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Authors

Forrester, Sydney
O'Shaughnessy, Eric
Barbose, Galen

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Sydney P. Forrester, Eric O'Shaughnessy & Galen Barbose

Title

Evaluating technology upgrades as a complement to traditional bill assistance programs

Author list

Sydney P. Forrester[1]*, Eric O'Shaughnessy[1], and Galen Barbose[1]

Affiliations

[1] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley CA 94720

[*] Corresponding author. Email: SPForrester@lbl.gov

Abstract

State programs to improve energy affordability and reduce energy burden (the share of income spent on energy) could mitigate concerns about rising electricity prices. Many states offer bill assistance and rebates for weatherization and rooftop solar to income-qualifying households. Here, we analyse how these approaches may complement one another to improve energy affordability. Results illustrate trade offs between program costs and energy burden reduction, as well as between a program's upfront and ongoing costs. Generally, the three strategies complement one another to improve energy affordability at lower net present cost than bill assistance alone, with varying effects across regions. Weatherization can reduce the solar installation capacity needed, and both together can reduce or eliminate ongoing reliance on bill assistance. Under full uptake among cost-effective households, fully rebated weatherization and solar rebated at $0.48/Watt, combined with bill assistance, yield the same modelled net present cost as bill assistance alone while reducing the share of low-income owner-occupied households with high energy burdens from 66% to 19%, compared with 34% under bill assistance alone. Absent tax credits, weatherization still reduces energy burden and bill assistance program costs, whereas solar may not be cost-competitive.

Introduction

Increasing prices for electricity and other fuel have raised concerns about energy affordability. States promote energy affordability via state appropriations, utility and ratepayer contributions, or voluntary mechanisms.[1] In addition to those broader efforts, targeted programs can provide direct relief to those most impacted by rising pricing, especially lower income households, who often have disproportionately higher energy burden, defined as the share of gross household annual income that goes towards electricity and non-electric heating costs.[2] One study estimated that low-income households' median energy burden was triple that of non- low- or moderate-income households,[3] and some states have created parallel policy goals focused on reducing energy burden across households.[4]

Historically, bill assistance is a common strategy to decrease energy burden. Some U.S. states have Percent of Income Payment Plan (PiPP) programs, whereby eligible customers receive a discount on their utility bill sufficient to reduce their energy costs to some specified percent of their income. That percentage is often set at 6%, the level often defined as equating to a "high" energy burden (see Table SI.2 for a summary of state PiPP programs).[3] PiPP can provide immediate relief, and one survey illustrates that bill assistance was effective in maintaining a comfortable temperature for participants and avoiding utility disconnection.[5] However, that relief is short-term and does not address the underlying causes of high energy burden or provide co-benefits. These programs can therefore become expensive over the long term if households re-apply over multiple years, which increases ongoing programmatic costs and applicant burden.[6] In addition, PiPP programs may provide only a partial solution for many participants, as bill discounts are typically capped at some maximum dollar amount per customer, leaving many participating customers still facing high energy burdens above 6%.

Alternatively, or in addition, to direct bill assistance, many states offer programs for income-qualifying customers to adopt home energy upgrades. Historically these programs have focused primarily on weatherization, but more recently some states have expanded their programs to include rooftop solar.[1,4] Compared to PiPP, installed measures have higher upfront costs, but offer long-term savings, as well as potential non-energy benefits such as improved home comfort, increased property value, reduced energy insecurity, and ability to afford other necessities.[7] These programs can be combined with PiPP to either close the gap for customers where the maximum dollar limit is reached, or to reduce the amount of direct bill relief needed to reduce energy burdens to the targeted level. This decreases bill assistance program cost directly, but also creates indirect avoided costs from reduced disconnections and arrearages or non-payment.[7] In tandem with income-qualified programs, some states and utilities have leveraged private and public dollars to introduce alternative financing via community development financial institutions or state investment banks and/or utility on-bill financing programs. These programs can mitigate high upfront measure costs and often offer lower interest rates through credit enhancements such as a loan-loss reserve or a guarantee to reduce financier risk.[8] When repayment is lower than bill savings throughout the loan term, households can pursue energy upgrades that reduce their energy burden.

Prior studies have demonstrated the savings potential from installed measures for low-income households. For example, Blasnik et al. (2014) found that participants in the federal weatherization assistance program saw an average 12.4% decrease in bills, or $283 per year,[9] and Tonn et al. (2015) found that the share of participants who struggled to pay energy bills declined from 74% before the program to 59% one year after.[10,11] Another income-qualified pilot program of a fully-incentivized 3.5 kW system produced $587 in savings, or a 45% bill reduction, for participants.[4] Analyses of rooftop solar adoption by low-income households have found that, in the U.S., low-income rooftop solar has reduced the incidence of high energy burden from an estimated 67% to 52% and have reduced the incidence of energy insecurity.[10,12] A gap remains in the existing body of literature that considers multiple strategies applied at once. One study analyzes multiple strategies, but across 15 representative households and by applying uniform storage, solar-plus-storage, weatherization, and appliance efficiency upgrades together.[13]

As states grapple with growing energy affordability challenges, it is important to consider a broad range of programmatic options and understand their complementarity. Our study aims to address that by evaluating the performance of a PiPP program compared to income-qualifying weatherization and rooftop solar programs, as well as all combinations thereof while also considering varying applications of loan-financing versus upfront rebates. We perform this analysis on a modeled dataset of 111,410 low-income, owner-occupied households across the U.S., used widely in other published research studies.[14] Complementarity is defined here where a combination of strategies outperforms either strategy on its own in terms of two primary metrics: efficacy in reducing the percentage of low income households with high energy burdens (defined as exceeding 6% of income) and the program's net present cost, assuming only cost-effective measures are installed. The results illustrate key tradeoffs and indicates that income-qualifying weatherization and rooftop solar programs can often be coupled with PiPP to improve both efficacy and cost compared to PiPP alone.

Results

In the following results, we begin by presenting outcomes for a PiPP program designed to reduce the incidence of high (>6%) energy burdens among low-income households (incomes less than or equal to 80% of their area median income). Outcomes are presented in terms of efficacy in reducing the incidence of low-income households with high energy burdens, as well as the net present cost (NPC) per low-income household. We then evaluate two installed measure programs—weatherization and rooftop solar—as alternative programmatic models for reducing energy burden, first considering each individually and in combination with each other, and then later in combination with PiPP. We highlight complementarity where a pareto improvement may occur, i.e., where a combination of strategies can improve efficacy at a lower net present cost, or decrease net present cost while maintaining equivalent efficacy, when compared to either strategy alone.

For these installed measures, we consider varying levels of upfront rebates and the remaining customer cost financed through loans with lower interest rates funded under a loan-loss reserve program. Those two financing models represent the most common approaches used in low-income technology upgrade programs.

Both PiPP and the installed measures are constrained in their scale of implementation, though in different ways. In the case of PiPP, we assume all eligible low-income households receive assistance but limit the total annual bill discount to the lesser of: (a) the amount required to reduce energy burden to 6% or (b) a total annual bill discount of $1,800. That cap is based roughly on current program designs in the United States (see Methods and Table SI.2). The installed measures instead are limited to households where two cost-effectiveness criteria are both met: (1) the measure package has a savings to investment (SIR) ratio greater than or equal to 1 from the program perspective—that is, the total cost of the program (rebates and any capital for a loan-loss reserve) cannot exceed the gross value of the total lifetime energy savings—and (2) the upgrade is immediately cash-flow positive for the household—that is, the bill savings exceed any loan repayment costs. The first of those criteria is a standard screening metric used for income-qualified programs such as in the federal Weatherization Assistance Program for installed energy conservation measures.[15] The second is intended to represent the bare minimum financial return necessary to motivate a household to participate, recognizing that actual household decision-making is considerably more complex.[16–18] Within our analysis, those criteria are evaluated on a household-by-household basis, based on modeled energy and net bill savings for each individual household and the associated programmatic costs.

Each strategy is limited in its respective ability to reduce energy burden below 6%. Since PiPP only provides a maximum annual bill discount of $1,800, the program does not eliminate high energy burdens for households that require additional relief. For installed measures, weatherization is limited to the upgrades considered in this study and only those relevant to each home while rooftop solar is limited by capacity size. Additional details on the application of these criteria are described in the Methods. The results presented below focus on national and regional outcomes.

Bill assistance: Percent of Income Payment Plan

Within our sample of modeled low-income households, 66% have an initial (pre-intervention) energy burden above 6% and are therefore eligible for PiPP. The $1,800 cap on annual bill discounts would be binding for roughly 37% of those participating households, thus reducing the incidence of high energy burdens from 66% to 34% of total low-income households. Provided continuously over 25 years, this level of bill assistance would incur a NPC of roughly $18,600 per participant, on average. That 25-year period is used to correspond roughly to the lifetime of the alternative installed measures considered.

As illustrated in Figure 1, outcomes vary across regions in terms of both the efficacy of the PiPP program in reducing energy burdens to below 6% and its cost, reflecting underlying regional differences in energy costs and incomes. The baseline incidence of high energy burden is considerably lower in the West than other regions, due in part to generally milder climates and thus lower overall energy costs. Consequently, PiPP leads to the lowest incidence of high energy burdens there, albeit starting from a much lower baseline. Among the other three regions, which all have a similar baseline incidence of high energy burdens, PiPP efficacy is greatest in the South, largely as a result of lower energy prices and costs. Conversely, efficacy is lowest in the Northeast, due to relatively high energy prices and thus more frequently binding caps on the annual bill discount. The NPC of PiPP is inversely related to its efficacy, with higher costs in regions where the funding cap is more frequently an active constraint. Of all PiPP-eligible participants, 52% of Northeast households require more than the maximum level of assistance whereas 41% do in the Midwest, 32% in the South, and 25% in the West.

Installed measure programs: Participation potential

The efficacy of technology-based programs in reducing the incidence of high energy burden among low-income households is a function of participation rates and the net savings among participants. Focusing first on participation rates, these depend on what fraction of eligible households pass the requisite set of cost-effectiveness thresholds. That fraction, in turn, depends on the funding model: a higher upfront rebate reduces cost-effectiveness to the program administrator (due to lower SIR), while a lower upfront rebate and correspondingly higher reliance on financing reduces cost-effectiveness to the household (due to lower net customer savings). In addition to those factors, participation may also be constrained by eligibility rules. In our analysis, the weatherization measures do not apply to the 1% of low-income households with high energy burdens whose homes are already well-sealed (Table SI.3), and the rooftop solar program does not apply to the 3% in multi-family dwellings (see Table SI.3 and Table SI.4).

Figure 2 illustrates how the program financing model (rebate vs. loan) impacts the set of households that pass the two cost-effectiveness screens. As illustrated, the solar-only program is most sensitive to the choice of financing, due to higher measure cost. Substituting even just a portion of the loan support with an upfront rebate (e.g. at the $0.5 or $1/W level) substantially increases the portion of households for which the measure is cost-effective, while still satisfying the program administrator SIR constraint. At a roughly $1.5/W rebate, the solar measure is cost effective for almost all eligible households, and any further increases in rebate level yield rapidly diminishing returns due to the program SIR constraint. By comparison, the cost effectiveness of the weatherization (Wx) measures is much less sensitive to the choice of financing, due to lower measure costs. It is partly for this reason that we model only the full-loan and full-rebate financing scenarios for weatherization, rather than intermediate steps as with solar. To illustrate the potential complementarity, we consider a program that combines fully rebated weatherization measures with solar under a varying loan/rebate mix. Notably, this combined program design generally improves cost-effectiveness for both the customer and the program administrator, leading to an upward shift in the curves for the combined measures (relative to the rightmost points on the corresponding weatherization-only curves). The combined program design also allows for households that could not benefit from one technology alone to benefit from the other, increasing potential further.

Depending on the rebate level, either the customer cost-effectiveness or the program administrator SIR constraint may be binding. Combining these two, Figure 3 highlights the percentage of the target population that passes both cost-effectiveness thresholds (we call this the "participation potential") across the range of rebate/loan combinations for each program design and region. Not surprisingly, participation potential for the weatherization-only program is less impacted by the form of financial support and ranges from roughly 89% to 93% of the target population across the four regions, when fully rebated. Participation potential is somewhat lower in the West and South compared to the other regions, due to milder climates in the West and low energy prices in the South. For the solar program, participation potential is generally highest around a rebate of $1.5/W, reaching over 97% of the target population in each region apart from the Northeast, which is lower due to higher costs of solar (see Table SI.7) as well as lower bill reduction potential and high non-electric energy costs. When combined, weatherization provides more savings per dollar up to a limit while solar provides deeper savings, but at a higher cost. Weatherization can reduce the solar size in some cases, avoiding further cost while providing the same level of bill savings. Results indicate that, when weatherization is fully rebated, this allows for high participation potential for the combination across all regions regardless of solar rebate level and far less regional sensitivity.

Installed measure programs: Net bill savings

Net bill savings are the difference between the direct savings on the customer's utility bills (inclusive of electricity, natural gas, and other heating fuels) and any loan repayment costs. The modeled weatherization program includes a standard set of insulation and air sealing measures, which generally yield relatively modest bill savings, but at a modest cost (see Methods and Table SI.5). Compared to the weatherization measures, the rooftop solar program offers greater bill savings potential, but at a substantially greater cost. The solar program assumes a maximum 5 kW installation, subject to each home's usable roof space and limited in size such that annual solar production is no greater than the customer's regional average annual ratio of solar to electricity consumption (see Methods and Table SI.6). These size limitations bind differently across regions, depending mostly on the intensity of heating/cooling loads and the prevalence of electric space heating, and are also impacted when solar is combined with weatherization (see Table SI.4).

Figures 4 and 5 compare the net bill savings for each technology-based program to PiPP—focusing on the full national sample of low-income households in Figure 4 and the regional results in Figure 5. While Figures 2 and 3 illustrate how weatherization and solar complement one another to increase cost-effective participation, Figure 4 demonstrates that the complementarity extends to deeper participant savings that compete with PiPP levels. Alone, net annual bill savings from weatherization are $546 if loan-financed or $636 if financed entirely via upfront rebate. By comparison, median bill savings under the PiPP program are more than double that amount, at $1,373 per year. Weatherization bill savings vary to some extent by region (Figure 5)—with the greatest savings in Northeast, due to relatively high energy prices and cold winter temperatures—though in all cases are well below the median bill savings under PiPP. The weatherization measures considered in this analysis are rather modest. As such, deeper investments and savings could compete better with PiPP levels.

Alone, solar provides a deeper investment and is considerably more expensive than the weatherization measures considered. Thus, net savings are more sensitive to the form of financing provided. If financed entirely through a loan, the median net bill savings across all participants are $195 annually, but grows to $1,107 with a full upfront rebate. However, even at that higher level, the savings are still less than PiPP for the full national sample. The West offers an exception when fully rebated, owing to greater solar production levels and a milder winter climate throughout much of the region.

The combination of solar and weatherization alleviates the issue of deep potential savings for weatherization alone as well as the issue of high sensitivity to incentive levels for solar alone and can reach net savings comparable to that of PiPP. If financed fully through upfront rebates, median annual bill savings reach $1,633 across all participants nationally, which exceeds the benefit provided under PiPP. Notably, the same dynamic holds across all regions. Of course, as the financing model shifts away from upfront rebates and toward low-cost loans, the net savings diminish; with a fully loan-financed design, the median net bill savings in all regions falls below PiPP. Among the regions, the Northeast and West are closest to retaining parity with PiPP in terms of net bill savings, owing largely to the set of factors previously noted for those two regions.

Comparing efficacy and cost across alternate program models

Based on the preceding participation rates and participant net bill savings, Figure 6 compares the efficacy and cost of each of the technology-based program models to PiPP (regional results are illustrated in Figure SI.1).

As shown, the combination of weatherization measures and rooftop solar funded fully through upfront rebates compete directly with PiPP, providing better efficacy (reducing high burden incidence to 31% vs. 34%) at a very slightly lower program net present cost (25-year NPC of $12,227 vs. $12,288).

When combined with PiPP, cost-effective installed measures reduce ongoing reliance on PiPP. When weatherization with solar are combined with PiPP, there is some “Pareto improvement” compared to PiPP alone (i.e., greater efficacy at the same or lower cost, or lower cost at the same or greater efficacy). This occurs either by allowing deeper energy burden reductions than can occur through bill assistance alone (due to the per-participant annual limits) and/or by reducing the amount of bill assistance needed to reduce energy burdens to the 6% threshold. These Pareto improvements are highlighted in Fig. 6 by outcomes in the lower left-hand quadrant. In the case of weatherization, Pareto improvements occur whenever cost-effective measures are combined with PiPP, regardless of the financing model. Instead, for rooftop solar, Pareto improvements are more likely to occur when the larger portion of the cost is loan-financed, rather than relying solely on upfront incentives. When fully rebated weatherization and rooftop solar rebated at $0.48/W are both combined with PiPP, they can substantially reduce the incidence of high energy burden to 19% of low-income households (compared to 34% with PiPP alone), at the same NPC.

Sensitivity to tax credit availability and other factors

The preceding results assume a 30% tax credit for the modeled technology upgrades, similar to the Investment Tax Credit for rooftop solar and the Energy Efficient Home Improvement Credit for weatherization. We also assume state solar tax credits and the Home Efficiency Rebates administered at the state level (see Methods). Since a subset of these tax credits soon expire, we consider here the extreme case of how elimination of all tax credits (including state-administered credits) would impact the performance of the technology-based programs relative to PiPP.

The loss of tax credits reduces cost-effective adoption of installed measures, and increases the cost for the remaining cost-effective participants (see Figure SI.2 for participation potential). This shifts the performance curves in Figure 7 upward (lower efficacy) and to the right (higher cost). This may require either lower rebates to achieve better program economics, which would reduce household savings; or higher rebates to improve affordability, which may lead to fewer households served.

Without tax credits, installed measures cannot compete with PiPP on their own. Even with full rebates, efficacy of PiPP is superior to the combined installed measures. When combined with PiPP, providing access to low-cost capital still provides marginal improvements both in efficacy and reduced cost. For example, access to financing for weatherization and solar, separately, reduces NPC $1,547 and $80 per low-income household and reduces the incidence of high energy burden 5.8 and 0.6 percentage points, respectively, compared to PiPP alone. Close to Pareto improvement, fully rebated weatherization with PiPP would have a NPC similar to PiPP alone, but reduce high energy burden an additional 11.8 percentage points. We explore further sensitivities including solar tariff design and fixed electricity charges as well as some that impact future costs and savings such as electricity cost rate trends and discount rates in Figure SI.3a-d.

Discussion

Energy affordability programs have expanded in recent years beyond direct bill assistance to include various cost-effective installed measures that can provide ongoing bill reduction such as weatherization and rooftop solar. Program goals may have multiple, sometimes competing, objectives such as those for households in reducing incidence of high energy burden, maximizing participation, or capturing non-energy benefits; and those for the program administrators such as controlling upfront and ongoing program costs, achieving state or utility targets or goals for affordability or DER deployment. There is no single best program design and administrators must balance these tradeoffs. On its own, direct bill assistance is flexible, does not require long installation time or large upfront investment, and can be applied to any household that pays their own utility bill regardless of building type or ownership status. However, bill assistance does not provide non-energy benefits or a long-term solution. The pros and cons for installed measures such as weatherization or solar are just the opposite. As such, programs have begun to explore the complementary relationship between direct bill assistance and installed measures. For example, an income-qualified solar program demonstrated economic benefits to the utility due to reduced assistance spending, reduced defaults and delinquencies, and reduced administrative costs.[19] Another program that used weatherization funds for solar acknowledged that solar unlocked the potential for much higher savings, however, at a higher cost that required supplemental funds and could limit the number of households served by a fixed program budget.[4]

Our results find that bill assistance, weatherization, and solar—each with their respective tradeoffs—can complement one another. Together, weatherization reduces the size of solar required and improves the benefit-to-cost ratio while solar deepens potential savings. If further combined with PiPP, ongoing bill savings from weatherization and solar decreases or eliminates bill assistance that a household may require and serves more households. Results are optimized when rebates are set high enough to produce meaningful household savings, but low enough for a program to accommodate a larger number of participants. Indeed, our results indicate that the combination of cost-effective weatherization and solar with a full rebate decreases incidence of high energy burden among low-income households more than PiPP would, and at a slightly lower NPC. Combined with PiPP, all three interventions achieve the lowest incidence of high energy burden compared to any other scenario. Specifically, fully rebated weatherization together with solar rebated at $0.48/Watt with PiPP reduced incidence of energy burden 15 percentage points at the same NPC compared to PiPP alone.

These results illustrate a spectrum of options for affordability program design. For example, if a program instead is not aiming to optimize a PiPP program, but to encourage cost-effective weatherization and solar without a large level of funding, our results suggest that low-cost loans with customer protections could improve affordability, even without PiPP or upfront rebates. Indeed, weatherization with solar reduced the incidence of high energy burden 11 points with access to low-interest loans alone compared to no intervention (Fig. 4). In another scenario, if a program solely aimed to maximize deployment of weatherization and solar without PiPP, it may focus on higher rebate levels instead. For a program with constrained upfront time and capital, PiPP could provide immediate affordability to any qualified household while allowing time for complementary program design. In these cases, pairing PiPP alone with financing and low-cost capital to allow for households to adopt cost-effective measures on their own improves both cost and efficacy.

Our study includes several limitations. This work is based on modeled households and interventions, which do not account for actual measure performance or behavioral rebound effects such as a case where a household may offset some savings for improved comfort if they had been rationing energy use to save on bills.[20,21] Actual energy rationing behavior with a rebound effect could decrease initial energy burden and increase post-treatment energy burden, leading to a smaller total decrease and perhaps lower efficacy. We also do not include other strategies that could impact home energy burden such as demand response, community solar, energy storage, or electrification. Community solar, in particular, is a strategy that several states are pursuing to alleviate low-income energy burden and could benefit from additional analysis.[22] It also only includes a set portfolio of weatherization measures without other energy efficient upgrades such as appliance replacement. Due to the focus on weatherization and rooftop solar, we do not consider renter-occupied households, which may require custom strategies or other technologies to reduce energy burden. While renters only make up 36% of the occupied households, they made up over half (53%) of low-income occupied households. As such, further work could explore strategies that specifically alleviate energy burden in renter-occupied, low-income households. Another limitation is that we make state-specific tariff assumptions to apply our findings across the United States that may not reflect nuances found in individual utility territories or programs. We also do not consider the cost of net energy metering or impacts on non-participating households of these programs. Another limitation is that we do not account for programmatic funding constraints that are binding in almost all actual cases. In reality, any assistance program may face funding limitations, and the level of allocated dollars may fluctuate greatly from year to year.[1,23] This would impact participation, which we assume as a high bookend without considering funding or other assumptions that would decrease actual participation. For example, assuming PiPP enrollment for the entire 25-year timeframe was necessary for comparison, however, administrative burden for participants and funding constraints for the program would likely result in incomplete enrollment over time, which would reduce both program cost as well as efficacy from a portfolio standpoint. For adoption of installed measures, a study found that unsecured loans for these upgrades had much lower default rates than unsecured consumer loans, potentially due to net bill savings and safeguards against predatory lending.[24] While this can expand access and reduce upfront costs for households, in cases where energy costs remain unaffordable, financing may expose vulnerable households that remain at risk for non-payment and deter participation.

This study builds on a body of literature to better understand how states or utilities could employ multiple energy affordability strategies and how they may complement one another. Thoughtfully combining access to a series of interventions could help achieve broader affordability goals, decrease risk of customer shut off or non-payment, improve home comfort and health, and reduce reliance on bill assistance.

Methods

Filtering household models

For this study, we specifically focused on households that would be candidates for bill assistance, weatherization, and/or low-income solar incentives. As such, we narrowed NREL's full set of End Use Load Profiles (EULP) building models to those that were owner-occupied and with area median incomes (AMI) at or below 80%.[25] Data for each building model include building characteristics (e.g., units in structure, building envelope), household characteristics (e.g., tenure, number of occupants, income range), location (e.g., climate zone, municipal area, county), and energy use (e.g., fuel and electricity demand by end use). We used EULP data on each household's county, number of occupants, and income range to determine AMI. Choosing a randomly selected value within the range and using the respective county and number of occupants, we assigned a percent AMI value to each household by comparing to the Housing and Urban Development specifications.[26] From a total set of 548,916 total building models, 307,480 were owner-occupied. Of those, 111,411 had an area median income at or below 80%. One household had $0 income, which we remove to avoid an infinite energy burden value. The resulting 111,410 households make up the base of our study (see Table SI.1 for sample size of each step and other summary metrics by state). All monetary pricing and income data are taken from 2022 for consistency.

Electricity prices

Building models in EUSS include end-use electricity, natural gas, propane, and heating oil usage. Using the Energy Information Administration's Form 861 electricity data, each utility has data on residential revenue, residential electricity sales, and residential customer counts.[27] Since these data do not include whether, or at what level, fixed charges or minimum bills are in place, we assume a monthly fixed charge of $10 for each residential customer, consistent with values across utilities that typically range from $5 to $20 per month (a $20 fixed charge sensitivity is run in Figure SI.3b).[28] As a result, each utility's volumetric rate is established by subtracting all fixed charges collected (equivalent to $120 annually by the total number of residential customers) from the total revenue collected and dividing that by the number of residential sales in kWh.

For each county associated with more than one utility, the utility with the most customers for each respective state was selected as the county's assigned utility. With this, each building model was linked to a specific utility and corresponding volumetric electricity rate. Flat rates were assumed as the baseline with net metering-- i.e., compensation for solar generations, including exports, at the retail rate value. Time sensitive rates were not considered the base case because only 10% of residential customers were enrolled in time-sensitive rates in 2023.[27] Only nine states had above-average shares of customers on time sensitive rates while the rest had near-zero shares. The states with the above-average shares include Delaware (57% of customers), Maryland (47%), Missouri (44%), Colorado (37%), Arizona (37%), Michigan (37%), Oklahoma (33%), California (30%), and Montana (15%).[27]

Other energy prices

For non-electric energy prices, we used EIA 2022 state data (concurrent with electricity prices) for residential natural gas, propane, and heating oil.[29,30] All EULP energy consumption is in kWh. So, all non-electric prices were converted to kWh with: 1,039 British thermal unit (BTU) to 1 cubic foot of natural gas; 91,452 BTU to gallon of propane; 138,500 BTU to gallon of fuel oil; and 3,412 BTU to kWh.[31]

Cost projections for Net Present Cost calculations

In order to determine cost projections, we use the same EIA data that was used to determine prices described above.[27,29,30] However, we include the preceding five years of data from 2018 through 2022 to get the average year-over-year percentage change, accounting for inflation, to use for the main analysis (Table 1).

While residential electricity prices have remained fairly flat when taking inflation into account, there is concern that an increase in large load interconnection and the infrastructure needed to support it may cause rates to increase faster in coming years. We display the results instead assuming a 1% increase (and decrease) in real electricity prices in Figure SI.3c.

Bill assistance: Percent of income payment plan (PiPP) design

Percent of income payment plans (PiPP) are offered in specific states or utility territories and are structured such that income-qualified customers are given assistance on their energy bills that drives their energy burden down to a specified level (most often 6%, but sometimes 10% if bills include more than solely electricity). Often these programs have a maximum annual discount of $150 per month, or $1,800 per year. Table SI.2 summarizes existing programs across the U.S. We use values modeled after existing programs to structure our PiPP bill assistance for this study, offering the smaller between a discount that would reduce household energy burden to 6% or $1,800 per year. As such, customers with a baseline energy burden below 6% would not receive additional bill assistance. The level of bill assistance changes based on how installed weatherization or solar may impact costs. This includes both bill savings as well as on-bill loan repayment, where applicable.

Weatherization measures, costs, and incentives

NREL's EULP building models have corresponding upgrade scenarios (End-Use Savings Shapes (EUSS)). For the weatherization case, we consider the "Enhanced Enclosure" scenario, which includes attic, wall, and basement insulation as well as air and duct sealing (see Table SI.5).[32] NREL includes detailed logic on which buildings got what upgrades, based on baseline measures and housing condition as well as climate.[32] As such, each building is prescribed a different level of upgrades. For example, a building with no or very poor insulation in a region with many heating degree days may be prescribed more insulation in the weatherization scenario whereas a building with sufficient insulation in a mild climate may not. Additionally, some measures may not apply to certain buildings. For example, insulation for finished attics is not applied in housing without a finished attic.

To best pair with EUSS measures, we drew costs from NREL's National Residential Efficiency Measures Database, which represents the total cost to implement the retrofit measure. The database presents one primary value as well as a range, depending on the pre-measure condition and measure selected. For each category, the database provides additional information on cost drivers. See Table SI.5 for the cost (and range) of each relevant measure. We use this pricing for each building's characteristics (e.g., square footage of various conditioned spaces) to determine the total cost of the weatherization upgrade for each home.[33] NREL's EUSS database then provides the consequent changes in energy consumption as a result of the upgrades, which we can use to quantify savings from weatherization for each building.

Where federal tax credits are included, we consider two separate incentives. The first is modeled after the energy efficiency home improvement credit, which allows for 30% of the installed price up to a maximum limit of $1,200.[34] We also consider the Home Efficiency Rebates (HOMES) program, which is a rebate for home weatherization that is allowed to be stacked on top of other incentives. This only applies to households with 80% AMI or lower, which includes all households in our sample. The rebate provides differing levels of incentives based on the amount of modeled savings from the proposed upgrade. An 80% rebate is offered for households with AMI at or below 80% and energy savings more than 20% above the baseline. For measures leading to 20%-35% of savings, the maximum limit is $4,000 while, for savings above 35%, the maximum limit is $8,000. Measures that produce savings less than 20% are not offered this incentive.

Rooftop solar sizing, cost, and incentives

Generation is determined using the centroid of each household's county and inputting that locational information into NREL's System Advisor Model. We assume a South-facing array, tilt at latitude, fixed array with a 1.2 inverter loading ratio and 14% system losses. For system degradation, we assume 0.5% degradation per year. We then determine each household's solar array sizing, taking into account restrictions created by either rooftop square footage or total annual load.

Using public Energy Sage data, we find the median ratio of household annual solar generation to annual load (see Table SI.6).[35] We apply that ratio to buildings based on their state as one constraint. We also consider rooftop square footage, where we assume that 70% may be suitable to host a solar array,[36] and that each square foot could host 15 Watts as the second constraint. The final rooftop solar array size is selected as the minimum between 5 kW, the solar generation to load ratio, or the available rooftop size restriction (see Table SI.4 for share of binding constraints). The hard limit of 5 kW is used in existing low-income rooftop solar programs such as the Disadvantaged Communities Single-Family Solar Homes in California.[37]

Rooftop solar costs are taken for each region. These data originate from Berkeley Lab's Tracking the Sun. These include both material and soft costs in addition to any upfront or performance based incentives, but exclude state and federal tax credits as well as solar renewable energy credits. System costs are filtered to exclude third-party owned arrays and only include systems purchased with cash. For each region, 2022 median solar system costs were assigned to respective households (see Table SI.7).

Since tax credits and renewable energy credits are *not* included in the Tracking the Sun values, we apply them separately. Where federal tax credits are considered, we assume 30%. Some states offer additional incentives which are considered (see Table SI.8). Since we assume host-ownership, we do not include any additional adders applicable for third parties such as energy community or low-income adders.

Upfront rebates and loan assumptions

We consider an income-qualified rebate program that provides capital required for low-income households with high or severe energy burdens to adopt weatherization and/or rooftop solar. Rebates may represent the full amount, intermediate levels (only for solar), or none at all. If provided in full, the program administrator covers all costs of adoption after relevant state and/or federal incentives. Intermediate levels are in various $/W levels for solar and it is assumed that the household would pay for the rest via a loan. Consistent with programs that allow use of bill assistance and/or weatherization to go towards solar installations,[4] we assume that programs only provide solar incentives where the savings-to-investment ratio is greater than 1 (i.e., savings over lifetime of solar asset are more than upfront cost).

As described in the Introduction, there are various programs that provide low-cost capital with consumer protections to households that seek to install energy technology such as weatherization measures or rooftop solar. These often include credit enhancement such as loan-loss reserves to buy down interest rates and zero/low levels of loan origination fees. Funds for loan-loss reserves may be supplied by a one-time grant or influx of money from public or ratepayer dollars and the capital itself may be supplied by financiers such as community development financial institutions or other impact oriented or local institutions. Where they exist, regional community development financial institutions or state investment banks may play a role in facilitating these partnerships.

We assume that a program administrator could create a loan-loss reserve with 5% of the capital lent to install these weatherization and/or solar measures. We then assume that this could reduce loan origination fees to negligible levels and provide interest rates with a mean of 7% and

1.25% standard deviation, determined randomly via standard distribution for each customer. We assume a household uses the loan to cover the full upfront cost that they are responsible for (i.e., after all rebates and tax credits) such that no money is required upfront. We take into consideration the loan repayment on the customer's bill. As such, the resulting energy burden post-intervention includes both the consequent bill savings in addition to repayment of both loan principal and interest. Consequently, we assume that a household does not adopt if the investment causes their net energy costs to increase.

It is important to note that the level of participation considered for this study is much higher than is realistic because, on the program side, there may be limits to spending either in terms of available capital for rebates or ongoing money for bill assistance. On the customer side, there may be households that are unaware of the program or their qualification, are unable to undertake the time and administrative burden to apply, are unwilling to adopt, may not qualify for loans, or may want to avoid debt. Rather, this study is meant to illustrate and compare how different interventions could improve affordability and their subsequent programmatic costs.

Data availability

The datasets generated during the current study are available in the figshare repository, https://doi.org/10.6084/m9.figshare.31173922.

Code availability

Code generated to create the initial dataset, generate intermediate datasets (see "Data Availability"), and create the figures and tables found in both the main body of the document and Supplementary Information file are available in the figshare repository, https://doi.org/10.6084/m9.figshare.31173922.

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Author Contributions

SPF conceived and designed the analysis, collected the data, contributed data or analysis tools, performed the analysis, wrote the paper. EO provided feedback on scope, provided edits. GB provided feedback on scope, assisted with writing, provided edits.

Competing Interests

The authors declare no competing interests.

Tables

Table 1: Mean year-over-year percent change in energy prices between 2018 and 2022

VARIABLE	MEAN ANNUAL REAL % CHANGE (2018-2022)
INCOME	1.80%
ELECTRICITY	0.29%
NATURAL GAS	5.59%
PROPANE	3.21%
FUEL OIL	8.81%

Figure legends/captions

Figure 1: Cost and efficacy of modeled percent-of-income payment plans (PiPP): Assistance is bound to a $1,800 annual maximum. Results are presented across regions, with the top of each line segment (diamond) corresponding to the baseline pre-intervention share of low-income households with high energy burdens and the bottom of the line segment (circle) showing the share after PiPP.

Figure 2: Cost effective share of eligible households as a function of incentive level: Dotted lines follow the cost-effective share from a program perspective, and solid lines from a household perspective. For the combination of solar and weatherization, weatherization is fully rebated while solar is incentivized at varying $/Watt levels.

Figure 3: Participation as a function of incentive level: Levels represent the share of households that yield both household net savings and program savings-to-investment ratio (SIR) greater than 1. Results are shown for (a) weatherization, (b) rooftop solar, and (c) weatherization + rooftop solar. Note that in (c), weatherization is fully rebated and rebates only vary for solar.

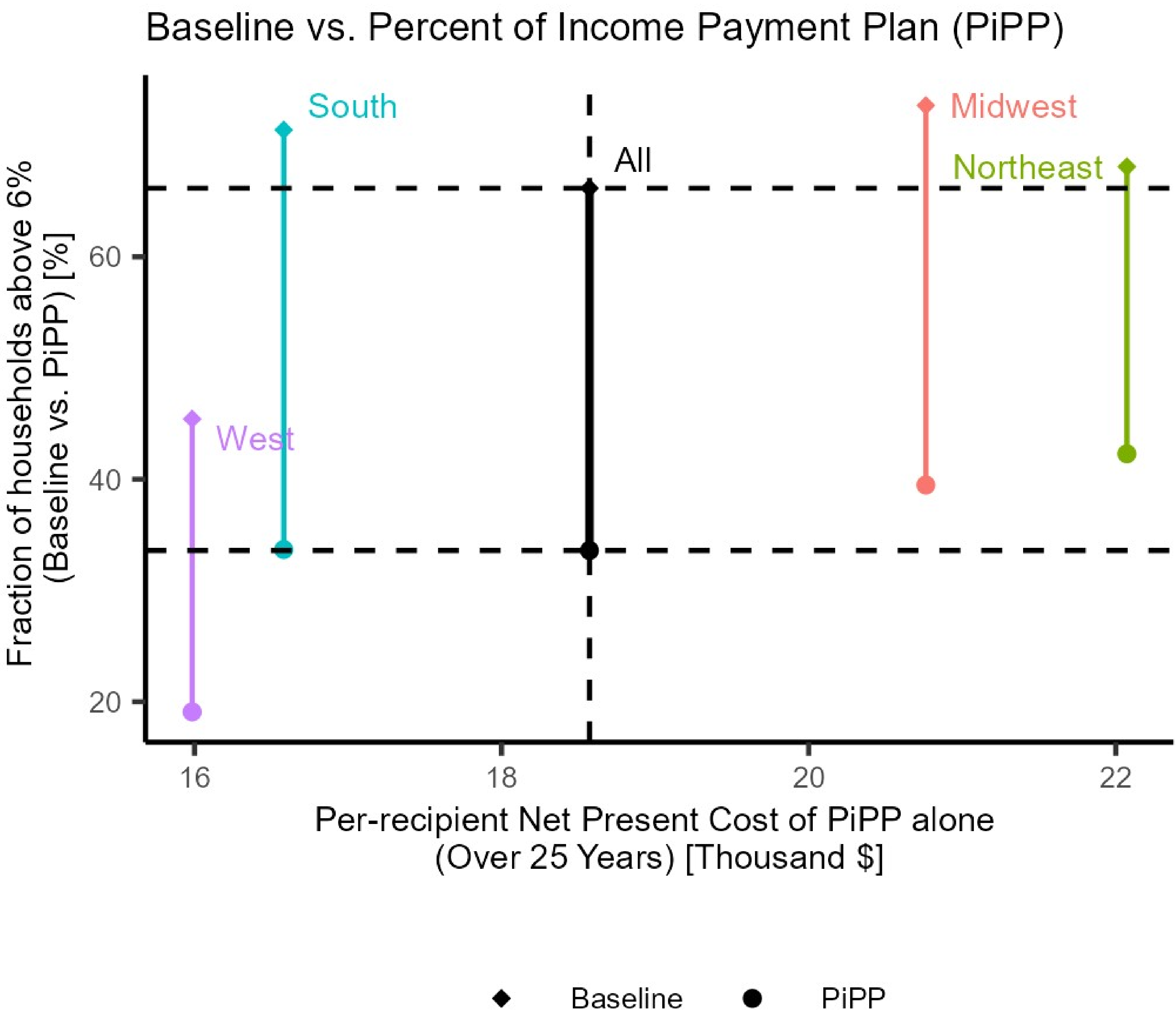
Figure 4: Net bill savings across participant households from installed measures compared to that of percent of income payment plan (PiPP): Participant households include only those that receive net savings and have a SIR>1. The percentage shown is the percent of low-income, energy burdened (i.e., PiPP-eligible) households that the participants represent. Boxes indicate median

and 25th/75th percentiles while whiskers indicate 5th and 95th percentiles. Weatherization measures are fully subsidized in the solar + weatherization case.

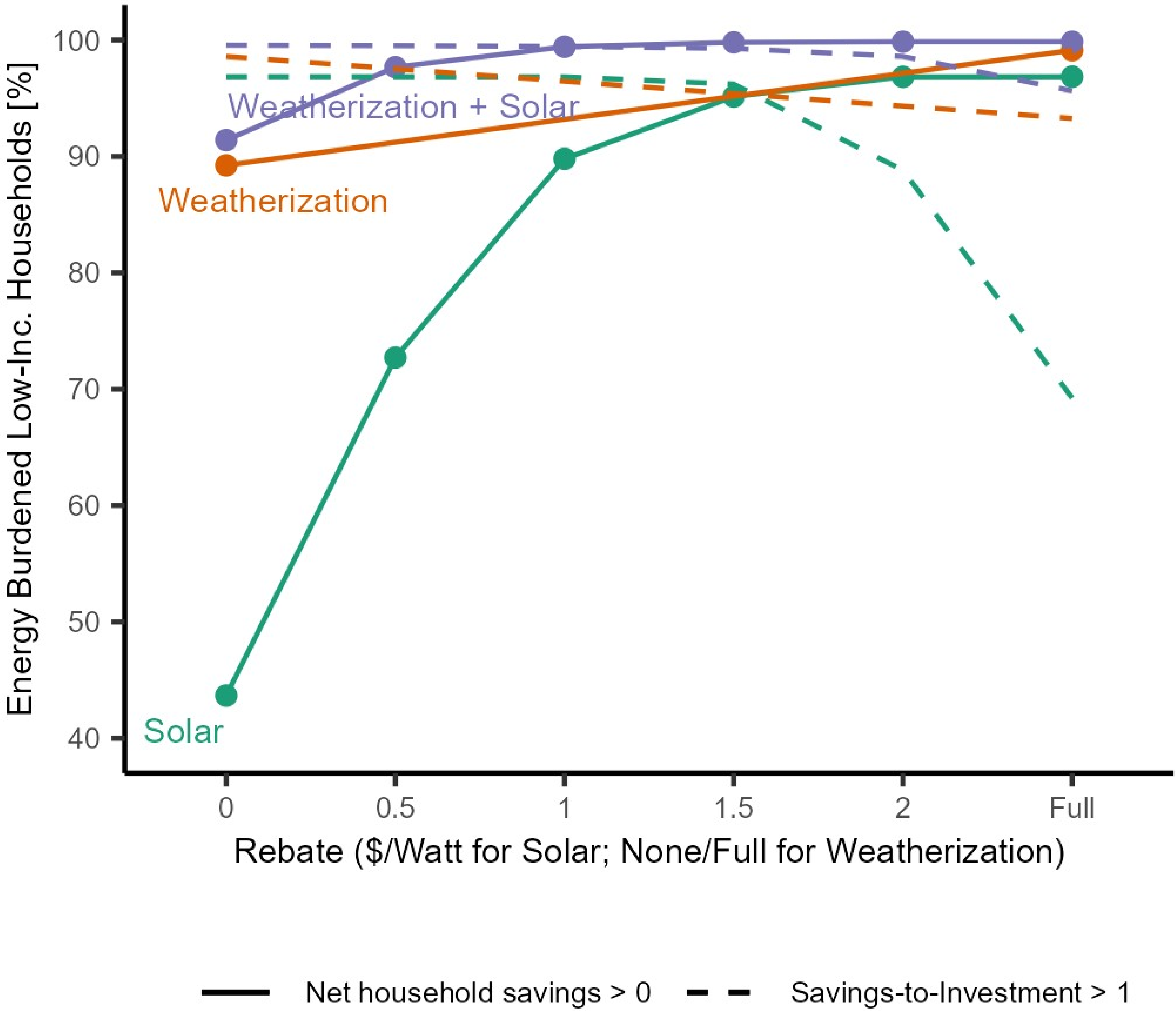
Figure 5: Regional net bill savings across participant households from installed measures compared to that of percent of income payment plan (PiPP): Participant households include only those that receive net savings and have a SIR>1. The percentage shown is the percent of low-income, energy burdened (i.e., PiPP-eligible) households that the participants represent. Boxes indicate median and 25th/75th percentiles while whiskers indicate 5th and 95th percentiles. Weatherization measures are fully subsidized in the solar + weatherization case.

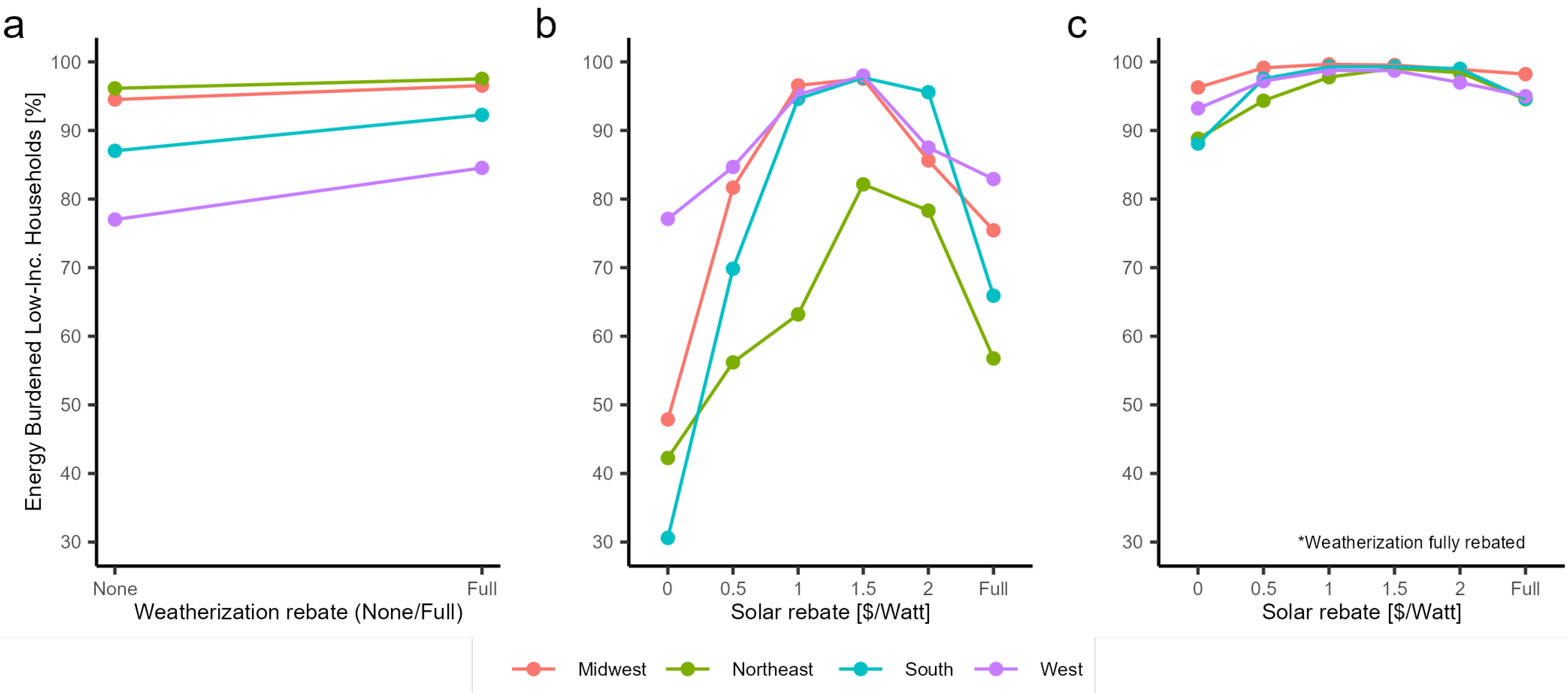
Figure 6: Comparison of various program designs: Dotted lines include the installed measures with the percent of income payment plan (PiPP). Line segments represent changes moving (left to right) from fully loan-financed (empty circle) to a full upfront rebate. For the weatherization + solar case, weatherization is fully rebated. Dotted axes show efficacy and NPC of PiPP. Thus, points in the upper-left quadrant are cheaper, but less effective; lower-left are both cheaper and more effective; lower-right are more expensive and more effective when compared to PiPP alone.

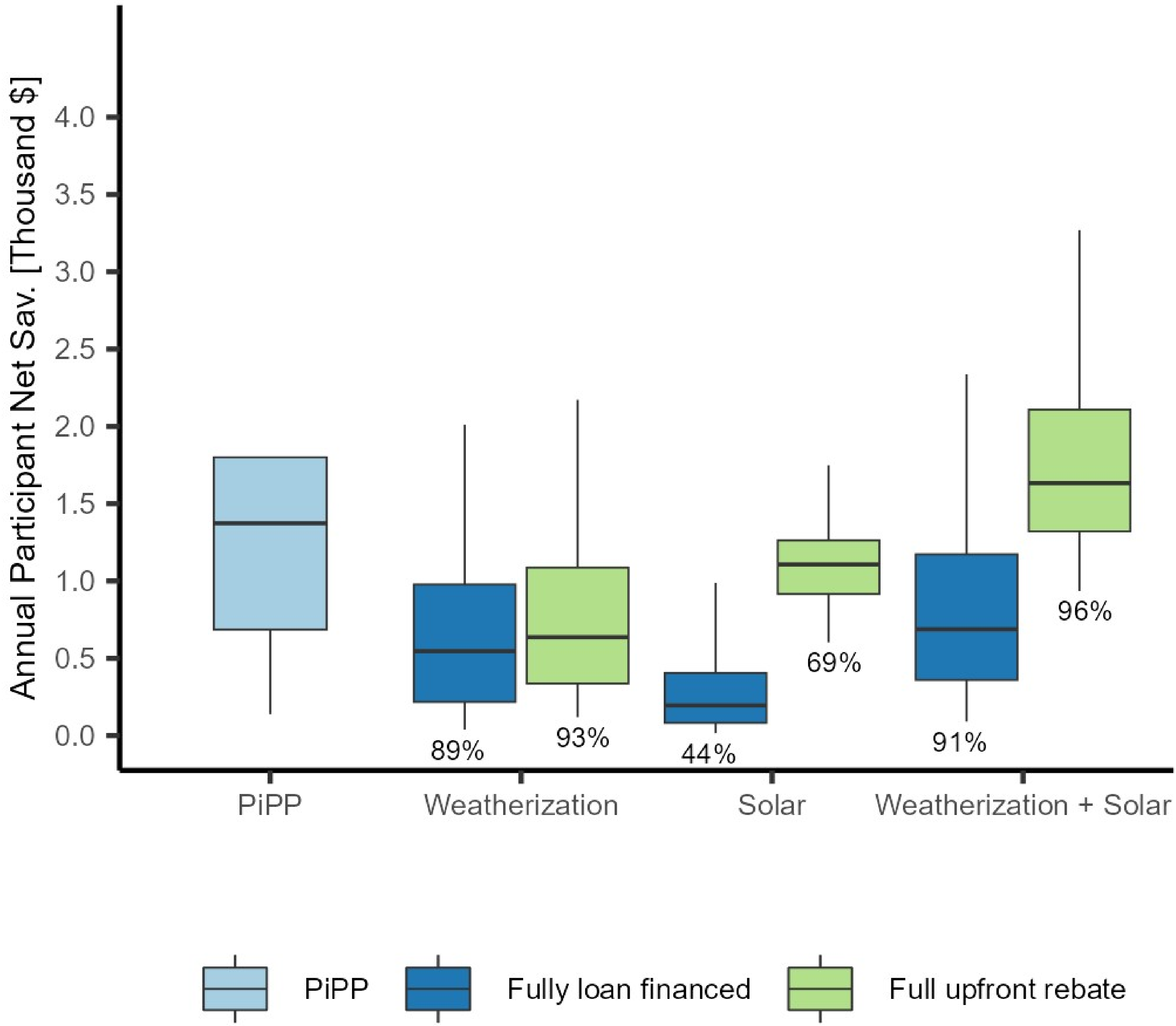
Figure 7: Comparison of various program designs without state or federal tax credits: Dotted lines include the installed measures with the percent of income payment plan (PiPP). Line segments represent changes moving (left to right) from fully loan-financed (empty circle) to a full upfront rebate. For the weatherization + solar case, weatherization is fully rebated. Dotted axes show efficacy and NPC of PiPP. Thus, points in the upper-left quadrant are cheaper, but less effective; lower-left are both cheaper and more effective; lower-right are more expensive and more effective when compared to PiPP alone.

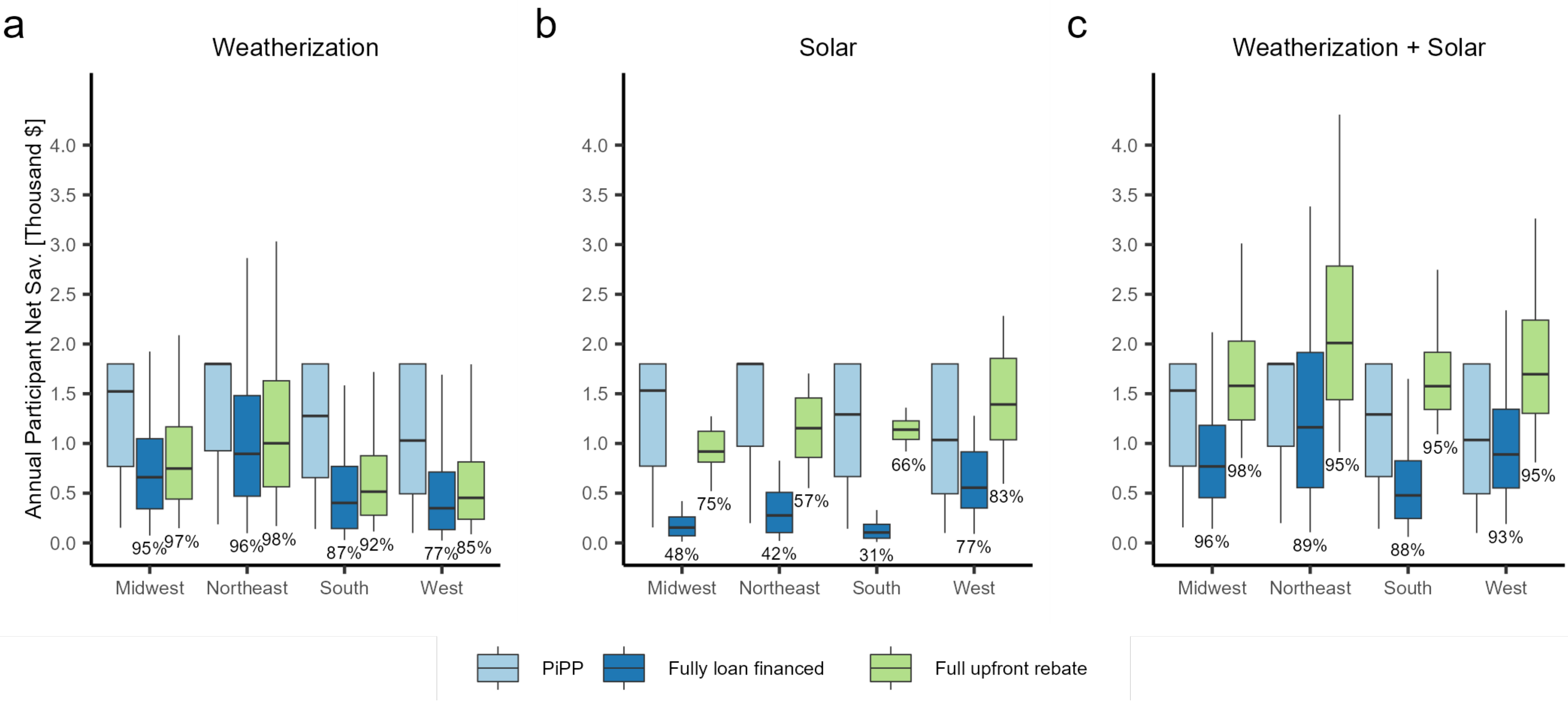


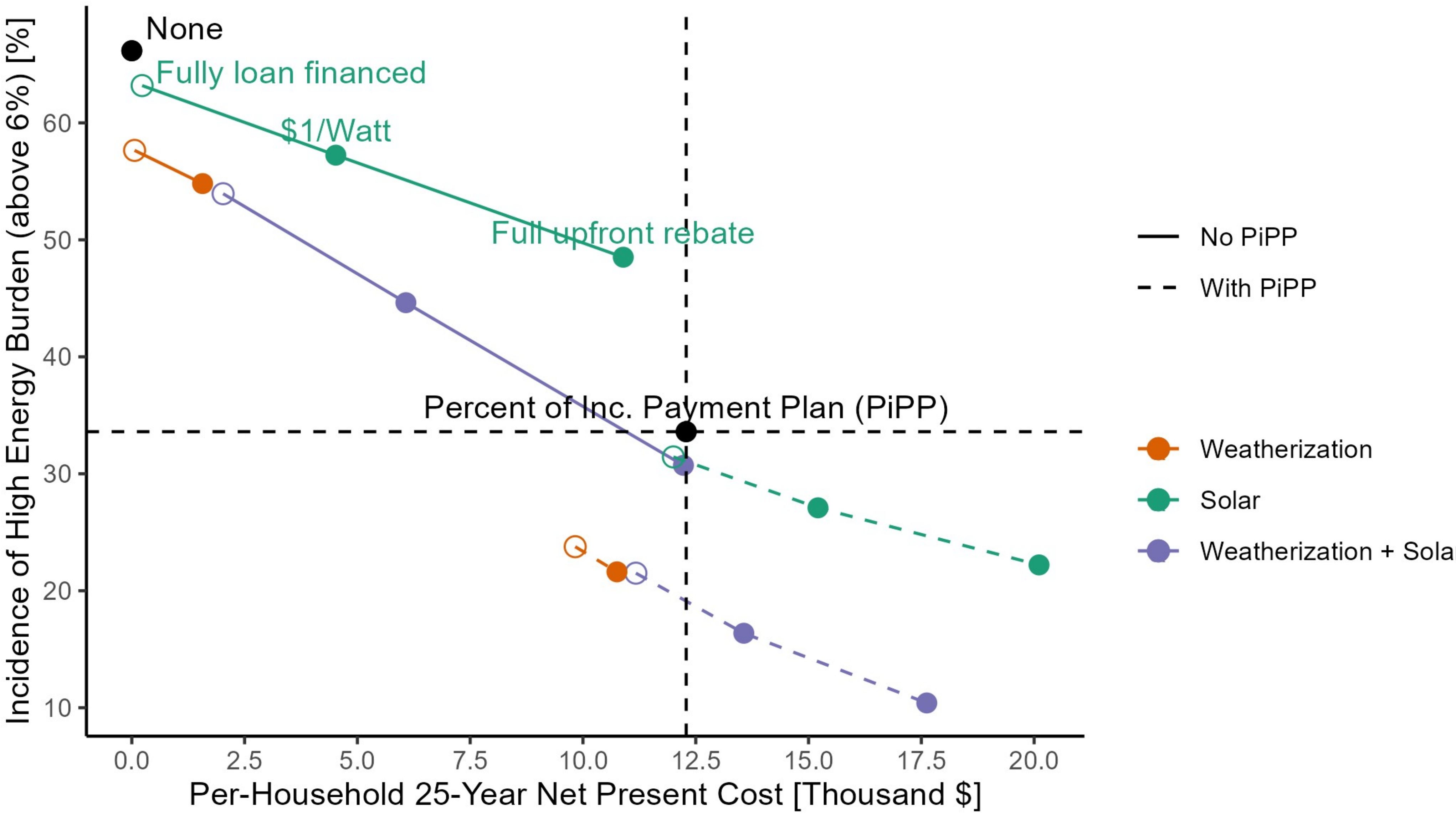
Baseline vs. Percent of Income Payment Plan (PiPP)
South
Midwest
All
Northeast
West
60
40
20
16
18
20
22
Fraction of households above 6%
(Baseline vs. PiPP) [%]
Per-recipient Net Present Cost of PiPP alone
(Over 25 Years) [Thousand $]
Baseline
PiPP

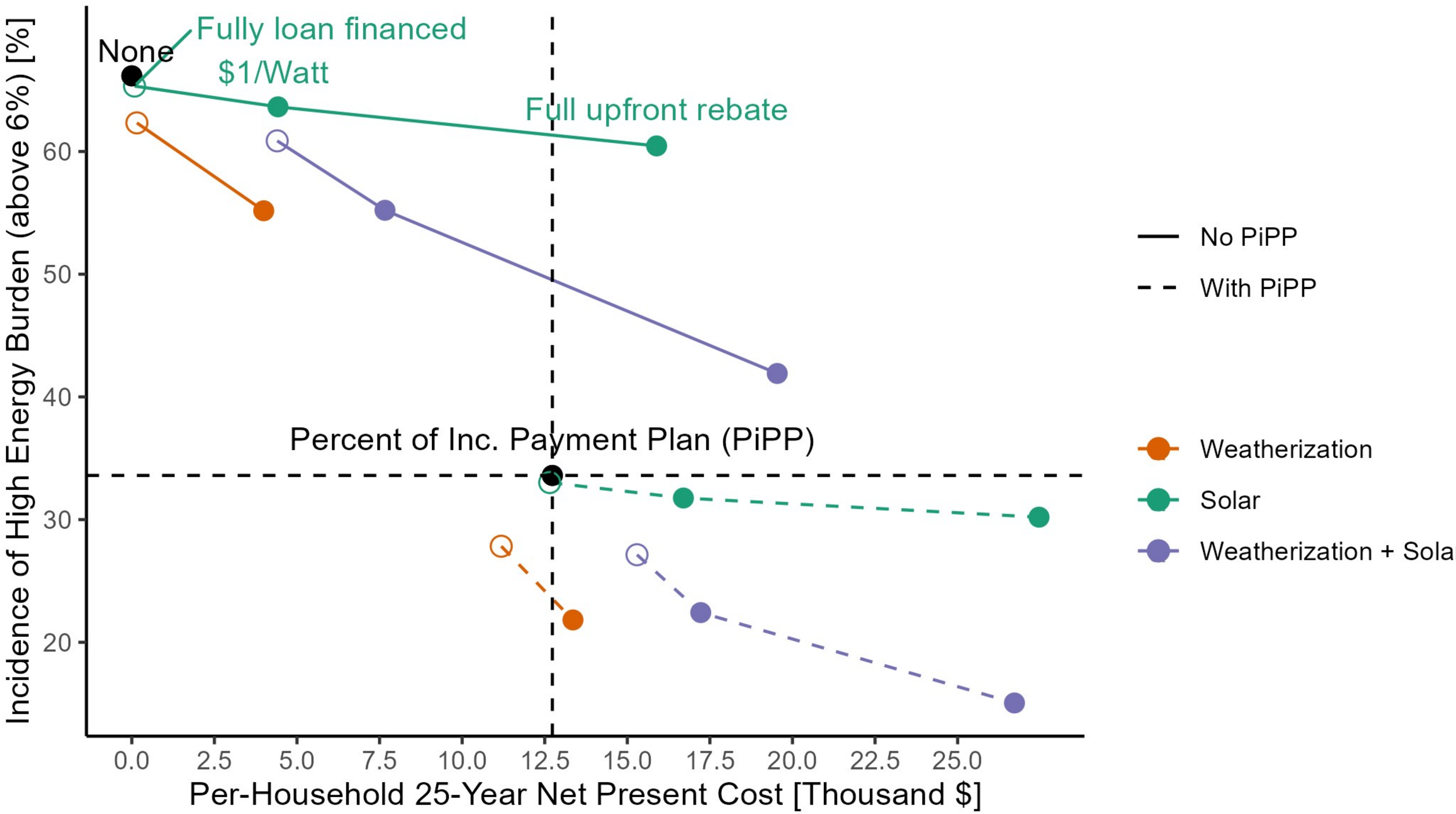

Energy Burdened Low-Inc. Households [%]
100
90
80
70
60
50
40
Weatherization + Solar
Weatherization
Solar
0
0.5
1
1.5
2
Full
Rebate ($/Watt for Solar; None/Full for Weatherization)
Net household savings > 0
Savings-to-Investment > 1


a
b
c
Energy Burdened Low-Inc. Households [%]
100
90
80
70
60
50
40
30
None
Full
Weatherization rebate (None/Full)
0
0.5
1
1.5
2
Full
Solar rebate [$/Watt]
*Weatherization fully rebated
Midwest
Northeast
South
West


Annual Participant Net Sav. [Thousand $]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
89%
93%
44%
69%
91%
96%
PiPP
Weatherization
Solar
Weatherization + Solar
PiPP
Fully loan financed
Full upfront rebate


a
Weatherization
b
Solar
c
Weatherization + Solar
Annual Participant Net Sav. [Thousand $]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Midwest
Northeast
South
West
95%
97%
96%
98%
87%
92%
77%
85%
48%
75%
42%
57%
31%
66%
77%
83%
96%
98%
89%
95%
88%
95%
93%
95%
PiPP
Fully loan financed
Full upfront rebate


None
Fully loan financed
$1/Watt
Full upfront rebate
Percent of Inc. Payment Plan (PiPP)
Incidence of High Energy Burden (above 6%) [%]
Per-Household 25-Year Net Present Cost [Thousand $]
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
10
20
30
40
50
60
No PiPP
With PiPP
Weatherization
Solar
Weatherization + Solar


Fully loan financed
None
$1/Watt
Full upfront rebate
Percent of Inc. Payment Plan (PiPP)
Incidence of High Energy Burden (above 6%) [%]
60
50
40
30
20
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
25.0
Per-Household 25-Year Net Present Cost [Thousand $]
No PiPP
With PiPP
Weatherization
Solar
Weatherization + Solar