	Typical	ESTAR Connected Smart Thermostat	Typical	ESTAR Connected Smart Thermostat	Typical	ESTAR Connected Smart Thermostat
Typical Capacity (kBTU/hr)	36	36	-	36	36	36	36	36	36
SEER	South: 14.0 North: 13.0	15.0-16.0	-	15.2-16.0	-	15.2-16.0	-	15.2-16.0	-
Average Life (yrs.)	South: 18 North: 24	South: 18 North: 24	8-10	South: 18 North: 24	8-10	South: 18 North: 24	8-10	South: 18 North: 24	8-10
Retail Equipment Cost (2020)	$2,771 $2,845	$2,990 $3,081	$115 $199	$3,007 $3,081	$77 $133	$3,007 $3,081	$71 $122	$3,007 $3,081	$67 $116
Total Installed Cost (2020)	$4,344 $4,417	$4,563 $4,653	$215* $299*	$4,597 $4,653	$177* $233*	$4,597 $4,653	$171* $222*	$4,597 $4,653	$167* $216*
Annual Maintenance Cost (2020)	$21 $133	$21 $133	-	$21 $133	-	$21 $133	-	$21 $133	-
Reported Energy Savings	-	-	Cooling 7% 10%	-	Cooling 7% 10%	-	Cooling 7% 10%	-	Cooling 7% 10%

*Smart thermostats can be self-installed so installation costs would be $0. Consumers may choose to have mechanics/electricians install them which ranges from about $100-$200. This does not include the cost of additional wiring.

Definitions: Data shown for split system central AC, blower coil, 3-ton capacity. Smart thermostat add-on controls are defined as ENERGY STAR Connected certified smart thermostats: a device that controls HVAC equipment to regulate the temperature of the room or space and has the ability to communicate with sources external to the HVAC system. They provide flexibility by a setpoint offset of +4 degrees for cooling and -4 degrees for heating relative to current setpoint during peak periods. Smart thermostats, as characterized here, are typically not used with mini-splits.

Residential Central AC/Smart Thermostats

Assumptions

- Smart thermostat prices will continue to decrease to 2030 as adoption increases, manufacturing capacity increases, and vendor competition increases.
  - After 2030, the rate of price decline will slow.
- Lifetime of central AC and smart thermostats will remain constant over time
- Retail, installation, and maintenance costs for central AC will remain stagnant as the market is mature.
- Assumes smart thermostats are installed by an HVAC mechanic/electrician.
- Typical AC efficiency levels will increase due to amended standards that will take effect in 2023.
- Smart thermostat prices do not include any utility incentives, though some utilities offer rebates (around $100) for enrolling in smart thermostat DR programs.

Interview/Research Findings (Smart Thermostats)

- Market barriers are primarily interoperability and cybersecurity.
  - Data privacy is a major concern for many people.
- The lifetime of smart thermostats is uncertain.
  - One study on smart thermostats estimated a lifetime of 8-10 years, but they have not been in the market long enough to know the true lifetime.
  - Manufacturer security updates/patches can potentially limit the practical lifetime.

Residential Heat Pumps/Smart Thermostats

Data	2020			2030		2040		2050	
	Current Standard	Typical	ESTAR Connected Smart Thermostat	Typical	ESTAR Connected Smart Thermostat	Typical	ESTAR Connected Smart Thermostat	Typical	ESTAR Connected Smart Thermostat
Typical Capacity (kBTU/hr)	36	36	-	36	-	36	-	36	-
SEER	14.0	15.1	-	15.5	-	15.5	-	15.5	-
		16.0		16.0		16.0		16.0	
HSPF	8.2	8.5	-	8.8	-	8.8	-	8.8	-
		9.0	-	9.0	-	9.0	-	9.0	-
Average Life (yrs.)	South: 15	South: 15	8-10	South: 15	8-10	South: 15	8-10	South: 15	8-10
	North: 16	North: 16		North: 16		North: 16		North: 16	
Retail Equipment Cost (2020)	$3,601	$3,733	$115	$3,965	$77	$3,965	$71	$3,965	$67
		$3,977	$199	$3,977	$133	$3,977	$122	$3,977	$116
Total Installed Cost (2020)	$5,173	$5,305	$215*	$5,537	$177*	$5,537	$171*	$5,537	$167*
		$5,549	$299*	$5,549	$233*	$5,549	$222*	$5,549	$216*
Annual Maintenance Cost (2020)	$21	$21	-	$21	-	$21	-	$21	-
	$133	$133		$133		$133		$133	
Reported Energy Savings	-	-	Heating 6%	-	Heating 6%	-	Heating 6%	-	Heating 6%
			8%		8%		8%		8%
			Cooling 7%		Cooling 7%		Cooling 7%		Cooling 7%
			10%		10%		10%		10%

*Smart thermostats can be self-installed so installation costs would be $0. Consumers may choose to have mechanics/electricians install them which ranges from about $100-$200. This does not include the cost of additional wiring.

Definitions: Data shown for split system air source heat pumps, blower coil, 3-ton capacity. Smart thermostat add-on controls are defined as ENERGY STAR Connected certified smart thermostats: a device that controls HVAC equipment to regulate the temperature of the room or space and has the ability to communicate with sources external to the HVAC system. They provide flexibility by a setpoint offset of +4 degrees for cooling and -4 degrees for heating relative to current setpoint during peak periods. Smart thermostats, as characterized here, are typically not used with mini-splits.

Residential Heat Pumps/Smart Thermostats

Assumptions

- Smart thermostat prices will continue to decrease to 2030 as adoption increases, manufacturing capacity increases, and vendor competition increases.
  - After 2030, the rate of price decline will slow.
- Lifetime of heat pumps and smart thermostats will remain constant over time.
- Retail, installation, and maintenance costs for heat pumps will remain stagnant as the market is mature.
- Assumes smart thermostats are installed by an HVAC mechanic/electrician.
- Typical heat pumps efficiency levels will increase due to amended standards which will take effect in 2023.
- Smart thermostat prices do not include any utility incentives, though some utilities offer rebates (around $100) for enrolling in smart thermostat DR programs.

Interview/Research Findings (Smart Thermostats)

- Market barriers are primarily interoperability and cybersecurity.
  - Privacy is also a major concern for many people.
- The lifetime of smart thermostats is uncertain.
  - One study on smart thermostats estimated a lifetime of 8-10 years, but they have not been in the market long enough to know the true lifetime.

Residential Mini-Splits

Data		Current Standard	2020 Typical	2020 Connected	2020 Add-On Control	2030 Typical / Connected	2030 Add-On Control	2040 Typical / Connected	2040 Add-On Control	2050 Typical / Connected	2050 Add-On Control
Typical Capacity (kBTU/hr)	Cooling	12	12	12	-	12	-	12	-	12	-
	Heating	12	12	12	-	12	-	12	-	12	-
SEER*		14	15	15	-	15	-	15	-	15	-
			28	28	-	28	-	28	-	28	-
HSPF*		8.2	10	10	-	10	-	10	-	10	-
			14	14	-	14	-	14	-	14	-
Average Life (yrs.)		15	15	15	8	15	8	15	8	15	8
					10		10		10		10
Equipment Cost (2020)**		$1,958	$1,958	$1,958	$97	$1,958	$78	$1,958	$74	$1,958	$71
		$2,819	$2,819	$2,819	$152	$2,819	$122	$2,819	$116	$2,819	$111
Total Installed Cost (2020)**		$3,698	$3,698	$3,698	$97	$3,698	$78	$3,698	$74	$3,698	$71
		$4,559	$4,559	$4,559	$152	$4,559	$122	$4,559	$116	$4,559	$111

* Mini-split heat pumps must meet both a minimum Seasonal Energy Efficiency Ratio (SEER) and a Heating Seasonal Performance Factor (HSPF).
** The costs are representative of a 12 kBTU/hr unit. Cost generally increases as capacity increases, though it is not a scalable trend.

Definitions: Data shown here are for 12 kBTU/hr single-zone ductless mini-split heat pumps with both cooling and heating capabilities. The connected case refers to mini-splits with Wi-Fi or Bluetooth and remote management capabilities. The add-on control case refers to external thermostat controls which communicate with mini-splits via infrared signals and can enable demand flexibility. These add-on controls do not include the smart thermostats as characterized for residential central AC and heat pumps. Flexibility could be provided through changing temperature setpoints and pre-cooling or pre-heating during off-peak hours. Retail equipment costs are not scalable according to capacity.

Residential Mini-Splits

Assumptions

- Analyzed mini-splits with heating and cooling capabilities at a cooling and heating capacity of 12 kBTU/hr.
- Add-on controls can enable demand flexibility.
- Typical case will become connected by 2030 due to the minimal incremental cost increase of connectivity, but grid-interactive add-on controls will not become typical through 2050.
- The equipment costs in the table reflect the cost of the equipment plus an additional contractor markup.
  - Consumers usually purchase mini-splits through contractors, who add an additional markup of approximately $900 to the cost of the equipment. This figure is included in the equipment costs for mini-splits.
- Equipment costs for mini-splits are not scalable according to capacity.
- Capacities, SEERs, HSPFs, lifetimes, costs will remain constant through 2050 as this is a mature market and there are no known significant technological innovations on the horizon.
- Maintenance costs are negligible.

Residential Mini-Splits

Interview/Research Findings

- Convenience is the primary driver for connected capabilities, not grid-interactivity.
- Grid-interactivity is more commonly enabled through add-on controls than built-in controllers.
- Some add-on controls communicate with multiple mini-split units via infrared transmitters connected to a central node.
- Costs of mini-splits have remained relatively stable historically.
- Consumers typically purchase mini-splits through contractors, not major retailers. Contractors typically purchase higher-end equipment from manufacturers such as Fujitsu and Mitsubishi and may include a markup of approximately $900. The cost of the high-end equipment plus the additional markup reflects the retail cost of equipment that the consumer pays.
- In reviewing online retail data, the 25th and 75th percentile costs of a non-connected (typical) mini-split closely matched the costs of a connected mini-split. This indicates connectivity is a negligible incremental cost. We assume the capacities, energy performances, and costs align and will continue to align through 2050.
- According to SMEs, mini-splits are a mature technology and there are no upcoming technologies that will make them significantly more efficient or less expensive.
- Market research shows built-in grid-interactivity is extremely rare for mini-splits. Utility programs are more popular for central AC/smart thermostat systems.
- According to researchers, the primary barrier for grid-interactivity is utility-rate structures, which do not offer incentives for consumers to participate in demand response programs.
- The relatively small number of installed mini-splits, compared to other types of AC/heating equipment, is the main barrier for the development of utility programs for mini-splits.

Residential Room ACs

Data	2020				2030		2040		2050	
	Current Standard	Typical	ESTAR Connected	Connected	Typical / Connected	ESTAR Connected	Typical / Connected	ESTAR Connected	Typical / Connected	ESTAR Connected
Typical Capacity (kBTU/hr)	10	10	10	10	10	10	10	10	10	10
Combined Energy Efficiency Ratio	10.9	11	11	11	12	12	12	12	12	12
		12	12	12	15	15	15	15	15	15
Average Life (yrs.)	6	6	6	6	6	6	6	6	6	6
	13	13	13	13	13	13	13	13	13	13
Retail Equipment Cost (2020)	$346	$346	$361	$386	$415	$415	$415	$415	$415	$415
	$560	$560	$385	$580	$672	$672	$672	$672	$672	$672
Total Installed Cost (2020)	$483	$483	$498	$523	$552	$552	$552	$552	$552	$552
	$697	$697	$522	$717	$809	$809	$809	$809	$809	$809

* Maintenance costs are assumed to be negligible.

Definitions: Data shown here are for through-the-window, louvered room ACs without a reverse cycle with a 10kBTU/hr capacity. According to the ESTAR Connected Criteria, room ACs must be able to increase temperature setpoint by 4 degrees for at least 4 hours during specified peak period and pre-cool during off-peak hours. The connected case refers to room ACs with Wi-Fi and/or Bluetooth and remote management capabilities.

Residential Room ACs

Assumptions

- This analysis is based on through-the-window room ACs with louvered sides, without reverse cycle, and with a 10 kBTU/hr capacity.
- The typical case will become connected by 2030, primarily driven by added convenience for customers.
- Grid-interactivity will not become typical through 2050 due to the limited added value proposition offered by grid-interactivity for consumers.
- In 2030, the typical capacities, CEERs, and costs of grid-interactive room ACs will align with the typical/connected case, as the addition of grid-interactivity is negligible to connected room ACs and the primary difference between grid-interactive and connected room ACs is related to software capabilities.
- By 2030, we assume variable-speed compressors will be included in the typical case. As a result, CEERs will improve and retail equipment costs will increase by 20% by 2030. After 2030, CEERs and retail equipment costs will remain constant through 2050.
- The installation costs for room ACs include the installation of support brackets, mounting rails, or additional side panels.
- Annual maintenance costs are negligible.

Residential Room ACs

Interview/Research Findings

- SMEs found the adoption of variable-speed compressor technology in room ACs will increase the energy efficiency performance of room ACs. Variable-speed room ACs are predicted to make up more than half of the market share between 2030-2040.
- Connectivity in room ACs offers consumers a better experience due to more control over pre-cooling schedules and remote control. We predict that connectivity in room ACs will become typical by 2030.

Residential Electric Resistance Water Heaters

Data	2020				2030			2040			2050		
	Current Standard	Typical	Add-on Control	Grid-Enabled	Typical	Add-on Control	Grid-Enabled	Typical	Add-on Control	Grid-Enabled	Typical	Add-on Control	Grid-Enabled
Typical Capacity (gal)	50	50	-	90	50	-	90	50	-	90	50	-	90
Uniform Energy Factor*	0.92	0.93	-	0.92	0.93	-	0.92	0.93	-	0.92	0.93	-	0.92
Average Life (yrs.)	6	6	6	6	6	6	6	6	6	6	6	6	6
	20	20	20	20	20	20	20	20	20	20	20	20	20
Retail Equipment Cost (2020)	$289	$317	$100	$1,165	$317	$100	$1,165	$317	$100	$1,165	$317	$100	$1,165
	$504	$573	$267	$1,280	$573	$267	$1,280	$573	$267	$1,280	$573	$267	$1,280
Total Installed Cost (2020)**	$565	$630	$173	$1,486	$630	$173	$1,486	$630	$173	$1,486	$630	$173	$1,486
	$1,060	$1,153	$389	$1,735	$1,153	$389	$1,735	$1,153	$389	$1,735	$1,153	$389	$1,735

*Beginning in 2016, the efficiency metric for water heaters changed from EF to UEF based on DOE test procedures. Analysis is based on an average of low and medium draw pattern units, as this is most reflective of the market

** Installed cost reflects differences in installation cost between typical and high efficiency products. The high UEF products have a larger size (due to insulation differences) and therefore require more installation work. Standard-size grid-interactive water heaters should be priced as the combination of the Typical and Add-on Control columns.

Definitions: Data shown here are for electric resistance water heaters used in a residential setting. The grid-enabled product class specifically refers to electric resistance water heaters with capacities above the 55-gallon limit (DOE prohibited electric resistance WH above 55 gallon, unless it was grid-enabled). Grid-enabled electric resistance water heaters must be installed as part of a utility grid response program and cannot be installed by consumers without participation in such a program. Grid-enabled product controls and add-on controls refer to bi-directional controls (generally an external control box and mixing valve) that enables water heaters to respond to DR signals from grid operators, shift loads, pre-heat, and take on load when there is excess through changes in setpoint temperatures. The Add-on Control column reflects the incremental cost to upgrade a Typical unit to be fully grid-interactive.

Residential Electric Resistance Water Heaters

Assumptions

- No imminent standards change is on the horizon.
- No utility incentive values are calculated into retail cost. The cost of the add-on controls for DR are paid for by the utility as part of enrollment into the DR program.
- Thirty minutes of electrician labor for add-on controls.
- R&D effort is not focused on improving product UEF as the market is already mature.
- Performance and cost assumed to remain flat, due to market maturity and saturation.
- Utility DR programs increasingly incorporate WHs as a grid asset. However, lack of TOU rates for residential customers and unclear customer education remain significant barriers to adoption. Because of market barriers, add-on control costs are assumed to remain flat over the projection period.

Residential Electric Resistance Water Heaters

Interview/Research Findings

- Grid-enabled product class specifically created by EPCA as a workaround to DOE rule prohibiting electric resistance water heaters above 55 gallons.
- Grid-enabled WH cost reflects the increase due to higher capacity.
- Most demand response pilot programs use pre-existing WHs with technician installed add-on controls rather than installing the large capacity grid-enabled product class of water heaters.
- DR programs employ dedicated LTE or 5G, rather than wireless connection via Wi-Fi. This is because of the unreliability of Wi-Fi for immediate response to grid signals.
- Water heater DR programs must be carefully managed to ensure hot water is available to maintain long-term customer participation.
- Residential hot water demand is difficult to predict individually. However, large aggregated groups (hundreds) of water heaters can be accurately and predictably managed over a 24-hour period.
- Controls companies are designing systems to be under constant, 24/7 control aggregately, which allows the cloud-based system to regulate energy input to the water heaters depending on grid events (such as excess energy from renewables or high demand coupled with low generation).

Residential Heat Pump Water Heaters

Data	2020		2030		2040		2050	
	Typical/ Connected	Add-on Control	Typical/ Connected	Add-on Control	Typical/ Connected	Add-on Control	Typical/ Connected	Add-on Control
Typical Capacity (gal)	50	-	50	-	50	-	50	-
Uniform Energy Factor*	3.45	-	3.45	-	3.45	-	3.45	-
Average Life (yrs.)	6	6	6	6	6	6	6	6
	20	20	20	20	20	20	20	20
Retail Equipment Cost (2020)	$1,242	$100	$1,242	$100	$1,242	$100	$1,242	$100
	$1,327	$267	$1,327	$267	$1,327	$267	$1,327	$267
Total Installed Cost (2020)	$1,654	$173	$1,654	$173	$1,654	$173	$1,654	$173
	$2,105	$389	$2,105	$389	$2,105	$389	$2,105	$389
Annual Maintenance Cost (2020)	$20	-	$20	-	$20	-	$20	-

*Beginning in 2016, the efficiency metric for water heaters changed from EF to UEF based on DOE test procedures. Analysis is based on an average of low and medium draw pattern units, as this is most reflective of the market

Definitions: Data shown here are for electric heat pump water heaters used in a residential setting. Most residential HPWH on the market include networked connectivity (e.g., EcoNet). Add-on controls refer to bi-directional controls (generally an external control box and mixing valve) that enable water heaters to respond to DR signals from grid operators, shift loads, pre-heat, and take on load when there is excess.

Residential Heat Pump Water Heaters

Assumptions

- Thirty minutes of electrician labor for add-on controls.
- Most WHs have some level of connectivity (generally EcoNet) but will most likely require add-on control box for DR program participation.
- Retail cost reflected in the analysis does not include rebates that customers can receive through utility incentive programs. The cost of the add-on controls for DR are paid for by the utility as part of enrollment into the DR program.
- Performance and cost will remain relatively flat since the heat pump water heater market is limited due to high cost and long pay back period for customers.
- Utility DR programs increasingly incorporate WHs as a grid asset. However, lack of TOU rates for residential customers and unclear customer education remain significant barriers to adoption. Because of market barriers add-on control costs are assumed to remain flat over the projection period.
- Maintenance costs include annual cleaning of the air filter and a preventative maintenance cost to check the evaporator and refrigeration system.

Residential Heat Pump Water Heaters

Interview/Research Findings

- Heat pump water heaters have relatively low adoption in the market due to high capital cost.
- Sales driven partly by rebates and tax credits at the utility, local, state, and Federal level.
- Federal standards that came into effect in April 2015 effectively mandate heat pump technology for electric storage water heaters with storage volume >55 gallons (except in the case of grid-enabled electric resistance water heaters).
- Recovery rate of a heat pump water heater (up to 5 hours for a 50-gallon residential unit) is too slow for participation in many demand response programs without compromising user comfort, or a backup heating element to be used. In general, heat pump water heaters not used in utility DR programs.
- DR programs employ dedicated LTE or 5G, rather than wireless connection through Wi-Fi. This is because of the unreliability of Wi-Fi for immediate response to grid signals.

Residential Clothes Washers (Top-Loading)

Data	2020				2030			2040		2050	
	Current Standard	Typical	Connected	ESTAR Connected	Typical	Connected	ESTAR Connected	Typical / Connected	ESTAR Connected	Typical / Connected	ESTAR Connected
Typical Capacity (ft^3)	3.65	3.65	4.96	5.23	3.65	4.41	4.41	3.85	3.85	3.85	3.85
	4.78	4.78	5.41	5.30	4.78	5.28	5.28	5.15	5.15	5.15	5.15
Integrated Modified Energy Factor (ft^3/kWh/cycle)	1.26	1.57	2.06	2.06	1.57	1.82	1.82	1.57	1.57	1.57	1.57
		2.06	2.23	2.06	2.06	2.14	2.14	2.06	2.06	2.06	2.06
Product Lifetime (yrs.)	8	8	8	8	8	8	8	8	8	8	8
	18	18	18	18	18	18	18	18	18	18	18
Retail Equipment Cost (2020)	$674	$674	$987	$1,074	$674	$858	$858	$730	$730	$730	$730
	$957	$957	$1,162	$1,164	$957	$1,116	$1,116	$1,071	$1,071	$1,071	$1,071
Total Installed Cost (2020)	$824	$824	$1,137	$1,224	$824	$1,008	$1,008	$880	$880	$880	$880
	$1,107	$1,107	$1,312	$1,314	$1,107	$1,266	$1,266	$1,221	$1,221	$1,221	$1,221
Annual Maintenance Cost (2020)	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10

Definitions: Data shown here are for top-loading, standard-sized, 27” width clothes washers. The connected case only includes clothes washers with Wi-Fi and/or Bluetooth and remote management capabilities. According to the ESTAR Connected Criteria, certified products shall be able to temporarily (for a duration of 10 minutes) reduce load to less than 50 watts or shift 100% of the load by delaying the start for at least 4 hours.

Residential Clothes Washers (Top-Loading)

Assumptions

- The connected case will become the typical case by 2040.
- ESTAR Connected case will not become typical case due to lack of value proposition of grid-interactivity for consumers.
- The typical capacities, IMEFs, and costs of the ESTAR Connected case will align with the connected case starting in 2030 since the only technological difference between connected and ESTAR Connected washers is software-related.
- Retail equipment costs, installation costs, maintenance costs, capacities, lifetimes, energy efficiency performances will remain constant through 2050.
- The maintenance cost is the annualized cost of typical total costs to repair a clothes washer over the course of its lifetime.

All Residential Appliances (Clothes Washers, Clothes Dryers, Refrigerators, Dishwashers)

Interview/Research Findings

- The adoption of GEB technologies is occurring more rapidly in the residential sector. This can be attributed to consumer demand for more connectivity energy performance information.
- Within the next 10-15 years, connected appliances will make up majority of appliance sales.
  - The incremental cost of making an appliance smart is inexpensive compared to the cost of the appliance—and it is declining.
  - Manufacturers are making more connected appliances and sales are increasing.
- There are not many incentives for manufacturers to produce grid-interactive appliances.
- Utility rate structure is the primary driving factor for the adoption of smart appliances.
- Compared to space heating and cooling products, grid-interactivity for appliances is more risky and more difficult to implement due to potential impacts to consumer convenience.
- Greatest barriers are interoperability and value proposition for grid-interactive appliances.
  - Smart home energy management systems/hubs have the potential to drive improvements in the interoperability of different types of devices from different manufacturers.
  - The adoption of smart home energy management systems will increase the adoption of smart appliances.
- Most appliances (clothes washers, dryers, dishwashers) follow similar price trends and have remained relatively stable in the past 10 years.
- There are no refrigerators with top-mounted freezers certified according to the ENERGY STAR Connected Criteria, which includes requirements for grid-interactivity. Connectivity is more prevalent in refrigerators with side or bottom-mounted freezers and so refrigerators with top-mounted freezers are not included in this report.

Residential Clothes Washers (Front-Loading)

Data	2020				2030			2040		2050	
	Current Standard	Typical	Connected	ESTAR Connected	Typical	Connected	ESTAR Connected	Typical/ Connected	ESTAR Connected	Typical/ Connected	ESTAR Connected
Typical Capacity (ft^3)	3.90	3.90	4.55	2.20	3.90	4.42	4.42	4.29	4.29	4.29	4.29
	4.50	4.50	5.10	3.60	4.50	4.94	4.94	4.79	4.79	4.79	4.79
Integrated Modified Energy Factor (ft^3/kWh/cycle)	1.84	2.74	2.78	2.22	2.74	2.77	2.77	2.76	2.76	2.76	2.76
		2.92	2.92	2.57	2.92	2.92	2.92	2.92	2.92	2.92	2.92
Product Lifetime (yrs.)	8	8	8	8	8	8	8	8	8	8	8
	18	18	18	18	18	18	18	18	18	18	18
Retail Equipment Cost (2020)	$899	$899	$1,137	$1,254	$899	$1,087	$1,087	$1,037	$1,037	$1,037	$1,037
	$1,387	$1,387	$1,580	$1,344	$1,387	$1,430	$1,430	$1,280	$1,280	$1,280	$1,280
Total Installed Cost (2020)	$1,049	$1,049	$1,287	$1,404	$1,049	$1,237	$1,237	$1,187	$1,187	$1,187	$1,187
	$1,537	$1,537	$1,730	$1,494	$1,537	$1,580	$1,580	$1,430	$1,430	$1,430	$1,430
Annual Maintenance Cost (2020)	$10	$10	$10	$10	$10	$10	$10	$10	$10	$11	$12

Definitions: Data shown here are for front-loading, standard-sized, 27" width clothes washers. The connected case only includes clothes washers with Wi-Fi and/or Bluetooth capabilities. According to the ESTAR Connected Criteria, certified products shall be able to temporarily (for a duration of 10 minutes) reduce load to less than 50 watts or shift 100% of the load by delaying the start for at least 4 hours.

Residential Clothes Washers (Front-Loading)

Assumptions

- The connected case will become the typical case by 2040.
- ESTAR Connected case will not become typical case due to lack of value proposition of grid-interactivity for consumers.
- The typical capacities, IMEFs, and costs of the ESTAR Connected case will align with the connected case starting in 2030 since the only technological difference between connected and ESTAR Connected washers is software-related.
- Retail equipment costs, installation costs, maintenance costs, capacities, lifetimes, energy efficiency performances will remain constant through 2050.
- The maintenance cost is the annualized cost of typical maintenance costs for a clothes washer over the course of its lifetime.

All Residential Appliances (Clothes Washers, Clothes Dryers, Refrigerators, Dishwashers)

Interview/Research Findings

- Adoption of GEB technologies is occurring more rapidly in the residential sector. This is attributed to consumer demand for more connectivity energy performance information.
- Within the next 10-15 years, connected appliances will make up majority of appliance sales.
  - The incremental cost of making an appliance smart is inexpensive compared to the cost of the appliance—and it is declining.
  - Manufacturers are making more connected appliances and sales are increasing.
- There are not many incentives for manufacturers to produce grid-interactive appliances.
- Utility rate structure is the primary driving factor for the adoption of smart appliances.
- Compared to space heating and cooling products, grid-interactivity for appliances is more risky and more difficult to implement due to potential impacts to consumer convenience.
- Greatest barriers are interoperability and value proposition for grid-interactive appliances
  - Smart home energy management systems/hubs have the potential to drive improvements in the interoperability of different types of devices from different manufacturers.
  - The adoption of smart home energy management systems will increase the adoption of smart appliances.
- Most appliances (clothes washers, dryers, dishwashers) follow similar price trends, and have remained relatively stable in the past 10 years.
- There are no refrigerators with top-mounted freezers certified according to the ENERGY STAR Connected Criteria, which includes requirements for grid-interactivity. Connectivity is more prevalent in refrigerators with side or bottom-mounted freezers and so refrigerators with top-mounted freezers are not included in this report.

Residential Electric Clothes Dryers

Data	2020				2030			2040		2050	
	Current Standard	Typical	Connected	ESTAR Connected	Typical	Connected	ESTAR Connected	Typical / Connected	ESTAR Connected	Typical / Connected	ESTAR Connected
Typical Capacity (ft^3)	7.1	7.1	7.4	7.33	7.1	7.28	7.28	7.15	7.15	7.15	7.15
	7.45	7.45	7.65	7.4	7.45	7.58	7.58	7.5	7.5	7.5	7.5
Combined Energy Factor (lb./kWh)	3.73	3.73	3.93	3.93	3.73	3.83	3.83	3.73	3.73	3.73	3.73
		3.93	3.94	3.93	3.93	3.94	3.94	3.93	3.93	3.93	3.93
Product Lifetime (yrs.)	8	8	8	8	8	8	8	8	8	8	8
	18	18	18	18	18	18	18	18	18	18	18
Retail Equipment Cost (2020)	$757	$757	$936	$1,197	$757	$872	$872	$809	$809	$809	$809
	$1,205	$1,205	$1,259	$1,412	$1,205	$1,242	$1,242	$1,225	$1,225	$1,225	$1,225
Total Installed Cost (2020)	$872	$872	$1,051	$1,312	$872	$987	$987	$924	$924	$924	$924
	$1,330	$1,330	$1,384	$1,527	$1,320	$1,357	$1,357	$1,340	$1,340	$1,340	$1,340

Definitions: Data shown here are for electric, vented, standard-sized clothes dryers. The connected case only includes dryers with Wi-Fi and/or Bluetooth capabilities. According to the ESTAR Connected Criteria, certified products shall be able to temporarily (for a duration of 10 minutes) reduce load during a cycle that reduces consumption by 20% relative to baseline, or 100% shift the load by delaying the start for at least 3 hours.

Residential Electric Clothes Dryers

Assumptions

- The connected case will become the typical case by 2040.
- ESTAR Connected case will not become the typical case due to lack of value proposition of grid-interactivity for consumers.
- The typical capacities, IMEFs, and costs of the ESTAR Connected case will align with the connected case starting in 2030 since the only technological difference between connected and ESTAR Connected dryers is software-related.
- Retail equipment costs, installation costs, maintenance costs, capacities, lifetimes, energy efficiency performances will remain constant through 2050.
- Maintenance costs are assumed to be negligible.

All Residential Appliances (Clothes Washers, Clothes Dryers, Refrigerators, Dishwashers)

Interview/Research Findings

- Adoption of GEB technologies is occurring more rapidly in the residential sector. This is attributed to consumer demand for more connectivity energy performance information.
- Within the next 10-15 years, connected appliances will make up majority of appliance sales.
  - The incremental cost of making an appliance smart is inexpensive compared to the cost of the appliance—and it is declining.
  - Manufacturers are making more connected appliances and sales are increasing.
- There are not many incentives for manufacturers to produce grid-interactive appliances.
- Utility rate structure is the primary driving factor for the adoption of smart appliances.
- Compared to space heating and cooling products, grid-interactivity for appliances is more risky and more difficult to implement due to potential impacts to consumer convenience.
- Greatest barriers are interoperability and value proposition for grid-interactive appliances
  - Smart home energy management systems/hubs have the potential to drive improvements in the interoperability of different types of devices from different manufacturers.
  - The adoption of smart home energy management systems will increase the adoption of smart appliances.
- Most appliances (clothes washers, dryers, dishwashers) follow similar price trends, and have remained relatively stable in the past 10 years.
- There are no refrigerators with top-mounted freezers certified according to the ENERGY STAR Connected Criteria, which includes requirements for grid-interactivity. Connectivity is more prevalent in refrigerators with side or bottom-mounted freezers and so refrigerators with top-mounted freezers are not included in this report.

Residential Dishwashers

Data	2020				2030			2040		2050	
	Current Standard	Typical	Connected	ESTAR Connected	Typical	Connected	ESTAR Connected	Typical / Connected	ESTAR Connected	Typical / Connected	ESTAR Connected
Typical Capacities (Place Settings)	13	13	15	13	13	14	14	14	14	14	14
	16	16	16	16	16	16	16	16	16	16	16
Annual Energy Use (kWh/yr.)	307	254	256	269	254	254	254	252	252	252	252
		270	270	269	270	270	270	270	270	270	270
Product Lifetime (yrs.)	10	10	10	10	10	10	10	10	10	10	10
	19	19	19	19	19	19	19	19	19	19	19
Retail Equipment Cost (2020)	$747	$747	$934	$1,799	$747	$841	$841	$749	$749	$749	$749
	$1,185	$1,185	$1,578	$2,399	$1,185	$1,394	$1,394	$1,209	$1,209	$1,209	$1,209
Total Installed Cost (2020)	$919	$919	$1,106	$1,971	$919	$1,013	$1,013	$921	$921	$921	$921
	$1,357	$1,357	$1,750	$2,571	$1,357	$1,566	$1,566	$1,381	$1,381	$1,381	$1,381

Definitions: Data shown here are for standard-sized dishwashers (which have capacities of 8 place settings or higher). The connected case only includes dishwashers with Wi-Fi or Bluetooth capabilities. According to the ESTAR Connected criteria, certified products shall be able to temporarily (for a duration of 10 minutes) reduce load during a cycle that reduces power consumption to less than 250 watts and be able to delay start for 4+ hours.

Residential Dishwashers

Assumptions

- The connected case will become the typical case by 2040.
- ESTAR Connected case will not become typical case due to lack of value proposition of grid-interactivity for consumers.
- The typical capacities, IMEFs, and costs of the ESTAR Connected case will align with the connected case starting in 2030 since the only technological difference between connected and ESTAR Connected dryers is software-related.
- Installation costs, lifetimes will remain constant through 2050.
- Maintenance costs are assumed to be negligible.

All Residential Appliances (Clothes Washers, Clothes Dryers, Refrigerators, Dishwashers)

Interview/Research Findings

- Adoption of GEB technologies is occurring more rapidly in the residential sector. This is attributed to consumer demand for more connectivity energy performance information.
- Within the next 10-15 years, connected appliances will make up majority of appliance sales.
  - The incremental cost of making an appliance smart is inexpensive compared to the cost of the appliance—and it is declining.
  - Manufacturers are making more connected appliances and sales are increasing.
- There are not many incentives for manufacturers to produce grid-interactive appliances.
- Utility rate structure is the primary driving factor for the adoption of smart appliances.
- Compared to space heating and cooling products, grid-interactivity for appliances is more risky and more difficult to implement due to potential impacts to consumer convenience.
- Greatest barriers are interoperability and value proposition for grid-interactive appliances
  - Smart home energy management systems/hubs have the potential to drive improvements in the interoperability of different types of devices from different manufacturers.
  - The adoption of smart home energy management systems will increase the adoption of smart appliances.
- Most appliances (clothes washers, dryers, dishwashers) follow similar price trends, and have remained relatively stable in the past 10 years.
- There are no refrigerators with top-mounted freezers certified according to the ENERGY STAR Connected Criteria, which includes requirements for grid-interactivity. Connectivity is more prevalent in refrigerators with side or bottom-mounted freezers and so refrigerators with top-mounted freezers are not included in this report.

Residential Refrigerators (Side-Freezers)

Data	2020			2030		2040	2050
	Current Standard	Typical	ESTAR Connected	Typical	ESTAR Connected	Typical / ESTAR Connected	Typical / ESTAR Connected
Typical Capacity (ft^3)	21.7	21.7	22.4	21.7	22.1	21.8	21.8
	25.1	25.1	24.2	25.1	24.7	25.2	25.2
Annual Energy Use (kWh/yr.)	665*	658	640	660	647	655	655
	704**	705	664	705	681	698	698
Average Life (yrs.)	11	11	11	11	11	11	11
	21	21	21	21	21	21	21
Retail Equipment Cost (2020)	$1,399	$1,399	$2,104	$1,399	$1,770	$1,437	$1,437
	$1,999	$1,999	$2,412	$1,999	$2,282	$2,152	$2,152
Total Installed Cost (2020)	$1,399	$1,399	$2,104	$1,399	$2,104	$1,437	$1,437
	$1,999	$1,999	$2,412	$1,999	$2,412	$2,152	$2,152
Annual Maintenance Cost (2020)	$25	$25	$25	$25	$25	$25	$25

* Based on an adjusted volume of 27.2 ft^3, which is the average for this type of refrigerator at capacities between 20 and 23 ft^3.

** Based on an adjusted volume of 31.8 ft^3, which is the average for this type of refrigerator at capacities between 23 and 27 ft^3.

Definitions: Data shown here are for refrigerators with side-freezers and through-the-door ice service. According to the ESTAR Connected Criteria, certified products shall be able to delay use for more than 4 hours by shifting defrost cycle/shifting ice maker cycle or reducing power draw during the delay period by 13% relative to average power consumption. Certified products shall also be able to temporarily (typically for a duration of 10 minutes) reduce its power draw to no more than 50% of its average power draw.

Residential Refrigerators (Side-Freezers)

Assumptions

- Analysis is based on refrigerators with side-freezers and through-the-door ice service.
- Refrigerators with connected capabilities are usually certified according to the ENERGY STAR Connected criteria and so are usually grid-interactive.
- ESTAR Connected case will become typical by 2040.
- Refrigerators are a mature technology and so retail equipment costs, capacities, and energy performances will remain constant for the typical case.
- The maintenance cost is the annualized cost of typical maintenance cost for a refrigerator over the course of its lifetime.

All Residential Appliances (Clothes Washers, Clothes Dryers, Refrigerators, Dishwashers)

Interview/Research Findings

- Adoption of GEB technologies is occurring more rapidly in the residential sector. This is attributed to consumer demand for more connectivity energy performance information.
- Within the next 10-15 years, connected appliances will make up majority of appliance sales.
  - The incremental cost of making an appliance smart is inexpensive compared to the cost of the appliance—and it is declining.
  - Manufacturers are making more connected appliances and sales are increasing.
- There are not many incentives for manufacturers to produce grid-interactive appliances.
- Utility rate structure is the primary driving factor for the adoption of smart appliances.
- Compared to space heating and cooling products, grid-interactivity for appliances is more risky and more difficult to implement due to potential impacts to consumer convenience.
- Greatest barriers are interoperability and value proposition for grid-interactive appliances
  - Smart home energy management systems/hubs have the potential to drive improvements in the interoperability of different types of devices from different manufacturers.
  - The adoption of smart home energy management systems will increase the adoption of smart appliances.
- Most appliances (clothes washers, dryers, dishwashers) follow similar price trends, and have remained relatively stable in the past 10 years.
- There are no refrigerators with top-mounted freezers certified according to the ENERGY STAR Connected Criteria, which includes requirements for grid-interactivity. Connectivity is more prevalent in refrigerators with side or bottom-mounted freezers and so refrigerators with top-mounted freezers are not included in this report.

Residential Refrigerators (Bottom-Freezers)

Data	2020			2030		2040	2050
	Current Standard	Typical	ESTAR Connected	Typical	ESTAR Connected	Typical / ESTAR Connected	Typical / ESTAR Connected
Typical Capacity (ft^3)	23.1	23.1	22.3	23.1	22.7	23	23
	27.3	27.3	27.7	27.3	27.5	27.4	27.4
Annual Energy Use (kWh/yr.)	744*	684	671	684	674	677	677
	781**	725	727	725	729	732	732
Average Life (yrs.)	11	11	11	11	11	11	11
	21	21	21	21	21	21	21
Retail Equipment Cost (2020)	$2,637	$2,637	$3,170	$2,637	$3,009	$2,848	$2,848
	$3,566	$3,566	$4,033	$3,566	$3,932	$3,832	$3,832
Total Installed Cost (2020)	$2,637	$2,637	$3,170	$2,637	$3,009	$2,848	$2,848
	$3,566	$3,566	$4,033	$3,566	$3,932	$3,832	$3,832
Annual Maintenance Cost (2020)	$25	$25	$25	$25	$25	$25	$25

* Based on an adjusted volume of 29 ft^3, which is the average for this type of refrigerator at capacities between 22.8 and 23.6 ft^3.

** Based on an adjusted volume of 33 ft^3, which is the average for this type of refrigerator at capacities between 26.8 and 27.6 ft^3.

Definitions: Data shown here are for French-door style refrigerators with bottom-freezers and through-the-door ice service. According to the ESTAR Connected Criteria, certified products shall be able to delay use for more than 4 hours by shifting defrost cycle/shifting ice maker cycle or reducing power draw during the delay period by 13% relative to average power consumption. Certified products shall also be able to temporarily (typically for a duration of 10 minutes) reduce its power draw to no more than 50% of its average power draw.

Residential Refrigerators (Bottom-Freezers)

Assumptions

- Analysis is based on French-door style refrigerators with through-the-door ice service.
- Refrigerators with connected capabilities are usually certified according to the ESTAR Connected criteria and so are usually grid-interactive.
- ESTAR Connected case will become typical by 2040.
- Refrigerators are a mature technology and so retail equipment costs, capacities, and energy performances will remain constant for the typical case.
- The maintenance cost is the annualized cost of typical maintenance cost for a refrigerator over the course of its lifetime.

All Residential Appliances (Clothes Washers, Clothes Dryers, Refrigerators, Dishwashers)

Interview/Research Findings

- Adoption of GEB technologies is occurring more rapidly in the residential sector. This is attributed to consumer demand for more connectivity energy performance information.
- Within the next 10-15 years, connected appliances will make up majority of appliance sales.
  - The incremental cost of making an appliance smart is inexpensive compared to the cost of the appliance—and it is declining.
  - Manufacturers are making more connected appliances and sales are increasing.
- There are not many incentives for manufacturers to produce grid-interactive appliances.
- Utility rate structure is the primary driving factor for the adoption of smart appliances.
- Compared to space heating and cooling products, grid-interactivity for appliances is more risky and more difficult to implement due to potential impacts to consumer convenience.
- Greatest barriers are interoperability and value proposition for grid-interactive appliances
  - Smart home energy management systems/hubs have the potential to drive improvements in the interoperability of different types of devices from different manufacturers.
  - The adoption of smart home energy management systems will increase the adoption of smart appliances.
- Most appliances (clothes washers, dryers, dishwashers) follow similar price trends, and have remained relatively stable in the past 10 years.
- There are no refrigerators with top-mounted freezers certified according to the ENERGY STAR Connected Criteria, which includes requirements for grid-interactivity. Connectivity is more prevalent in refrigerators with side or bottom-mounted freezers and so refrigerators with top-mounted freezers are not included in this report.

Residential Lighting

Data	2020		2030		2040		2050	
	ESTAR	ESTAR Connected	ESTAR	ESTAR Connected	ESTAR	ESTAR Connected	ESTAR	ESTAR Connected
Typical Output (lm)	800 1,100	800	800 1,100	800 1,100	800 1,100	800 1,100	800 1,100	800 1,100
Luminous Efficacy (lm/W)	84 100	80 89	109 129	109 129	126 150	126 150	139 165	139 165
Average Life (hours)	15,000 25,000	25,000	10,000 25,000	25,000	10,000 25,000	25,000	10,000 25,000	25,000
Total Cost (2020 $/klm)	$7	$12 $29	$7	$10 $22	$7	$9 $20	$7	$9 $20

Definitions: Data shown for ENERGY STAR certified residential general service LED lamps, E26 base, and A19 bulbs. ENERGY STAR Connected LED lamps are defined as an ENERGY STAR lamp plus hardware and software needed for communication and remote control; they are capable of remote management and operation status reporting, but do not have DR capability built-in.

Residential Lighting

Assumptions

- Connected residential lighting will not become typical by 2050.
  - Adoption of connected lighting is slower than other smart home technologies as value is not proven.
  - Adoption increases as the cost premium declines.
- LED typical prices remain stagnant.
- Cost premium for connected will go down over time.
- Efficacy continues to increase from 2020-2050, though at a slower rate than historical trends have shown.
- Lifetime will decrease for low-end market products.

Residential Lighting

Interview/Research Findings

- Residential lighting is unlikely to be used for DR in the future.
- Connected lighting has limited value; price is also a significant barrier.
- Increasing lifetime is not a focus in residential lighting.
  - It is likely that lower tier products could emerge with lower lifetimes.
- Efficacy still has room for improvement; theoretical max efficacy is high (250 lm/W).
- LED costs are already low and manufacturer profit margins are low.
  - Prices are unlikely to fall any lower than they are currently.
  - LED market is already mature.
- Lighting research has shifted toward improving on non-energy features of LEDs.
- Grid-interactive lighting currently has little potential in the residential sector. Lighting loads in the residential sector are decreasing with increased LED adoption.
- Value proposition is the biggest barrier for connected lighting.
  - Software development and interoperability are also barriers.

Smart Home Energy Management Systems

Data	2020 Connected Smart Home Hub	2020 SHEMS	2030 Connected Smart Home Hub	2030 SHEMS	2040 Connected Smart Home Hub	2040 SHEMS	2050 Connected Smart Home Hub	2050 SHEMS
Average Life (yrs.)	15	15	15	15	15	15	15	15
Retail Cost (2020)	$80 $130	$1,328	$62 $100	$973 $1,123	$57 $92	$896 $1,034	$53 $86	$854 $966
Total Devices/ Sensors	1	30	1	30	1	30	1	30
Total Installed Cost	$80 $130	$1,965*	$62 $100	$1,610* $1,761*	$57 $92	$1,534* $1,671*	$53 $86	$1,491* $1,603*
Installed Cost/Device	$80 $130	$65	$62 $100	$54 $59	$57 $92	$51 $56	$53 $86	$50 $53
Installed Cost/sq. ft	-	$0.98	-	$0.80	-	$0.76	-	$0.74
Reported Energy Savings for Connected Loads	-	5% 22%	-	10% 27%	-	15% 32%	-	15% 32%

*This assumes installation by professionals for $600, though SHEMS can be self installed ($0).

Definitions: Smart home hubs control compatible smart home technologies including lighting, TV, security systems, thermostats, and smart plugs. SHEMS use a combination of software, controls, sensors, and smart devices that are designed to work together to deliver occupancy-based optimization of energy use in a home including lighting, HVAC, and plug loads. SHEMS enable flexibility through turning off and shifting unused plug loads. Assumptions on SHEMS technologies is defined on page 51. Smart home hubs are included in the costs for SHEMS but are also shown separately in the table as a reference.

Smart Home Energy Management Systems

Assumptions

- SHEMS and smart home hub prices decline as adoption increases, manufacturing capacity increases, and vendor competition increases from 2020 to 2030.
  - From 2030-2050, the rate of price decline slows.
  - From 2020-2040, price declines for SHEMS is partially offset by increases in functionality that result in increased energy savings.
- SHEMS pricing data assumes these smart technologies: hub (1), lights (10), switches (3), plugs (5), meter (1), occupancy sensors (5), geo-fencing sensors (4), and thermostat (1).
- Price/sq. ft is determined using the average household size of 2,008 sq. ft in 2015.
- Installation costs are estimated based on labor for installing and setting up smart home devices, though some tech-savvy consumers can self install the equipment at no additional cost.
- Lifetime remains constant.
- Installation costs remains constant.
- Maintenance costs are negligible.
- Prices do not include utility incentives/rebates, though some utilities offer rebates for smart plugs and smart thermostats for enrolling in DR programs.

Smart Home Energy Management Systems

Interview/Research Findings

- SHEMS currently on the market are not grid-interactive; there are several pilots and research projects working on their development.
- It will be about 5 years until commercialization of a grid-interactive SHEMS.
  - Utility programs will drive adoption.
- Current market barriers are primarily interoperability and cybersecurity.
  - Privacy is a major concern for many people.
- Control of smart devices in utility programs depends on the program design.

Residential Window Attachments

Data	2020				2030			2040			2050		
	Typical	Add-On Control	Connected		Typical	Connected		Typical	Connected		Typical	Connected	
	Manual Venetian Blinds	Add-On Motorized Control	Motorized Roller Shade	Motorized Cellular Shade	Manual Venetian Blinds	Motorized Roller Shade	Motorized Cellular Shade	Manual Venetian Blinds	Motorized Roller Shade	Motorized Cellular Shade	Manual Venetian Blinds	Motorized Roller Shade	Motorized Cellular Shade
Delta SHGC	0.03	N/A	0.01	0.03	0.03	0.01	0.03	0.03	0.01	0.03	0.03	0.01	0.03
	0.21		0.20	0.19	0.21	0.20	0.19	0.21	0.20	0.19	0.21	0.20	0.19
Delta U-Factor	0.03	N/A	0.01	0.03	0.03	0.01	0.03	0.03	0.01	0.03	0.03	0.01	0.03
	0.05		0.14	0.17	0.05	0.14	0.17	0.05	0.14	0.17	0.05	0.14	0.17
Average Life (yrs.)	7	7	7	7	7	7	7	7	7	7	7	7	7
	10	10	10	10	10	10	10	10	10	10	10	10	10
Total Cost (2020)	$9/sq. ft	$119	$32/sq. ft	$33/sq. ft	$9/sq. ft	$29/sq. ft	$30/sq. ft	$9/sq. ft	$27/sq. ft	$28/sq. ft	$9/sq. ft	$27/sq. ft	$28/sq. ft
	$15/sq. ft	$159	$94/sq. ft	$73/sq. ft	$15/sq. ft	$85/sq. ft	$66/sq. ft	$15/sq. ft	$80/sq. ft	$62/sq. ft	$15/sq. ft	$80/sq. ft	$62/sq. ft
Reported Heating/ Cooling Savings	0%	12%	12%	12%	0%	12%	12%	0%	12%	12%	0%	12%	12%
		13%	13%	13%		13%	13%		13%	13%		13%	13%

Definitions: Data shown for both traditional venetian blinds, automatic motorized attachments for a manual blind, and an automated motorized window shade system. Smart motorized shades and controls include the capability to control the window shades via an app or smart home hub and set automated custom schedules to control the SHGC from the windows. They can provide flexibility through adjusting SHGC of windows to help shift HVAC loads, but do not have DR capability built-in. Cost data is shown in sq. ft of blind or shade area.

Residential Window Attachments

Assumptions

- Add-on controls will be obsolete by 2030.
- Automated window attachment prices decline from 2020 to 2030 as more products enter the market and competition increases; prices remain stagnant from 2030-2050.
- Manual blind prices remain constant as the market is mature.
- Performance of shading systems remain constant as improving performance of window shades is not a priority for researchers/manufacturers and consumers typically do not purchase blinds for energy savings.
- Automated window attachments adoption increase over time but will not become typical in the market.
- Automated window attachments will not participate in DR directly, only (potentially) through scheduling to align with TOU pricing.
- Maintenance costs are negligible.

Residential Window Attachments

Interview/Research Findings

- Automated window attachments are generally designed for occupant comfort to enable control of thermal comfort and glare, and not for energy savings.
- Automated window attachments systems have seen some adoption in the commercial space but little adoption in the residential space. Some adoption has been seen in the high-end residential multifamily sector.
- Recently energy efficiency labeling for window attachments has emerged, which could potentially drive more adoption and energy savings in the future.
- Automated attachments made up about 10% of the window attachments market in 2018 and is expected to grow.

Residential Advanced Power Strips

Data	2020			2030		2040		2050	
	Connected			Connected		Connected		Connected	
	Smart Outlets	Tier 1 APS	Tier 2 APS	Smart Outlets	Tier 2 APS	Smart Outlets	Tier 2 APS	Smart Outlets	Tier 2 APS
Average Life (yrs.)	8	8	8	8	8	8	8	8	8
	10	10	10	10	10	10	10	10	10
Total Cost (2020)	$18	$20	$72	$18	$72	$18	$72	$18	$72
		$27	$95		$95		$95		$95
Active Outlets	1	2	5	1	5	1	5	1	5
		4	6		6		6		6
Cost/Outlet (2020)	$18	$7	$13	$18	$13	$18	$13	$18	$13
		$12	$16		$16		$16		$16
AV Equipment Reported Energy Savings	N/A	Load Sensing 18%	Engagement Sensing 49%	N/A	Engagement Sensing 59%	N/A	Engagement Sensing 59%	N/A	Engagement Sensing 59%
	N/A		Infrared + Occupancy Sensing 19%	N/A	Infrared + Occupancy Sensing 29%	N/A	Infrared + Occupancy Sensing 29%	N/A	Infrared + Occupancy Sensing 29%

Definitions: Data shown for both a single smart outlet which integrates with smart home hubs, Tier 1, and Tier 2 advanced power strips. Smart outlet are capable of Wi-Fi enabled control via app of any device plugged to switch on/of, check the status, and program schedules; they are compatible with smart home hubs but do not require them. Tier 1 power strips use either programming/scheduling or current sensing. Tier 2 advanced power strips use additional sensors, software, and algorithms to sense real time power use; tier 2 power strips reduce standby and wasteful active loads. They can provide flexibility by shifting plug loads (i.e., PC workstations). Engagement sensing monitors the consumers use of the equipment, occupancy sensors detect motion, and infrared sensors detect heat.

Residential Advanced Power Strips

Assumptions

- After 2030, Tier 1 advanced power strips will be obsolete as smart home technologies become more prevalent.
- From 2020-2030, the cost of smart plugs and advanced power strips decline 25% but there will be an increase in features that equally offset price declines.
  - Advanced features will lead to 10% higher energy savings on average.
- Tier 2 power strips will exit the market between 2030-2050, as home electronics and energy management systems become more efficient and expand their capabilities; integrated control capabilities for these products will become more prevalent than control through strips.
  - Prices will remain stagnant during this period.
  - Lifetime will remain constant.
- Assumes power strips are used to control home AV equipment (TV, audio system, game console, DVD).
- Assumes no utility incentives are applied to cost estimates, though some utilities offer them free or at a low cost ($10-$20) in exchange for participating in utility programs.

Residential Advanced Power Strips

Interview/Research Findings

- APS has the most potential for AV and home entertainment in the residential sector and PC workstations (laptops/desktops) in the commercial sector.
- Tier 2 APS provide significant energy savings through detecting occupant engagement and automatically shutting off equipment when not in use.
- APS are just an interim technology; in the future, BAS/SHEMS and smart technologies replace APS.
  - This may happen within 10-20 years; manufacturers are already shifting to other markets.
  - Computers/electronics will likely be efficient enough and will not require external controls to manage energy use in the future.

Residential Pool Pumps

Data	2020				2030		2040		2050	
	Current Standard (2021)	Typical	ESTAR Connected	Add-On Control	Typical	ESTAR Connected	Typical/ Connected	ESTAR Connected	Typical/ Connected	ESTAR Connected
Typical Capacity (hhp)	0.95 1.88	1.42	2.04	-	1.42	2.04	1.42	2.04	1.42	2.04
Weighted Energy Factor (WEF)	6.9 5.2	3.7	6.1	-	6.0	6.4	6.0	6.7	6.0	7
Average Life (yrs.)	7.3	7.3	7.3	-	7.3	7.3	7.3	7.3	7.3	7.3
Retail Equipment Cost (2020)	$787 $1,048	$672	$1,499	$155 $170	$920	$1,383	$1,049	$1,266	$1,033	$1,250
Total Installed Cost (2020)	$809 $1,070	$833	$1,522	$155 $170	$942	$1,405	$1,072	$1,289	$1,056	$1,273
Average Annual Maintenance Cost (2020)	$91 $120	$70	$120	-	$105	$120	$105	$120	$105	$120

Definitions: Data shown here are for variable speed self-priming pool filter pump (standard size) which are used in in-ground residential pools. ENERGY STAR connected pool pumps consist of an ENERGY STAR pool pump plus hardware and software that enables communication and control. They can provide flexibility by a 67% speed reduction for 4+ hours or turning off for 20+ minutes for 100% load shift. Currently there is only 1 ENERGY STAR connected pool pump certified on the market.

Residential Pool Pumps

Assumptions

- In 2030, the typical case will be the standard efficiency level for the 2021 standard.
- Typical efficiency levels remain constant at 2021 standard level.
- Pool pumps will be used in more DR programs in the future.
- The typical case will be connected in 2040.
- The cost of the typical case will increase according to the increased efficiency level.
- Cost increases in 2040 related to the connected controls added on.
- Capacity levels remain consistent for the typical case and ENERGY STAR Connected over time.
- The price of ENERGY STAR Connected pool pumps decrease steadily over time as more products enter the market, and more manufacturers make them (there is only one product currently certified).
  - Add-on controls become obsolete as more connected pool pumps enter the market.
- Repair costs are constant over the next 30 years.
- Annual maintenance costs is estimated using the typical repair costs for motor replacement and the frequency of repair (3.7 years).
- Add-on control prices do not include utility incentives/rebates, though some utilities offer them free or at low cost for enrolling in DR programs.

Residential Pool Pumps

Interview/Research Findings

- Pool pumps are a major emerging area for utility programs and incentives in warmer regions of the US (California, Florida).
  - Connected pool pumps likely will see high adoption in these regions in the future.
- The first efficiency standard for pool pumps will go into effect in 2021 and the standard is above current market averages.
  - This will be expensive for manufacturers to comply with in terms of R&D, testing, and certification.
  - It is expensive to make pool pumps more efficient.
  - Typical efficiency levels for pool pumps are likely to remain at standard level in the future.
- Payback periods for higher efficiency pool pumps is low (around 1 year).

Commercial Technologies

Commercial Chillers/Ice Storage

Data	2020			2030			2040			2050		
	Typical	Connected		Typical	Connected		Typical	Connected		Typical	Connected	
	Centri-fugal Chiller	Modular	Site-Built	Centri-fugal Chiller	Modular	Site-Built	Centri-fugal Chiller	Modular	Site-Built	Centri-fugal Chiller	Modular	Site-Built
Typical Capacity	400 tons	100 ton-hrs	5,000 ton-hrs	400 tons	100 ton-hrs	5,000 ton-hrs	400 tons	100 ton-hrs	5,000 ton-hrs	400 tons	100 ton-hrs	5,000 ton-hrs
	600 tons	1,000 ton-hrs	250,000 ton-hrs	600 tons	1,000 ton-hrs	250,000 ton-hrs	600 tons	1,000 ton-hrs	250,000 ton-hrs	600 tons	1,000 ton-hrs	250,000 ton-hrs
Efficiency [full-load] (kW/ton)	0.51	-	-	0.46	-	-	0.43	-	-	0.42	-	-
Efficiency [IPLV] (kW/ton)	0.35	-	-	0.35	-	-	0.34	-	-	0.33	-	-
COP [full-load]	6.9	-	-	7.6	-	-	8.2	-	-	8.4	-	-
COP [IPLV]	10.0	-	-	10.0	-	-	10.3	-	-	10.7	-	-
Average Life (yrs.)	25	30	30	25	30	30	25	30	30	25	30	30
		50	50		50	50		50	50		50	50
Retail Equipment Cost (2020)	$375/ton	$80/ton-hr	$65/ton-hr	$375/ton	$80/ton-hr	$65/ton-hr	$375/ton	$80/ton-hr	$65/ton-hr	$375/ton	$80/ton-hr	$65/ton-hr
	$425/ton	$200/ton-hr	$130/ton-hr	$425/ton	$200/ton-hr	$130/ton-hr	$425/ton	$200/ton-hr	$130/ton-hr	$425/ton	$200/ton-hr	$130/ton-hr
Total Installed Cost (2020)	$450/ton	$160/ton-hr	$65/ton-hr	$450/ton	$160/ton-hr	$65/ton-hr	$450/ton	$160/ton-hr	$65/ton-hr	$450/ton	$160/ton-hr	$65/ton-hr
	$500/ton	$400/ton-hr	$130/ton-hr	$500/ton	$400/ton-hr	$130/ton-hr	$500/ton	$400/ton-hr	$130/ton-hr	$500/ton	$400/ton-hr	$130/ton-hr
Annual Maintenance Cost (2020)	$26/ton	$0	$0	$26/ton	$0	$0	$26/ton	$0	$0	$26/ton	$0	$0
	$37/ton	$125	$125	$37/ton	$125	$125	$37/ton	$125	$125	$37/ton	$125	$125

Definitions: Data shown here are for 1) centrifugal chillers, 2) modular tanks ice storage for chillers, which represent fully factory-built units that are shipped to site for integration with the chiller system, and 3) coils for site-built ice storage tanks. Modular units represent both the heat transfer coils and the insulated tank. Modular units are generally used incrementally (adding more tanks) to fit the thermal energy storage needs of the project. Typical storage capacities are generally 1,000 ton-hours of cooling or lower, per modular unit. Projects often include multiple modular tanks. Site-built coil only figures represent the costs and characteristics of coils used in site-built thermal energy storage, and does not include the cost of tank construction, which can vary widely depending on numerous construction conditions. Site-built projects generally have very large TES capacities and are usually reserved for district cooling applications. Commercially available ice storage systems typically provide grid flexibility through shifting load off-peak through scheduling, rather than grid-interactivity.

Commercial Chillers/Ice Storage

Assumptions

- Costs for modular units represent the cost of the storage tank and ice coils but do not include costs of the chiller system.
- Costs for site-built coil only represent the cost of the ice coils but do not include costs of the site-built storage tank or chiller system.
- Industry estimate for total installed cost is generally two times the retail equipment cost.
- A range of maintenance cost of the ice storage system based on maintenance needs of polyethylene solution to ensure the solution has the right properties and pH levels. A maximum of 5 hours per year of HVAC technician labor, including sending samples to the lab to be tested.
- Performance and costs will remain constant as the markets for these technologies are already mature.

Commercial Chillers/Ice Storage

Interview/Research Findings

- Ice storage is practically nonexistent for commercial or residential AC units. Only large commercial chiller projects deploy ice storage (cooling loads above 100 tons).
- By total project number, most installed ice storage projects are modular tank installments, rather than site-built units.
- Water storage generally requires 10 times the volume of ice storage, and so is not viable unless there is significant space available.
- Large projects for district cooling can reach up to 250,000 ton-hours of thermal energy storage.
- Projects requiring peak cooling loads of 5,000 or less generally tend to use modular tank units.
- For many large commercial customers, ice storage enables downsizing of chiller plants while maintaining the same ability to meet peak cooling demands.
- System designs can accommodate full storage (fully offloading the cooling load from the chiller system onto the ice storage system for a set period) or partial storage (partially offloading the chiller system for a set period). The design choice is generally determined by geography and time of day rates or building demand charges.

Commercial Electric Resistance Water Heaters

Data	2020		2030		2040		2050	
	Typical	Add-on Control	Typical	Add-on Control	Typical	Add-on Control	Typical	Add-on Control
Typical Capacity (gal)	119	119	119	119	119	119	119	119
Typical Input Capacity (kW)	18	18	18	18	18	18	18	18
Thermal Efficiency (%)	98	98	98	98	98	98	98	98
Average Life (yrs.)	12	12	12	12	12	12	12	12
Retail Equipment Cost (2020)	$2,842	$100	$2,842	$100	$2,842	$100	$2,842	$100
	$3,355	$267	$3,355	$267	$3,355	$267	$3,355	$267
Total Installed Cost (2020)	$3,991	$173	$3,991	$173	$3,991	$173	$3,991	$173
	$4,189	$389	$4,189	$389	$4,189	$389	$4,189	$389
Annual Maintenance Cost (2020)	$48	-	$48	-	$48	-	$48	-

Definitions: Data shown here are for electric resistance water heaters used in a commercial setting, with capacities from 55 to 120 gallons, although most units are near the upper end of the range. Commercial units are typically constructed similar to residential units, though with significantly higher input capacities and higher storage volumes. Add-on controls refer to bi-directional controls (generally an external control box and mixing valve) that enable water heaters to respond to DR signals from grid operators, shift loads, pre-heat, and take on load when there is excess.

Commercial Electric Resistance Water Heaters

Assumptions

- No imminent standards change is on horizon.
- No utility incentive values are calculated into retail cost. The cost of the add-on controls for DR are paid for by the utility as part of enrollment into the DR program.
- Thirty minutes of electrician labor for add-on controls.
- Mature market; R&D effort is not focused on improving product UEF.
- Performance and cost remain flat due to market maturity and saturation.
- Add-on control costs assumed to remain flat due to limited market incentive for adoption.
- Most customers do not have TOU rates.

Interview/Research Findings

- Commercial electric resistance water heaters are built similarly to residential units, but with generally larger input capacity (kW) and larger storage volume.
- Utility programs implementing DR capable water heaters have been focused on the residential sector, with no known pilot programs with commercial customers.

Commercial Ice Machines

Data	2020			2030			2040			2050		
	Current Standard	Typical	Add-On Control	Typical	Add-On Control	ESTAR Connected	Typical	Add-On Control	ESTAR Connected	Typical	Add-On Control	ESTAR Connected
Capacity (lb. ice/24 hours)	360	360	N/A	360	N/A	360	360	N/A	360	360	N/A	360
Energy Use (kWh/100 lbs.)	6.15	5.7 / 5.5	N/A	5.7 / 5.5	N/A	5.3	5.7 / 5.5	N/A	5.3	5.7 / 5.5	N/A	5.3
Average Life (yrs.)	8 / 9	8 / 9	8 / 9	8 / 9	8 / 9	8 / 9	8 / 9	8 / 9	8 / 9	8 / 9	8 / 9	8 / 9
Retail Cost (2020 $)	$2,625	$2,148 / $2,982	$200 / $300	$2,148 / $2,982	$200 / $300	$3,048 / $3,561	$2,148 / $2,982	$200 / $300	$3,048 / $3,561	$2,148 / $2,982	$200 / $300	$3,048 / $3,561
Total Installed Cost (2020 $)	$2,974	$2,498 / $3,332	$200 / $300	$2,498 / $3,332	$200 / $300	$3,671 / $4,184	$2,498 / $3,332	$200 / $300	$3,671 / $4,184	$2,498 / $3,332	$200 / $300	$3,671 / $4,184
Annual Maintenance Cost (2020 $)	$841	$841	-	$841	-	$841	$841	-	$841	$841	-	$841
Annual Subscription Cost (2020 $)	-	-	$120	-	$120	$120	-	$120	$120	-	$120	$120

Definitions: Data shown here are for batch, ice-making head, air cooling ice machines of small capacity, typically used in restaurants or hotels. Currently there are no ENERGY STAR Connected Certified ice machines. ENERGY STAR defines these as: base ENERGY STAR commercial ice maker plus hardware and software that enables communication and control. They provide flexibility through: automatic load shift exit points based on ice bin level; shuts off during DR event when 25% min level is reached.

Commercial Ice Machines

Assumptions

- Connected ice machines enter the market between 2020-2030.
- Connected ice machines will not have significant market share and adoption will be slow (generally there is little market demand from restaurants and hotels).
  - Connected ice machine prices remain stagnant as a result.
- Typical efficiency levels and prices remain stagnant because the market is mature.
  - The typical case on the market is already well-above standard levels and a large portion of the market is made up of ENERGY STAR certified products.
  - This assumes no new disruptive technologies enter the market (variable speed compressors).
- Lifetime and maintenance costs remain stagnant.
- ENERGY STAR Connected price is estimated based on the cost of ENERGY STAR certified products on the market and the cost of additional controls and software add-ons.

Commercial Ice Machines

Interview/Research Findings

- There are no connected ice machines on the market today and no evidence that manufacturers are developing them in the near future.
  - An add-on control is available on the market, but it is not widely adopted.
  - Restaurants and hotels purchasing ice machines generally are not willingly to pay the extra cost for the add-on control.
- Connected ice machines value proposition is not proven; they are unlikely to ever become standard on the market.
- Ice machines are not an ideal candidate for DR based on usage patterns.
- Efficiency improvements for commercial ice machines are likely to improve.
  - Compressor efficiencies generally improve over time.
  - Variable-speed compressors could be integrated into the market in the future.
- There are no new planned efficiency standards for ice machines.

Walk-In Coolers/Thermal Energy Storage

Data	2020		2030		2040		2050	
	Current Standard / Typical	TES System	Typical	TES System	Typical	TES System	Typical	TES System
Typical Capacity (kBTU/h)	12.28	N/A	12.28	N/A	12.28	N/A	12.28	N/A
Annual Walk-In Energy Factor (BTU/Wh)	6.45	N/A	9	N/A	9	N/A	9	N/A
Annual Energy Consumption (kWh/year)	7,063	5,650*	6,694	5,355*	6,694	5,355*	6,694	5,355*
Average Life (yrs.)	9 – 14	20	9 – 14	20	9 – 14	20	9 – 14	20
Equipment Cost (2020 $)	$1,379	$4.0/sq. ft – $5.0/sq. ft	$1,420	$3.2/sq. ft – $4.0/sq. ft	$1,420	$2.6/sq. ft – $3.2/sq. ft	$1,420	$2.6/sq. ft – $3.2/sq. ft
Total Installed Cost (2020 $)	$2,530	$8.0/sq. ft – $10.0/sq. ft	$2,571	$6.4/sq. ft – $8.0/sq. ft	$2,571	$5.2/sq. ft – $6.4/sq. ft	$2,571	$5.2/sq. ft – $6.4/sq. ft

*These value corresponds to the estimated annual energy consumption of a typical walk-in cooler with the addition of a TES system.

Definitions: Data shown here are for unit walk-in coolers combined with medium temperature outdoor condensing equipment. The TES System case refers to only the characteristics of a TES system made up of individual PCM cells stacked on shelving within a cold storage area. The annual energy consumption characterization for the TES system is based on the energy savings of a walk-in freezer with TES which is similar for a walk-in cooler with TES. According to Viking Cold, the characterization of refrigerated and cold storage warehouses with TES are similar to small walk-in coolers and freezers for percentage of energy savings.

Walk-In Coolers/Thermal Energy Storage

Assumptions

- Typical capacities, lifetimes, and maintenance costs remain constant through 2050.
- According to the EERE Standards Walk-In Coolers 2017 Technical Support Document, most walk-in coolers on the market are at the baseline level. For 2020, the baseline case is the typical case.
- By 2030, the AWEF of a typical walk-in cooler will improve to the baseline standards that went into effect July 2020. These AWEFs will remain constant through 2050 since we are not making assumptions on potential future energy conservation standards.
- By 2030, equipment and installation costs of walk-in coolers will increase based on improved AWEF performance. These costs then remain constant through 2050.
- For the TES system case, the equipment costs reflects the cost of the individual PCM cells and the control/monitoring equipment.
  - The control/monitoring equipment includes the communication hardware between the user and the refrigeration system and sensors that monitor the temperatures of the PCM material and the refrigerated product.
- For the TES system case, as adoption increases through 2040, the cost of the equipment will decrease and remain constant after 2040.

Walk-In Coolers/Thermal Energy Storage

Interview/Research Findings

- TES can be installed in refrigeration systems of all sizes.
- The addition of TES can also result in lower maintenance costs for refrigeration equipment, as the TES system may reduce the run-time of equipment.
- The demand for TES is increasing, and Viking Cold predicts that in the future the adoption of TES will be widespread in cold storage applications.
- Researchers found the cost of installation will remain relatively constant.
- The cost of the PCM material will decrease as demand increases.
- The cost of the control hardware will decrease as demand increases.
  - Control/monitoring equipment includes communication hardware between the user and the refrigeration system and sensors that monitor the temperatures of the PCM material and the refrigerated product.
- Further software improvements can optimize the operation of the refrigeration system, which needs to be tailored to the size of the refrigerated space and desired temperature setpoints to maximize energy/cost savings.
- Equipment costs for large facilities can be significantly reduced due to scale.

Commercial Lighting (LED Troffer/Panel)

Data	2020			2030		2040		2050	
	Baseline	Dimming	Connected Controls	Baseline (Dimming)	Connected Controls	Baseline (Dimming)	Connected Controls	Baseline (Dimming)	Connected Controls
Typical Output (lm)	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Luminous Efficacy	125	125	131	150	150	170	170	200	200
Average Life (hrs.)	60,000	60,000	70,000	60,000	70,000	60,000	70,000	60,000	70,000
Retail Equipment Cost (2020 $/klm)	$34	$34	$50	$23	$34	$21	$32	$20	$30
Total Installed Cost (2020 $/klm)	$38	$38	$60	$27	$43	$26	$41	$25	$39

Definitions: Data shown here are for 2 ft. x 4 ft. LED troffer or panel luminaires. The baseline product refers to non-connected luminaires with no integrated controls. Dimming products indicate the ability to dim the light in response to input from occupancy sensors. Connected controls products are those with fully networked and integrated luminaire level lighting controls, and the costs in this column reflect the fully integrated product (luminaire with controls). Connected controls provide grid flexibility as part of a larger building management platform and have the ability to shed non-essential loads. However, the connected control products shown here do not interface directly with the grid.

Commercial Lighting (LED Troffer/Panel)

Assumptions

- Assumes continued R&D effort at manufacturers to improve luminaire luminous efficacy (lm/W) and cost improvements through 2050.
- Efficacy is assumed to improve toward the theoretical limit for phosphor-converted LED technology.
- Assumes all baseline LED commercial troffers/panels will have basic dimming drivers by 2030.

Interview/Research Findings

- Connected lighting systems have limited potential for DR. Currently, few utility programs use lighting for DR.
- These lighting systems have high product lifetimes due to the integrated design of luminaire and light source.
- Commercial luminaires generally have significantly higher performance than residential LED lighting due to market forces such as DLC.
- Efficacy still has much room for improvement; theoretical max efficacy is high (250 lm/W).
- LED costs are already low and manufacturer profit margins are low.

Building Automation Systems

Data	2020	2030	2040	2050
	Connected	Connected	Connected	Connected
Average Life (years)	10	10	10	10
	12	12	12	12
BAS Retail Equipment Cost (2020 $/sq. ft)	$1.58	$1.58	$1.58	$1.58
	$7.36	$7.36	$7.36	$7.36
Total Installed Cost (2020 $/sq. ft)	$1.89	$1.89	$1.89	$1.89
	$8.58	$8.58	$8.58	$8.58
Automated Demand Response Costs ($/kW)	$293	$293	$293	$293
	$379	$379	$379	$379
Reported Whole-Building Energy Savings	10%	10%	10%	10%
	25%	25%	25%	25%

Definitions: Data shown here are for building automation systems that utilize direct digital control (DDC) systems with sensors to measure various metrics inside the building environment and control various HVAC, lighting, and other load systems. BAS characteristics vary widely depending on building type, number of integrated systems, sensor types, sensor densities, control system density, and the intended design purpose.

Building Automation Systems

Assumptions

- Costs scale directly with stringency of building environment (i.e., costs scale with system complexity and number of sensors/controls)
- Lifetime shown is reflective of when the system would be updated, but not necessarily due to failure.
- The installed costs shown are representative of retail costs combined with commissioning costs, and do not include installation technician labor.
- System level costs remain constant. While sensors, controls, and other hardware costs decline, the total system's features and complexity will continue to increase.

Interview/Research Findings

- Buildings with sensitive building parameters (such as hospitals) typically cost more per sq. ft, whereas regular office buildings are at the lower range of costs.
- Most BAS currently focus on controlling and optimizing HVAC and lighting but are not used in DR programs aside from few select regions of the US.
- Manufacturers indicated that the lack of market incentive (TOU rates) and lack of clear price signals are key barriers to implementing BAS as part of DR program.
- Manufacturers provided feedback that many customers feel there are not enough established best practices for using BAS holistically as part of a building DR program. Customer adoption of using BAS for DR would require more case studies be conducted and best practices be developed for dimming lights, reducing/shutting off non-essential plug loads, and shifting HVAC loads.

Dynamic Glazing/Commercial Fenestration

Data		2020				2030			2040			2050		
		Typical	2018 IECC Standard	Thermo-chromic	Electro-chromic	Typical	Thermo chromic	Electroc hromic	Typical	Thermo-chromic	Electro-chromic	Typical	Thermo-chromic	Electro-chromic
SHGC	AIA CZ1	0.39	0.38			0.37			0.36			0.35		
	AIA CZ2	0.38	0.38			0.35			0.34			0.32		
	AIA CZ3	0.25	0.36	0.37 to 0.17	0.49 to 0.09	0.24	0.37 to 0.17	0.49 to 0.09	0.23	0.37 to 0.17	0.49 to 0.09	0.22	0.37 to 0.17	0.49 to 0.09
	AIA CZ4	0.25	0.27			0.24			0.23			0.22		
	AIA CZ5	0.24	0.25			0.24			0.23			0.21		
Visible Light Transmittance		-	-	0.54 to 0.08	0.63 to 0.02	-	0.54 to 0.08	0.63 to 0.02	-	0.54 to 0.08	0.63 to 0.02	-	0.54 to 0.08	0.63 to 0.02
U-Factor	AIA CZ1	0.32	0.34			0.27			0.23			0.20		
	AIA CZ2	0.34	0.36			0.27			0.23			0.20		
	AIA CZ3	0.37	0.36	0.24	0.28	0.28	0.24	0.21	0.24	0.24	0.18	0.21	0.24	0.16
	AIA CZ4	0.41	0.41			0.31			0.26			0.22		
	AIA CZ5	0.52	0.44			0.36			0.29			0.25		
Average Life (yrs.)		$20	$20	$20	$20	$20	$20	$20	$20	$20	$20	$20	$20	$20
		$30	$30	$30	$30	$30	$30	$30	$30	$30	$30	$30	$30	$30
Installed Cost (2020 $/sq. ft)		$61	$61	$80	$91	$72	$80	$87	$68	$80	$83	$68	$80	$83
		$68	$68	$88	$98	$80	$88	$95	$76	$88	$91	$76	$88	$91

Definitions: Typical data shown here are for standard commercial windows installed to meeting building codes. Electrochromic data is based on an insulated glass unit with 90% Argon filled gap, low-iron pane. Thermochromic data is based on a double low-e, insulated glass, with 90% Argon filled gap. Electrochromic windows with additional controls can provide flexibility by adjusting SHGC to reduce HVAC energy use in response to pricing/grid signals. Thermochromic windows can provide passive flexibility (HVAC energy/peak savings) by adjusting SHGC automatically in response to temperature changes. Sq. ft in this table refers to the area of glass.

Dynamic Glazing/Commercial Fenestration

Assumptions

- Thermochromic glazing will not provide grid services directly but may provide passive flexibility.
- Electrochromic glazing is controllable and can participate in DR through TOU/scheduling or responding to grid signals directly.
- Electrochromic glazing adoption is slow and steadily increases in the US from 2020-2050.
- Thermochromic glazing adoption is low and stagnant in the US from 2020-2050.
- Electrochromic U-factor decreases at same rate as typical commercial fenestration as building codes become more stringent in the future.
- Thermochromic glazing U-factor remains constant because market adoption is stagnant.
- Delta SHGC is constant for dynamic glazing over time.
- Dynamic glazing costs decreases to meet DOE goal ($15/sq. ft price premium by 2030).
- Typical window costs decrease at a rate of 10% per decade, but these price declines are partially offset by increases in efficiency performance over time.

Dynamic Glazing/Commercial Fenestration

Interview/Research Findings

- Primary applications for dynamic glazing are education, public buildings, office buildings.
- Cost is a significant barrier for all dynamic glazing.
- Manufacturing capacity is limited; there are only a few manufacturers globally for electrochromic glazing.
  - There are even less thermochromic glazing manufacturers.
- Electrochromic glazing makes up most of the dynamic glazing market.
- Market adoption for electrochromic glazing is driven by aesthetics and occupant comfort and health benefits.
- Durability issues are also key barriers (high failure rate) of the glass systems.
- Thermochromic windows have lower satisfaction from consumers because the tinting is not controllable.
- The average cost of windows decreased 10% over 2010-2020.
- Current research is focused on lowering costs, extending lifetimes, and developing novel technologies.
  - Emerging technologies in dynamic glazing include switchable Low-E, switchable tinting, integrated PV.

Commercial Envelope/PCMs

Data		2020			2030			2040			2050		
		Typical	Inorganic PCM (Add-On)	Organic PCM (Add-On)	Typical	Inorganic PCM (Add-On)	Organic PCM (Add-On)	Typical	Inorganic PCM (Add-On)	Organic PCM (Add-On)	Typical	Inorganic PCM (Add-On)	Organic PCM (Add-On)
R Value	AIA CZ1	20.19			24.13			28.89			33.17		
	AIA CZ2	17.84			22.09			26.84			31.66		
	AIA CZ3	15.85	M-Value: 27 to 37 Btu/sq. ft	M-Value: 27 to 55 Btu/sq. ft	19.64	M-Value: 27 to 37 Btu/sq. ft	M-Value: 27 to 55 Btu/sq. ft	24.40	M-Value: 27 to 37 Btu/sq. ft	M-Value: 27 to 55 Btu/sq. ft	29.21	M-Value: 27 to 37 Btu/sq. ft	M-Value: 27 to 55 Btu/sq. ft
	AIA CZ4	13.42			17.36			22.12			26.93		
	AIA CZ5	11.17			15.03			19.78			24.60		
Average Life (yrs.)		100+	30+	100+	100+	40+	100+	100+	40+	100+	100+	40+	100+
Installed Cost (2020 $/sq. ft)		$27.4	$5.4	$5.0	$27.4	$5.1	$4.7	$27.4	$4.8	$4.5	$27.4	$4.6	$4.2
			$10.3	$6.5		$9.7	$6.1		$9.3	$5.8		$8.8	$5.5

Definitions: Typical represents average thermal performance of commercial new construction building envelopes. The PCM add-on is applied to existing interior walls or to replace existing insulation in walls or ceilings. Organic PCMs refer to bio-PCMs and inorganic PCMs refer to salt hydrates (gypsum). PCM envelope add-ons provide only passive flexibility (HVAC energy/peak savings) through storing and releasing thermal energy in response to temperature changes. M-Value represents the latent heat capacity storage for the materials. Sq. ft in this table refers to the area of building envelope (walls/ceilings).

Commercial Envelope/PCMs

Assumptions

- PCM add-ons are installed in either the interior wall or the ceiling tiles.
- PCM installation costs are the same as typical building insulation installation costs.
- A shop markup cost of 25% and a field markup cost of 20%.
- Typical wall costs remain constant; technology price decreases are offset by improvements in performance from 2030-2050.
- Lifetimes for typical walls and organic PCMs remain constant.
  – Inorganic PCMs increase lifetime.
- Maintenance costs are negligible.
- Although other materials are used in inorganic PCMs, prices are shown for gypsum for simplification.
- PCMs for envelope applications remain a niche market in the US.
- Costs decline slowly for PCMs for envelope applications, driven by manufacturing scaling of PCM production (likely for other applications outside of building envelope).
  – Cost of chemicals and packaging remain constant.
- Projections do not account for novel PCM materials entering the market.
- Assumes that typical M-values for PCMs remain constant (higher M-value products are available today but these products are most common).

Commercial Envelope/PCMs

Interview/Research Findings

- PCMs for envelope applications are a niche market today.
  - Government/utility incentives are needed to accelerate market adoption.
  - Europe and Australia have seen much adoption of PCMs for envelope than the US because of incentive offerings.
- Other applications for PCMs have much higher potential for energy savings and adoption (mechanical systems).
  - The market for PCMs for all applications is expected to grow, but envelope applications are uncertain.
- Bio-PCMs are most common technology on the market today.
- Bio-PCMs have longer lifetimes/durability than salt-hydrate PCMs.
- No maintenance is needed for PCMs.
- The cost of chemicals and packaging for PCMs is stable but cost improvements could be made though scaling manufacturing.
- There is a need to find a better way to evaluate and value PCMs, which could help drive adoption.
- Active PCMs including controls and sensors is likely to emerge in the future.

Commercial Advanced Power Strips

Data	2020		2030	2040	2050
	Connected		Connected	Connected	Connected
	Tier 1 APS	Tier 2 APS	Tier 2 APS	Tier 2 APS	Tier 2 APS
Active Outlets	2	5	5	5	5
	4	6	6	6	6
Average Life (yrs.)	8	8	8	8	8
	10	10	10	10	10
Total Cost (2020 $)	$20	$72	$72	$72	$72
	$27	$95	$95	$95	$95
Total Cost/Outlet (2020 $)	$7	$13	$13	$13	$13
	$12	$16	$16	$16	$16
PC Office Workstation Reported Energy Savings	Schedule Timer: 26%	Software + Load Sensing: 27%	56%	56%	56%
	Load Sensing Control: 4%	Software + Load Sensing: 65%			
	Schedule Timer + Load Sensing: 11%	Occupancy Control: 15%	25%	25%	25%

Definitions: Data shown here are for Tier 1 and Tier 2 advanced power strips used for PC office workstations. Tier 1 power strips use either programming/scheduling or current sensing. Tier 2 power strips use additional sensors, software, and algorithms to sense real time power use; tier 2 power strips reduce standby and wasteful active loads. They provide flexibility by shifting plug loads (i.e., PC workstations). Load sensing detects energy use of the equipment, occupancy sensors detect motion, and infrared sensors detect heat.

Commercial Advanced Power Strips

Assumptions

- Tier 1 power strips will be obsolete by 2030 as the market shifts to Tier 2 power strips.
- From 2020-2030, the cost of advanced power strips will decline 25%, but there will be an increase in features which will offset price declines.
  - Advanced features lead to 10% higher energy savings on average.
- Tier 2 power strips will exit the market between 2030-2050, as computer BAS become more efficient and expand their capabilities; integrated control capabilities for these products will become more prevalent than control through power strips.
  - Prices will remain stagnant during this period.
  - Lifetime will remain constant.
- Assumes power strips are used to control computer workstations in office settings.
- Assumes no utility incentives are applied to cost estimates, though some utilities offer them free or at a low cost ($10-$20) in exchange for participating in utility programs.

Commercial Advanced Power Strips

Interview/Research Findings

- APS has the most potential for AV and home entertainment in the residential sector and PC workstations (laptops/desktops) in the commercial sector.
- Tier 2 APS provide significant energy savings through detecting occupant engagement and automatically shutting off equipment when not in use.
- APS are just an interim technology; in the future, BAS/SHEMS and smart technologies will replace APS.
  - Could happen within 10-20 years.
  - Manufacturers are already shifting to other markets.
  - Computers will likely be efficient enough and will not require external controls in the future to manage energy use.

Appendix

Interview Questions

Manufacturers

- What is the best-selling product within the ___ technology? What are typical applications for this technology (building type and region)?
- What is a typical range of prices for ____ technology today? How does this compare to similar technologies on the market today? What are estimates for the installation costs and maintenance costs?
- What are a range of lifetimes that can be expected for the _____ technology? How does this compare to similar technologies on the market?
- Do you have any case studies or other materials you can provide that details the energy performance, energy savings, and peak savings?
- Are there any potential technological improvements that would drive cost reduction, higher adoption, or increased performance (whether efficiency or DR capability) for these technologies?
- What is driving manufacturer production of DR capable products listed in the table above?
- What is the market size for the products listed in the table above? How do you expect this to change in the US in the coming years?
- Are you planning on expanding your product offerings, size, or scope of your DR capable products in the near future?
- Are you expecting any changes in manufacturing capacity in the future (10-20 years)? How much?

Note: These questions serve as a general guide. Actual interview questions varied based on the technology of interest and manufacturer representative expertise.

Interview Questions

Researchers

- Can you describe some of the research projects you are working on with connected/demand response technologies?
  - What stage is the research in currently? Have there been any demonstration projects or case studies published that you could provide to us?
- What are the key challenges that you hope your research will address for these technologies?
  - What are the mid-term and near-term goals of these research projects?
- How do you expect your research (or other ongoing research) to have an impact on cost, performance, and lifetime of these technologies? Can you provide quantitative estimates?
- Can you provide an overview of other ongoing research efforts in the space outside of your work at other labs or by private companies?
- What do you think is the greatest market barrier to adoption for these technologies in the US?
  - What do you see as the greatest market driver for these technologies in the US?
- How do you expect your research (or other ongoing research) to have an impact on adoption of the technology?
  - What would you estimate the change in market size to be for this technology over the next 10-20 years?
- How do you expect your research (or other ongoing research) to have an impact on manufacturing of the technology?
  - Are you currently working with any manufacturers for this research?
  - What would you estimate the change in manufacturing capacity to be for this technology over the next 10-20 years?

Note: These questions serve as a general guide. Actual interview questions varied based on the technology of interest and researcher experience.

Appendix:
Residential Technologies Sources

Residential Central AC/Heat Pump/Smart Thermostats

Sources

- Manufacturer Interview
- DOE EERE Appliance Standards, *Technical Support Document for Residential Central Air Conditioners and Heat Pumps,* 2016.
- CCMS database for split system central AC
- ENERGY STAR Connected smart thermostat database
- Price data for smart thermostats from online retailers (Amazon, Best Buy, Lowes, Home Depot)
- Guidehouse Insights, *Market Data: Advanced Thermostats*, 2018.
- ACEEE, *Energy Impacts of Smart Home Technologies*, 2018.

Residential Mini-Splits

Sources

- ASHRAE Equipment Life Expectancy Chart
- Price data from online retailers (Amazon, BestBuy, TotalHomeSupply)
- Manufacturer websites (EcoBee, Cielo, Sensibo)
- Guidehouse internal expert guidance
- Navigant Consulting, Inc., *Massachusetts Ductless Mini-Split Heat Pump Cost Study*, 2018.
- Northwest Energy Efficiency Alliance (NEEA), *Ductless Heat Pump Initiative Market Progress Evaluation Reports 1-8*, 2010–2019.
- Bureau of Labor Statistics (producer price index trend for ductless air conditioning equipment)

Residential Room ACs

Sources

- Guidehouse internal expert guidance
- DOE EERE Appliance Standards, *Technical Support Document for Room Air Conditioners,* 2020.
- Price data from online retailers (AJMadison, HomeDepot, Amazon, Lowes)
- ENERGY STAR product database for room ACs

Residential Electric Resistance Water Heaters

Sources

- EERE, *Energy Conservation Program: Energy Conservation Standards for Residential Water Heaters, Direct Heating Equipment, and Pool Heaters; Final Rule,* 2010.
- AHRI, *Directory of Certified Product Performance,* (n.d.).
- CCMS database for electric resistance water heaters
- Manufacturer interviews (Sequentric, Steffes Corporation)
- ACEEE, E Source, *Grid Interactive Water Heaters - How Water Heaters Have Evolved Into a Grid Scale Energy Storage Medium*, 2016.
- Price data from online distributors (Home Depot, Lowes, Supply House)
- RSMeans 2020 (labor costs for installation)

Residential Heat Pump Water Heaters

Sources

- EERE, *Energy Conservation Program: Energy Conservation Standards for Residential Water Heaters, Direct Heating Equipment, and Pool Heaters; Final Rule*, 2010.
- AHRI, *Directory of Certified Product Performance,* n.d.
- CCMS database for heat pump water heaters
- Manufacturer interviews (Sequentric, Steffes Corporation)
- ACEEE, E Source, *Grid Interactive Water Heaters - How Water Heaters Have Evolved Into a Grid Scale Energy Storage Medium*, 2016.
- Price data from online distributors (Home Depot, Lowes, Supply House)
- RSMeans 2020 (labor costs for installation)

Residential Clothes Washers (Top-Loading)

Sources

- DOE EERE Appliance Standards, *Technical Support Document for Clothes Washers,* 2012.
- CCMS database for clothes washers
- ENERGY STAR database for clothes washers
- Guidehouse internal expert guidance
- Price data from online retailers (AJMadison, HomeDepot, Amazon, AppliancesConnection)

Residential Clothes Washers (Front-Loading)

Sources

- DOE EERE Appliance Standards, *Technical Support Document for Clothes Washers.* 2012.
- CCMS database for clothes washers
- ENERGY STAR database for clothes washers
- Guidehouse internal expert guidance
- Price data from online retailers (AJMadison, HomeDepot, Amazon, AppliancesConnection)

Residential Electric Clothes Dryers

Sources

- DOE EERE Appliance Standards, *Technical Support Document for Clothes Dryers,* 2011.
- CCMS database for clothes dryers (Appendix D1 and D2)
- ENERGY STAR database for clothes dryers
- Guidehouse internal expert guidance
- Price data from online retailers (AJMadison, HomeDepot, CompactAppliance, Goedekers)

Residential Dishwashers

Sources

- DOE EERE Appliance Standards, *Technical Support Document for Dishwashers,* 2016.
- CCMS database for residential dishwashers
- ENERGY STAR Connected database for residential dishwashers
- Guidehouse internal expert guidance
- Price data from online retailers (AJMadison, HomeDepot, BestBuy)

Residential Refrigerators (Side-Freezers)

Sources

- DOE EERE Appliance Standards, *Technical Support Document for Consumer Refrigerators and Freezers,* 2011.
- CCMS database for residential refrigerators
- ENERGY STAR database for residential refrigerators
- Guidehouse internal expert guidance
- Price data from online retailers (AJMadison, HomeDepot, BestBuy)

Residential Refrigerators (Bottom-Freezers)

Sources

- DOE EERE Appliance Standards, *Technical Support Document for Consumer Refrigerators and Freezers,* 2011.
- CCMS database for residential refrigerators
- ENERGY STAR database for residential refrigerators
- Guidehouse internal expert guidance
- Price data from online retailers (AJMadison, HomeDepot, BestBuy)

Residential Lighting

Sources

- Researcher interviews (Michael Poplawski and Morgan Pattison)
- Guidehouse Lighting Market Model
  - Efficacy data from DLC Qualified Products List, EnergyStar Certified Products Database, and the former Lighting Facts database
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