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A targeted approach to energy burden reduction measures: Comparing the effects of energy storage, rooftop solar, weatherization, and energy efficiency upgrades

Jessica Kerby, Trevor Hardy, Jeremy Twitchell, Rebecca O'Neil, Bethel Tarekegne *

Pacific Northwest National Laboratory, 902 Battelle Blvd, Richland, WA, 99354, USA

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ABSTRACT

As energy prices rise and climate change brings more extreme and frequent days of heating and cooling, households must allocate more of their income to energy bills, increasing their energy burden. Many strategies are employed to alleviate high energy burden, such as weatherization, energy efficiency, and energy storage and rooftop solar, though the benefits of each scale based on factors such as climate, housing characteristics, and energy behaviors. This study used variation in these factors across the United States to create a set of representative houses to investigate the variable responses to different energy burden reduction measures in the simulation environment GridLAB-D. Comparison of modeled energy and bill savings determined weatherization to have the most variability in energy and bill savings, often providing comparable and even greater energy and bill savings to energy storage plus rooftop solar at a fraction of the cost; energy storage provided the most consistent bill savings, determined primarily by the rate tariff used for energy arbitrage; and appliance efficiency upgrades provided minimal energy and bill savings. The results of the analysis can be used by policymakers, utilities, communities, and individuals to tailor energy burden reduction programs, policies, and spending to maximize local benefit.

1. Introduction

High energy burden, or the high percentage of median income spent on energy bills, is the result of more than just low-income households subject to high electricity prices. Climate change, energy usage patterns, energy efficiency of household appliances, and household conditions such as age, insulation levels, and deferred maintenance are all exacerbating factors of energy burden and energy poverty (Drehobl et al., 2020; Bednar et al., 2017; Helbach, 2019). This paper offers a targeted approach to prioritize the most effective energy burden reduction measure based on these factors, as no one solution is inherently the most effective for all households. For example, an older home built before energy-efficiency standards with leaky windows and poorly sealed doors in a cold, dry climate will likely benefit from a different solution than a home in a hot, humid climate that relies exclusively on window air-conditioning (AC) units. Additionally, housing configuration alone paints an incomplete picture of household energy burden. For some low-income households, deferred maintenance not only contributes to high energy burden, but presents an additional barrier to its relief, as these repairs must be completed before participating in energy improvement measures (Helbach, 2019).

Energy burden is a particularly illustrative metric of energy equity, which encompasses the past, present, and future performance of the energy system and its relationship to the people who depend on it (Tarekegne et al., 2021b). High energy burden, considered to be more than 6% of median income (Drehobl et al., 2020; Helbach, 2019), can be the result of the physical condition of one's housing (i.e., age, size, insulation, and maintenance level); socioeconomic factors such as persistent poverty, systemic inequalities, and poor credit; policy factors such as inadequate funds or access to weatherization, efficiency, or utility payment programs; and behavioral factors such as high energy use due to advanced age, health concerns, multi-generational housing (Drehobl et al., 2020), or information disconnect. A manifestation of procedural injustice, pertaining to the representation and engagement of the community in the decision-making process (Tarekegne et al., 2001), information disconnect is used here to refer to the multiple mechanisms that lead to sub-optimal energy decisions, including those that arise from lack of access to information, distrust of government or utility initiatives, and lack of access to educational or assistance programs (Drehobl et al., 2020). To adequately address energy burden, even the most optimal energy or programmatic solution must contend

* Corresponding author.
E-mail address: bethel.tarekegne@pnnl.gov (B. Tarekegne).

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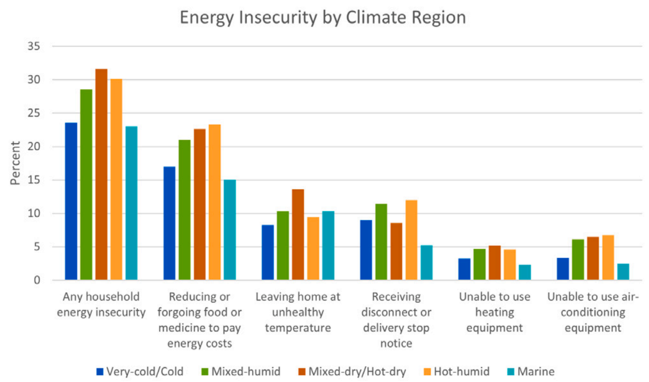

Fig. 1. Energy insecurity by climate region (U.S. Energy Information Administration, 2022).

with the substantial hurdle of information disconnect, as no solution can succeed if those being offered it do not know it exists, do not understand the potential benefits, or do not trust those designing the program or the solution being employed.

High energy burden often leads to energy insecurity, or the inability to meet basic household energy needs, which can force people to choose between affording food, medicine, or energy, leaving the home at unhealthy temperatures, or receiving a disconnection notice from the utility (Tarekegne et al., 2001). The U.S. Energy Information Administration's 2020 Residential Energy Consumption Survey (RECS) data captures the percentage of households that experienced forms of energy insecurity by climate region (U.S. Energy Information Administration, 2022), shown in Fig. 1.

While high energy burden and energy insecurity are pervasive across all climate regions, there is no archetypal energy-burdened household. There are many contributing factors to energy burden, including the housing stock, energy behaviors, energy efficiency of household appliances, and climate. The goal of this paper is to offer a targeted approach to prioritizing energy burden reduction measures based on these factors to assist policymakers, utilities, and households to effectively reduce energy burden. To determine the most effective energy burden reduction measure for a household, the energy and bill savings resulting from the energy burden reduction measures (1) energy storage, (2) energy storage plus rooftop solar, (3) weatherization, and (4) appliance energy efficiency upgrades, described in Section 3, were modeled using GridLAB-D power simulation for the most common housing configurations in the five climate regions of the United States, based on 2020 RECS data. The estimated upfront cost to implement each measure was then used to compare the payback periods to determine the cost-effectiveness of each. The efficacy of each measure is compared first for each individual house and climate region in Section 4, followed by a discussion of the efficacy and variability of the measures in Section 5. Section 6 summarizes the results, applicability, policy implications, and future work.

2. Background: Energy burden reduction measures

2.1. Energy storage

Energy storage devices are an important grid asset as they bolster grid reliability, facilitate the increasing penetration of renewable generation, and defer expensive infrastructure upgrades by reducing transmission congestion as electricity demand increases and the electricity generation mix shifts toward more renewables (Tarekegne et al., 2021a). Energy storage has long been considered a critical tool to address the mismatch between energy generation and demand, and more recently energy storage is being considered to address energy inequities through improved resiliency, wealth-building, and emissions reduction (Tarekegne et al., 2021a). Energy storage can lead to emissions reduction through multiple pathways, including increasing self-consumption of renewables and increasing renewables penetration (Anisie and Boshell, 2019a), reducing reliance on the most polluting plants called on in times of high demand (Anisie and Boshell, 2019a; Richardson, 2019), enabling the decommissioning of fossil-fuel plants (Tarekegne et al., 2021a), and providing resiliency in an outage without relying on diesel-powered backup generators.

Energy storage is categorized by its capacity, location on the grid, and ownership model. Of particular interest in this study is the impact of energy storage on energy burden for individuals and families; therefore, residential behind-the-meter (BTM) energy storage is considered in this analysis. Many homeowners adopt BTM energy storage to provide energy backup in case of extreme weather or grid-related outages, to increase their energy independence, or in conjunction with rooftop solar installations to avoid energy curtailment (Anisie and Boshell, 2019a). BTM energy storage can also be used to provide energy bill savings for time-of-use (TOU) rate payers via energy arbitrage, charging at a low price and discharging at higher prices (Anisie and Boshell, 2019a,b). The wealth-building potential of energy storage depends on the difference between high and low prices of electricity, the inherent inefficiencies of energy storage technologies (Balducci et al., 2018), and the number of opportunities for arbitrage within the rate schedule. A 2018 energy storage valuation study of TOU rates found that the average annual savings available from energy arbitrage was $65/kW of system size, ranging from $2-266/kW (Balducci et al., 2018). The average price of residential electricity has risen from 12.87 ¢/kWh in 2018 to 15.12 ¢/kWh in 2022, and is projected to plateau at 15.64 ¢/kWh in 2023 before beginning to decline (U.S. Energy Information Administration, 2023a), providing even greater potential for bill savings than reported in Balducci et al. (2018).

While BTM energy storage offers substantial resiliency benefits and energy savings potential, the upfront cost of storage remains a barrier to its accessibility, especially for low-income individuals. The market price of energy storage has continually declined since commercialization and is projected to continue to do so (Anisie and Boshell, 2019a); however, financial incentives remain necessary to increase access to energy storage for more than just the wealthy few. Under the Residential Clean Energy Credit, standalone energy storage systems of 3 kWh or more are now eligible for a tax credit equal to 30% of the total cost, including labor and installation (Internal Revenue Service, 2023). While this expanded eligibility could lead to increased adoption of BTM storage, tax-based incentives are predicated on tax liability, which can overlook low-income households (Richardson, 2019), as this non-refundable credit cannot exceed the taxes owed by the system owner (Internal Revenue Service, 2023). The tax credit can be rolled over into subsequent years to receive the full credit (until 2033), though this cost recovery mechanism does not alleviate the burden of upfront cost.

2.2. Energy storage plus rooftop solar

Residential storage installations are most often paired with a rooftop solar array (Barbose et al., 2021), as the economics of storage are rarely favorable when relegated to a single use (Fitzgerald et al., 2015), such as TOU bill management. By pairing storage with solar, excess solar production can be stored during the sunlight hours for use after the sun sets, increasing the amount of renewable energy consumed on site. Storage plus solar provides many additional benefits to the system owner: including increased resilience to outages, increased energy independence by reducing reliance on utility power during periods of high prices or outages, and additional revenue from the export of excess solar generation via net metering agreements. While the potential benefits are even greater than those of standalone storage, rooftop solar requires adequate installation space contingent on the orientation, age, and condition of the roof. For homes that are heavily shaded, or homes with older roofs that would require expensive repairs or replacement, solar may not be a feasible option. Like the energy storage measure, storage plus solar is eligible for the same 30% Residential Clean Energy Credits, though many state and utility incentives exist to further reduce system costs.

2.3. Weatherization

Weatherization addresses energy burden by improving the physical condition of inefficient housing, which is typically the result of inadequate sealing or insulation and is exacerbated by the age of the housing stock and deferred maintenance. On average, low-income households have a 27% higher energy use intensity than high-income households (Reames, 2016), indicating that low-income housing stock requires substantially more energy per area due to inefficient energy use. Unaddressed, inefficient housing can be unsafe, as these conditions are often coupled with excess moisture and mold growth due to fluctuating and uncomfortable temperatures that can also lead to cold- or heat-related urgent care or emergency room visits (Drehobl et al., 2020). These conditions also increase the prevalence of pests that contribute to environmental and airborne allergies, asthma, and respiratory illness (Drehobl et al., 2020).

The Department of Energy (DOE) has maintained a Weatherization Assistance Program (WAP) since 1973. The goal of this program is to reduce heating bills for low-income families (at or below 200% of the federal poverty level (FPL)) through the process of weatherization (Pigg et al., 2021). The program has evolved since its inception to now include health and safety as well as energy improvements; it consists of an energy audit of the homeowner's energy bills, a pressurized blower-door test of air sealing, and appliance and energy equipment inspection, followed by a workplan detailing the most cost-effective measures to improve energy conservation (U.S. Department of Energy Office of Energy Efficiency & Renewable Energy, 2023).

The latest evaluation of the WAP via pre- and post-WAP surveying of a sampling of program participants reported a 20% reduction in those having difficulty paying their energy bills after participating in the program, a 23% increase in those reporting comfortable winter temperatures, and a 13% increase in comfortable summer temperatures inside the home (Applied Public Policy Research Institute for Study and Evaluation, 2018). The evaluation also reported an average annual energy bill savings of $223 or 12% for single family homes, $190 or 10% for mobile homes, and $392 or 13% for homes that relied on heat from fuel oil in the first year (Applied Public Policy Research Institute for Study and Evaluation, 2018).

Complementary to the WAP and incepted in 1981 is the Department of Health and Human Services' Low Income Home Energy Assistance Program (LIHEAP), which provides home energy bill assistance to those that are income-eligible (Bednar and Reames, 2020). While funding for these two programs varies, LIHEAP is allocated an average of $3 billion a year while the WAP only receives $0.4 billion on average, though up to a quarter of LIHEAP funds can be used to supplement the WAP budget at a state's discretion (Bednar and Reames, 2020). It is noteworthy that every year these two programs have been active besides 2008, substantially more funds have been allocated to provide temporary relief from high energy burden than have been used to address the inadequate housing conditions that directly contribute to it (Bednar and Reames, 2020).

While both WAP and LIHEAP are designed to reduce energy bills and therefore address energy burden, their limited programmatic funds and strict income or demographic-based qualifications fail to reach many low-to-moderate income (LMI) households; the WAP can only serve approximately 100,000 homes per year (Drehobl et al., 2020). Whether due to program limitations or prospective program participants' incomes being just above the threshold for qualification, the households facing high energy burden that fall through this assistance net are left to either attempt to obtain loans for energy efficiency improvements, engage in energy limiting behaviors, or forgo other necessities to afford their energy bills. Moderate-income loan-seekers face the added challenge of needing a higher credit score to achieve the same likelihood of approval as those with higher income but lower credit scores (Forrester and Reames, 2020), making the process of seeking energy efficiency improvements without assistance all the more challenging.

2.4. Energy efficiency

Improving energy efficiency, or the ability to perform the same function using less energy, can help to reduce energy burden. Energy efficiency improvements can be made via weatherization when related to heating or cooling but can also be made through simple appliance upgrades. A 2019 study evaluated the potential savings from energy efficiency improvements for low-income households using a combination of data from the 2009 RECS, the American Community Survey, and the American Housing Survey as inputs for energy modeling using the residential building stock model, ResStock™ (Wilson et al., 2019). Their simulations estimated the annual energy and cost savings (based on flat energy rates) from various efficiency improvement scenarios such as individual appliance upgrades or insulation improvements, grouped by county and percentage of FPL of the households (Wilson et al., 2019). The average savings resulting from efficiency upgrade packages designed to maximize the net present value of the investment was estimated to be $726 per year for households with incomes < 200% of the FPL (Wilson et al., 2019). While (Wilson et al., 2019) presented the estimated savings from optimized improvement packages containing measures falling into both the weatherization and appliance upgrade categories, this analysis focuses on comparing the efficacy of improvement measures including energy generation and storage to provide insights based on climate region, housing stock, and energy behaviors.

In this study, energy efficiency improvements refer to improving the efficiencies of residential end-use appliances. The DOE reviews the efficiency standards for over 60 appliances, corresponding to nearly 90% of home energy use, every 6 years. Compared to the 1990s, 2017-standard clothes washers use approximately 70% less energy, dishwashers use 40%, air conditioners use 50%, and furnaces use 10% less energy (U.S. Department of Energy Office of Energy Efficiency & Renewable Energy, 2017). As these efficiency improvements are substantial and these end-uses account for a large portion of the energy use in the home, upgrading old and inefficient appliances can amount to substantial energy savings and reduction of energy burden. Point-of-sale financial incentives would likely still be required for low-income households to access the greatest efficiency savings, as newer high-efficiency appliances can be prohibitively expensive for households with limited disposable income compared to less efficient appliances.

3. Methodology

The objective of this analysis was to determine the most effective energy burden reduction measure based on climate region, housing stock, and energy behaviors. To achieve this, the energy and energy bill savings achieved by (1) energy storage, (2) energy storage and rooftop solar, (3) weatherization, and (4) appliance energy efficiency upgrades were compared for a set of representative houses in each climate region. The power system modeling and simulation environment GridLAB-D was used to perform this analysis (Chassin et al., 2008), and the houses were added to the IEEE-13 node feeder. The thermodynamics of GridLAB-D's house model used in this analysis has been validated and calibrated to temperature, thermostat setpoint, HVAC power consumption, and solar insolation data from the Pacific Northwest National Laboratory's Lab Homes (Goodman et al., 2022). The 2020 RECS data

Table 1
Time of use rate (Portland General Electric, 2023).

Tier	Hours	Price [¢/kWh]
Off-peak	Weekdays: 10 PM–8 AM Weekends: all day	7.43
Mid-peak	Weekdays: 8 AM–6 PM	11.9
Peak	Weekdays: 6 PM–10 PM	32.8

organized by climate region was used to inform the characteristics of the representative houses created for this analysis to resemble the typical housing stock of each climate region.

For example, a typical home in the Cold/Very Cold climate region is likely to be built before 1950 (24%), have two stories (34%), and be considered adequately or normally insulated (53%) (U.S. Energy Information Administration, 2022). The perceived adequacy of insulation reported in the RECS was used to define the thermal integrity attribute of each representative house in this analysis. Additional housing parameters informed by the RECS include type of glass in windows (single/double pane glass or glazing layers), window frame material, heating system type, and AC type. The RECS data was also used to establish energy usage behaviors in terms of heating and cooling thermostat setpoints. As many utilities either already use or are considering adopting TOU rates for their residential customers, all energy bill calculations in this analysis were performed with a TOU rate adapted from Portland General Electric's time of day rate (Portland General Electric, 2023), described in Table 1, chosen for the significant price differential that provides the opportunity for energy storage devices to engage in energy arbitrage. TOU rates such as this one are becoming increasingly useful mechanisms to reduce peak emissions and demand and thereby defer infrastructure investments and grid operating costs, as consumers have been found to be responsive to price signals (Anisie and Boshell, 2019b). However, the bill savings reported in this analysis may be less applicable to those on flat rate or differently structured rate tariffs; the dataset used in this analysis is available for rate customization by the reader (Kerby and Hardy, 2023).

The following sections describe the experimental setup of the representative houses and the energy burden reduction measures analyzed for each. A schematic illustrating the steps of this methodology is provided in Fig. 5 of Appendix.

3.1. Representative houses

A set of representative houses were modeled in GridLAB-D to study the effects of various energy burden reduction efforts across each climate region for various housing types and energy behaviors. The metrics directly measured in this analysis were annual energy usage and energy bills, indicative of energy affordability and energy burden. Three households were created for each climate region; the first two correspond to the two most common housing configurations of that region, informed by the 2020 RECS data, and the third was common to all regions, representing a home of poor-quality housing stock whose inhabitants engage in energy limiting behaviors. The decision to model energy limiting behaviors for the inefficient and poorly insulated households was made because those facing energy insecurity often forgo comfort in order to limit energy use, and can be missed from reported high energy burden data (Cong et al., 2022). The configurations of the representative homes are detailed in Table 2, by climate region. The two most commonly reported characteristics are presented for each region, accompanied by the percentage of respondents that reported that characteristic. Additional information about these parameters is provided in Appendix.

To limit unnecessary variability, only the parameters listed in Table 2 differed between each house before implementation of an energy burden reduction measure. Other characteristics that could influence energy usage such as housing size, ceiling height, and window-to-wall ratio were kept the same for all scenarios. Each house was modeled as a closed system in GridLAB-D, meaning that the houses were subject to the outdoor temperatures defined by the typical meteorological year (TMY3) weather data for their respective climate regions (Wilcox and Marion, 2008), with only their heating, ventilation, and air-conditioning (HVAC) system to regulate the indoor temperature. This means that while many households may open their windows when the weather is pleasant to reduce their energy bills, the houses in this analysis were not modeled to include such behavior.

The annual energy usage in kWh and utility costs in $/year of each representative house were simulated based on the annual heating and cooling loads and the end-use loads of the refrigerator, dishwasher, clothes washer and dryer, and water heater. No additional household end-use loads such as lighting or smaller appliances were considered in this analysis. For comparability, all end-use loads were operated according to the same scaled version of the appliance schedules widely used in GridLAB-D modeling, an updated version of the schedules originally based on the End-Use Load and Consumer Assessment Program study (End-Use Load and Consumer Assessment Program (ELCAP), 1989). The scaling factor for each appliance definition was chosen to normalize the estimated annual energy consumption of each device to those quoted in the 2009 energy efficiency standards (U.S. Energy Information Administration, 2023b). This normalization to 2009-era appliances was set as a baseline to investigate the impact of appliance upgrades.

3.2. Energy storage

The addition of a BTM energy storage system to the household is one mechanism to reduce energy bills and therefore utility burden. A 13.5-kWh battery was chosen to represent this improvement measure as it represents one of the most commonly installed battery capacities for residential BTM energy storage as of 2020 (Barbose et al., 2021). The cost associated with implementation of the energy storage measure was set to be $18,295, which includes the cost of the battery pack, inverter, balance of system, engineering, and other fees (Ramasamy and Blair, 2022). Energy storage in this analysis was used entirely for TOU bill management through energy arbitrage, dispatched using a GridLAB-D schedule to charge off peak, idle mid-peak, and discharge on peak while maintaining a 20% reserve state of charge.

3.3. Energy storage plus rooftop solar

For the energy storage plus solar measure, the same 13.5-kWh battery from the prior case was paired with a rooftop solar array of 7 kW, considered standard for residential systems (Barbose et al., 2021). The additional cost of the solar array was set to be $2.65/W_{DC}$ (Ramasamy and Blair, 2022), or $18,550, for a combined cost of $36,845 with the battery. Each of the five climate regions had a slightly different tilt angle for the solar array, corresponding to the latitude of the TMY3 weather file selected to represent that region (Wilcox and Marion, 2008). The TMY3 location and latitude for each region was set to R1: Portland, OR: 45.5°; R2: New York, NY: 40.7°; R3: San Diego, CA: 32.7°; R4: Cincinnati, OH: 39.1°; and R5: Orlando, FL: 28.5°.

3.4. Weatherization

The next energy burden reduction measure modeled in this analysis was participation in the WAP to improve the energy efficiency of households, reduce energy costs, and improve health and safety (Applied Public Policy Research Institute for Study and Evaluation, 2018). The work performed by the WAP varies on a case-by-case basis as determined by a professional energy audit, with an average cost reported to be $4695 per household (U.S. Department of Energy Office of Energy Efficiency & Renewable Energy, 2022). While not every weatherization measure in this program would directly contribute to an improvement

Table 2
Representative house characteristics by climate region (U.S. Energy Information Administration, 2022).

House no.	R1 marine		R2 (Very) Cold		R3 Mixed/Hot-dry		R4 Mixed-Humid		R5 Hot-Humid		Limiting house
	0	1	2	3	4	5	6	7	8	9	10
Number of stories	One 34.7%	Two 25.4%	Two 34.0%	One 32.0%	One 47.0%	Two 17.3%	One 34.7%	Two 25.4%	One 50.4%	Two 15.2%	One
Window frame	Vinyl 39.2%	Alum 33.7%	Wood 40.0%	Vinyl 32.3%	Alum 54.6%	Wood 22.9%	Alum 37.0%	Wood 34.4%	Alum 59.0%	Wood 25.0%	Wood
Glazing layers	Two 72.3%	One 26.3%	Two 68.9%	One 29.0%	Two 57.4%	One 41.3%	Two 64.9%	One 33.8%	Two 50.0%	One 48.0%	One
Heating system type	Gas 42.2%	Built-in 17.9%	Gas 50.1%	Central 8.3%	Gas 43.4%	Central 12.9%	Gas 33.9%	HeatPump 21.3%	HeatPump 28.9%	Central 25.3%	Built-in
Cooling system type	Central 32.5%	None 48.8%	Central 58.2%	Window 24.3%	Central 65.9%	Window 13.2%	Window 18.2%	Central 72.3%	Central 83.7%	Window 8.6%	Window
Heating setpoint °F	67–69 30.9%	70 20.2%	67–69 32.6%	70 23.9%	>74 21.5%	67–69 19.7%	67–69 27.7%	70 22.9%	>74 25.0%	71–73 21.1%	<63
Cooling setpoint °F	74–76 13.1%	None 48.8%	<69 24.0%	71–73 19.7%	74–76 22.6%	77–79 19.7%	71–73 23.0%	<69 22.4%	74–76 33.7%	71–73 20.5%	>80
Adequacy of insulation	Adequate 49.9%	Well 27.7%	Adequate 52.5%	Well 27.9%	Adequate 49.9%	Well 23.1%	Adequate 52.5%	Well 27.9%	Adequate 51.5%	Well 23.1%	Not

Table 3
Thermal integrity & insulation.

GridLAB-D thermal integrity	RECS survey insulation response
Very little	Not insulated
Below normal	Poorly insulated
Normal	Adequately insulated
Good	Well insulated

Table 4
Energy improvement measure.

Case	Improvement measure	Upgrade cost[a]
Energy storage	13.5 kWh	$12,807
Storage plus solar	13.5 kWh plus 7.5 kW	$25,792
Weatherization	Improved insulation	$3287
2017-standard	Appliance upgrades	$2312
2020-typical	Appliance upgrades	$2460

[a] After Home Energy Tax Credit.

in thermal integrity, many of the measures involve improving the household's insulation or sealing, which directly improves the building shell and thermal integrity. In this analysis, weatherization was modeled as an increase in the household thermal integrity level to the GridLAB-D category Very Good, such that every house, even those who responded that their house was well insulated, still experienced at least marginal benefit from weatherization improvements. The RECS responses to the question of insulation and the GridLAB-D thermal integrity levels to which they were assigned are provided in Table 3. The R-values, a measure of resistance to heat flow, corresponding to each thermal integrity level used in GridLAB-D, can be found in Appendix A.7.

3.5. Energy efficiency

The RECS data provides the most common ages of household appliances, which were primarily between 2–4 years or 5–9 years (U.S. Energy Information Administration, 2022). The age range of the appliances was used to assign the energy efficiency values from the DOE efficiency standards that most closely align with those manufacturing years; the 2–4 year old appliances would align with typical values for 2020, since the latest standards are older, and the 5–9 year age range would align with the current standards set in 2017 (U.S. Energy Information Administration, 2023b). As the houses were modeled with 2009-era appliances as a baseline, two energy efficiency cases were modeled: one with 2017-standard appliances and one with 2020-typical appliances.

Unlike the end-use appliances, the water heater upgrades were modeled not by age, but instead by converting electric resistance water heaters to more efficient heat pump models. This was achieved in GridLAB-D by using the built-in electric resistance and heat pump models for water heaters. The decision to model water heater upgrades by type rather than base efficiency was made for a few reasons: (1) the increase in efficiency between an electric resistance water heater and a heat pump water heater is substantially greater than that between energy standard years for electric resistance water heaters (U.S. Energy Information Administration, 2023b); (2) heat pump water heaters benefit from a reduction in annual fuel costs over both gas and electric appliances; and (3) heat pump water heaters align with electrification and indoor air quality improvement goals when converting from gas appliances. Additionally, the High-Efficiency Electric Home Rebate Act (HEEHRA) provides immediate point-of-sale rebates for heat pump water heaters, covering 100% of the purchase price, installation, and labor costs for low-income households and 50% for moderate-income households, up to $1750, starting in 2023 (Rewiring America, 2023), making the upgrade to heat pump water heaters more economically accessible than ever before. With the water heater upgrade costs covered by HEEHRA, the estimated cost of the 2017-standard upgrade case was set to the combined cost of the refrigerator, dishwasher, clothes washer, and clothes dryer, at $2312, and the 2020-typical case at $2460 (U.S. Energy Information Administration, 2023b).

To determine the base power setpoints for each end-use appliance, the most common usage rates quoted in the RECS were used to convert the energy standards given per cycle into annual energy usage in kWh. The estimated annual energy usage of each year's appliance was used to scale the base power definitions in the GridLAB-D model. Each appliance was added to the houses as a ZIP load with constant impedance, current, and power.

It must be noted that the WAP includes the following measures that would be captured by this case: repair or replace water heater or refrigerator with energy-efficient models (U.S. Department of Energy Office of Energy Efficiency & Renewable Energy, 2022). For this analysis, the weatherization case includes only measures to improve the household's thermal integrity and the energy efficiency case includes appliance upgrades.

Table 5
Marine - House 0 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−588	$773	16.6
Storage plus solar	4617	$1428	18.1
Weatherization	6	$3	1096
2017-standard	978	$122	19.0
2020-typical	1048	$132	18.6

Table 6
Marine - House 1 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−576	$778	16.5
Storage plus solar	4628	$1431	18.0
Weatherization	4105	$460	7.1
2017-standard	454	$55	42.0
2020-typical	490	$60	41.0

Table 7
Marine - House 10 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−559	$777	16.5
Storage plus solar	4640	$ 1428	18.1
Weatherization	43 061	$ 4813	0.7
2017-standard	429	$ 55	42.0
2020-typical	456	$ 60	41.0

4. Results by climate region and house condition

Each of the representative houses described in Table 2 were simulated for a year with a temporal resolution of 60 s to capture the energy use, energy bill, HVAC operation, temperature inside and outside of the homes, and battery and solar power and energy, where applicable. The base case for each house without any energy improvement measure was used to calculate the energy and energy bill savings from each measure. The estimated cost of each energy improvement measure was used to calculate the payback period of each case. For the energy storage, storage plus solar, and weatherization cases, the 30% Home Energy Tax Credits were accounted for in these calculations. The appliance upgrade case does not benefit from this tax credit, but the costs in this table incorporate the heat pump water heater point-of-sale rebate from HEEHRA. The improvement measures and their upgrade costs are described in Table 4.

4.1. R1 - Marine

The Marine climate region was modeled using TMY3 weather data for Portland, Oregon, and the solar panel tilt angle was set to the latitude of that location, 45.5°.

4.1.1. House 0

House 0 is a one-story house with normal insulation, gas heating and central cooling, with the temperature set to 69 °F for heating and 74 °F for cooling. As shown in Table 5, house 0 experienced the greatest bill savings from the storage plus solar improvement measure but the shortest payback period from the energy storage measure. The combination of the temperate marine climate and the 5 °F temperature setpoint range meant that weatherization improvement measures afforded negligible energy or bill savings for this house.

4.1.2. House 1

House 1 is a two-story house with good insulation, built-in resistance heating, and no cooling system, with the temperature set to 70 °F for heating. As shown in Table 6, house 1 experienced the greatest bill savings from the storage plus solar improvement measure but the shortest payback period from the weatherization measure. This house has no cooling system, yet improvement in thermal integrity allowed for energy savings by decreasing reliance on the built-in resistance heating system.

This house is the only one modeled without a cooling system, as historically houses in this region could remain comfortable throughout the summer months without one. As this GridLAB-D simulation models the houses as closed systems, this house experiences unsafe summer temperatures for all cases. In a real-world scenario, however, those living in a house such as this would likely regulate summer indoor temperatures by opening windows after the sun sets, through the night and into the morning, closing the windows just as temperatures rose to an undesirable level, keeping cool air inside the house for the hottest hours of the day until sunset, when the windows could be open again. With this strategy, a well-insulated house would be able to maintain a comfortable temperature for a longer duration after the windows are shut. However, as climate change results in more extreme temperatures, this strategy alone will prove insufficient on the hottest days of the year, leaving those in homes without AC at risk of adverse health effects.

4.1.3. House 10

House 10 is a one-story house with very little insulation, built-in resistance heating, and window-unit cooling, with the temperature set to 63 °F for heating and 80 °F for cooling. As shown in Table 7, house 10 experienced the greatest bill savings and shortest payback period from the weatherization measure. Despite the temperate marine climate, the thermal integrity improvement provided substantial energy and bill savings by dramatically reducing reliance on the heating system.

Fig. 2 compares the base case indoor temperature (green) and heating and cooling system usage (red and blue, respectively) to the weatherization case for this house in the marine climate with outdoor temperatures (yellow) ranging from roughly 30 °F to 85 °F except for a few days of extreme temperatures. The Cool and Heat ON lines are adjusted to fit on the same plot, where the zero-width values represent OFF and the unit-width values represent ON. The weatherization measure leads to a smaller heating season, with June through September primarily without heating load, compared to the base case, which only had a few days during that period without heating. However, in the summer months, the improved insulation results in increased reliance on the cooling system, as the house is unable to adequately cool down at night. The average temperature inside the house also increases with weatherization, seen in green on Fig. 2, resulting in a likely noticeable difference in comfort during the summer months if the windows are not used for cooling.

4.2. R2 - Cold/Very Cold

The Cold/Very Cold climate region was modeled using TMY3 weather data for New York, New York, and the solar panel tilt angle was set to the latitude of that location, 40.7°.

4.2.1. House 2

House 2 is a two-story house with normal insulation, gas heating, and central cooling, with the temperature set to 69 °F for both heating and cooling. As shown in Table 8, house 2 experienced the greatest bill savings from the storage plus solar improvement measure but the shortest payback period from the energy storage measure. The gas furnace and extremely narrow temperature range for this house were such that the weatherization improvement measure had little impact on energy and bill savings since natural gas fuel costs were not captured in this analysis.

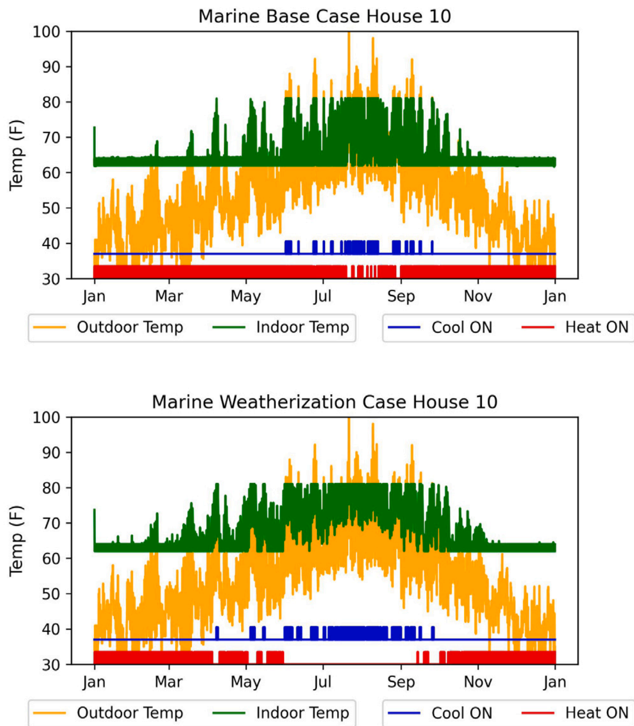

Fig. 2. Household conditions in base (top) and weatherization case (bottom) for Marine Climate, house 10. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 8
Cold/Very Cold - House 2 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−586	$777	16.5
Storage plus solar	5368	$1480	17.4
Weatherization	471	$71	46.3
2017-standard	1033	$129	17.9
2020-typical	1106	$139	17.7

Table 9
Cold/Very Cold - House 3 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−578	$780	16.4
Storage plus solar	5380	$1482	17.4
Weatherization	4800	$564	5.8
2017-standard	611	$80	28.9
2020-typical	651	$85	28.9

4.2.2. House 3

House 3 is a one-story house with good insulation, central heating, and window-unit cooling, with the temperature set to 70 °F for heating and 71 °F for cooling. As shown in Table 9, house 3 experienced the greatest bill savings from the storage plus solar improvement measure but the shortest payback period from weatherization measure. Like house 2, this house had a narrow setpoint range, but unlike house 2, this house relied on a central heating system such that energy savings could be realized from improving the thermal integrity of the house.

4.2.3. House 10

House 10 is a one-story house with very little insulation, built-in resistance heating, and window-unit cooling, with the temperature set to 63 °F for heating and 80 °F for cooling. As shown in Table 10, house 10 experienced the greatest bill savings and the shortest payback period from the weatherization measure. In this cold climate region, the substantial improvement in thermal integrity from weatherization

Table 10
Cold/Very Cold - House 10 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−555	$777	16.5
Storage plus solar	5392	$1482	17.4
Weatherization	50 879	$5847	0.6
2017-standard	540	$65	35.6
2020-typical	586	$73	33.7

Table 11
Mixed-Dry/Hot-Dry - House 4 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−587	$777	16.5
Storage plus solar	4764	$1387	18.6
Weatherization	−397	$-45	−73.0
2017-standard	1002	$125	18.5
2020-typical	1074	$135	18.2

Table 12
Mixed-Dry/Hot-Dry - House 5 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−588	$778	16.5
Storage plus solar	4764	$1389	18.6
Weatherization	852	$62	53.0
2017-standard	823	$109	21.2
2020-typical	882	$118	20.8

decreased reliance on the heating system. The primary heating months for the base case were from mid-September through June, whereas the weatherized house's primary heating months were only from mid-October through mid-May. This reduced heating season is substantial enough that the weatherization improvement measure could be paid off within the year.

4.3. R3 - Mixed-Dry/Hot-Dry

The Mixed-Dry/Hot-Dry climate region was modeled using TMY3 weather data for San Diego, California, and the solar panel tilt angle was set to the latitude of that location, 32.7°.

4.3.1. House 4

House 4 is a one-story house with normal insulation, gas heating and central cooling, with the temperature set to 74 °F for both heating and cooling. As shown in Table 11, house 4 experienced the greatest bill savings from the storage plus solar improvement measure but the shortest payback period from the energy storage measure. Interestingly, in this mixed-dry climate region, with such a narrow temperature set-point range, the improvement in thermal integrity from weatherization actually resulted in this house using more energy and increasing the energy bills for the year. This unintended consequence is likely due to the fact that in this warmer climate region, even in the winter months, a house with very good thermal integrity may be so well insulated that the house is unable to adequately cool down at night without heavily relying on the cooling system if the windows are not used for cooling.

4.3.2. House 5

House 5 is a two-story house with good insulation, central heating, and window-unit cooling, with the temperature set to 69 °F for heating and 77 °F for cooling. As shown in Table 12, house 5 experienced the greatest bill savings from the storage plus solar improvement measure but the shortest payback period from the energy storage measure. Similarly to house 4, weatherization increases the reliance on the cooling system for these houses in the Mixed Dry climate region.

Table 13
Mixed-Dry/Hot-Dry - House 10 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−569	$776	16.5
Storage plus Solar	4783	$1390	18.6
Weatherization	8340	$774	4.2
2017-standard	728	$92	25.1
2020-typical	780	$99	24.8

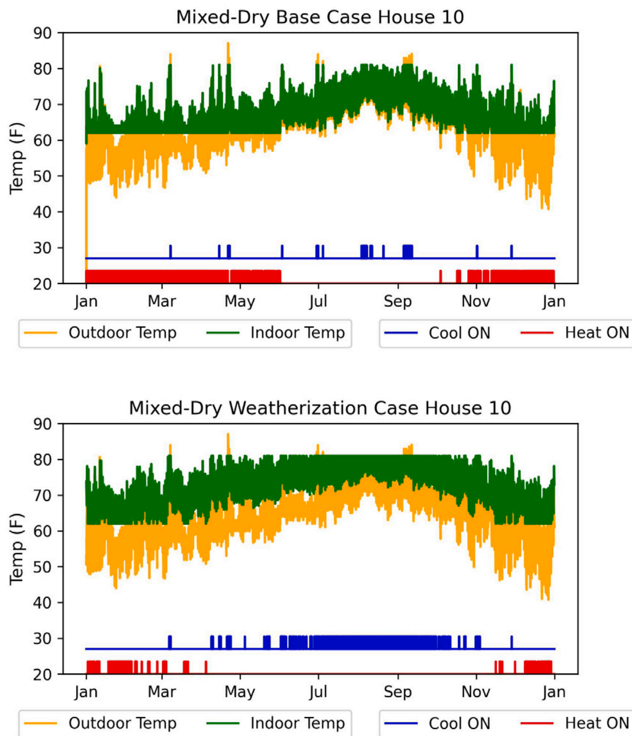

Fig. 3. Household conditions in base (top) and weatherization case (bottom) for Mixed-Dry/Hot dry climate, house 10.

4.3.3. House 10

House 10 is a one-story house with very little insulation, built-in resistance heating, and window-unit cooling, with the temperature set to 63 °F for heating and 80 °F for cooling. As shown in Table 13, house 10 experienced the greatest bill savings from the storage plus solar improvement measure but the shortest payback period from the weatherization measure.

Improving the thermal integrity through weatherization reduced the house's reliance on the heating system such that the heat gained during the day was retained to keep the house warm at night during the majority of the year, whereas in the base case the house relied on the heating system from November through June, as shown in Fig. 3. The improved insulation also means that the house retains more heat during the summer, raising the indoor temperature and again causing the cooling system to be used more often after the weatherization measure, from June through October, whereas the base case only required the cooling system for a handful of days out of the year due to the high temperature setpoint range for cooling.

4.4. R4 - Mixed-Humid/Hot-Cold

The Mixed-Humid/Hot-Cold climate region was modeled using TMY3 weather data for Cincinnati, Ohio, and the solar panel tilt angle was set to the latitude of that location, 39.1°.

Table 14
Mixed-Humid/Hot-Cold - House 6 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−587	$776	16.5
Storage plus solar	4791	$1468	17.6
Weatherization	471	$68	48.3
2017-standard	1031	$128	18.1
2020-typical	1103	$139	17.7

Table 15
Mixed-Humid/Hot-Cold - House 7 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−593	$773	16.6
Storage plus solar	4784	$1464	17.6
Weatherization	3672	$419	7.8
2017-standard	849	$106	21.8
2020-typical	942	$118	20.8

Table 16
Mixed-Humid/Hot-Cold - House 10 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−560	$779	16.4
Storage plus solar	4815	$1470	17.5
Weatherization	51 987	$5753	0.6
2017-standard	543	$72	32.1
2020-typical	581	$77	31.9

4.4.1. House 6

House 6 is a one-story house with normal insulation, gas heating, and window-unit cooling, with the temperature set to 69 °F for heating and 71 °F for cooling. As shown in Table 14, house 6 experienced the greatest bill savings from the storage plus solar improvement measure but the shortest payback period from the energy storage measure. Weatherization reduces the reliance on the heating system for this house, but as bill savings from natural gas utilities are not captured in this analysis, reduction in gas heating requirements from weatherization are not accounted for in bill savings.

4.4.2. House 7

House 7 is a two-story house with good insulation, heat pump heating, and central cooling, with the temperature set to 70 °F for heating and 69 °F for cooling. As shown in Table 15, house 7 experienced the greatest bill savings from the storage plus solar improvement measure but the shortest payback period from the weatherization measure. Unlike house 6, this house has a heat pump heating system for which bill savings are captured in this analysis.

4.4.3. House 10

House 10 is a one-story house with very little insulation, built-in resistance heating, and window-unit cooling, with the temperature to 63 °F for heating and 80 °F for cooling. As shown in Table 16, house 10 experienced the greatest bill savings and the shortest payback period from the weatherization measure. In the Mixed-Humid climate regions, both extreme low and high temperatures can occur depending on the season, making insulation incredibly important to maintaining comfortable temperatures year round. The weatherization measure reduced reliance on the heating system and slightly increased reliance on the cooling system for this house, resulting in a payback period within the year. The substantial variation in benefit from weatherization between the three houses in this climate region may also be due to the very narrow temperature setpoints of houses 6 and 7 compared to this house. With such a small range of acceptable temperatures, the insulation has little opportunity to keep those houses at an acceptable temperature. However, if the occupants are willing to tolerate a wider temperature range, weatherization can provide greater savings.

Table 17
Hot-Humid - House 8 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−583	$775	16.5
Storage plus solar	5194	$1473	17.5
Weatherization	3257	$369	8.9
2017-standard	969	$121	19.1
2020-typical	1043	$131	18.8

Table 18
Hot-Humid - House 9 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−581	$767	16.7
Storage plus solar	5142	$1456	17.7
Weatherization	7479	$875	3.8
2017-standard	921	$116	19.9
2020-typical	985	$124	19.8

4.5. R5 - Hot-Humid

The Hot-Humid climate region was modeled using TMY3 weather data for Orlando, Florida, and the solar panel tilt angle was set to the latitude of that location, 28.5°.

4.5.1. House 8

House 8 is a one-story house with normal insulation, heat pump heating, and central cooling, with the temperature set to 74 °F for both heating and cooling. As shown in Table 17, house 8 experienced the greatest bill savings from the storage plus solar improvement measure but the shortest payback period from the weatherization measure. Though weatherization was able to provide the shortest payback period for this house, it is still almost 9 years, which is one of the highest payback periods for weatherization in this analysis where it proved beneficial. This is likely because there is only marginal opportunity for reduced reliance on the cooling system in this Hot-Humid climate region.

4.5.2. House 9

House 9 is a two-story house with good insulation, central heating, and window-unit cooling, with the temperature set to 73 °F for heating and 71 °F for cooling. As shown in Table 18, house 9 experienced the greatest bill savings from the storage plus solar improvement measure but the shortest payback period from the weatherization measure. Similar to house 8, the payback period for weatherization is higher in the Hot-Humid climate than in other regions.

4.5.3. House 10

House 10 is a one-story house with very little insulation, built-in resistance heating, and window-unit cooling, with the temperature set to 63 °F for heating and 80 °F for cooling. As shown in Table 19, house 10 experienced the greatest bill savings from the storage plus solar improvement measure but the shortest payback period from the weatherization measure. Interestingly, though this house received a greater improvement in thermal integrity from weatherization, House 9 actually had a shorter payback period for weatherization. This is likely due to the energy limiting behavior of this house, where in this case the wide temperature setpoint range in this Hot-Humid climate actually presented less opportunity for energy savings from reduced heating requirements, in contrast to houses 6 and 7 in the Mixed-Humid/Hot-Cold climate region, where the opposite effect was observed.

5. Discussion by energy burden reduction measure

The average and range of energy savings, bill savings, and payback period for each energy burden reduction measure are summarized in Table 20. The intent of this analysis was to develop a targeted approach to prioritize energy burden reduction measures based on climate region and typical housing stock to aid policymakers, utilities, and households. These results must be considered within the full context of the energy and equity benefits of each measure. For example, the value of resiliency and protection from Public Safety Power Shutoffs is an important benefit of energy storage; storage plus rooftop solar provides energy independence, protection from price volatility, and can enable household electrification; weatherization is critical to household health and safety; and energy efficiency upgrades can substantially reduce household water use, further increasing discretionary income as well as water conservation. The following discussion of the modeling results of each energy burden reduction measure can serve as a starting point to the wider conversation of the energy and equity benefits of these measures.

Table 19
Hot-Humid - House 10 results.

Case	Energy savings [kWh]	Bill savings	Payback period [Years]
Energy storage	−576	$773	16.6
Storage plus solar	5202	$1473	17.5
Weatherization	7598	$773	4.3
2017-standard	894	$111	20.8
2020-typical	958	$120	20.5

5.1. Energy storage

The 13.5-kWh energy storage used for energy arbitrage in conjunction with the TOU rate described in Table 1 provided consistent bill savings for the households regardless of climate region or housing stock. As the battery's dispatch was scheduled exclusively based on a price signal, this consistency is expected. The addition of any standalone energy storage device will increase electricity consumption due to the inherent inefficiencies in battery charging and discharging. This average 578-kWh increase in annual energy consumption from the 90% round-trip efficiency of the battery should be considered in the wider context of the balance between generation and demand. While the overall energy consumption of the household increases, if used for energy arbitrage, the charge/discharge cycle will not only provide revenue, but will provide grid benefit by reducing demand during peak energy prices where generation is most expensive and often most polluting (Krieger et al., 2016), and likely even provide increased consumption of renewables by charging when the price is low and renewable generation is highest.

The average annual bill savings for a battery of this size dispatched based on the TOU rate in this analysis was $776, which is not enough to provide a payback period within the battery's expected lifetime of 10 years. However, this payback period only takes into account the 30% Residential Clean Energy Credit, and other incentives exist at the state and local level that could be used to reduce the capital expenditure required to obtain a battery and therefore improve the payback period. Additionally, with the exception of the supply chain issues caused by the global COVID-19 pandemic, the price of energy storage technologies has been and is projected to continue declining (Anisie and Boshell, 2019a).

In this analysis, the TOU rate did not have any seasonal variation; as such, this measure would yield a consistent bill savings of approximately $65 a month to the household. As energy burden is calculated based on the percentage of median income spent on energy bills, this bill savings would have a different impact on energy burden depending on household income. However, increasing monthly discretionary income by $65 has the potential to provide substantial relief for low-income households, assuming the capital cost of the battery and any ongoing maintenance is fully subsidized.

Table 20
Annual energy burden reduction measures summarized results.

Case	Energy savings [kWh]		Bill savings [$]		Payback period [year]	
	Avg	Range	Avg	Range	Avg	Range
Energy storage	−578	−593–−555	776	767–780	16.5	16.4–16.7
Storage plus Solar	4951	4617–5392	1447	1387–1482	17.8	17.4–18.6
Weatherization	12 439	−396–5847	1387	−45–5892	91.9[a]	0.6–1096[a]
2017-standard	789	429–1033	99	55–129	25.5	17.9–42.0
2020-typical	846	456–1106	107	60–139	25.0	19.7–41

[a] Negative payback period from house 4 excluded from this calculation.

5.2. Storage plus rooftop solar

The addition of a 7-kW rooftop solar array to the energy storage case provides considerable energy savings via energy generation. The average annual energy savings for this case was 4951 kWh, providing on average $1447 in annual energy bill savings. Despite the variation in climate region, this measure provided consistent annual energy and bill savings amongst the representative houses, with only a 775-kWh range in simulated energy savings and a $95 range in bill savings. The average payback period of 17.8 years is within the 25+ year lifetime of a PV system; however, this payback period could again be improved with the addition of state and utility incentives on top of the 30% Residential Clean Energy Credit. While the upfront cost of the storage plus solar measure is high, the bill savings amounts to approximately $120 a month with the battery control strategy described in this analysis, which could almost or completely cover a household's electric utility bill. Note that net metering constraints could place limitations on these savings to not exceed the total household load.

5.3. Weatherization

The weatherization measure in this analysis improved the thermal integrity of the houses to the level of Very Good. For some of the households, that was only a marginal improvement; for the energy limiting household, it was a substantial change in insulation and reduction in air change per hour, a volumetric measure of air exchange within the house. While weatherization provided an average bill savings of $1387 in this analysis, the benefits were inconsistent. While some households experienced substantial energy savings and therefore bill savings of hundreds or even thousands of dollars, others saw negligible savings, resulting in a wide range of payback periods from less than a year to essentially infinite. The Mixed-Dry/Hot-Dry climate's house 4 provided an interesting example of what can happen if a house is made to be so well insulated that it traps excess heat and overburdens the cooling system to compensate. The negative impact of weatherization for this house highlights a limitation of this analysis, i.e., that no passive cooling techniques were simulated. The TMY3 weather data for this region provided temperatures which were lower than the cooling setpoint for the majority of the year, ranging from the mid-40s to low-80s except for rare occasions, shown in Fig. 4. The narrow temperature setpoint range also highlights the behavioral aspects of energy use, as the unwillingness to experience indoor temperature variation comes at the cost of increased energy use and high energy bills.

For many of the other houses, weatherization provided considerable energy and bill savings. In 10 of the 15 houses, weatherization provided the shortest payback period; for those that were energy limiting houses, this was also the largest bill savings, beating out even self-generation from the storage plus solar measure and resulting in a payback period within the year. The payback period for the weatherization measure was calculated based on the average household cost of the WAP, $4695 (U.S. Department of Energy Office of Energy Efficiency & Renewable Energy, 2022). This generalization does not capture the cost difference between bringing an adequately insulated house and a house without insulation to the same well-insulated level, the latter requiring substantially greater effort. For those energy limiting households that fall within the eligibility criteria and receive WAP assistance, the upfront costs will not stand in the way of energy savings. For those that fall through the assistance net and whose cost of weatherization improvement measures are at or above this average, the benefits of weatherization may be out of reach unless state or utility programs are made available.

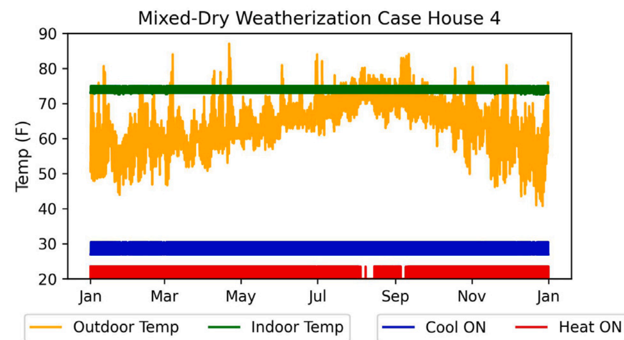

Fig. 4. Household conditions in weatherization case for Mixed-Dry/Hot-Dry climate, house 4.

5.4. Energy efficiency upgrades

The energy efficiency upgrade measure provided minimal energy and bill savings for both the 2017-standard and 2020-typical appliance efficiency cases. The average bill savings of roughly $100 a year is inadequate to provide a reasonable payback period for these upgrades from 2009-era appliances. These energy and bill savings are also dependent on the frequency of use, defined by appliance schedules in GridLAB-D. The more frequently an appliance is used, the greater the opportunity for savings, meaning that households who more frequently use their high-energy appliances will have a greater opportunity for bill savings from an upgrade.

This analysis focused on energy efficiency standards, or typical appliance efficiencies where a new standard was not yet available. When upgrading appliances, however, the standard energy efficiency is not the only option. The national standard represents the minimum efficiency an appliance class must meet (U.S. Department of Energy Office of Energy Efficiency & Renewable Energy, 2017). The typical efficiencies represent a market average, and are inherently higher than the standard. An Energy Star certified appliance has higher efficiency still, meeting the Environmental Protection Agency's energy efficiency specifications (U.S. Department of Energy Office of Energy Efficiency & Renewable Energy, 2017). The availability of appliances in the higher performance range means that the energy and bill savings in this analysis should be considered as the minimum potential benefit. Upgrading to an Energy Star or higher efficiency appliance could provide considerable additional savings, depending on the age and efficiency of the original appliance model. However, without financial incentives, the average energy savings from appliance upgrades are too small to justify proactive replacement before the end of the appliance's lifetime.

6. Conclusion and policy implications

The purpose of this analysis was to assist policymakers, utilities, and households with the task of prioritizing the most effective energy burden reduction measure for common household conditions within the five climate regions of the US. The metrics used to compare the effectiveness of the energy burden reduction measures modeled in this analysis were energy savings, bill savings, and the simple payback period, based on the upfront cost assumptions described in Section 3.

Of the measures studied in this analysis, energy storage provided the most consistent bill savings across all climate regions and household configurations when used for TOU bill management, reducing energy burden by roughly $65 every month. The payback period for this measure averaged over 16 years, indicating the need for either a TOU rate schedule with greater savings potential or additional financial incentives to lower the upfront cost. Energy storage plus rooftop solar also provided fairly consistent bill savings, reducing energy burden by roughly $120 per month, with some seasonal variability expected. The payback period for this measure averaged over 17 years, also suggesting the need for additional financial incentives. The weatherization measure had the highest variability in energy burden reduction between climate regions, household configurations, and energy behaviors. The energy limiting household with very little insulation experienced the greatest benefit from weatherization in all climate regions, with an average energy burden reduction of $300 per month and a payback period from as little as within the year to slightly over four years. Some houses saw negligible and even negative bill savings from this measure. The extreme variability in energy burden reduction potential from weatherization highlights that this measure may not be appropriate in all cases, however it has the potential to have the greatest impact at one of the lowest costs for many. The energy efficiency appliance upgrade measure had minimal impact on energy burden reduction, providing on average less than $10 in monthly savings. The average 25-year payback period implies that this measure requires careful consideration such that appliance upgrades are not made prematurely, with several useful years of life left, but also not left until appliance failure when consumers are forced to make decisions from a place of desperation rather than one of careful consideration of available products and energy efficiency ratings.

The results of this study affirm that there is no one size fits all energy burden reduction measure, and that households, utilities, and policymakers alike must consider the full context of climate, household characteristics, energy behaviors, and state and local financial incentives to adequately prioritize the most effective energy burden reduction measures. For those whose goals are to increase the discretionary income of LMI households with high energy burden, programs and policies to increase access to storage plus rooftop solar could be designed to reduce the upfront cost of this measure with point-of-sale rebates rather than tax credits that require the full upfront cost to participate.

While this study was designed to be widely applicable, the bill savings reported in this analysis were based on a specific rate schedule; the structure and price differential of other rates may not provide the same opportunity for arbitrage as the rate chosen in this analysis. Another limitation of this study is the schedule-based energy usage profile of the simulated households that does not reflect behavior changes that may follow from certain measures, such as shifting high-energy use activities to peak sun hours to increase self-consumption of solar generated electricity. Further research is also needed to explore the role of energy behaviors, such as temperature setpoints, range of acceptable temperatures, and the decision to open or close windows.

The results presented here are intended to provide readers with three representative cases in their climate region as an immediate resource to aid in energy decision-making processes. The authors also make available in Data Availability section the methodology and data used in this study for readers to explore and tailor further analysis to support customized housing configurations, energy improvement measures or combinations of measures, utility rate structures, locations, and more. The lens of energy equity provided a household-centered analytical framework for this study; that same equity lens is absolutely vital for program designers and policymakers that strive to ensure that the most vulnerable energy system stakeholders are not continually burdened but are instead afforded much-needed relief. The authors hope that readers will be empowered to align policies or utility programs to increase the accessibility of the most efficacious energy burden reduction measures for those they serve.

CRediT authorship contribution statement

Jessica Kerby: Conceptualization, Methodology, Software, Investigation, Writing – original draft. **Trevor Hardy:** Technical advising, Writing – review & editing. **Jeremy Twitchell:** Writing – review & editing. **Rebecca O'Neil:** Writing – review & editing. **Bethel Tarekegne:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Datasets related to this article can be found at https://doi.org/10.25584/1992425, an open-source online data repository hosted at DataHub by Pacific Northwest National Laboratory (PNNL).

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Appendix

This appendix provides a detailed explanation of the housing characteristic parameters and how they were modeled in the simulation environment GridLAB-D. A schematic diagram is provided in Fig. 5 to illustrate the pre-processing, simulation, and post-processing steps used in this analysis. GridLAB-D™ is an open-source project to develop the next generation of power system simulation technology. It was initiated in 2004 by the US Department of Energy's Office of Electricity Delivery and Energy Reliability at the Pacific Northwest National Laboratory and has been continued since in collaboration with industry and academia. GridLAB-D incorporates advanced load modeling techniques, with high-performance solution algorithms to solve electrical and thermodynamic models on a quasi-static time-series basis, coupled with power system models, market models, distribution automation models, and software integration tools for users of many power system analysis tools. The representative houses and energy burden reduction measures simulated in this analysis were populated on the IEEE-13 test feeder using a modified version of the Transactive Energy Simulation Platform (TESP) python feeder generator API. For more information, see the readme file in the included dataset.

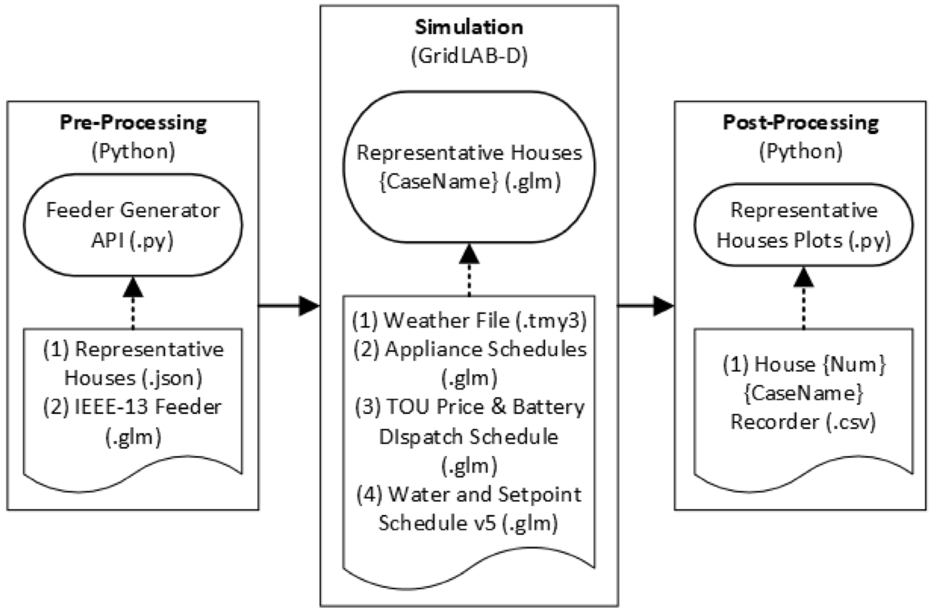

Fig. 5. Schematic diagram of the methodology used in this analysis, describing the tools (in parenthesis), scripts (rounded shape), and included files (document shape).

A.1. Number of stories

The houses in this analysis were modeled as either one- or two-story buildings, while keeping the area of the buildings constant by setting the conditioned floor area to 1818 square feet, or the average square footage per housing unit (U.S. Energy Information Administration, 2022). The energy limiting household was modeled as a one-story building as was most common in the lower income brackets and overall (U.S. Energy Information Administration, 2022).

A.2. Window frame

The possible window frame material responses in the RECS were metal (aluminum), wood, vinyl, fiberglass, and composite. The available window frame material types built-in to GridLAB-D are insulated, wood, thermal break, aluminum, and none. The most common RECS responses were vinyl, aluminum, and wood. The latter are available as inputs, while vinyl does not exist directly as a GridLAB-D parameter; thermal break was used for vinyl responses as it is the class used to represent all but the most thermally insulated frames. The energy limiting household was modeled to have wood window frames as it is the least insulating frame type.

A.3. Glazing layers

RECS data reported single-, double-, and triple-pane as possible types of glass in windows. These responses were used to set the number of glazing layers in GridLAB-D, with either 1 or 2 being the most common responses. The energy limiting household was modeled to have a single glazing layer as it is the least insulating.

A.4. Heating system type

Information on the heating system reported in the RECS is reported under responses for main heating fuel and equipment and main heating equipment (including all fuels); the former was used to inform the housing characteristics in this analysis. Natural gas central warm-air furnaces (Gas in Table 2) was the most common response for many climate regions and was modeled in GridLAB-D by setting the heating system type to gas and the fan type to one speed. There were three common responses for electric-based heating: central warm-air furnace, built-in electric units, and heat pump. The RECS glossary defines central warm-air furnaces to be duct-based while built-in electric units are permanent installations in floors, walls, ceilings, or baseboards (U.S. Energy Information Administration, 2022); based on this distinction, central warm air furnaces were considered to have a fan, while built-in units were assumed to be baseboard heating. Electric central warm-air furnaces (Central in Table 2) were modeled by setting the heating system type to resistance and the fan type to one speed. Built-in electric units (Built-In in Table 2) were modeled as baseboard heating by setting the heating system type to resistance and the fan type to none. Lastly, heat pump heating systems (Heat Pump in Table 2) were modeled by setting the heating system type to heat pump, the auxiliary system type to electric, the auxiliary strategy type to deadband (rather than timer or lockout), and the fan type to one speed. The energy limiting household was modeled to have built-in baseboard heating as it is the least efficient heating system type.

Table 21
Thermal integrity GridLAB-D parameters (Chassin et al., 2008).

Thermal integrity level	R Value					Air change per hour
	Roof	Wall	Floor	Doors	Windows	
Very little	11	4	4	3	1/1.27	1.5
Little	19	11	4	3	1/0.81	1.5
Below normal	19	11	11	3	1/0.81	1
Normal	30	11	19	3	1/0.6	1
Above normal	30	19	11	3	1/0.6	1
Good	30	19	22	5	1/0.47	0.5
Very good	48	19	22	5	1/0.47	0.5

A.5. Cooling system type

The most common RECS responses to the question of main type of air-conditioning equipment were central AC equipment (including central heat pump) and window or wall AC. As heat pumps are included in this first response, houses with a heat pump heating system with central AC were modeled for consistency to also have a heat pump cooling system (house 7 in Mixed-Humid/Hot-Cold climate and house 8 in the Hot-Humid Climate), with a coefficient of performance set to 4.5 to align with typical units installed in 2020 (U.S. Energy Information

Administration, 2023b); otherwise, central AC was modeled by setting the cooling system type to electric, fan type to one speed, and cooling coefficient of performance to 4.1 to align with typical units installed in 2020 (U.S. Energy Information Administration, 2023b). The window AC unit, the second most common response for all climate regions besides marine, is not a standard cooling system type in GridLAB-D. While GridLAB-D simulates the cooling system as a single unit controlled by the thermostat setting, to approximate the inefficiencies of a window AC unit, the oversizing factor was set to −10% and the cooling coefficient of performance was set to 3.5 to match the typical combined energy efficiency ratio (CEER) rating of a room AC unit (U.S. Energy Information Administration, 2023b). The energy limiting household was modeled to have window AC units as it is the least efficient cooling system type.

A.6. Heating and cooling setpoint

The heating and cooling setpoint of the HVAC system in GridLAB-D was set to the most common responses to the RECS questions on winter and summer indoor daytime temperature when someone is home (U.S. Energy Information Administration, 2022). These responses were given in temperature ranges, for example: 71 °F to 73 °F. For cooling system setpoint, the lower temperature was used, and for heating system setpoint, the upper temperature in the range was used. Note that while most RECS responses included three possible temperatures within the range, 70 °F was a single setpoint response, and the lowest and highest setpoints were reported as less/greater than or equal to. The energy limiting house was modeled to withstand the most discomfort before turning on their heating or cooling system in order to reduce their energy bills, with a cooling setpoint of 80 °F and a heating setpoint of 63 °F.

A.7. Insulation

The perceived adequacy of insulation was reported by the RECS survey, with four possible responses: well insulated, adequately insulated, poorly insulated, and not insulated. The corresponding GridLAB-D parameter of thermal integrity level has seven possible responses, ranging from very little to very good, which scale the parameters of the R-levels for the roof, wall, floor, doors, and windows as well as the air change per hour. Table 21 describes the GridLAB-D thermal integrity levels and their corresponding R-values. The energy limiting household was set to not be insulated (Very Little in GridLAB-D), indicating poor housing stock.

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