BRINGING DIGITALIZATION HOME SYMPOSIUM

Empowering Up, Powering Down

The Evolution, Effects, and Efforts to Digitize Energy Controls and Digitalize Energy Information in US Homes

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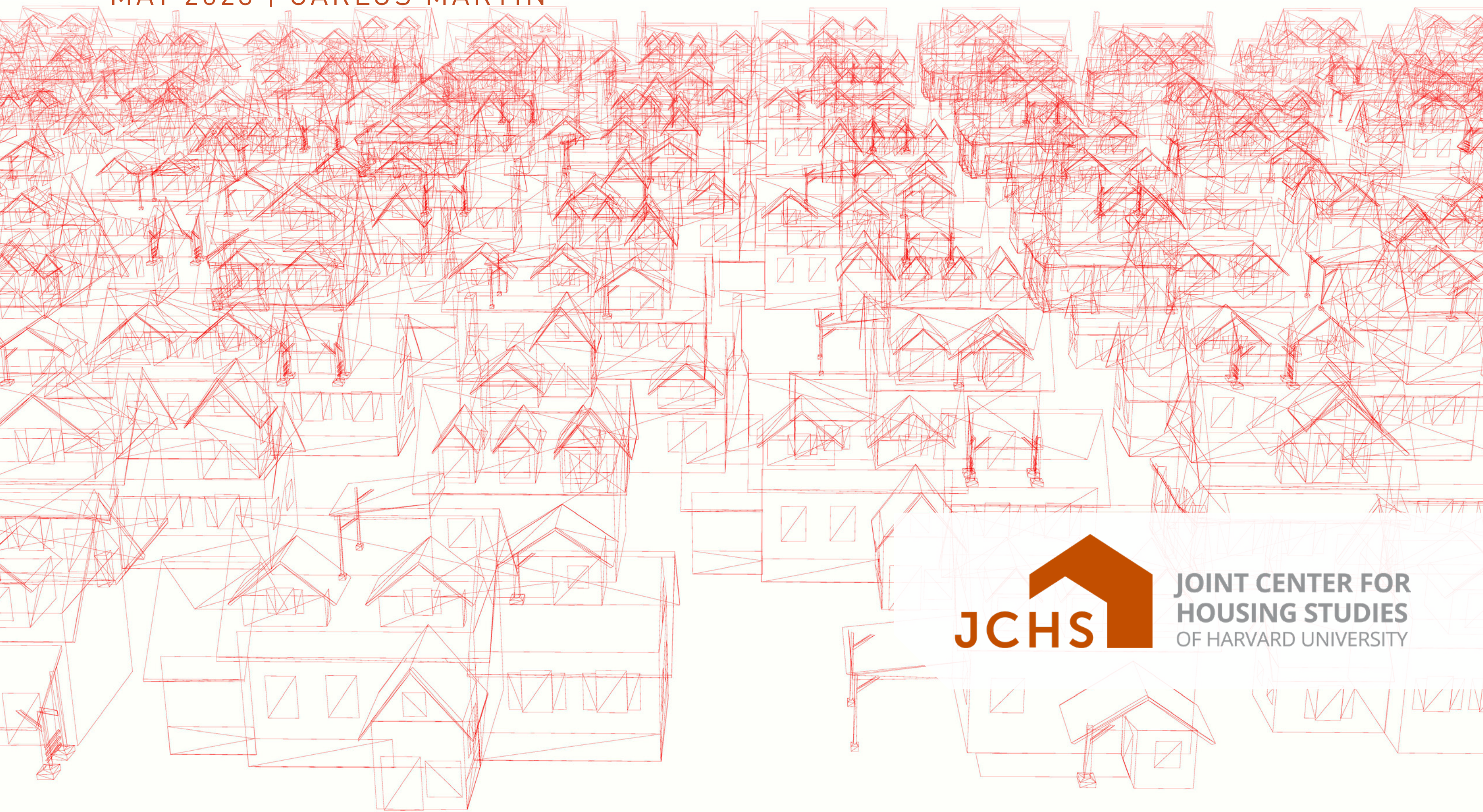

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Empowering Up, Powering Down: The Evolution, Effects, and Efforts to Digitize Energy Controls and Digitalize Energy Information in US Homes

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This paper was presented as part of "Panel 4: How Is Digitalization Transforming How Housing Is Used?" at the symposium "Bringing Digitalization Home: How Can Technology Address Housing Challenges?", hosted by the Harvard Joint Center for Housing Studies in March 2022 and funded by Qualcomm. Participants examined the changes that digitalization—the use of automated digital technologies to collect, process, analyze, distribute, use, and sell information—is spurring in the way housing is produced, marketed, sold, financed, managed, and lived in.

Abstract

The digitization of residential energy—aided by the digitalization of information about energy usage—has spurred a revolution in energy-efficiency investments and helped spawn the "smart home" movement. Electrifying both homes and home monitoring (usually simultaneously) has provided opportunities to reduce individual households' energy consumption, which stood at almost 23 percent of the total national energy use at last count, and reduce the nation's overall residential energy demand. This paper covers the wide terrain of residential energy digitalization by reviewing the current state of residential energy digitalization and the diffusion of its "smart" meters, controls, and network connections and information exchanges, and their evolution within the broader policy contexts of residential energy consumption (or, rather, the slow transition to residential decarbonization over the last half-century). More significantly, the paper addresses housing affordability and quality (and the technological obduracy of non-electrified residential systems) that pose industrial parameters to comprehensive digitalization. Further, the author introduces additional considerations that temper the energy digitalization's momentum: equity and privacy. In reviewing the factors that alternately encourage and constrain a uniform transition to comprehensive energy digitalization across all US homes, the paper considers alternative paths for reaching societal goals that include energy digitalization, but not exclusively. Ultimately, the paper poses the questions: must an "energy smart" home be digitalized, and, if so, who benefits from its digitalization?

Introduction

Energy use, its conservation and efficiency, was an early catalyst for managing information about residential occupancy and its digitalization. Some of the earliest interventions in the home digitalization movement, in fact, were the electrical sensors, meters, and controls in centrally wired and interconnected appliances and mechanical systems. Today, components of digitalized residential energy systems are commonplace. Yet there are many kinds of components as well as combinations of them.[1]

For decades now, inventions for heating, ventilating, and cooling (HVAC) homes have provided nearly instantaneous information to occupants regarding their own specific energy loads, on the one hand, while advanced metering technologies have informed servicing utilities about the overall demand across residential customers on the other. Regarding the latter, most US homes now have "smart

[1] Ehrhardt-Martinez, Donnelly, and Laitner.

meters" that provide the utility with account-level, total energy use for the home that is digitized and allows for such interactions. Among the former user group of digitalization techniques in the home are the many homeowners who have learned to program their programmable thermostats to heat or cool their homes at predefined temperatures at certain times of the day and seasons of the year. A more select group has incorporated advanced home automation technologies, ranging from voice control technologies that can control energy-consuming appliances to more comprehensive systems that track a wider range of appliances and systems and integrate programmable logarithms for self-monitoring as part of larger home automation networks, often tied to global internet and data providers. Other exclusive groups of homeowners benefit from coordinating their homes' energy data with shared networks to compare themselves to neighbors. Still others live in homes that benefit from residential renewable energy units (e.g., home solar photovoltaics) that necessitate more sophisticated monitoring of the energy flows in and out of the home for better management across the entire distributed grid.[2]

To varying degrees, these digitized technologies allow the occupants, their energy provider, or an external intermediary to program energy consumption more efficiently and coordinate its timing in relation to the peaks of the larger energy grid in which the home is connected—all the while collecting detailed information about energy behaviors and occasionally sharing it with third-party energy service providers. These techniques are at least well known in the US, if not yet physically ubiquitous.[3]

Yet the awesome potential of fully digitalized energy information management blinds us to several darker realities. The first constraint is found in our national energy system. Digitalized information management requires that the data which are its currency be, obviously, digital. Electrical energy is inherently and ontologically digital. However, most US homes do not run solely on electrical energy—a fact that is becoming more challenging as the societal need to wean homes off fossil fuel-based energy becomes more urgent. Consequently, energy-efficiency advocates have sought to use energy management systems including digitalization to reduce energy consumption and increase awareness of our energy use's climate contributions for decades. But the legacy of non-electric energy production and distribution in the US is a formidable obstacle to digitalization.

Our homes' construction and the requirements of digitalization technologies are a second concern. Not everyone's home electrical energy is currently fully digitizable, or "smart." Many—in fact, over one-half—of public and private utilities have switched to digital "smart meters" to monitor a

[2] Cappers, MacDonald, Page, Potter, and Stewart.
[3] Elliott, Molina, and Trombley.

home's total electrical energy consumption (and occasionally, fossil fuel-based residential energy consumption) since the technology was first patented fifty years ago. Smart meters are the locus of home energy digitalization. They allow for real-time energy use information that can be shared with the utility or energy supplier and frequently communicate this information to the home occupant in easily understood ways through user-friendly controls. Essentially, smart meters are the gatekeepers for a home's energy information, providing two-way communications between the occupant (and occasionally, each of a home's energy-using systems), through the meter, and with the utility's larger network. The largest private utilities began installing smart meters about two decades ago after state regulators began permitting their installation at scale; at last count, there were almost 91 million residential advanced meters installed in the US.

However, there are still many homes that have "one-way" meters that only report on total usage at a periodic timeframe (e.g., every month) unilaterally to the utility for billing purposes. Further, most meters currently in use measure total energy use in a home or provide feedback loops tied exclusively to one specific home component such as "smart thermostats" connected to HVAC systems that are not necessarily tracked with the utility's metering. A fully advanced smart-metered home, in theory, would monitor and collect data from each energy-using component in a home, communicate over a home area computer network (often wirelessly) that could manage internal energy use, and share this detailed information with the utility grid's larger meter data management system.

Though many homes currently have one or a combination of smart components and many utilities are building out their advanced metering infrastructure, the technology is far from fully diffused and faces considerable adoption challenges given most of our housing stock's past construction quality and the challenges of comprehensive retrofitting. Further, because of the current state of smart metering diffusion, both full-house energy digitalization and its individual metering, management, and program components still elicit some hesitancy and even occasional opposition. The collection of behavioral and perceptual insights that digitalization provides is, in itself, a source of some public concern across a few fronts. Some concerns, based on consumer confusion, are more readily dismissed or addressed: these include fears over the health risks from wireless meter radiation, fire hazards from increased active wiring, or household cybersecurity.

Other concerns, such as those regarding personal privacy, are less easily dismissed or addressed. Increasingly frequent reporting of a home's total energy use is designed for better grid management, but that reporting may also yield inferences about a household's activities and behaviors—especially as more sophisticated information management techniques that monitor individual appliances or systems become commonplace. Exposure to privacy invasion, and the possible misuse of the information gleaned during its occurrence, has resulted in several consumer complaints about smart metering; many consumers are concerned about the extraction of personally identifiable information from a broader pool of modern information technologies. Almost three-quarters of US energy consumers are served by private, investor-owned electric utilities, adding to concerns about who owns and buys these data. A few high-profile policing cases where utility data were harnessed to track criminal activity or immigration status have heightened the alarm. State regulators have allowed consumers to opt out of utilities' smart metering programs—thereby defeating the purpose of fully digitalized, comprehensive home energy management. This backlash, combined with studies showing minimal peak energy use reductions for utilities and only modest changes in consumers' energy behavior from certain digitalization components, has led to questions about whether digitalization is worth the effort and, if so, who benefits.

Finally, there are broader equity concerns regarding which households currently access these technologies and whether digitalization should be the primary intervention for those that do not have access. The most understudied aspects of digitalization and, indeed, of any home-specific energy modification, are the diffusion rates across specific populations—particularly by household income or wealth, tenure (e.g., renters), race and ethnicity, age, and physical ability. The persistence of high rates of energy overburden and poverty and of oversubscribed public energy bill assistance programs suggests that lower-income households' homes are among the last to be rewired for energy digitalization. The benefits of information management in the form of improved peak-load planning, energy-efficiency programs, or weatherization assistance then pass them by, while these households are also the least financially capable of voluntarily upgrading their homes or affording new, more efficient, and fully digitalized homes.

Wealthier homeowners can insist on fossil fuel-consuming appliances such as gas stoves. Current national energy data estimate that wealthier households consume more energy per capita and per home square footage than their poorer counterparts. Yet these households have taken advantage of the intervention opportunities that digitalization opens at disproportionately higher rates. This landscape of energy disparities brings under-asked questions to this forum: which households benefit from digitalization, and at what cost?

Ultimately, despite all these concerns, energy must be managed. A globally demanded transition from fossil fuels to meet net-zero greenhouse gas commitments in thirty years will require data and coordination. Transitioning America's old housing stock for this energy future will need synchronization between public, private, and individual household stakeholders. Preparing the energy-inefficient homes whose occupants are least likely to be able to pay for that transition but are most likely to be burdened by energy bills requires information about those homes and their occupants.

Yet at what cost do we undertake this management? Is digitalization required to transform our energy system and our homes' energy use? Along with reviewing digitalization's technological potential, this paper explores how advanced energy management is an idealized path towards improved energy outcomes—but it is just one path on the bigger map of energy goals.

The Circuits

In February 2022, Xcel Energy announced to its Coloradan customers that it would start charging variable rates for their energy consumption based on the time of day that each household turned equipment on—for example, rewarding late evening and weekend users with lower rates per kilowatt-hour.[4] Such time-of-use rate policies are designed to manage the utility's supply, particularly around peak early evening demand; they have become commonplace throughout the country as utilities respond to increasing technical requirements to decrease demand fluctuations and regulations in support of transitioning individual homes' use through energy efficiency, distributed (usually renewable) energy networks, and conservation. Announcements like Xcel's are not only common in the contemporary energy landscape, but they are also increasingly standard. For the last two decades, utilities have increasingly sought to access more granular and precise information about their customers' energy use and its timing.

Underpinning Xcel Energy's ability to monitor information about the timing and quantity of each home's energy use at such discrete timeframes—and intervene accordingly—is a key technology: the smart meter. Traditional analog meters measure a home's total consumption of electricity and natural gas by mechanically translating energy use into physically visible readings; these are manually checked periodically, typically in time for consumers' monthly billing.

In contrast, digitized meters measure energy use electrically, a relatively easy measurement tool for electricity use given that it is already electric.[5] These measurements can also be transmitted electrically, allowing for nearly constant reading and, in turn, creating a digitalized record of information that can then be monitored and managed. The meters can either repeat the one-way reporting

[4] Bordelon.
[5] US Department of Energy.

structure of previous analogs while automating these data collections, or they can provide two-way reporting that allows both utilities and consumers access to the resulting information and the ability to control underlying energy use. When installed in every energy-consuming property across a broader geographic area, smart meters unleash a treasure trove of data about the entire energy network as well as each home within it.

Though they are pivotal data gatekeepers, smart meters are only one of several technologies in the vast technological and industrial terrain of contemporary residential energy digitalization. Individual energy-using systems and appliances first began having digital controls and operational circuits after the electronics revolution of the 1970s.[6] Now, with wireless signals and transmitters, energy producers and users have exponentially expanded their ability to collect that digital information and analyze it for patterns across an appliance's use, its contribution to a home's total energy consumption, and the home's interaction with the entire energy network. In a few pilots, energy users and producers are taking advantage of these technologies, and the diffusion rates have grown dramatically.[7]

The shared access to information and its management is predicted to provide energy savings on the order of 88 gigawatts from residential use alone—the equivalent of almost 25 million photovoltaic panels.[8] Combined with digitalization across other building sectors and industries, residential energy digitalization, then, is only likely to continue expanding.[9] But what exactly constitutes the hardware that digitalizes energy information, and how is it coming to be wired into our homes?

Technology

Many technologies and information systems can be classified under the rubric of residential energy digitalization, but one helpful way to categorize them is by two simple groupings: first, by each technology's physical location or scale in relation to the home (that is, inside or outside); and second, by the technology's functional purpose (collecting and analyzing data or presenting it to an appropriate actor). These two groups form a matrix of technological groupings (Figure 1). Along with providing a sense of the size and detail of any one technique for managing a home's energy use, these categories also map onto the primary agents and direct beneficiaries: the energy-paying consumer (i.e., the

[6] Broad.
[7] US Department of Energy Better Buildings Network.
[8] Holden.
[9] Rogers, Elliott, Kwatra, Trombley, and Nadadur.

homeowner or resident), the energy provider or utility, and the third-party energy-efficiency programs and technology vendors.

Figure 1. Conceptual Grouping of Home Digitalization Technologies by Placement & Function

Home Digitalization Technologies	Inside the home	Outside the home
Data Sources	• Programmable thermostats • "Smart" appliances • "Smart" lighting fixtures • "Smart" plugs and switches	• "Smart" meters
Data Controls or Displays	• In-home energy displays • Online portals and hubs • Monitors and phone apps	• Home services platforms • Utility online services • Third-party energy service providers

Source: Cooper and Shuster.

The first criterion for grouping is the techniques that support energy management within the home in contrast to those that support a utility's energy management across the energy grid. These are then further divided between every home electronic device, appliance, and mechanical system that consumes energy and relays that consumption discretely to another technology (e.g., a control or display), and then those same digital controls or displays from which a consumer can turn a system on and off (e.g., televisions), can set for different outputs (e.g., digital light dimmers or refrigerator temperatures), or can digitally program to do these tasks automatically (most commonly, programmable thermostats).

In theory, turning any one of these on and off produces information about its energy use that could be digitalized, shared, aggregated, and analyzed in ways to, finally, manage it. Consequently, there has been an explosion of digitalized appliances and home systems in the digital home automation movement and wireless broadband expansion over the turn of the last century.[10] One contemporary study tracked 313 different product types of digitalized energy-consuming technologies internal to the

[10] Harper.

home.[11] Advanced lighting, connected water heaters, and entertainment devices—all increasingly labeled "smart"—allow occupants not only to monitor and control each home device but do so through a range of digital displays or their computers, smart phones, and smart speakers.[12] Wireless home networks have enabled this sharing, with devices and systems sending digital signals to central data repositories.

Virtual assistant technologies (e.g., Amazon's Alexa or Echo and Apple's Siri) have also increasingly been wired to manage energy-using systems in homes, many of which are operable with centralized energy information systems. For example, Amazon's Echo supports Ecobee controls, competing with Google's Nest (and its now-defunct PowerMeter) and products from Honeywell, Johnson, and other traditional sensor and control technologies, along with energy digitalization start-ups such as Sense, Neurio, and Smappee.[13] There are a few digitalization systems that are beginning to integrate machine learning and artificial intelligence to set internal energy loads that are even more aligned to perceived user behaviors. These technologies are all now on the market but have proliferated primarily in the most energy-intensive systems, like HVAC controls, and with only modestly innovative and autonomous digital controls.

The growth of the second group of technologies outside of the home, however, has been transformational. Within this group, the "smart" meter reporting a home's total energy use to the utility is the locus. Automated meters (i.e., one-way digital reporting devices) have replaced analogs and, in turn, are quickly being replaced by two-way advanced metering infrastructure. Enabled by this smart meter, whole-house automation and information-sharing technologies that convey a home's total energy use to its energy providers and their third parties have grown in every region of the country. Along with the utility's benefits from the smart meter, this information has been offered to home occupants, both for their real-time energy tracking and to provide access to information about their neighbors or peer energy-using groups. Third-party pioneers such as OPower (now owned by Oracle) that aggregate and analyze homes' total energy patterns and provide this information to both utilities and consumers are now commonly offered by most investor-owned utilities, provided that a participating consumer consents to uploading their data to the third party's tools.

[11] Ford, Karlin, Sanguinetti, Nersesyan, and Pritoni; Karlin, Ford, Sanguinetti, Squiers, Gannon, Rajukumar, and Donnelly.
[12] Rogers and Junga.
[13] Nest.

The ability to manage this information externally and with greater refinement has yielded a fourth set of technologies that blur the lines between utilities and consumers. For the purposes of this paper, these are collectively referred to as "residential building energy management" systems. These technologies share more detailed information than a home's total energy use (i.e., from the HVAC thermostat and other major energy-using systems, fixtures, and appliances); these technologies can increasingly identify loads that need to change when the broader utility grid needs to be managed. These technologies come into play especially when there is distributed energy production (e.g., home photovoltaics) that are part of the home's physical composition and contribute directly to the energy grid and home automation technologies that share energy information from individual components (e.g., sub-meters) to entities outside the home itself. Data gatekeepers within the home, now including Nest or Ecobee, can read the utility's smart meter data, programmed to any rate changes or fluctuations, and respond by automatically controlling a specific system or set of devices within the home as well as any distributed energy sources such as residential photovoltaics.[14]

Connecting in-home energy information with home-to-network information across all of these grouping and typically through internet-enabled systems such as wireless-connected thermostats is the holy grail of residential energy digitalization.[15] Referred to most recently as "grid-interactive efficient buildings," efforts to enable smart technologies to respond comprehensively to, for example, real-time pricing transforms the currently commonplace programmable thermostats into distributed energy resources in their own right.[16] The US Department of Energy has an active research agenda in this area.[17]

Several utilities have begun experiments with full digitalization—that is, automation across these home and utility scales. One provider in Ohio is offering residents a home energy management device that displays energy use from light bulbs, door sensors, motion sensors, and smart thermostats as well as the home's total energy use while also connecting them to the utility's smart meter readings. Residents are then notified of demand-response events and offered suggestions about which systems to turn down. Utilities in North Carolina and Virginia are providing free smart and wireless thermostats to encourage their customers' projected savings, while an Oregon energy provider has tested grid-

[14] York, Relf, and Waters.
[15] Blasnick.
[16] US Department of Energy; Koliner, Bawn, Christopher, and Gately; Perry, Bastian, and York; Neukomm, Nubbe, and Fares.
[17] Sofos and Langevin.

connected water heaters. However, there are currently no complete automation experiments, that is, where a utility or third-party can alter energy flows to specific systems or appliances; nonetheless, machine-learning based automation programs have been proposed.[18] Many of the current privately manufactured technologies are also not necessarily interoperable across brands and home systems.

Policy

Indeed, the ambition of digitalization technology visionaries is far-reaching, but the current diffusion is still mixed: it plays out modestly on programmable thermostats inside the home and extensively on smart meters outside it. But the range of available technologies is vast, and countless more are currently under research and development or envisioned for the future.

The history of residential energy digitalization might appear to be a continuous narrative of technological progress were not it for the public energy policies and, more recently, climate change policies and regulatory frameworks for the largely private-sector energy industry. This backdrop of national energy management illustrates a pull for the methods that could produce more energy use information that is as strong, if not more so, as the push from technological advances in energy measurement and its dissemination. In fact, consumers and utilities have adopted each of the home energy digitalization components for different reasons and under different policy contexts.

This evolution is a confluence of technological innovation, industrial growth and capital, and social and environmental policy going back at least to the 1970s energy crisis—if not to the mass installation of the energy grids and meters that were locked into our residential landscape in the early twentieth century. President Richard Nixon’s interests in governmental research and President Jimmy Carter’s focus on energy efficiency and renewable energy as a response to skyrocketing gas and petroleum fuel costs launched a massive research, development, and deployment infrastructure—Carter’s “moral equivalent of war”—from which today’s patents and products can trace their origins.[19] The consequent financial and intellectual resources allowed public and private state utility commissions and utilities to experiment with alternative means of delivering energy (largely electric) and reducing its use.[20] Sensor and control technology advanced rapidly, paralleling the private-sector advances in

[18] Todd-Blick, Spurlock, Jin, Cappers, Borgeson, Fredman, and Zuboy.
[19] Hakes.
[20] Fehner and Holl.

computing and communications that led to the digital revolution a decade later and the advent of the "smart house."[21]

The massive changes in utility regulation in the 1980s provided the institutional framework that would lead to utility incentives to manage the grid and individual consumers' part in it. The National Energy Policy Act, signed into law by President George H.W. Bush in 1992, created the outlines of the competitive and more deregulated wholesale electricity generation market in place today; it also laid the groundwork and precedent for the creation of incentives for energy efficiency and renewable energy installations for utilities and customers and ignited a range of state, local, and utility programs, consumer guides, and rebates for energy-consuming products and home modifications. The Energy Policy Act, signed by President George W. Bush in 2005, transferred the regulation of utilities from the Securities and Exchange Commission to the Federal Energy Regulatory Commission, further increasing utilities' incentives for managing their grids—just in time for the internet boom and growth in home automation.

With the 2009 passage of the American Recovery and Reinvestment Act, massive investments in grid modernization and management were made for a range of industrial, consumer, and national benefits (including cybersecurity). The Act led to the first full-scale installation of smart meters and utilities' energy management software infrastructure, the diffusion of smart systems and appliances (especially programmable thermostats) and new display and control devices; it also supported consumers' adoption of distributed energy technologies like photovoltaics that would feed into regional energy grids. In addition, the Act permitted utilities to experiment further with time-of-use incentives, rate variations, and other demand management techniques and the methods for accommodating distributed energy resources and managing across them (i.e., net metering).[22] The 2012 Green Button initiative under Barack Obama, championed by digitalization industry leaders, gave a push to democratize access to energy information and enable consumers to access open and transparent utility information.

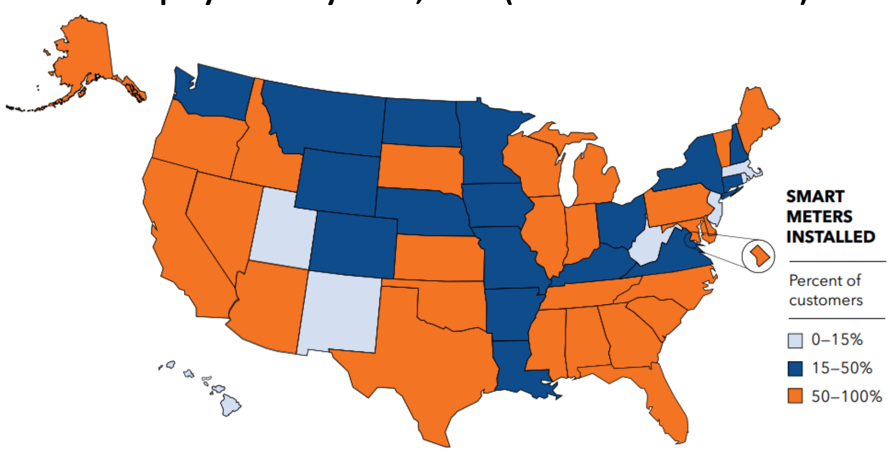
These federal supports for expanding residential energy digitalization have also been echoed in other areas of recent advocacy. Most important, digitalization is now held as a necessary partner to home electrification, efficiency, and renewable energy distribution for residential buildings' contributions to mitigating climate change.[23] Given the urgency of reaching carbon neutrality by 2050,

[21] Campbell-Kelly, Aspray, Ensmenger, and Yost; Kidder.
[22] US Department of Energy, Office of Electricity Delivery and Energy Reliability.
[23] NASEM.

advocates argue for digitalization plans (particularly advanced metering infrastructure) and regulatory reforms that allow them to be in place within the next five years.[24]

Yet national energy policy is highly regional, due in large part to the deregulation of the 1990s. The explosion of opportunities—if not their realization—for residential energy digitalization in the last decade has been tempered by the role of state governments and their utility and energy commissions in determining the pace of uptake for these specific management techniques. This has resulted in a high level of legislative and regulatory variability for the three enablers of digitalization—advanced metering, demand response management (for data, efficiency programs, and pricing controls), and net metering—across states.[25] Consequently, these state policy parameters have determined the gross geography of residential energy digitalization as much as national incentives and the underlying technologies have; nonetheless this has often taken place in unexpected ways, depending on the political strength of each state's utilities and environmentalists as well as concerns about data privacy, owner costs, and extant home physical conditions (Figure 2).

Figure 2. Smart Meter Deployments by State, 2019 (Percent of Customers)



Source: Cooper and Shuster.

Other recent factors beyond energy are also contributing to changes on this map, always in the direction of increased residential digitalization. For example, the tangible consequences of grid reliability as witnessed after the 2021 Winter Storm Uri in Texas have led to new calls by state governments to

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[24] Specian, Gold, and Mah.
[25] SAIC; NEEP.

increase advanced metering infrastructure and its accompanying management tools.[26] Cutting energy costs has also increased calls for digitalization within the home and across the grid.[27] Together, these disparate messages are altering state policies, with resulting increases on the order of 12 to 19 percent annually in the number of consumers enrolled in demand response and dynamic pricing programs.[28]

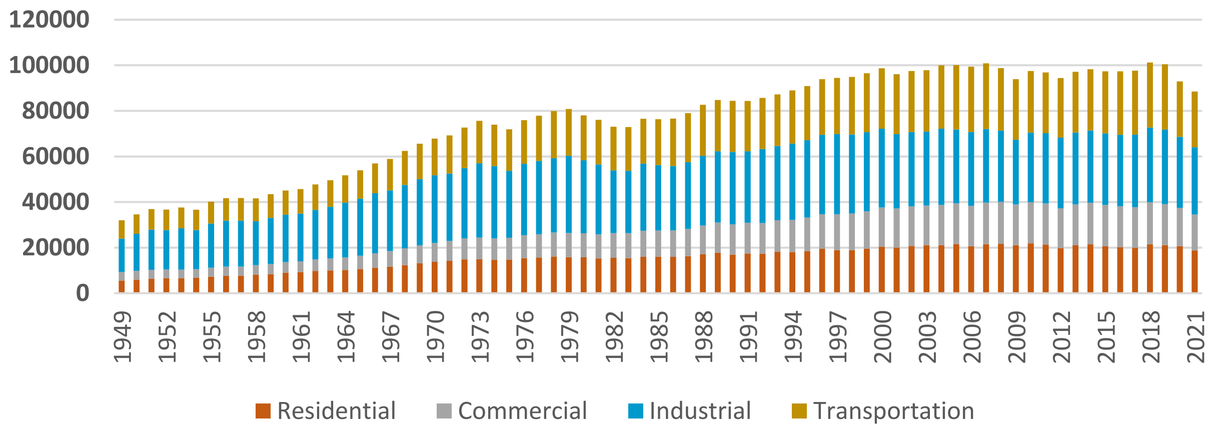
Demand

At the core of all these policy arguments and adoptions is the underlying fact that home occupants use energy. Residential primary energy use—that is, just the energy used within the home—accounts for 7 percent of all actual US energy demand but over 22 percent of all energy costs when transmission and related costs are included (Figure 3). Most of this use is fossil fuel-based, leaving US homes' energy consumption equating to about 20 percent of the nation's greenhouse gas emissions—the equivalent of the entire nation of Brazil's annual emissions.

Over the last century, home energy consumption amounts to a large amount of energy absolutely and proportionally when compared to energy consumption in other economic sectors, even though the residential share of overall energy consumption has remained relatively consistent due to and despite conservation and efficiency efforts in new homes, retrofits of older systems, and the replacement of older energy guzzling appliances since 1970s. Consequently, the drive to reduce energy consumption within and to the home matters.

[26] Reitman and Bourdon; Pecan Street; University of Houston.
[27] Chen; Reinicke.
[28] FERC.

Figure 3. Total Energy Consumption by Sector, 1949-2021 (Trillion BTUs)



Source: US Energy Information Administration, Monthly Energy Review February 2022: https://www.eia.gov/totalenergy/data/monthly/pdf/sec2_3.pdf.

Yet any technological, pricing, and policy interventions attempting to alter this relationship must understand both the homes (the design, construction, and maintenance that determine their energy consumption and intensity) and the occupants (their preferences and behaviors in using energy and in understanding the technologies that deliver energy). These characteristics determine not only the potential for digitalization, but its implementation challenges.

Diffusion

Energy digitalization is far from uniform.[29] Yet the techniques that allow users to manage their own data use on specific appliances or systems—or allow utility providers or third parties to manage them—are less diffused than the technologically determinist narrative may suggest. For example, a recent academic study notes that adoption rates of digitized energy components are modest compared to overall populations, ranging from estimates of 12.5 to 21 percent of American households in 2017 and 2018 surveys, respectively.[30] In the latter survey, smart thermostats were, by far, the most reported

[29] LaMarche, Cheney, Roth, Sachs, and Pritoni.

[30] Paxton; Karlin, Sanguinetti, Davis, Bendanna, Holdsworth, Baker, Kirkby, and Stokols; US Department of Energy Better Buildings Network.

individually digitalized home equipment (14 percent of respondents), followed by smart lighting devices (7 percent) and smart appliances and smart plugs (both at 5 percent). The last federal survey reports a slightly higher rate of 17 percent of households using programmable thermostats.[31]

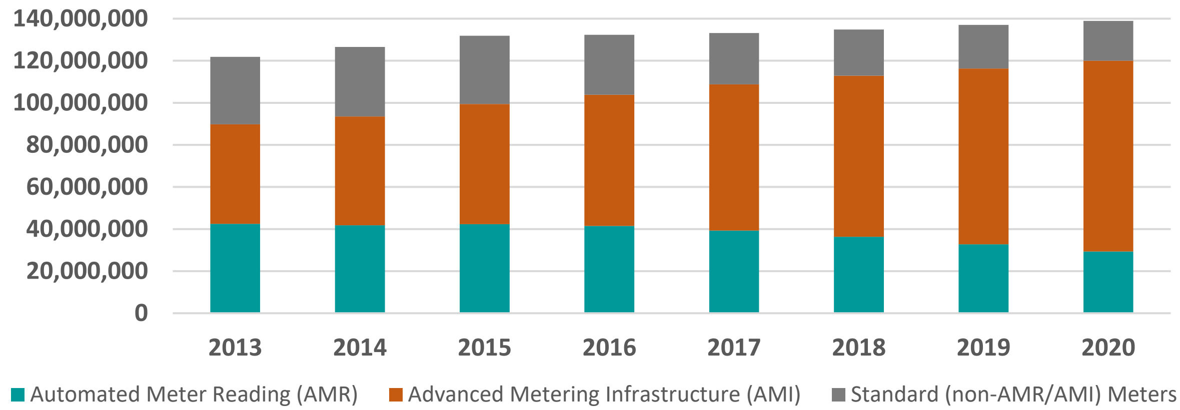
These rates coincide with 2019 market research reports that estimate 18 percent of homes having some component of home automation device in general (not necessarily energy-related), and 11 percent having programmable thermostats.[32] Only one quarter of consumers who had not installed smart thermostats intend to purchase them in the future, on par with those intending to purchase digitalized doorbells, smoke detectors, and security cameras. Market studies attempting to understand the reasons for recent purchasers' acquisitions of digitalization technologies report similarly modest adoption rates and even lower rates of participation in the energy management programs that the technologies are designed to enable.[33] In most cases, smart thermostats came as consumers upgraded or replaced older or broken thermostats. Almost half (40 to 45 percent) of the 18 percent of adopting consumers received utility discounts for digitalizing thermostats or other components such as lighting controls. A portion of these early adopters (15 to 20 percent) also participate in utilities' demand response, tiered pricing, and time-of-use rates, though this group is less than half of the households that report that their utilities offer the energy management services.

In contrast, the smart meter used by utilities to record and manage property owners' usage is much more diffused. At last count, 65 percent of residential meters had been integrated into the advanced metering infrastructure (AMR)—that is, had two-way smart meters installed (Figure 4). Industry projections place the current proportion of smart meters at 83 percent, or 115 million installations.[34]

The total number of AMR meters has nearly tripled in just one decade. Most smart meters are in residential installations (88 percent) compared to commercial and industrial buildings, minutely higher than the overall proportion of residential electric meters (87 percent). Investor-owned utilities also have installed approximately 74 percent of AMR meters, on par with these providers' overall share of the residential electricity market (72 percent); the remainder of home installations are served by public utilities or electric cooperatives.

[31] US Energy Information Administration.
[32] Parks Associates.
[33] Parks Associate.
[34] Cooper and Shuster.

Figure 4: Distribution of Residential Electrical Energy Metering by Meter Type, 2013-2020



Source: US Energy Information Administration, Forms EIA-861 and EIA-861S as tabulated in https://www.eia.gov/electricity/annual/html/epa_10_05.html (accessed February 1, 2022).

Ultimately, digitalization has, so far, modestly but notably changed how Americans use their home's energy-consuming systems and interact with their energy providers. Given support from technological, industrial, and policy advocates, this will expand. Yet households' appetite for adopting in-home residential energy management technologies has been substantially lower than that of utilities for smart meters.

The massive societal need for residential energy improvements has not translated into a universal welcome for home energy digitalization. Other highly variable customers in sectors like the commercial building and industrial sectors do not face the diversity of demographic and behavioral complexity for adopting digitalized energy management that is foundational to residential energy use.[35] Clarity of adoption decisions and constraints is needed.[36]

The Resisters

Residential energy digitalization's promise for current economic, social, and environmental visions will continue to be shaped by several concerns, the most fundamental of which is whether the technology even yields its purported energy benefits. With increasing and real consumer concerns over the sharing

[35] Rogers, Elliott, Kwatra, Trombley, and Nadadur.
[36] Will.

of information about their daily behaviors and preferences, the perceived ceding of physical control over their home environments through automated energy management, and possible abuses of bartering and profiting off their personal data, digitalization's promise calls faintly—even though the underlying visions ring true. The steady technological drumbeat has also muffled the sound of inequities that have persisted within the US energy grid and US housing conditions for decades—disparities that have not been fully considered in digitalization's implementation and in energy management schemes. For the shared vision of technologists and decarbonization advocates to be realized, these concerns must be considered.

Benefits

One concern is the reality of the technology's promised benefits. Indeed, the fundamental benefits of energy digitalization have not been fully realized for the utilities (because not every energy user's home has been fully digitalized nor has each energy user changed behavior when their home was digitalized), for the consumer (because energy reductions have not always resulted after installation), or for society (given the range of other policy interventions shaping greenhouse gas emissions and housing quality). However, the benefits from residential energy digitalization currently appear to accrue primarily to utilities.

There are numerous benefits to the utilities that have been promoted by them, by digitalization technology manufacturers and providers, and by energy advocates. Among these are the fundamental modernization of the energy infrastructure, whereby information about disruptions, flows and frequencies, and distributed energy supplies and demands can be analyzed and the grid made efficient.[37] From a basic practical sense, smart meters reduce utilities' costs for servicing individual customers for billing as well as automating connections and disconnections.[38] Utilities also report being able to provide better customer service for homes that have been digitalized.

Much of the promise of these benefits comes from the utilities' ability to manage and act on the information coming from individual homes as much as the technology itself—that is, from the software as much as the hardware. The resulting demand-response and related energy management tools are projected to stabilize the grid and manage demand—reducing peak demand by as much as 10 percent.[39]

[37] Carmichael, Jungclaus, Keuhn, and Hydras; Nadel.
[38] Navigant.
[39] Holmes, Gomatom, and Chuang.

Residential digitalization also provides utilities with opportunities to integrate the distributed sources (e.g., individual home photovoltaics) that are beginning to be required in building codes. Utilities can also use this information to support the expanding energy-efficiency and customer service requirements they face through national and state statute and regulation. [40] Combined with demographic and geospatial data, timely energy demand loads allow utilities to identify and recruit households for various energy efficiency programs.[41] In so doing, they also reduce the costs of measurement, verification, and management of these programs as well as the demand-response needs; they also mitigate the costs of producing and distributing the energy that would have been used without these reductions. The benefits accrued to utilities, then, depend in part on the aggregation of benefits that individual consumers can reap from digitalization through energy savings and consequent non-energy benefits to health, home quality, and convenience.[42] Equipment performance diagnostics and replacement notifications are also listed as helpful consumer benefits from digitalization.[43]

However, the evidence to support this broader pot of benefits is remarkably mixed.[44] Several pilots and demonstration studies estimate preliminary reductions in energy use due largely if not completely to the integration of digitalized energy information techniques and the resulting management they enable. Among those for individual component's digitalization, for example, the largest and most rigorous evidence addresses programmable thermostats' benefits. Energy reductions during peak load periods have been found, along with possible overall energy savings.[45] These savings were found for a range of specific digitalized components.[46] Larger home automation networks (e.g., Nest) were found to have positive effects on individual component's energy reductions as well.[47]

The studies also have included a range of behavioral experiments that include different types of devices, messages, population sub-group targeting, and utility management programs and incentives. One study looking at the treatment of smart meter-based time-of-use pricing across households by pre-treatment mean and maximum energy consumption, found the effect on high energy users to be over

[40] Sreedharan, Price, Angel and Stevens.
[41] Harris and Gilbert; Jin, Spurlock, Borgeson, Fredman, Hans, Patel, and Todd.
[42] Rogers and Junga.
[43] US Department of Energy Better Buildings Network.
[44] Ehrhardt-Martinez, Donnelly, and Laitner.
[45] Robinson, Narayanamurthy, Clarin, Lee, and Bansal; Harding and Lamarche; Jessoe and Rapson; Morris and Smith.
[46] King.
[47] Kelsven and Weber; Brannan.

double that of households with low mean and maximum consumption before the experiment.[48] Another study that randomly encouraged households to activate a feature on their existing smart thermostat to automate responsiveness to time-of-use electricity pricing reported reduced air-conditioning use, raising indoor temperatures above a household's preferred temperature but not prompting feature deactivation.[49] Another study outside the US supports these findings but provides further nuance around the motivating factors (such as consumer reminders) that lead to consistent energy use reductions.[50] These pilots and demonstrations have suggested energy reductions on the order of 4 to 12 percent.

However, more recent rigorous studies of wider energy digitalization installations suggest that any consumer benefits are short-lived, due largely to the behaviors of the consumers themselves or at least how they interact with the control devices that provide them with information and allow them to manage their homes' systems.[51] A study on energy information sharing throughout the network finds a relatively quick decay in behavioral change after the immediate reaction from installation—requiring a persistent long-term provision of information for the largest group of consumers to change habits.[52] Other preliminary studies suggest that expanding automation to other energy-using systems beyond HVAC may result in even less savings because of the offsetting effects of the energy-using controls and wireless communications that are meant to provide consumers information—that is, that the digitalization technologies, controls, and sensors actually consume significant amounts of energy themselves.[53]

Similar findings from other studies led one group of researchers to refer to digitalization technologies as "early adopter toys" more than effective energy management tools.[54] Most studies and the underlying regulations that allow for energy management experiments include opt-in or opt-out participation, leading to varying take-up and outcomes but ultimately still inscribing bias in their findings.[55] Selection bias has been noted in many of the studies associated with initial installations of digitalization equipment—that is, the consumers that are most likely to take and act on the information

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[48] Patel, Borgeson, Rajagopal, Spurlock, Jin, and Todd.
[49] Blonz, Palmer, Wichman, and Wietelman.
[50] Carroll, Lyons, and Denny.
[51] Brandon, Clapp, List, Metcalfe, and Price.
[52] Allcott and Rogers.
[53] Iaccarino, Kelly, Cofer, and Fontain.
[54] Goetzler, Young, and Rosenblatt.
[55] Todd, Cappers, and Goldman.

are also more likely to be interested in positive energy action to begin with. Some of the bias could be mitigated with tailored and responsive messaging on the part of utilities, metering, and automation providers.[56] Yet even selection bias manifests in complex ways; another study found that participants who felt most strongly about the need to reduce their energy use were often not the ones who do it through digitalization channels because they felt that they were already "doing their part."[57]

Ultimately, the wider group of rigorous studies whose populations are all utility customers rather than self-selected adopters estimates the range of energy savings at a more modest 0.4 to 6 percent. The core factors influencing these outcomes are:

- the periodicity or frequency of the *information* provided to the consumer (e.g., real-time, daily, or weekly) and the consequent immediacy of its expected consumer response (direct feedback during energy use versus indirect reporting after)
- the medium of information such as smart devices or wall displays, particularly their interface and legibility or interpretability across populations, that provide *insight* into their behaviors
- the type of action, response, or *influence* that is expected of the consumer (including manually changing temperature controls or allowing automatic responses from the technologies, the management tools, or the utility and its third parties)
- the *duration* of the action or expected behavioral changes (once or repeatedly)
- the strength of incentives to induce action, e.g., reduced rates or free installations
- the desired *objective* of the action (e.g., shifting energy use to non-peak times or reducing energy use altogether)[58]

Of course, any attempts to measure the consumer benefits from digitalization assume that the technologies actually provide accurate information, which is often not the case.[59] Nor is it always the case that competing controls and communications devices across individual components can share information or work in interoperable ways.[60] Concerns regarding basic occupant safety have also been raised regarding the hardware components that have resulted in unintended negative consequences.[61]

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[56] Karlin.
[57] Moran, Forster, and Gettig.
[58] Ehrhardt-Martinez, Donnelly, and Laitner.
[59] Shishido.
[60] US Department of Energy Better Buildings Network.
[61] California Council on Science and Technology; Sickinger; CBC News.

In short, digitalization works—but only sometimes.

Privacy

Ostensibly, digitalization products are meant to provide consumers with detailed energy information from which to make choices about when and how to turn on devices in their homes. The potential provision of more granular data by time and specific equipment's use to utilities and third-party vendors, however, causes pause—particularly as researchers attempt to describe detailed occupant activities and behavioral status based on energy data. The potential to describe occupant activity based on smart meter data alone is still far from being realized; for example, one study using commercially available disaggregation products found that vendor estimates were markedly inaccurate for individual months or homes but approached accuracy for the whole analysis period.[62] These products (particularly if tied to sub-meters) have been in the making for some time.[63] High-profile cases of police using utility bills to track criminal activity and federal immigration officers identifying undocumented residents show the power of matching more granular energy data with other databases.[64] Presumably, landlords who pay utilities would also have access to information about their tenants in order to track, record, and report the building's energy use—a "benchmarking" process that is increasingly required by cities and states.

State utility regulators vary widely in their approach to consent and data-sharing, depending on who has collected and who wants the data—for example, a consumer that wants to share their data with a third party as opposed to a utility that creates a demand-response program. In turn, utilities within each state also vary in their approach to consent, to sharing with third parties, and in the mechanisms for sharing (automatically or manually). Vendors of full home automation systems and residential energy management systems (especially those that are not utility-controlled or otherwise affiliated) are often left with a complex and incomplete network of customers and data. Consent protocols for the consumer and data sharing agreements between interested parties abound in size and detail.

There is consensus among most regulators that energy data should be available when the customer wants access to their own information and if they have authorized third-party access.[65] Many

[62] Baker, Fuller, Hicks, and Rodriguez-Anderson.
[63] Alahmad, Sordiashie, Wisnieski, Sharif, and Aljuhaish.
[64] Harwell; Getts; Bayoumi; Shoch.
[65] SEE Action.

energy efficiency programs, including those for low-income consumers, support such policies for the very reason that data regarding energy use and demography are critical to improving households' lot.[66] Consequently, some states, like California, require utilities to remove all personally identifiable information from energy datasets and permit sharing only for energy efficiency or energy efficiency evaluation services.

Debates over energy data privacy are also tied into broader societal discussions about the use of social media, financial transactions, and other information about individual activities and behaviors. Recent legislative attempts for national privacy regulations or guidelines have centered on those broad consumer data protections which implicate energy use data produced through digitalization. Yet for regulators and providers, these debates go back decades; the push for the 2012 Green Button to encourage utility data sharing was accompanied by the voluntary code of conduct known as DataGuard to protect consumer data.[67] The subject of energy data privacy remains contentious and has resulted in a legal patchwork.[68]

Profit

Concern regarding households' energy information and its privacy and protection, however, appear to center less on the existence of these data and the overall vision of their management, and more on who owns and profits from them. For example, a market research study noted that 40 to 49 percent of households would be willing to adjust the timing and setting of their thermostats, dishwashers, and lighting for better energy management—but only 25 to 30 percent would be willing to allow their utility to perform the adjustment. Presumably, willingness to allow a third party is even lower.

In one study, issues of trust with the utilities and their third parties as well as confidence that these organizations would protect their information were significant to home residents.[69] Trust is particularly complicated given that many households, particularly lower-income ones, have had negative relationships with their energy providers. Any publicized negative cases of information mismanagement or abuses of privacy through digitalization could implicate all digitalization efforts as well as any direct and positive energy interventions.

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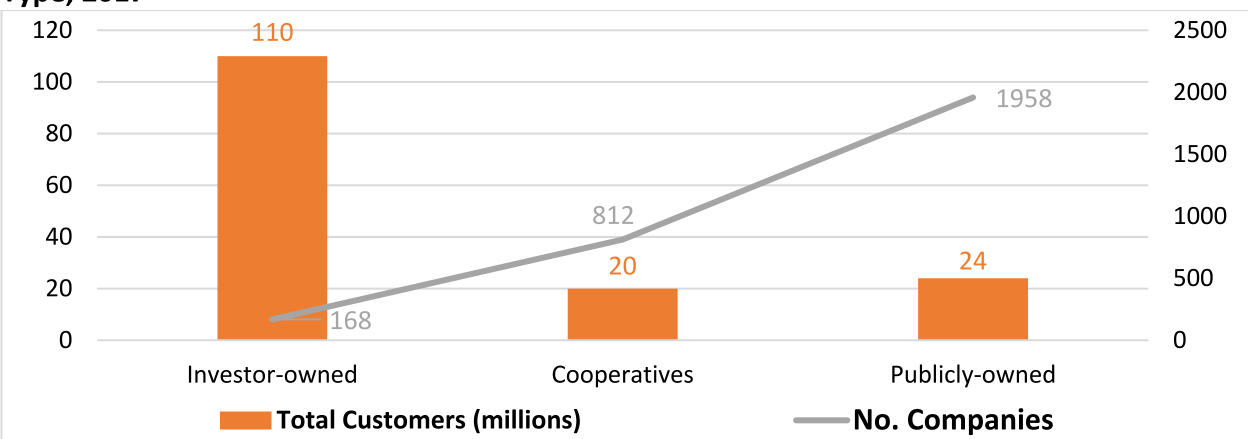
[66] McKibben; ACEEE.
[67] US Department of Energy, Office of Electricity.
[68] US Department of Energy.
[69] Fredman.

Further, the continued diffusion of smart meters, ostensibly to help consumers gain access to their energy information, has primarily assisted private utilities' operations and finances—potentially eroding trust and creating a backlash for additional submetering and in-home digitalization that connects to wider energy management. The dominance of investor-owned utilities in providing electricity for US residential consumers combined with their increasing profits over the last decade have led to reasonable questions from community activists and the households themselves (Figures 5 and 6).

Figure 5: Number of Companies and Total Customers of US Electric Utilities by Ownership Type, 2017

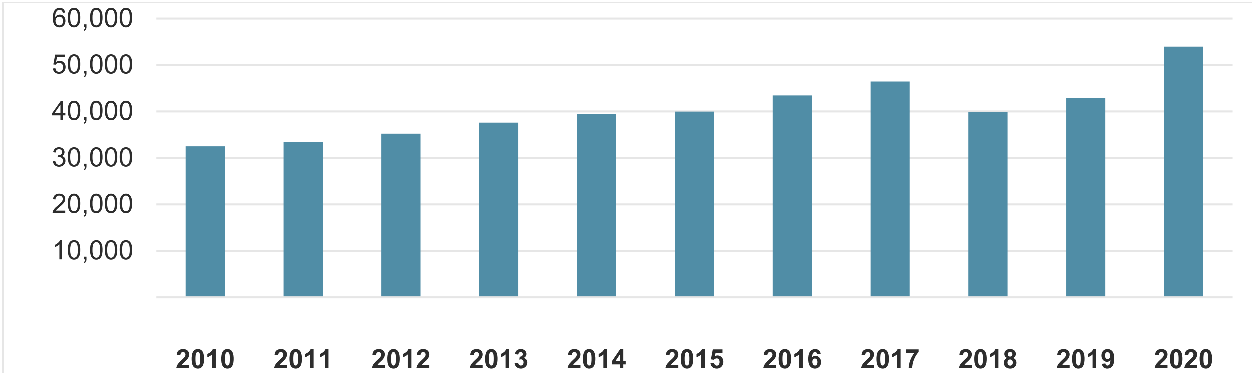


Source: Author tabulations of US Energy Information Administration, 2017 Annual Electric Power Industry Report and 2020 Electric Power Annual, Revenue and Expense Statistics for Major U.S. Investor-Owned Electric Utilities

Most consumers may not be aware of or understand their participation in demand response programs, and they may perceive digitalization as an additional burden. As one low-income resident noted after her home was outfitted with a smart meter: "Before the smart meters, I probably get a bill that's $169 or $159... it wasn't ever always $200, but since the smart meter it has just been a set price, or something. I don't know how they do it."[70]

[70] Hernández.

Figure 6: Total Net Utility Operating Income for US Investor-Owned Electric Utilities, 2010-2020 (Million $)



Source: Author tabulations of Revenue and Expense Statistics for Major US Investor-Owned Electric Utilities in 2010-2020 Electric Power Annuals.
Note: Total Net Utility Operating Income = Revenues – Expenses as reported.

Ultimately, the benefits for consumers and global climate visions also translate into profit for specific players, even beyond private utilities. The suppliers and installers of digitalization hardware technologies along with the creators of analysis and management software (and investors for both) have been among the biggest proponents of massive energy digitalization within homes and over the entire grid. For households interested in home automation, these groups may seem like reasonable parties with which to engage and provide access to one's detailed energy data. But for other households concerned with their privacy as well as those that simply cannot afford or understand the technologies, digitalization purveyors may appear as profiteers from and intermediaries to the energy-efficient and renewable-energy intervention that the technologies are meant to enable.

Consequently, there is still another group of stakeholders set to profit from this technology: residential energy improvement vendors such as insulation, HVAC, appliance and lighting manufacturers, and the remodelers, builders, and trades that install these products. These vendors' actions support direct energy improvements that need to be undertaken to meet climate goals and that could be targeted to overcome energy inequities. Information gleaned from energy audits, home inspections, and equipment diagnostics is just as critical to a home's overall energy use as that produced from digitalization for utilities' management.

Ultimately, most utilities are transitioning to house-level smart meters and will continue to do so in the next decade to the point of covering virtually all US homes. The question then becomes not one of who will profit from residential energy digitalization, but whether the profit will be gleaned from the vendors that will provide the biggest benefits to national decarbonization and climate goals. Digitalization certainly has its place in that profit-sharing, but its costs must be weighed against other fundamental energy improvement strategies to produce the maximum benefit to consumers and for meeting our climate goals.

Equity

Housing and households are far more diverse than utilities. Users use energy differently. Yet most of the studies noted in the benefits above relied on eligible and interested users—most of whom were either energy- or environmentally progressive and had the bandwidth, literally and figuratively, to respond. But a recent study looking at residential digitalization adopters found that there was minimal consistency in profiles by homeownership, income, and other factors across the distinct digitalization components and, more critically, that uptake across a whole population for any of them was modest at best.[71]

Differences in energy use and digitalization take-up manifest in many ways and are due to several underlying causes. The first is the access to energy information that digitalization is designed to harness. One study noted how lack of wireless bandwidth as well as the resources to invest in the upfront costs associated with a programmable thermostat prohibited several households from participating in a pilot—suggesting that lower-income households and households headed by older individuals might be the least able to access digitalization's benefits.[72] Moreover, renters who do not pay their own utilities are completely in the dark.

Even with access, another cause of disproportional benefits is the ability to understand energy use and associated technologies. Energy illiteracy can be found at all levels of income and formal education. In fact, units of energy measurement beyond total dollars billed are not easily comprehensible to all individuals. Consequently, digitalization must also be accompanied with translation—either as relative costs for energy or comparative usage. Inability to comprehend and translate energy information may partially explain the modest in-home digitalization diffusion rates.[73]

The ability to respond to information quickly might also not be uniform.[74] The types of communication channels and devices for understanding energy information are critical.[75] Evidence from

[71] Karlin, Sanguinetti, and Ford.
[72] Smith.
[73] US Energy Information Administration.
[74] Ben and Mazur-Stommen.
[75] Peffer, Perry, Pritoni, Aragon, and Meier.

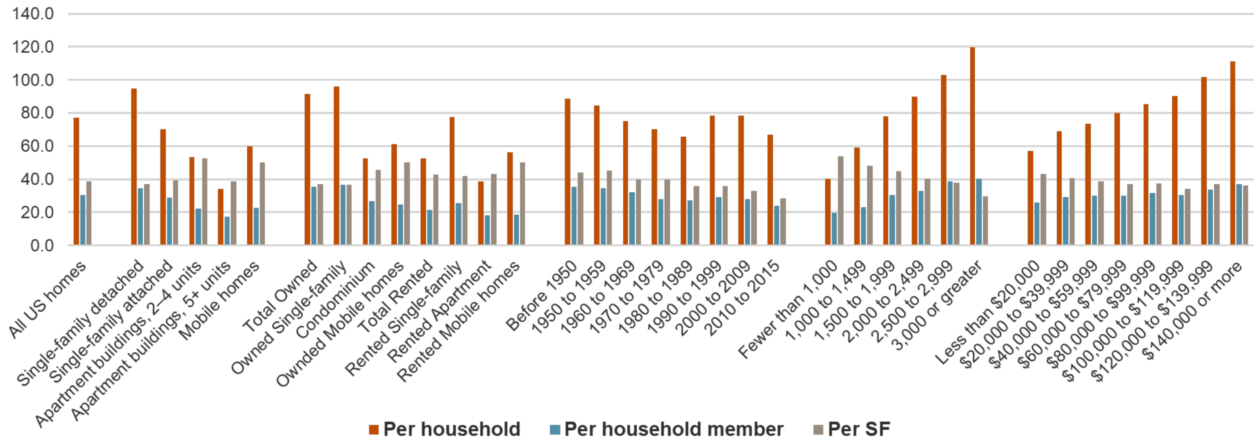
one study testing for combined in-home information communications with smart meters showed that intensive energy counseling had been a partial predictor of energy savings in addition to the technologies' installation.[76] The study also suggested that having an in-home display dedicated just to the energy usage of digitized systems was preferable to having an web-accessible portal—further suggesting equity implications as well as basic consumer preferences for receiving information.[77]

If energy information access and literacy are not uniform, neither are the original motivations for changing energy behaviors or taking up energy-conserving actions, with other factors such as home quality, home ownership, and familiarity with home repairs playing a role.[78] There are increasing numbers of studies reporting patterns of commitment or interest in energy information and energy savings.[79] Differences in digitalization interest may even be cultural and political, with one meta-review of consumer energy feedback programs over time noting that more recent programs within the current climate change policy context have produced lower savings than their earlier counterparts.[80]

Not surprisingly, however, these differences also play out demographically and in terms of housing conditions. Appendix 1 and Figure 7 present data regarding current residential energy uses by various demographic and housing characteristics that form the broader social background for digitalization efforts, some of which are also summarized. These data reveal several important patterns that question both the equitable adoption rates of home digitalization as well as the fundamental energy interventions that certain populations (namely, low- to moderate-income households) need most.

[76] Donovan, Bleything, and Enterline.
[77] Hartman and LeBlanc.
[78] Costanzo, Archer, Aronson, and Pettigrew; Christie, Donn, and Walton.
[79] Moran, Forster, and Gettig found in a preliminary study that there were no clear demographic or attitudinal predictors of either participants in a home display pilot or their willingness to curtail energy use in response to high-peak demand events, but rather that a sense of civic responsibility motivated them to participate.
[80] Ehrhardt-Martinez, Donnelly, and Laitner.

Figure 7: Total Energy Consumed by US Homes per Household, per Household Member, and per Home Square Footage (Billion BTUs)



Source: Author tabulations of US Energy Information Administration, 2015 Residential Energy Consumption Survey HC Table Series.

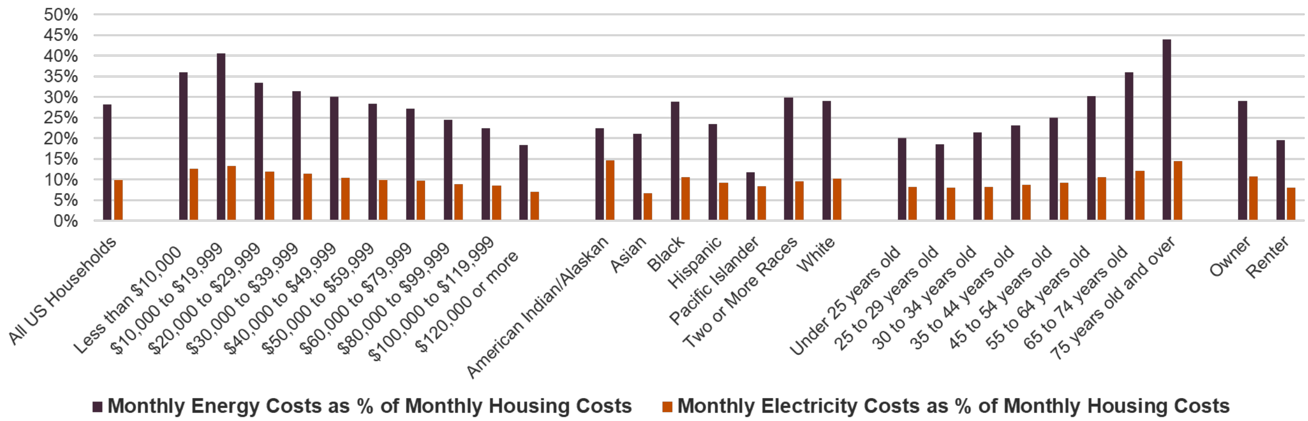
There is a significant number of homes that still rely on fossil fuels to fill some of their energy needs, with single-family homes, older homes, and homes occupied by wealthier households being more likely to use these fuels (see Appendix, Table 1). While information about their use can be digitized, smart gas meters are remarkably less diffused and their use in response programs is minimal. Further, digitalizing fossil fuel use contradicts climate goals.

Single-family housing consumes significantly more energy per household and household member than do multifamily and mobile homes (see Appendix, Table 2). Consequently, denser multifamily and mobile homes are more energy intensive (i.e., consume more energy per square foot). Also, the older and larger the home and the wealthier its occupants, the more energy it consumes per household and family member. This also means that lower-income households living in smaller homes are also paying for more energy per square foot.

Additional datasets describing energy costs affirm that costs for all kinds of fuels and electricity increase proportionally as annual household incomes lower, but the difference in mean and median energy bills across households is modest compared to their income differences (see Table 3 in Appendix, and Figure 8). A similar pattern can be found by race, with American Indian/Native Alaskan and Black households expending more for their energy bills than other racial groups.

These disparate energy burdens across household incomes and race have been corroborated in other studies, including those monitoring negative energy conditions such as shutoffs as well as cost burdens.[81] Lower-income households with older adults, children, and people with physical disabilities are particularly energy burdened.[82] Monthly housing costs including energy utilities as a proportion of household income, then, increase as a household's income decreases (see Appendix, Table 4).

Figure 8: Energy Burden By Group for Select Household Characteristics (Costs as Percentage of Household Income)



Source: Author tabulations of 2019 American Housing Survey.

Looking behind the walls of these different demographic groups reveals a few other patterns, particularly regarding the largest home energy uses, namely, heating and cooling (see Appendix, Table 5). Higher household incomes are associated with higher use of natural gas warm air furnaces (used, for example, in 48 percent of homes whose households have incomes of $150,000 or over), and with the presence of central air conditioning. Lower-income households are more likely to rely on electric heating equipment and often use room air conditioning units or have no air-cooling capacity at all. Energy-related housing inadequacy such as a lack of or failing heating equipment, consequently, is more common for lower-income households (see Appendix, Table 6). Other causes of potential indoor temperature hazards such as poor wiring, inadequate insulation, and high energy costs are also felt more acutely among lower-income households.

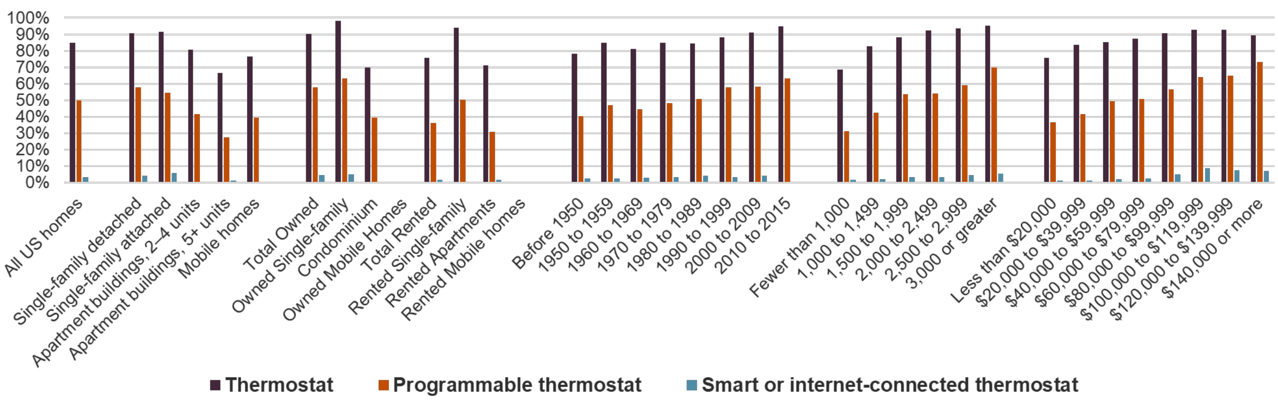
More directly relevant to energy digitalization, the associated technologies also fall along patterns of demography and housing quality (see Table 7 in Appendix, and Figure 9). The likely presence of programmable thermostats, including smart thermostats, increases significantly with household

[81] Hernández and Bird; Kontokosta, Reina, and Bonczak; Bednar, Reames, and Keoleian; Lyubich; Brown, Soni, Doshi, and King.
[82] Drehobl, Ross, and Ayala.

income. For example, 73 percent of households with incomes over $140,000 report having a programmable thermostat, and 7 percent have smart thermostats. In contrast, households with incomes less than $20,000 report having these controls at rates of 37 percent and 1 percent, respectively. Larger and newer homes, as well as single-family homes, are more likely to have technologies installed compared to peers of a similar income, as well.

In homes with temperature controls, wealthier households are more likely to program their thermostat to vary by time and season rather than leaving it at a constant temperature, manually adjusting it, or turning it on and off—which are more common in lower-income households. On the whole, then, the most energy-burdened households are the least likely to receive the benefits of positive energy interventions.

Figure 9: Percentage of Group with Any Thermostat, a Programmable One, and a Smart One (Percent)



Source: Author tabulations of US Energy Information Administration, 2015 Residential Energy Consumption Survey HC Table Series

These measured differences in energy use, housing conditions, and energy digitalization behaviors have already shaped access to other energy improvement interventions, such as energy-efficiency and renewable energy programs.[83] Income and education are especially associated with energy program participation.[84] The equity challenge for most residential energy digitalization efforts begins with their oversight of basic demographic factors and their relevance to the energy needs across homes.[85] This

[83] Reames; Reames; Reames; Reames, Reiner and Stacey.
[84] Frank and Nowak.
[85] Martín and Lewis.

approach leads to a preponderance of pilot applicants and resulting beneficiaries being largely white, wealthier homeowners compared to the general population—as witnessed in current digitalization program participation. Underlying these disparities in energy use are also concerns regarding the grid itself. [86] Energy-burdened households and those living in energy poverty would be justified in questioning calls for their support of technologies that would simply expedite their shutoffs.

If the benefits of digitalization are to be realized, they must manifest equitably. Yet the current history of interventions to improve households' energy consumption in societally beneficial ways suggests that digitalization faces a formidable challenge. These still-evolving interventions have not produced equitable benefits, nor have they even included energy-challenged households. Recent state-level attempts to monitor and rectify energy inequities have resulted in California Energy Commission's Low-Income Barriers Studies, beginning in 2016, as mandated by California Senate Bill 350; there are similar efforts under development in New York and Massachusetts as part of their climate justice plans. Recent efforts by the US Department of Energy to implement Presidential Executive Order 14008's requirement that agencies ensure that 40 percent of program benefits go to disadvantaged communities (commonly referred to as "Justice 40" efforts) have brought additional attention to the concerns of energy-burdened households.[87] However, the fundamental concerns remain the physical interventions in these households' homes to improve their efficiency, reduce their consumption, and lighten the energy burden. Improvements in the methods for understanding disparities in individual energy, housing, and residential energy digitalization conditions—but also in their implantation and outcomes on energy, finances, and well-being—are in order.[88]

The Power

Proponents describe digitalization as a vehicle for liberating energy data and harnessing its management potential to benefit planet and people. To both goals, then, we have asked: is digitalization the right vehicle? The growth of this technology must be viewed as part of a larger assemblage of interventions for reducing fossil fuel consumption across the grid, reducing energy consumption, and improving housing quality for every household. Energy digitalization is a convenient tool for these ends. It can exist at scale but with a granularity of information about a single home appliance that portends its potential.

[86] Brockway, Conde, and Callaway; Farley, Howat, Bosco, Thakar, Wise, and Su.
[87] US Department of Energy.
[88] Ling, Spurlock, Borgeson, Fredman, Hans, Patel, and Todd.

Yet proponents must address the distribution in digitalization with regard to its original profits and the inequity and concerns for protections in its current delivery. There must also be an honest accounting of the magnitude of its contributions.

The former goal is a global imperative. To meet the swiftly encroaching deadlines for climate neutrality, residential energy consumption and its flows must be managed, and good management requires constant, consistent, and accurate information. Yet better assessments of digitalization's costs at scale must be assessed against the costs of direct investments in residential energy efficiency, renewable energy, and electrification.[89] Expending public and private resources requires prioritizing actions and ensuring the appropriate and most efficient mix of residential energy activities.

The latter goal's focus—the occupants and owners of homes—are at the heart of digitalization's promise. Democratizing the energy grid through distributed energy, however, demands robust and comprehensive energy management. If consumers are wary of others owning and using their home information—and are less convinced that others should be able to directly act on and profit from it—the onus of information receipt, interpretation, and action lies on the household itself.

For the reasons discussed in this paper, this poses challenges. This paper starts with an anecdote taken from recent headlines about Xcel Colorado's new program for monitoring and charging for energy use depending on time. In response to that notification, one Coloradan mother reported: "I wouldn't like it, because sometimes I'm busy with my baby, I can't do laundry at the times that they would suggest."[90] For digitalization to be most effective, it must be paired with tangible assistance to eligible households (e.g., weatherization, renewables, electrification) and rate pricing alternatives, or follow these initiatives for eligible households—diffusing digitalization only, without the fundamental energy interventions, will result in exacerbated energy burdens and unwanted backlash. Further, states and utilities must work to create nationally uniform rules regarding data sharing and privacy to ensure that the maximum number of households, regardless of income and racial background, can participate. States and the federal government should also seek to ensure that the profits incurred by private utilities in the implementation of resulting demand-side management programs be directed to low-income energy interventions.

Continuing with the status quo of marketing and delivery methods will not produce equitable housing or energy outcomes; neither will a fully open system of collection nor managing energy

[89] Torriti.
[90] Bordelon.

information. Digitalization's vendors, advocates, utility supporters, and regulators must address the lived experiences of households and the real physical qualities of their homes and energy activity to design better, more accessible, more sensitive, and more affordable versions of their innovations. If they do so, digitalization will find its rightful place among the national energy strategies and in homes' internal wiring.

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Appendix

Table 1. Fuels Used and End Uses of Electric Fuels by Select Housing Characteristics (Percent of Homes)

		Fuels used					Electricity end uses			
	Homes	Electricity	Natural gas	Propane	Wood	Fuel oil/ kerosene	Heating	AC	Water heating	Cooking
All US homes	118.2	100%	58%	10%	11%	6%	49%	87%	47%	63%
Housing unit type										
Single-family detached	73.9	100%	61%	12%	14%	7%	46%	89%	43%	64%
Single-family attached	7.0	100%	69%	3%	4%	--	47%	86%	43%	57%
Apartments, 2–4 units	9.4	100%	64%	4%	--	5%	49%	80%	41%	60%
Apartments, 5 or more units	21.1	100%	53%	2%	2%	5%	55%	85%	53%	67%
Mobile homes	6.8	100%	25%	22%	15%	4%	65%	85%	78%	59%
Ownership of housing unit										
Owned	74.5	100%	60%	13%	14%	7%	45%	89%	43%	62%
Single-family and mobile *	66.2	108%	64%	15%	16%	7%	49%	96%	47%	68%
Apartments	3.3	100%	64%	--	--	--	36%	88%	45%	48%
Rented	43.7	100%	55%	4%	4%	4%	55%	83%	52%	65%
Single-family and mobile *	14.7	112%	61%	7%	9%	4%	62%	93%	61%	69%
Apartments	27.2	100%	55%	3%	2%	5%	55%	83%	50%	67%
Year of construction										
Before 1950	20.8	100%	75%	9%	13%	10%	38%	82%	34%	44%
1950 to 1959	12.6	100%	72%	7%	8%	10%	42%	86%	36%	56%
1960 to 1969	12.8	100%	65%	10%	8%	8%	38%	84%	38%	60%
1970 to 1979	18.3	100%	54%	8%	14%	5%	52%	87%	50%	70%
1980 to 1989	16.0	100%	47%	9%	11%	6%	56%	88%	56%	73%
1990 to 1999	16.8	100%	51%	13%	10%	2%	52%	89%	52%	68%
2000 to 2009	17.0	100%	48%	12%	10%	2%	58%	94%	54%	71%
2010 to 2015	3.8	100%	42%	13%	5%	--	58%	92%	63%	82%
Total square footage										
Fewer than 1,000	26.6	100%	56%	6%	4%	5%	53%	81%	50%	62%
1,000 to 1,499	26.1	100%	49%	7%	8%	3%	57%	87%	57%	65%
1,500 to 1,999	17.5	100%	57%	10%	11%	5%	50%	89%	49%	63%
2,000 to 2,499	14.1	100%	61%	13%	13%	6%	43%	89%	43%	62%
2,500 to 2,999	10.8	100%	67%	11%	15%	9%	44%	90%	36%	64%
3,000 or greater	23.1	100%	66%	15%	17%	9%	39%	91%	36%	65%
2015 annual household income										
Less than $20,000	22.9	100%	53%	9%	6%	6%	54%	80%	52%	59%
$20,000 to $39,999	27.3	100%	56%	8%	8%	4%	51%	84%	51%	64%
$40,000 to $59,999	18.4	100%	54%	9%	10%	6%	53%	90%	49%	66%
$60,000 to $79,999	15.2	100%	55%	11%	13%	7%	47%	89%	48%	69%
$80,000 to $99,999	9.7	100%	62%	7%	12%	5%	46%	90%	42%	65%
$100,000 to $119,999	8.1	100%	63%	12%	14%	5%	51%	90%	42%	60%
$120,000 to $139,999	5.4	100%	65%	13%	17%	7%	41%	91%	41%	63%
$140,000 or more	11.2	100%	72%	13%	15%	7%	35%	93%	30%	61%

Source: US Energy Information Administration, 2015 Residential Energy Consumption Survey HC Table Series.
Note: More than one fuel and electric end use may apply.

Table 2. Energy Consumption and Expenditures for US Homes by Select Housing Characteristics (Total and per Household, Household Member, and Home Square Footage)

		Energy consumption (trillion Btu)				**Energy expenditures** (dollars)			
	Homes	**Total**	**Per household**	**Per household member**	**Per SF**	**Total**	**Per household**	**Per household member**	**Per SF**
All US homes	118.2	9,114	77.1	30.3	38.4	219.34	1,856	728	0.92
Housing unit type									
Single-family detached	73.9	6,991	**94.6**	**34.6**	37.1	161.65	**2,188**	**801**	0.86
Single-family attached	7.0	491	70.0	28.6	39.5	11.23	1,602	655	0.90
Apartments, 2–4 units	9.4	503	53.5	22.3	**52.5**	12.48	1,329	555	**1.30**
Apartments, 5 or more units	21.1	724	**34.2**	**17.3**	38.8	22.10	**1,045**	**529**	1.18
Mobile homes	6.8	406	59.8	22.8	**50.0**	11.88	1,750	666	**1.46**
Ownership of housing unit									
Owned	74.5	6,825	91.6	35.4	37.1	159.90	2,146	829	0.87
Single-family	66.2	6,347	**95.9**	**36.5**	36.5	146.21	**2,208**	**840**	0.84
Apartments	3.3	175	52.4	26.6	45.5	4.92	1,476	748	1.28
Mobile homes	5.0	304	61.1	24.6	49.9	8.77	1,768	712	1.44
Rented[5]	43.7	2,289	52.4	21.2	42.7	59.43	1,360	550	1.11
Single-family	14.7	1,135	77.4	25.3	41.8	26.67	1,818	594	0.98
Apartments	27.2	1,052	**38.7**	**18.2**	43.1	29.66	**1,090**	**514**	1.22
Mobile homes	1.8	103	56.3	18.7	50.2	3.10	1,702	565	1.52
Year of construction									
Before 1950	20.8	1,842	**88.7**	**35.5**	**44.1**	39.48	1,901	762	0.94
1950 to 1959	12.6	1,067	84.4	34.5	45.2	23.52	1,861	760	1.00
1960 to 1969	12.8	961	75.0	32.0	40.0	22.50	1,756	750	0.94
1970 to 1979	18.3	1,290	70.3	27.9	39.8	32.36	1,765	700	1.00
1980 to 1989	16.0	1,053	65.7	27.3	35.9	27.99	1,747	725	0.95
1990 to 1999	16.8	1,317	78.3	29.1	35.9	32.57	1,937	719	0.89
2000 to 2009	17.0	1,328	78.2	28.0	32.7	34.21	2,013	721	0.84
2010 to 2015	3.8	257	**67.0**	**23.9**	**28.5**	6.72	1,755	626	0.75
Total square footage									
Fewer than 1,000	26.6	1,072	40.3	19.9	53.8	29.91	1,126	554	1.50
1,000 to 1,499	26.1	1,542	59.0	23.2	48.2	41.01	1,569	618	1.28
1,500 to 1,999	17.5	1,359	77.8	30.4	44.6	33.54	1,919	750	1.10
2,000 to 2,499	14.1	1,268	89.8	32.7	40.3	29.46	2,088	759	0.94
2,500 to 2,999	10.8	1,111	102.9	38.5	37.7	24.65	2,282	854	0.84
3,000 or greater	23.1	2,762	**119.6**	**40.4**	29.4	60.76	2,631	888	0.65
2015 annual household income									
Less than $20,000	22.9	1,303	57.0	25.9	**43.1**	32.47	1,421	645	**1.08**
$20,000 to $39,999	27.3	1,882	68.9	29.3	40.7	44.49	1,629	692	0.96
$40,000 to $59,999	18.4	1,354	73.6	29.9	38.7	32.73	1,778	723	0.93
$60,000 to $79,999	15.2	1,218	80.0	29.9	37.0	29.55	1,940	725	0.90
$80,000 to $99,999	9.7	827	85.4	31.5	37.4	19.50	2,014	741	0.88
$100,000 to $119,999	8.1	733	90.4	30.6	34.2	17.74	2,187	739	0.83
$120,000 to $139,999	5.4	552	101.7	33.7	37.1	13.00	2,396	794	0.87
$140,000 or more	11.2	1,244	**111.2**	**36.8**	36.0	29.87	**2,669**	**884**	0.86

Source: US Energy Information Administration, 2015 Residential Energy Consumption Survey HC Table Series.

Table 3. Monthly Total Housing and Energy Costs by Select Demographic Characteristic ($)

		Total Housing		Total Utilities		Electricity		Gas		Fuel Oil		Other Fuel	
	Total	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean
All US Homes	124,135	$1106	$1437	$210	$230	$109	$126	$53	$68	$125	$141	$25	$42
Household Income													
Less than $10,000	10316	648	927	142	161	82	95	43	56	83	111	25	47
$10,000 to $19,999	10312	631	828	152	169	84	97	47	59	100	127	25	41
$20,000 to $29,999	10481	767	925	168	185	92	105	47	59	92	122	25	46
$30,000 to $39,999	11009	857	1019	180	194	97	111	49	61	100	117	23	38
$40,000 to $49,999	9656	966	1144	189	205	100	115	50	62	108	144	33	43
$50,000 to $59,999	9280	1047	1232	199	213	104	119	51	64	117	128	25	39
$60,000 to $79,999	15803	1161	1363	214	229	112	126	53	68	125	142	25	39
$80,000 to $99,999	11589	1347	1518	231	246	119	136	56	69	125	142	29	41
$100,000 to $119,999	9193	1495	1694	248	265	128	144	56	71	125	144	25	45
$120,000 or more	26495	2000	2327	280	303	139	158	62	78	142	161	25	42
Race/Ethnicity													
American Indian/Alaskan	961	691	924	186	200	101	117	54	71	--	189	--	37
Asian	6204	1657	2100	228	248	111	132	51	63	167	163	19	--
Black	16132	962	1207	178	201	102	118	50	60	100	122	25	39
Hispanic	17299	1178	1416	195	215	108	124	44	53	125	150	--	33
Pacific Islander	333	1367	1537	202	219	115	129	46	56	--	--	--	--
Two or More Races	1567	1040	1401	189	210	100	115	47	66	131	153	33	35
White	81639	1098	1443	219	238	112	128	56	72	125	141	25	43
Age of Household Head													
Under 25 years old	4474	1050	1280	131	150	86	103	41	52	83	76	--	--
25 to 29 years old	7991	1212	1364	157	178	97	112	45	58	83	90	--	44
30 to 34 years old	10097	1339	1580	197	213	109	124	52	65	108	124	17	30
35 to 44 years old	21260	1417	1740	227	247	123	140	55	69	125	144	25	40
45 to 54 years old	22436	1306	1677	234	253	120	138	55	71	125	141	25	41
55 to 64 years old	25174	1038	1401	219	239	109	126	55	69	125	149	25	45
65 to 74 years old	18620	855	1175	208	227	104	119	53	68	125	146	25	49
75 years old +	14082	687	995	202	218	99	113	54	68	125	141	24	33
Tenure													
Owner	79475	1137	1510	244	266	122	139	58	73	125	145	25	42
Renter	44660	1071	1301	133	157	86	101	41	52	83	115	--	39

Source: 2019 American Housing Survey

Note: Race categories excluded Hispanics; Hispanics includes all races

Table 4. Monthly Total Housing Costs as Percent of Household Income by Select Housing Characteristics (Percent of Homes)

	Total	< 5 %	5 to 9 %	10 to 14 %	15 to 19 %	20 to 24 %	25 to 29 %	30 to 34 %	35 to 39 %	40 to 49 %	50 to 59 %	60 to 69 %	70 to 99 %	100+ %	No income	No costs
All US Homes	124135	3%	10%	14%	14%	12%	9%	7%	5%	6%	4%	2%	3%	7%	2%	2%
Household Income																
< $10,000	10316	--	--	0%	0%	1%	2%	2%	2%	2%	2%	3%	6%	53%	21%	4%
$10,000 to $19,999	10312	--	1%	2%	4%	6%	8%	8%	6%	11%	10%	8%	16%	17%	--	3%
$20,000 to $29,999	10481	0%	2%	6%	8%	7%	9%	9%	10%	15%	11%	6%	8%	5%	--	2%
$30,000 to $39,999	11009	0%	4%	9%	10%	12%	11%	12%	10%	13%	7%	3%	4%	3%	--	2%
$40,000 to $49,999	9656	0%	6%	12%	13%	14%	12%	12%	8%	11%	5%	2%	2%	1%	--	2%
$50,000 to $59,999	9280	1%	9%	14%	14%	15%	14%	10%	6%	8%	3%	2%	2%	1%	--	1%
$60,000 to $79,999	15803	1%	11%	15%	18%	17%	13%	8%	5%	5%	2%	1%	1%	1%	--	1%
$80,000 to $99,999	11589	2%	15%	18%	20%	18%	12%	6%	4%	3%	1%	1%	0%	0%	--	1%
$100,000 to $119,999	9193	3%	17%	19%	22%	16%	9%	6%	2%	3%	1%	0%	--	0%	--	1%
$120,000 or more	26495	9%	21%	25%	22%	12%	5%	2%	1%	1%	0%	0%	0%	0%	--	0%
Race/Ethnicity																
American Indian/Alaskan	961	--	14%	13%	12%	9%	10%	6%	6%	4%	--	--	5%	5%	5%	5%
Asian	6204	3%	10%	13%	13%	12%	10%	7%	5%	7%	4%	2%	4%	7%	3%	1%
Black	16132	2%	7%	10%	12%	12%	10%	8%	6%	8%	5%	3%	4%	10%	3%	2%
Hispanic	17299	2%	7%	10%	12%	10%	10%	8%	6%	8%	5%	3%	5%	9%	2%	2%
Pacific Islander	333	--	--	13%	8%	17%	--	--	--	--	--	--	--	8%	--	--
Two or More Races	1567	3%	11%	13%	14%	12%	10%	8%	5%	8%	3%	--	--	5%	--	--
White	81639	3%	12%	16%	16%	13%	9%	6%	4%	6%	3%	2%	3%	6%	1%	2%
Age of Household Head																
Under 25 years old	4474	1%	4%	8%	11%	10%	10%	7%	7%	8%	6%	3%	5%	11%	5%	2%
25 to 29 years old	7991	1%	6%	13%	16%	15%	11%	8%	5%	6%	4%	2%	3%	5%	2%	2%
30 to 34 years old	10097	2%	8%	11%	17%	16%	12%	7%	5%	7%	4%	2%	3%	4%	2%	2%
35 to 44 years old	21260	2%	8%	14%	17%	14%	10%	7%	5%	6%	3%	2%	3%	4%	1%	2%
45 to 54 years old	22436	3%	11%	15%	16%	13%	8%	7%	5%	6%	3%	2%	3%	5%	2%	1%
55 to 64 years old	25174	3%	14%	15%	14%	11%	8%	6%	4%	6%	3%	2%	3%	6%	2%	1%
65 to 74 years old	18620	3%	12%	14%	11%	10%	8%	7%	5%	7%	4%	2%	4%	10%	1%	1%
75 years old and over	14082	2%	10%	13%	11%	9%	8%	6%	5%	6%	4%	3%	4%	13%	1%	2%
Tenure																
Owner	79475	4%	14%	17%	16%	12%	8%	6%	4%	5%	3%	2%	2%	5%	1%	--
Renter	44660	1%	3%	8%	11%	11%	10%	9%	7%	9%	5%	3%	5%	10%	3%	4%

Source: 2019 American Housing Survey

Note: Race categories excluded Hispanics; Hispanics includes all races

Table 5. Primary Home Heating and Cooling Types by Select Demographic Characteristic (Percent of Homes)

		Heating										Cooling		
	Total (1000s)	Warm-air furnace	Steam or hot water	Electric heat pump	Built-in electric units	Built-in hot air, no ducts	Room heaters, flue	Room heaters, no flue	Portable electric	Stoves	None	Central AC	Room AC	No AC
All US Homes	124135	66%	9%	12%	4%	5%	1%	1%	2%	1%	0%	71%	20%	9%
Household Income														
Less than $10,000	10316	60%	9%	10%	6%	6%	1%	1%	4%	1%	1%	63%	25%	12%
$10,000 to $19,999	10312	60%	8%	10%	7%	6%	1%	1%	3%	2%	1%	60%	29%	11%
$20,000 to $29,999	10481	61%	8%	12%	5%	7%	1%	1%	3%	1%	1%	64%	26%	10%
$30,000 to $39,999	11009	64%	9%	12%	4%	5%	1%	1%	2%	1%	0%	67%	24%	9%
$40,000 to $49,999	9656	64%	9%	13%	4%	5%	0%	1%	2%	1%	1%	69%	23%	8%
$50,000 to $59,999	9280	64%	8%	13%	4%	4%	1%	1%	2%	1%	0%	71%	21%	8%
$60,000 to $79,999	15803	68%	9%	12%	3%	4%	0%	0%	1%	1%	0%	74%	19%	8%
$80,000 to $99,999	11589	67%	9%	13%	3%	3%	1%	-	1%	1%	0%	75%	17%	8%
$100,000 to $119,999	9193	72%	8%	11%	3%	3%	-	-	1%	1%	-	79%	14%	7%
$120,000 or more	26495	72%	10%	10%	3%	3%	0%	0%	0%	0%	0%	79%	13%	8%
Race/Ethnicity														
American Indian/Alaskan	961	60%	3%	11%	6%	6%	-	-	-	-	-	55%	-	15%
Asian	6204	72%	8%	6%	4%	5%	0%	-	2%	-	2%	69%	16%	14%
Black	16132	67%	8%	12%	4%	4%	1%	1%	2%	-	-	71%	22%	7%
Hispanic	17299	63%	8%	8%	3%	9%	1%	1%	5%	-	1%	65%	24%	11%
Pacific Islander	333	54%	6%	-	-	-	-	-	-	-	11%	61%	11%	29%
Two or More Races	1567	58%	9%	11%	5%	6%	-	-	4%	-	5%	60%	25%	15%
White	81639	66%	9%	12%	4%	4%	1%	1%	1%	1%	0%	73%	19%	8%
Age of Household Head														
Under 25 years old	4474	63%	8%	13%	6%	6%	-	-	2%	-	1%	67%	23%	9%
25 to 29 years old	7991	65%	8%	12%	5%	5%	-	1%	1%	1%	-	70%	21%	9%
30 to 34 years old	10097	67%	8%	11%	5%	5%	1%	-	2%	1%	0%	71%	20%	9%
35 to 44 years old	21260	67%	9%	11%	4%	5%	0%	0%	2%	1%	0%	73%	19%	8%
45 to 54 years old	22436	68%	8%	11%	3%	4%	1%	1%	2%	1%	0%	72%	20%	8%
55 to 64 years old	25174	66%	9%	11%	4%	4%	1%	1%	2%	1%	1%	69%	21%	9%
65 to 74 years old	18620	66%	8%	12%	4%	4%	1%	1%	2%	1%	0%	72%	18%	9%
75 years old and over	14082	64%	10%	12%	5%	5%	1%	1%	1%	1%	1%	72%	19%	9%
Tenure														
Owner	79475	70%	8%	12%	2%	3%	1%	1%	1%	1%	0%	77%	16%	7%
Renter	44660	60%	10%	10%	7%	7%	1%	1%	2%	1%	1%	61%	27%	12%

Source: 2019 American Housing Survey

Note: Race categories excluded Hispanics; Hispanics includes all races

Table 6. Energy-Related Housing Adequacy by Select Demographic Characteristics (Percent of Homes)

		Housing inadequacy					Uncomfortable coldness					
	Total	Total Severely Inadequate Housing	Heating Inadequacy	Exposed wiring Inadequacy	Rooms without electric outlets	Uncomfortably cold for 24 hrs. or more	Cold due to equipment breakdown	At least one breakdown lasting 6+ hrs.	Due to utility interruption	Due to Inadequate heating capacity	Due to Inadequate insulation	Due to Cost of heating
All US Homes	124,135	1.2%	0.6%	2.7%	1.9%	6.1%	2.3%	1.3%	1.2%	0.7%	0.7%	0.4%
Household Income												
Less than $10,000	10,316	3.0%	1.3%	4.0%	3.2%	8.4%	3.5%	1.6%	1.2%	1.1%	1.2%	0.9%
$10,000 to $19,999	10,312	2.2%	1.1%	3.5%	2.7%	8.8%	3.2%	1.7%	1.3%	1.5%	1.6%	0.8%
$20,000 to $29,999	10,481	1.5%	0.8%	2.8%	2.5%	8.2%	2.9%	1.5%	1.5%	1.2%	1.0%	0.6%
$30,000 to $39,999	11,009	1.3%	0.7%	3.1%	2.3%	7.3%	2.5%	1.2%	1.1%	1.1%	1.1%	0.6%
$40,000 to $49,999	9,656	1.3%	0.8%	2.5%	1.8%	5.4%	2.5%	1.3%	0.9%	0.7%	0.7%	0.2%
$50,000 to $59,999	9,280	1.1%	--	2.6%	2.0%	6.0%	1.8%	1.1%	1.6%	0.6%	1.0%	--
$60,000 to $79,999	15,803	0.8%	0.5%	2.7%	1.8%	5.2%	2.4%	1.4%	0.9%	0.5%	0.4%	0.4%
$80,000 to $99,999	11,589	0.7%	0.4%	2.2%	1.4%	5.0%	1.9%	1.3%	1.4%	0.3%	0.4%	--
$100,000 to $119,999	9,193	0.5%	0.4%	2.4%	1.5%	5.3%	1.8%	1.0%	1.5%	0.5%	0.6%	--
$120,000 or more	26,495	0.5%	0.3%	2.2%	1.2%	4.2%	1.7%	1.2%	1.2%	0.3%	0.4%	0.2%
Race/Ethnicity												
American Indian/Alaskan	961	--	--	3.1%	--	11.1%	3.1%	--	--	--	--	--
Asian	6204	1.1%	--	3.1%	1.8%	4.0%	1.6%	0.6%	0.7%	0.5%	--	--
Black	16132	2.0%	1.2%	2.7%	2.4%	8.0%	3.7%	1.8%	0.8%	1.2%	1.1%	0.3%
Hispanic	17299	2.0%	1.1%	3.8%	2.1%	6.7%	3.0%	1.3%	0.7%	1.0%	0.8%	0.4%
Pacific Islander	333	--	--	--	--	--	--	--	--	--	--	--
Two or More Races	1567	--	--	2.0%	--	7.1%	--	--	--	--	--	--
White	81639	0.8%	0.4%	2.5%	1.8%	5.6%	2.0%	1.3%	1.5%	0.5%	0.7%	0.5%
Age of Household Head												
Under 25 years old	4474	2.2%	1.5%	3.1%	2.7%	6.6%	3.4%	1.6%	--	0.9%	--	--
25 to 29 years old	7991	1.3%	0.6%	3.0%	2.5%	6.6%	3.1%	2.1%	0.7%	0.7%	0.9%	0.5%
30 to 34 years old	10097	1.1%	0.5%	2.9%	1.6%	6.2%	2.5%	1.4%	0.9%	0.6%	1.1%	--
35 to 44 years old	21260	1.0%	0.5%	2.8%	2.5%	6.0%	2.2%	1.3%	1.3%	0.8%	0.9%	0.4%
45 to 54 years old	22436	1.3%	0.7%	2.8%	1.5%	6.1%	2.4%	1.3%	1.3%	0.7%	0.8%	0.4%
55 to 64 years old	25174	1.3%	0.7%	2.7%	1.8%	6.6%	2.3%	1.3%	1.5%	0.8%	0.9%	0.5%
65 to 74 years old	18620	0.9%	0.5%	2.3%	1.8%	5.9%	2.2%	1.3%	1.6%	0.5%	0.6%	0.5%
75 years old and over	14082	0.9%	0.5%	2.6%	1.7%	4.7%	1.6%	0.9%	1.1%	0.6%	0.4%	0.3%
Tenure												
Owner	79475	0.8%	0.4%	2.5%	1.6%	5.3%	1.9%	1.2%	1.5%	0.4%	0.5%	0.4%
Renter	44660	1.8%	1.0%	3.2%	2.4%	7.4%	3.1%	1.5%	0.8%	1.2%	1.1%	0.5%

Source: 2019 American Housing Survey

Note: Race categories excluded Hispanics; Hispanics includes all races. Uncomfortable coldness based on winter occupancy and the presence of heating equipment.

Table 7. Thermostat Presence, Types, and Control Behaviors by Select Housing Characteristics (Percent of Homes)

	Thermostat for main heating					Smart thermostat				Thermostat control behaviors					
	Presence			Programmable						Options					
	Yes	*No*	*Do not use*	*Yes**	*No*	*Yes*	*No*	*Don't know*	*Not asked*	*A*	*B*	*C*	*D*	*E*	*F*
All US homes	85%	11%	4%	50%	35%	3%	79%	5%	12%	38%	25%	16%	14%	3%	4%
Housing unit type															
Single-family detached	91%	7%	2%	58%	33%	4%	85%	4%	7%	39%	26%	21%	10%	1%	2%
Single-family attached	91%	6%	4%	54%	36%	6%	81%	7%	7%	37%	29%	14%	16%	--	4%
Apartments, 2–4 units	81%	14%	5%	41%	39%	--	68%	12%	18%	39%	21%	9%	22%	--	5%
Apartments, 5 or more units	66%	23%	11%	27%	39%	1%	64%	6%	28%	31%	22%	5%	22%	9%	11%
Mobile homes	76%	18%	4%	40%	38%	--	72%	6%	21%	50%	18%	7%	16%	--	4%
Ownership of housing unit															
Owned	90%	7%	3%	58%	32%	4%	84%	4%	7%	38%	25%	22%	10%	1%	3%
Single-family and mobile	98%	7%	2%	63%	35%	5%	91%	4%	7%	42%	27%	24%	11%	1%	2%
Apartments	70%	15%	15%	39%	30%	--	73%	9%	18%	24%	21%	18%	15%	--	15%
Rented	76%	18%	7%	36%	40%	2%	70%	7%	21%	38%	24%	6%	20%	5%	7%
Single-family and mobile	94%	14%	5%	50%	44%	--	89%	7%	15%	47%	30%	10%	18%	--	5%
Apartments	71%	21%	8%	31%	40%	2%	64%	8%	26%	35%	22%	4%	23%	8%	8%
Year of construction															
Before 1950	78%	20%	1%	40%	38%	2%	71%	5%	21%	36%	25%	14%	16%	8%	1%
1950 to 1959	85%	11%	4%	47%	38%	2%	78%	5%	15%	41%	26%	13%	13%	--	4%
1960 to 1969	81%	12%	7%	45%	37%	3%	75%	5%	16%	36%	24%	14%	15%	4%	7%
1970 to 1979	85%	10%	5%	48%	37%	3%	81%	3%	12%	41%	22%	15%	15%	2%	5%
1980 to 1989	84%	10%	6%	51%	33%	4%	79%	6%	11%	36%	24%	16%	15%	2%	6%
1990 to 1999	88%	8%	4%	58%	31%	4%	83%	5%	9%	39%	23%	20%	13%	--	4%
2000 to 2009	91%	5%	4%	58%	33%	4%	84%	8%	5%	38%	28%	18%	12%	--	4%
2010 to 2015	95%	--	--	63%	29%	--	92%	5%	--	34%	29%	21%	8%	--	--
Total square footage															
Fewer than 1,000	69%	23%	9%	31%	38%	2%	63%	6%	29%	36%	20%	5%	23%	8%	9%
1,000 to 1,499	83%	12%	6%	43%	40%	2%	77%	7%	13%	41%	26%	9%	16%	2%	6%
1,500 to 1,999	88%	7%	5%	54%	34%	3%	83%	5%	8%	40%	25%	16%	13%	2%	5%
2,000 to 2,499	92%	6%	2%	54%	38%	4%	87%	4%	5%	39%	27%	21%	11%	--	2%
2,500 to 2,999	94%	6%	--	59%	34%	5%	87%	3%	6%	39%	30%	19%	8%	--	--
3,000 or greater	95%	4%	1%	70%	26%	6%	88%	3%	3%	34%	26%	32%	7%	--	1%
2015 annual household income															
Less than $20,000	76%	20%	5%	37%	39%	1%	67%	9%	22%	44%	21%	6%	21%	4%	5%
$20,000 to $39,999	84%	11%	5%	42%	42%	1%	78%	7%	14%	44%	25%	8%	15%	3%	5%
$40,000 to $59,999	85%	10%	4%	49%	35%	2%	82%	4%	12%	38%	27%	16%	13%	3%	4%
$60,000 to $79,999	88%	8%	5%	51%	37%	3%	84%	3%	9%	38%	26%	16%	13%	3%	5%
$80,000 to $99,999	91%	5%	3%	57%	35%	5%	86%	3%	5%	35%	29%	23%	8%	--	3%
$100,000 to $119,999	93%	5%	2%	64%	28%	9%	84%	--	5%	30%	26%	30%	11%	--	2%
$120,000 to $139,999	93%	6%	4%	65%	28%	7%	83%	--	7%	28%	28%	31%	9%	--	4%
$140,000 or more	89%	7%	4%	73%	16%	7%	82%	3%	8%	28%	20%	36%	11%	--	4%

Source: US Energy Information Administration, 2015 Residential Energy Consumption Survey HC Table Series.

Note: Options for thermostat control behavior: A. Leave at one temperature most of the time; B. Manually adjust the temperature at night or when no one is at home; C. Program the thermostat to automatically adjust the temperature at certain times; D. Turn equipment on or off as needed; E. Household does not have control over the equipment; F. Do not use heating equipment